HUMAN MOTORICS AS A GUIDE IN RESEARCH: FROM HANDEDNESS TO NORMAL WEIGHT OBESITY

Collection of research studies

Associate Professor Thesis

Submitted to the Faculty of

Physical Education and Sport

Charles University

by

Martin Musálek

2019

I hereby declare that this thesis is the result of my own work. I have indicated all used information and literature sources. This thesis has not been used for obtaining either another or the same academic title.

Prague 28th of February 2019 ………………………………………..

Evidence list

I agree to loan this associate professor thesis for study purposes. User`s signature confirms that this thesis was used for studying purposes, and s/he declares that they have listed it in used sources.

First name/ Surname: Faculty/ Department: Date of loan: Signature:

ACKNOWLEDGEMENTS

A number of individuals contributed significantly to this thesis. First, I would like to thank my family. A huge debt of gratitude goes to my wife Monika for being infinitely supportive, understanding and patient, and to my two children Dalibor and Veronika, who have been providing me with a profound and endless inspiration for my research. Further, I would like to express my deepest gratitude to my parents, my aunt and Stanislav, for inexhaustible devotion and support.

Sincere appreciations are due to Prof. Frank Daneš from University of Puget Sound and Prof. Jana Pařízková, who gave me invaluable recommendations and ideas which pushed me beyond my expectations. I would like to especially thank Prof. Jiří Tichý from the Faculty of Medicine and to Doc. František Véle from the Faculty of Physical Education and Sport for their support and insightful comments during my initial research period, but who are unfortunately not with us anymore.

I am also extremely grateful to the Wilfried Laurier University and the Moscow State University for inviting me to visit and for arranging my research stays in such a comfortable and unforgettable way. Special recognition and thanks go to Prof. Pamela J. Bryden, Dr. Sara Scharoun, Prof. Elena Godina, Dr. Elvira Bondareva, Prof. Alexei Gusev, Prof. Aleksandr Veraksa and Doc. Sergei Leonov for their patience and great support and for the invaluable discussions we had. Your approachability and your excellent lectures provided crucial inspiration for me to start writing this thesis.

Dedication:

Dedicated to my family which I greatly appreciate and to the memory of Prof. Blahuš, Prof. Tichý and Doc. Véle who tought me how to do first own research steps.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. ORIGIN OF LATERALITY: ASYMMETRY, CHIRALITY AND PARITY

The word laterality is derived from the Latin word latus, meaning “side” (Smith & Lockwood, 1976; Kábrt, Kucharský, Schams, Vránek, Wittichová, & Zelinka, 2001). This meaning of side (or rather, side preference) was informed by the finding that most manifestations in living nature result from the spontaneous violation of symmetry.

We recognise two types of symmetry – spherical symmetry (static) and functional symmetry (dynamic). A lot of objects, even planets or stars, seem to be spherically symmetrical. This means that if we produced their mirror image, nothing would change from the structure perspective – we would just see a perfect mirror image (we do not consider its magnetic field properties, space orientation like south, north, west, east) (Fig. 1). We talk about their spherical symmetry. Nevertheless, this kind of symmetry exists only provided our observed object is not moving.

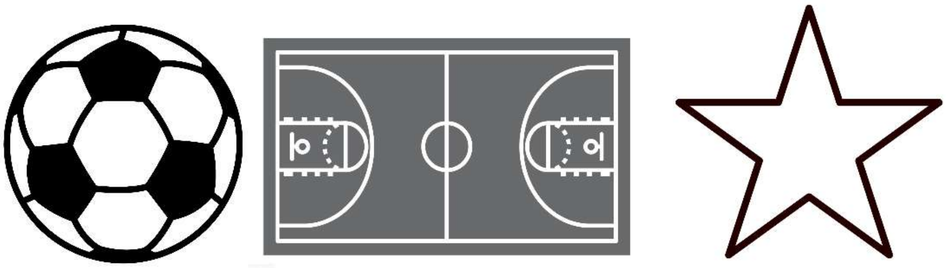


Figure 1. Examples of spherically symmetric object

Once we consider that the object performs some movement, for instance a spin, from this moment on it is necessary to assign handedness – laterality to this object (Gardner, 2005 p.47).

From the perspective of physics, the functional symmetry state is generally considered to be unstable (Coleman & Weinberg, 1973; Imry & Ma, 1975; Hambye & Teresi, 2016) because nothing is being produced. From the perspective of thermodynamics, the balance state of entropy represents a very good example of a symmetrical state. If an open system reaches an entropy thermodynamic balance (symmetry), this system produces zero energy. If we applied this state to a human or a plant, this individual or plant would be dead (Aoki, 1995). Therefore, violation – a loss of symmetry due to a transition from one energy state to another energy state (some symmetry is conserved in a certain energy state, but after the transition to a lower state, this symmetry disappears: spinning flywheel, stopping flywheel or vice versa) allows to spend or produce energy.

Possibly a more precise description of asymmetry was given from a molecular perspective (Decker, 1974; Peng et al., 1998). This asymmetry was well described by Pasteur in the 19th century on crystals of grape acid. When, for instance, the two types of crystals from industrially produced acid are separated, it was found that the crystals in one type of acid rotated polarised light clockwise, while the crystals in the other type rotated polarised light counter-clockwise. It is interesting to note that the acid-containing crystals that rotated polarised light clockwise enabled implemented microorganisms to reproduce and metabolize, while in the second type of acid (containing crystals that rotated polarised light counter-clockwise), microorganisms were not able to start the metabolism (Flack, 2009; Gal, 2011; Musálek, 2014). In other words, we have two molecules which contain the same elements – particles related to the same atoms. However, each of these molecules has a different property. This difference is due to different space distribution of atoms of which the molecule is composed, (Fig. 2), and refers to the specific kinds of asymmetry called chirality (Rauchfuss, 2008; Riehl, 2010)

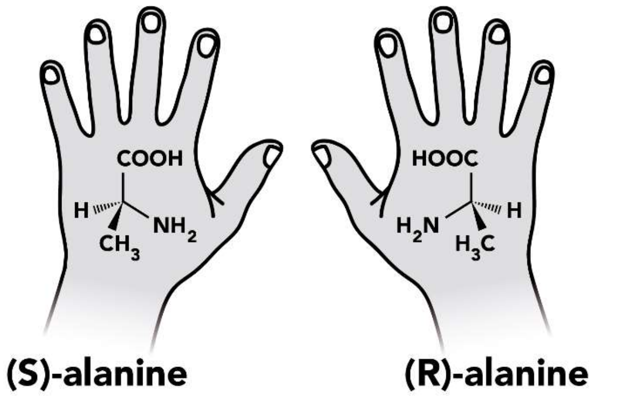


Figure 2. Chiral molecule of Alanin

At present, it is known that most molecules in laboratory conditions occur in two forms that are of a mirror character (stereoisomer) to each other (Nicolle, 1962). These are also known as chiral molecules (Woolley, 1976; Salam & Meath, 1998; Barron, 2009). It has been revealed that a certain property of molecules that depend on their spatial distribution of atoms is very important for living systems – including humans. Let's focus on proteins, which have many different functions in living organisms (e.g., building, transportation and storing, muscle contraction, protection). Proteins are composed of amino acids. Interestingly, these amino acids are almost exclusively L-amino acids, which rotate polarised light to the left. This selective preference of one specifically space distributed molecule is called homochirality (Huggins, 1952). It is important to note that there is also one amino acid without L or D polarisation – glycin. Glycin, which gives it a plane of symmetry about its α carbon (Fig. 3) (Lodish et al., 2000; Rauchfuss, 2008; Riehl, 2010; Michal & Schomburg, 2012).

Glycin

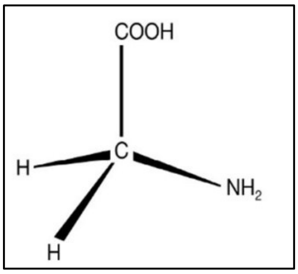


Figure 3. Glycin, amino acid without L or D polarisation

Another example of selective chirality is related to sugars where nature prefers D-sugars like D-glucose. Thus we can conclude that life is necessarily chiral. Just try to image what happens whether we reverse some things known for our daily life. How fast you would deal with them (Fig. 4)?

Figure 4. Different directions can imply in different behaving: Examples of reverse direction of thread in screw or side for driving car from left to right

The selective preference for almost exclusively one type, such as D- sugars or L- amino acids, prompted scientists to ask why life does not use D- amino acids or L- sugars. When we talk about compounds in both L and D forms, we talk about a racemic structure – for instance, the existence of amino acids in L and D form. This “sameness” is called parity which represents another type of symmetry. Therefore, violation of parity – sameness (Riehl, 2010) is crucial in order to understand how important it is to realize that life is full of asymmetry.

There were hypotheses 60 years ago that universe was perfectly symmetrical – conservation of parity: sum of the particles before and after each physical process must be equal. During decomposition of the 60Co nuclei, Wu, Ambler, Hayward, Hoppes, and Hudson, (1957) and Chien-Shiung Wu (1959) found that electrons are mainly emitted in the direction of the magnetic poles. Results showed that more electrons were set free at one pole than at the other. It was the first time when breaking of parity was verified. Spontaneous violation of symmetry leads to the creation of asymmetry (Senjanovic & Mohapatra, 1975; Viedma, 2007).

Asymmetry can be seen as spatial asymmetry – chirality; dynamic asymmetry – spin; movement preference, or violation of parity, etc. All these manifestations of asymmetry determine the property of higher systems and are common for open living systems – like humans. Therefore, when we look at the best known and continually investigated functional and structural asymmetry in humans – the handedness – we can look at it as a human property with different aspects like maturation, development, strength of handedness and its manifestation in different populations with different frequencies.

Summary:

In the past, numerous studies have been dedicated to human laterality, which represents a multidimensional, not only human trait/property (Corballis, 2010). It is well known, for instance, that in the adult population 90% of people prefer to use their right hand for common manual tasks, whereas about 10% of the population are so-called left-handers (Annett, 1994; Raymond et al., 1996; Bryden et al., 1997; McManus, 2004). Another important finding is that throughout human life, the development of laterality is a very active process affected by both genetic and environmental factors (see: Porac et al., 1980; Geschwind and Galaburda, 1987; Halpern & Coren, 1991; Annett, 2002; McManus, 2004).

References:

Annett, M. (1994). Handedness as a continuous variable with dextral shift: sex, generation, and family handedness in subgroups of left-and right-handers. *Behavior genetics*, *24*(1), 51-63.

Annett, M. (2002). *Handedness and Brain Asymmetry*. London: Psychology Press.

Aoki, I. (1995). Entropy production in living systems: from organisms to ecosystems. *Thermochymica Acta, 250*(2), 359–370.

Barron, L. D. (2009). *Molecular light scattering and optical activity*. Cambridge University Press.

Bryden, M. P., Roy, E. A., McManus, I. C., & Bulman-Fleming, M. B. (1997). On the

Coleman, S., & Weinberg, E. (1973). Radiative corrections as the origin of spontaneous symmetry breaking. *Physical Review D*, *7*(6), 1888.

Corballis, M. C. (2010). Handedness and Cerebral Asymmetry. In K. Hugdahl, & R. Westernhausen (Eds.), *The Two Halves of the Brain: Information Proceesing in the Cerebral Hemispeheres* (pp. 65–88). Cambridge MA: MIT Press.

Decker, P. (1974). The origin of molecular asymmetry through the amplification of "stochastic information"(noise) in bioids, open systems which can exist in several steady states. *Journal of molecular evolution*, *4*(1), 49-65.

Flack, H. D. (2009). Louis Pasteur's discovery of molecular chirality and spontaneous resolution in 1848, together with a complete review of his crystallographic and chemical work. *Acta Crystallographica Section A*, *65*(5), 371-389.

Gal, J. (2011). Louis Pasteur, language, and molecular chirality. I. Background and dissymmetry. *Chirality*, *23*(1), 1-16.

Gardner, M. (2005). *The new ambidextrous universe: Symmetry and asymmetry from mirror reflections to superstrings*. Courier Corporation. genetic and measurement of human handedness. *Laterality, 2*(3–4)*,* 314–336.

Geschwind, N., & Galaburda, A. M. (1987). *Cerebral lateralization: Biological mechanisms, associations, and pathology*. MIT press.

Halpern, D. F., & Coren, S. (1991). Handedness and life span. *The New England journal of medicine*, *324*(14), 998.

Hambye, T., & Teresi, D. (2016). Higgs doublet decay as the origin of the baryon asymmetry. *Physical review letters*, *117*(9), 091801.

Huggins, M. L. (1952). Polypeptide helices in proteins. *Journal of the American Chemical Society*, *74*(15), 3963-3963.

Imry, Y., & Ma, S. K. (1975). Random-field instability of the ordered state of continuous symmetry. *Physical Review Letters*, *35*(21), 1399.

Kábrt, J., Kucharský, P., Schams, R.,Vránek, Č., Wittichová, D., & Zelinka, V. (2001). *Latinsko-český slovník*. Praha: Leda.

Lodish, H., Berk, A., Zipursky, S. L., Matsudaira, P., Baltimore, D., & Darnell, J. (2000). Collagen: the fibrous proteins of the matrix. *Molecular Cell Biology*, (*4th ed.)*. New York: W. H. Freeman https://www.ncbi.nlm.nih.gov/books/NBK21582/

McManus, C. (2004). *Right hand, left hand: The origins of asymmetry in brains, bodies, atoms and cultures*. Harvard University Press.

Michal, G., & Schomburg, D. (2012). *Biochemical pathways: an atlas of biochemistry and molecular biology (2nd ed.).* Oxford: Wiley-Blackwell. *p. 5*

Musálek, M. (2014). *Development of Test Baterries for Diagnostics of Motor Laterality Manifestation: Link Between Cerebellar Dominance and Hand Performance*. Karolinum Press.

Nicolle, J. (1961). *Louis Pasteur: A master of scientific enquiry*. Hutchinson.

Peng, J. C., Garvey, G. T., Awes, T. C., Beddo, M. E., Brooks, M. L., Brown, C. N., ... & Gagliardi, C. A. (1998). d¯/ū asymmetry and the origin of the nucleon sea. *Physical Review D*, *58*(9), 092004.

Porac, C., Coren, S., & Duncan, P. (1980). Life-span age trends in laterality. *Journal of Gerontology*, *35*(5), 715-721.

Rauchfuss, H. (2008). *Chemical evolution and the origin of life*. Springer Science & Business Media.

Raymond, M., Pontier, D., Dufour, A. B., & Moller, A. P. (1996). Frequency-dependent maintenance of left handedness in humans. *Proceedings: Biological Sciences*, 1627-1633.

Riehl, J. P. (2010). *Mirror-image asymmetry: an introduction to the origin and consequences of chirality*. John Wiley & Sons.

Salam, A., & Meath, W. J. (1998). On enantiomeric excesses obtained from racemic mixtures by using circularly polarized pulsed lasers of varying durations. *Chemical physics*, *228*(1-3), 115-129.

Senjanovic, G., & Mohapatra, R. N. (1975). Exact left-right symmetry and spontaneous violation of parity. *Physical Review D*, *12*(5), 1502.

Smith, W., & Lockwood, J. (1976). *A Latin-English Dictionary*. Chambers.

the Cerebral Hemispeheres (pp. 65–88). Cambridge MA: MIT Press.

Viedma, C. (2007). Selective chiral symmetry breaking during crystallization: Parity violation or cryptochiral environment in control?. *Crystal Growth & Design*, *7*(3), 553-556.

Woolley, R. G. (1976). Quantum theory and molecular structure. *Advances in Physics*, *25*(1), 27-52.

Wu, C. S. (1959). Parity experiments in beta decays. *Reviews of Modern Physics*, *31*(3), 783.

Wu, C. S., Ambler, E., Hayward, R. W., Hoppes, D. D., & Hudson, R. P. (1957). Experimental test of parity conservation in beta decay. *Physical review*, *105*(4), 1413.

2. STRUCTURE OF MOTOR LATERALITY: CONCEPTS OF HANDEDNESS AND FOOTEDNESS THROUGH OPTIC OF CONFIRMATORY FACTOR ANALYSIS

Before we start to describe and assess the main outcomes of factor analysis studies in human laterality that offer interesting views on the structure of motor laterality, we should briefly explain the idea of confirmatory factor analysis.

Confirmatory factor analysis (CFA) represents one approach to data analysis from a wide range of structural equation modelling (SEM). The concept of SEM or casual modelling can be perceived as a complex statistical methodology consisting of many procedures which usually aims to find common factor/s (construct/s) for certain test items or verify relations or diagnostic quality of a test tool within a certain research domain. When someone wants to use the principles of CFA, it must be emphasized that the formulation of a structural hypothesis is always required. The formulation of a structural hypothesis means that based on a theoretical background and empirical experience the researcher determines a structural model (names of factors and relations with corresponding items) which they then compare with empirical data. In other words, the researcher looks into how well empirical data (results of tests, answers to questionnaires, etc.) fits the suggested structural model. In CFA as well as in other procedures within SEM, there are two kinds of variables. The first group represents a so-called indirectly measurable characteristic that determines the field and objective of the investigation. We usually call this variable a construct; a factor in mathematics. When considering our research, human laterality could be perceived as a very wide construct describing certain indirectly measurable human properties.

The construct is sometimes also called a "hypothetical construct" or a "latent variable" (Bollen, 2002). The second group of variables are directly measured indicators (test, task, questions from questionnaires) from which we get real data. These variables can have the nature of categorical, ordinal or continuous data. Each indicator used in research is composed of several parts.

$$X_i = \mu + \lambda_i F + E_i \quad (1.1)$$

In this model, X_j is a directly measured value – indicator (score in test, answer on Likert scale from questionnaire) on $_i$th item, μ represents a possible difficulty of indicator, F is an indirectly measurable characteristic (common attribute), λ_i is labelled as factor loading. Its values show the indicator sensitivity of attribute F, a so-called indicator – common factor relationship. The higher the factor loading, the better the indicator characterizes the indirectly measurable construct. The last symbol E_i covers indicator uniqueness which comprises random error and item specificity.

As Brown put it (2006, p.7): "*In the typical CFA, indicators are defined as linear functions of the latent variable, plus error; that is indicators are considered to be the effects of the underlying construct*."

We should remember that factor analysis is basically a method that reduces or divides certain amount of tests or items to several domains called factors. These factors can represent human properties, e.g. anxiety, movement ability, skills or laterality.

The use of factor analysis in handedness is nothing new. In the following part we will summarize the main findings and conclusions mostly related to the area of handedness. In the 1970s, the interest to use factor analysis for handedness grew. Between the 1970s and the turn of the millennium, the majority of authors used exploratory factor analysis or principal component approach. This approach does not require formulation of any structural hypothesis. In other words, you just have a group of items which you assume measure somehow a certain domain or property. However, you are not able to say or cluster them to common domains. Sometimes even researchers did not know how they should name these common domains (factors) which covered certain group of items with strong convergent validity. Nevertheless, it is important to note that "handedness" was also used as a good example for explaining the principles of factor analysis, see Smith (1950). Smith was one of the earliest researchers who described advantages of factor analysis using an example of a questionnaire that looked into the development of handedness. Later on, different authors used a variety of items and tests for assessing and modelling of the human laterality. In the past 60 years or so, diversity of test approaches along with the development of new and more precise statistical methods has shown that human laterality is a complicated multidimensional trait, within which left and right is by no means black and white.

Using exploratory factor analysis (EFA), Leonard (1960) verified the factor structure of hand performance and hand-eye coordination tests. He concluded that the results of the hand performance factor which consisted of tests of accuracy and speed were significantly related to the results of hand-eye performance tests. A thorough investigation of how many factors human handedness contains was done, for instance, by Barnsley and Rabinovitch (1970). Although these authors worked with a rather small research sample of just 50 males and 50 females who scored 61 independent variables in 32 tests of hand preference as well as hand performance, they revealed 9 interpretable factors of hand performance. Moreover, they pointed out that handedness questionnaires that assess hand preference cannot adequately represent the range of handedness or the degree of difference in manual proficiency between the preferred and non-preferred hand. In 1971, Oldfield (1971) published one of the most famous inventories assessing handedness. The Edinburgh handedness inventory (EHI), which has been cited more than 28,000 times (google scholar Autumn, 2018), is composed of 10 items (the activities include writing, drawing, throwing, scissors, toothbrush, knife (without fork), spoon, broom (upper hand), striking match (match) and opening box (lid) and many researchers use this inventory to determine the structure of handedness. White and Ashton (1976) was one of the first researchers who investigated structure of EHI by EFA and they found two factors within EHI. One was named "handedness" and contained items which have the character of preference for using a tool (in which hand you hold spoon, pen, knife, etc.). The second factor was dependent on the formulation of the task. Bryden (1977) arrived at very similar results; he assessed more than 1,000 participants, 620 men and 487 women, using both the Crovitz-Zener (1962) and EHI Oldfield (1971). EFA of the items from both questionnaires revealed three factors: a primary handedness these items had the character of preference for using a tool; and two factors that are specific to the wording of the questions. Further information about the usefulness of the factor analysis in the field of handedness was presented by Richardson (1978), who explained that factor analysis was valuable as a means of appraising multivariate instruments for measuring handedness and made a rather strong assumption to the effect that there is a single underlying dimension of handedness. McFarland and Anderson (1980) were the first authors who verified on adult population a psychometric quality of some handedness inventories, in particular EHI. They pointed out that EHI is a single factor inventory where certain portion of unimanual items (assessing the hand preference when using some tool in daily life) are stable but some of the original items, specifically those with bimanual character (using broom, opening lid), did not load well on the handedness factor and were generally unstable in relation to this factor. Moreover, it was suggested for the first time in this study that scores weighted by corresponding factor loading should be used. Slightly different approach was used by Williams (1986), who also investigated diagnostic properties of EHI, this time, though, using the principal component analysis. Results showed that EHI is rather a single factor diagnostic tool, which is in line with McFarland and Anderson (1980), who suggested that bimanual items broom and opening lid did not represent the handedness factor well and that they should be excluded from EHI.

Roszkowski, Snelbecker and Sacks (1981) assessed the item consistency of 15 preference tool items (like writing, drawing, cutting) in a wide age range population (8–70 years) and found high reliability Cronbach alpha = .96. Also these authors used EFA approach and found that hand preference tool indicators form a single dimension. A similar single dimension of handedness was reported by McFarland and Anderson (1980) and by Richardson (1978). Healey, Liederman and Geschwind (1986) used EFA on a wide range (61 items) of manual activities called hand preference tasks. Results showed four separate factors. Interestingly, one of the factors was composed of items that involved more strength than dexterity. It means that hand preference dimensions can be distinguished on the basis of those requiring movement of the distal musculature (fingers and hand) and those requiring movement of the proximal musculature. According to the authors, hand preference for items on this factor was less laterally biased than on factors which included such fine motor behaviours as writing or drawing. This represented a new finding in factor analysis which suggested that manual preference could involve more than one neural system and that these systems may be independently lateralized. Moreover, Healey, Liederman and Geschwind (1986) suggested that handedness is not a unidimensional trait. In the same year, a publication by Liederman and Healey (1986) also supported the suggestion that handedness in not unidimensional when a factor analysis used on a new sample confirmed the results of the previous study.

In contrast to both previous studies, Steenhuis and Bryden (1989) did not find any support for the aforementioned hypothesis that the handedness domain contains two independent factors related to 1) movement that requires proximal muscle groups and 2) movement of distal muscle groups. Instead, Steenhuis and Bryden determined, based on EFA factor, 1) "skilled" activities – the use of tools and manipulation of other objects writing, drawing, hammering, needling, scissors, knife when cutting, strike match, erasing, using tooth brush, using spoon, throw by ball, deal card Second and third factor “less skilled” or “unskilled” activities that included, for example, picking up objects were therefore linked to the 2nd and 3rd factor in the given model. A significantly lower level of lateralization was revealed for activities such as picking up objects, from small to relatively large ones. However, the involvement of strength in the given activity played a significant role that affected the level of preference. A fourth factor relates to the use of bats and axes, a bimanual activity.

Steenhuis, Bryden, Schwartz and Lawson (1990) verified the psychometric properties of the Waterloo Handedness Questionnaire (WHQ). The main aim was not to verify its structure but to show the applicability and reliability of this 32-item tool. This study also showed that left-handers were less consistent in test-rest scoring. In addition, the importance for determining the hand direction (hand preference) as well as the degree of handedness was emphasized. An interesting comment was offered by Peters and Murphy (1993), who claimed that previous research analysed handedness by factor analysis mainly by pooled data. *“The factor structure and item loadings that result from pooled data are misleading and cannot inform meaningfully about the relation of hand preference to handedness. Similar problems can be anticipated in other neuropsychological l applications of factor analysis, where data from heterogeneous groups is pooled”* (Peters & Murphy, 1993).

The structure of handedness was also analysed in relation to nationality. Possible differences in the structure of handedness assessed by WHQ between Indian and North American populations were analysed by Singh and Bryden (1994), who did not reveal any significant deviations from the previously suggested structure Steenhuis and Bryden (1989), where hand preference consists of two main factors – skilled activities and unskilled activities of hand preference. However, in this study the fact that Indian population had significantly lower prevalence for left-handedness compared to North American population can be attributed to social pressure. Nevertheless, in another study Bryden, Ardila and Ardila (1993) the structure of handedness in native Amazonians assessed by WHQ was significantly different compared to North American populations. In addition to skilled and unskilled factors, other handedness factors related to specific tool use and to strength were revealed in Amazonians. According to the authors, this data showed *“that hand preference can be modified through positive reinforcement at* *an appropriate age, and that hand preference is the precursor of skill differences rather than vice versa"*.

Investigations of structure of handedness was not constrained only to hand preference tasks. Hurley and Foundas (2001) aimed to verify whether principal component analysis carried out on hand preference items from EHI and Briggs and Nebes inventories in combination with cluster analysis of hand performance tests (grooved pegboard, finger-tapping and grip strength) will show reasonable categorisation of people according to their handedness with respect to the direction of hand preference and the degrees of handedness. They found that "skilled activities", mostly unimanual, had the strongest relation to hand preference. On the other hand, a single measure of hand performance tests did not always correctly classify an individual as right- or left-handed. Nevertheless, using both approaches – hand preference items along with hand performance tests – proved to be an optimal way to assess human handedness.

Van Strien (2003), like other authors before him, pointed out that some tasks or questions are influenced by social pressure, for instance writing. Therefore, this author excluded this item from the evaluation of hand preference. Nevertheless, other included indicators of hand preference questionnaire were strongly linked to the use of tools. The test, which includes 16 tool skilled preference items, revealed one single handedness dimension. This conclusion supported the suggestion of Steenhuis and Bryden (1989) to the effect that skilled motor activities form one/separate handedness factor.

Kang and Harris (2000) offered an extensive view on human laterality when they added information about the structure of footedness. These authors used two inventories – EHI and Waterloo footedness questionnaire (WFQ-R). Results of EFA of the EHI revealed two handedness factors, which is in conformity with previous studies. In addition, results from WFQ-R showed two footedness factors 1) skilled unipedal actions and 2) balancing-stabilizing.

We must not also forget that previous studies have mostly perceived human laterality as a continuous latent variable with a certain direction and certain degrees (strong, consistent, inconsistent). In contrast, McManus (1985), who proposed a genetic model of handedness with a single right-handedness gene, considers laterality as a dichotomously scored variable. Therefore, it is currently not absolutely clear whether human laterality represents discrete categories or rather a continuous domain (Annett, 1985; McManus 1991; Corey et al., 2001; Dragovic, Milenkovic, & Hammond, 2008).

At the beginning of the 21st century, further studies verifying the structure of handedness and using principal component analysis or EFA approaches confirmed previous findings about the existence of two or one factor in the handedness domain. The results mainly depended on the kind of indicators that were used – skilled or unskilled – and whether preference indicators were or were not combined with a performance test. This stagnation phase was interrupted by the use of new approaches linked to a wider methodology called structural equation modelling (SEM) which began to be used for assessing the structure of human laterality or re-evaluating the quality of previously developed diagnostic tools. The family of SEM methods also includes the confirmatory factor analysis (CFA) which by some authors (e.g. McDonald, 1991, 1999; Kline, 2011) represents a more suitable approach for verification of a defined structure because it enables to test structural hypotheses or theories. According to Costello and Osborne (2005), CFA, "*can allow researchers to test hypotheses via inferential techniques, and can provide more informative analytic options*".

This method requires knowledge or an assumption about a certain structure of the modelled domain. We can say that if we want to use CFA, it is necessary to develop a structural hypothesis about the relations within the modelled structure. Therefore, according to some psychometricians CFA is a more rigorous statistical technique than EFA (Jöreskog, Sörbom & Du Toit, 2001).

The first studies where CFA was used were focused on handedness questionnaires and still kept handedness is a latent continuum. Since items in handedness questionnaires are scored on two-, three- or five- point Likert scale, it was necessary to take into account a special type of correlations. In case of dichotomy scored items the tetrachoric correlations were used: (see Brown & Benedetti, 1977; Divgi, 1979; Muthén & Hofacker, 1988). In case of polytomous scored items Polychoric correlations were used (see Muthén, 1984; Jöreskog, 1994). One of the first researchers who used a more specific approach derived from factor analysis rather than EFA was Dragovic. Dragovic (2004) evaluated the structure of the Edinburgh Handedness Inventory (EHI) using CFA. For the first time the results showed a strong co-linearity between the items writing and drawing. It means that both these items assess handedness with almost the same power and their correlation is close to "1". Further, Dragovic encountered the same problems with items that were based on bimanual activity (broom, open lid) and supported the conclusions of previous studies which also found some problematic items (Bryden, 1977; McFarland & Anderson, 1980; Williams, 1986). Musálek (2012) analysed by CFA the structure of selected unimanual and bimanual hand preference tasks in a population of young adults. His results showed that unimanual items focused on hand preference when using tools like: knife, hammer, scissors, brush, pen; develop a very strong factor in contrast to unskilled – non-tool or bimanual – items. In addition, working with over 3,300 participants (data from Falnders study) Nicholls, Thomas, Loetscher and Grimshaw (2013) also found that the hand preference indicator could be divided to tools and object control factors. The main aim of this study was to show that questions in hand-preference questionnaires are time-dependent. It means that the type of questions must correspond to "technological progress". For instance, the question "which hand do you use to wind the clock" was perfectly OK in the 1970s but now, at the beginning of the 21st century, participants, in particular children, might find it difficult to understand what winding the clock actually means.

2.1 Reaching Tasks as Appropriate Indicator for Assessing of Handedness in Middle Age School Children

Even though it is clear that a lot of work has been done in modelling and investigating of the laterality structure, only a very small part of research has been devoted to the analysis of the structure in child population. One of the possible reasons is that laterality preference or side dominance in motor tasks and tests develop as the brain hemispheres mature and that the development of laterality is a very active process (Annett, 2002; McManus, 2004). Further, according to several theories, this maturity process can be influenced by genetic factors and many environmental factors can affect handedness, such as antenatal maternal stress (Talge et al., 2007; Reissland, Aydin, Francis & Exley, 2015), and prematurely born children, newborns or children who had problems in prenatal period are more likely to become non-right handers (Geschwind & Galaburda, 1987; Ross, Lipper, & Auld, 1987; Schwartz, 1988; Fride & Weinstock, 1989; Powls et al., 1996; Domellöf, Johansson, & Rönnqvist, 2011).

These factors, along with gradual brain maturation, imply that laterality preference or performance may not to be so clear in children. Research of laterality in children has shown that it has different phases. McManus et al. (1988) suggested that handedness in children contains one handedness factor which can be recognised and better fixed around the age of 3. After that the stabilization of handedness usually happens between 3 and 7 years of age. Surprisingly, according to the authors, stabilization gradually weakens between 7 and 9 years of age (McManus et al., 1988). Whittington and Richards (1987) or Cavill and Bryden (2003) proved that the direction of handedness (right or left) can be clinically observed in children relatively early; however, the strength/degree and consistency of handedness can vary significantly. Lateral consistency – mainly handedness in children was significantly clarified by researchers who used so-called reaching tasks (e.g., Bishop, Ross, Daniels, & Bright, 1996; Bryden & Roy, 2006; Carlier, Doyen, & Lamard, 2006). In this case, reaching tasks are focused on whether a child would also manipulate with a tool using the preferred upper limb in case the tool was placed counter-laterally to the preferred hand. These tasks are also called crossing midline tasks and previous research done on children aged 2 to 12 (Schofield, 1976; Cermak, Quintero, & Cohen, 1980; Stilwell, 1987) showed its association to handedness and the degree of the development of handedness. Results from reaching tasks, therefore, showed that consistency of handedness is age-dependent and complexity-dependent (Leconte & Fagard, 2004). Bryden and Roy (2006) and Carlier et al. (2006) found that 6- to 10-year-old children demonstrate a significantly more stable consistency of upper limb preference compared to younger children. In other words, consistency of handedness increased with age and with the level of motor demands. Highly complex, e.g. fine motor tasks, showed a higher handedness consistency. This complexity of certain motor tasks was also shown as major variable which influences the degree of performance differences between the preferred and non-preferred upper extremities (Annett, 1992). Research in the area of using Quantification of Hand Preference (QHP) also revealed that the degree of handedness is also complexity-dependent. In other words, it is necessary to consider the difficulty (pointing versus placing) of the task when assessing hand preference (Calvert, 1998; Pool, Rehme, Eickhoff, Fink, & Grefkes, 2015).

In summary, reaching tasks seem to represent a suitable approach to fine assessing of handedness in children. Overall, the findings reveal that younger children (i.e., 3- to 5-year-olds) have weaker cerebral lateralization and hand preference tendencies and are therefore less likely to cross the midline in comparison to older children (i.e., 7- to 12-year-olds), who are strongly lateralized, and thus reliant on their preferred hand. Nevertheless, the place of QHP in the structure of the hand preference domain remains unclear.

Based on the aforementioned observations, we identified two questions which had not been clearly answered yet: 1) what structure of the hand preference domain will be revealed in middle age school children when using common hand preference tasks; 2) whether the card reaching task usually used as a single test for assessment of handedness is valid in the structure of hand preference in middle age school children.

Even though literature provides a sufficient amount of validated laterality questionnaires or inventories, their usefulness in children is questionable, mainly with respect to understanding the questions and being able to imagine what each scale point (always, rather, both equally) means. Therefore, some authors suggest that performance-based measures are more objective for the evaluation of hand preference in children (Bryden, Roy, & Spence, 2007, Scharoun, & Bryden, 2014).

Research question:

Will the reaching task in middle age school children be a sufficiently valid indicator together with other unimanual tasks used for the assessment of hand preference?

In our case, we first had to select a proper item bank of preference tasks and verify its diagnostic quality. This selection of tasks and hand preference battery composition was carried out in line with the rules for validation studies (Štochl & Musálek, 2009; Lane, Raymond, & Haladyna, 2015). All steps included evaluation of content validity of indicators; the sample selection of children and data analysis are described in details in Musálek (2014).

Two of the selected tasks were reaching tasks. According to (Bishop et al., 1996), these motor tasks enable to quantify hand preference because they assess hand preference in reaching throughout the regions of hemispace. In fact, any hand preference task with repetition (e.g., throw three times ball on target, kick three times ball on goalie, throw dice in three attempts, etc.) quantifies the degree of hand preference. During the reaching task, participants repeat a movement under space constrained requirements because participants work in both ipsilateral and contra lateral hemispace, which often leads to manual midline crossing. Various authors claim that such behaviour corresponds to a shift from extracallosal to callosal control of interhemispheric communication (Liederman, 1983) and in this way it plays a crucial role in the development of a skilled preferred hand (Bochner, 1978; Provine, &

Westerman, 1979; Ayres, 1980). Originally, QHP was limited to one task (i.e., Bishop's card reaching task).

Bishop's card reaching tasks contained seven coloured cards placed at 30-degree intervals within hemispace in definite space. The task is to point or turn a card according to instructions by the examiner. The examiner usually repeats the instruction five or seven times. In this task the examiner investigates which hand worked as first when touching, pointing or turning the middle card, and if the participant also uses this hand when the examiner asks them to work with a card placed contralateraly to this hand (Fig. 5).

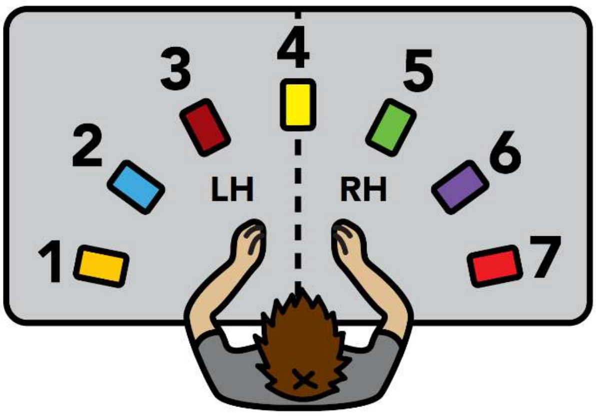


Figure. 5 Illustrative scheme of Bishop's card reaching tasks

Research sample:

For the purpose of this study, middle age school children aged 8 to 10 years were selected. Participants were pupils of state elementary schools of the Capital City of Prague, Czech Republic, and were selected using an intentional selection process. More specifically, participants were selected from schools without art, sport, language or technical specializations. Furthermore, children could not be enrolled in integrated classes for children with special needs. Nevertheless, we have to admit that other factors which may influence performance (e.g., activities outside of school, including sports, hobbies and activities) were not considered and we realize this is a limitation of the study. Participants were selected using the following purposeful method of sampling. In cooperation with the Institute of Educational and Psychological Counselling, a complete list of primary schools from each district in the City of Prague was obtained. Only those schools that were attended by at least 50 individuals of the given age were selected, the number of the participants per school was set at 40. Out of these schools, a list was created from which one primary school was randomly selected from each district of Prague. In total, 10 primary schools were selected. The Ethics commission of the Faculty of Physical Education and Sport, Charles University, granted an ethics approval. Written parental consent was obtained for all children. Research sample finally consisted of 376 children (184 boys and 192 girls), (M_{age} = 9.2, *SD* = 0.4).

Procedure:

In order to determine hand preference, five unimanual motor tasks and one reaching task were selected. These hand preference tasks have been validated for use with Czech children (Musalek, (2014).

The tasks included: (1) draw a leaf according to the model **(Draw)**;

(2) take the bell in one hand and ring it **(Ring)**;

(3) take the ball in one hand

and throw it at the target (three attempts; **Throw**);

(4) show how many points you can roll

with the dice (three attempts; **Cube**);

(5) demonstrate how you brush your teeth **(Brush)**.

All hand preference tasks were scored dichotomously, where 0 indicated the task was performed with the left hand and 1 indicated performance with the right hand. Throw, Cube, Cards and Matches tasks included repetition; therefore, the scores comprised of a sum of attempts performed with the right hand.

(6) Reaching task

Bishop's card reaching task (Bishop's).

Participants sit on a chair at a desk for the duration of the task. The researcher places a sheet of paper (42 cm x 29.7 cm; divided in half by a vertical line) on the desk in front of the participant. The paper contains seven rectangular boxes (6 cm × 3 cm) at successive 30 degree intervals forming a semicircle. There were three boxes in left space, one at the midline, and three boxes in right space. Each box is

labelled from -3 (far left) to +3 (far right), with the box at the midline labelled 0. The researcher placed a card (all different colours) in each box and asked the participant to

turn the card of a designated colour using one hand. The card placed at the midline was selected first. If the participant used the right hand, selection progressed in the following order: +2, ±2, +3, ±3. If the participant used the left hand, selection progressed in the following order: ±2, +2, ±3, +3. After each trial (i.e. after each card was selected) hand selection was recorded on a score sheet. A
value of 0 indicated left hand selection whereas a value of 1 indicated right hand selection. Musalek et al. (2016).

The hand used to pick up the card in each region of hemispace was recorded (Bishop et al., 1996). In previous studies the Bishop's card reaching task displayed high homogeneity and sufficient test-retest reliability (.78 - .80) (Doyen & Carlier, 2002). Furthermore, Bishop et al. (1996) were able to successfully identify right-handers based on the degree of hand preference.

Statistical analysis:

Since we wanted to evaluate a certain structure and investigate the relationship between manifest indicators (hand preference tasks) and a theoretical concept – hand preference, we used a specific approach from the "family" of Structural Equation Modelling (SEM). All hand preference tasks were dichotomous (or ordered categorical type) scoring items; therefore, categorical confirmatory factor analysis (CCFA) was selected as an appropriate psychometric approach from SEM. If we model a definite structure, it is also important to consider the criteria for acceptance of the model. In other words, it is essential to know when to decide that a suggested theoretical model explains sufficiently our empirical data. Literature contains many different fit indices (see Tucker, & Lewis, 1973; Muthén, 1984; Bentler, 1990; Steiger, 1990; McDonald, 1999) that are used to express the quality of a model. In this study, the quality of structural models was evaluated according to the recommended cut-off lines using five fit indices: (1) Chi-square test (Sattora-Bentler scaled chi-square) and significance of model $p>0.05$; (2) Comparative fit index (CFI) , >.95; (3) Root mean square of approximation (RMSEA) , < .06; (4) Tucker-Lewis index (TLI), >.95; and (5) Weighted Root Mean Square Residual (WRMR) < .80. Sensitivity of the QHP Bishop's card reaching task was evaluated using chi-square contingency tables. The data was analysed in M-plus 6 (Muthén & Muthén, 2010) and NCSS2007 (NCSS, LLC, Kaysville, UT).

Results:

The proposed unidimensional model with six indicators displayed very good values of fit and high factor loading of all six indicators of hand preference (Fig. 6, Tab. 1). In this one-factor structure, Bishop's card
reaching task proved to be a suitable indicator of hand preference (factor validity = .89) (Fig. 6, Tab. 2)

Table 1. Fit of the one-factor model.

Model	Chi-square	P-value	df	CFI	TLI	RMSEA	WRMR
1-factor	21.58	.08	9	.97	.97	.051	.522

doi:10.1371/journal.pone.0166337.t001

Table 2. One-factor model.

	Six items	
Items	Factor Loadings	Uniqueness
Draw a leaf according to the model–**Draw**	.96	.08
Take the bell in one hand and ring it–**Ring**	.90	.19
Take the ball in one hand and throw it at the target–**Throw**	.92	.15
Show how many points you can roll with the dice on three attempts–**Cube**	.98	.04
Demonstrate how you brush your teeth–**Brush**	.94	.12
Bishops' card reading task–**Bishop's**	.89	.21
Cronbach's α	.89	

doi:10.1371/journal.pone.0166337.t002

Figure 6. Fit of the one factor model with factor loadings
Adapted from Musalek, Scharoun and Bryden (2016). Using Bishop's Card Reaching Task to Assess Hand Preference in 8-to 10-Year-Old Czech Children. *PloS one*, *11*(11)

So the first impression was that the results were exactly as expected. In conformity with previous findings it was revealed that tool using tasks (using pen, throwing ball, ringing by bell, tooth brushing) strongly discriminate handedness. Further, we can see that Bishop's reaching task corresponds sufficiently to the hand preference structure λ=.89. However, when the structure of definite concept is analysed, it is important to check whether high factor loads are not in conflict with possible multicollinearity of some motor tasks (i.e., excessive mutual correlation). The question of multicollinearity is linked to the redundancy of some items/indicators/tests in the model which can artificially inflate the model fit. It is a common methodologist question: Why have three or four tests which measure exactly the same? For this reason a correlation matrix was created to verify the discriminant and convergent validity of each used indicator. In this case, based on the data character, the polychoric correlations were used for ordered categorical data, and tetrachoric correlations were used for dichotomously (binary) scored data (Fig. 7).

Table 3. Correlation matric of six motor tasks (including Bishop's card reaching task).

Items	Brush	Throw	Ring	Draw	Bishop's	Cube
Brush						
Throw	.988					
Ring	.956	.968				
Draw	.985	.983	.957			
Bishop's	.921	.896	.859	.868		
Cube	.959	.918	.897	.918	.864	

doi:10.1371/journal.pone.0166337.t003

Figure 7. Correlation matrix of had preference tasks
Adapted from Musalek et al. (2016). Using Bishop's Card Reaching Task to Assess Hand Preference in 8-to 10-Year-Old Czech Children. *PloS one*, *11*(11)

The correlation matrix clearly displays a strong (>.90) correlation between the individual indicators (Fig. 7). On average, the weakest correlations (though still at high levels) were recorded for Bishop's card reaching task. A detailed analysis showed that two motor tasks, **Brush** and **Draw**, displayed the strongest correlations with other tasks. Previous research showed that hand preference in some daily motor activities could be caused by socio-cultural pressures on hand preference (Harris, 1990; Medland et al., 2004; Zverev, 2006). Therefore, we decided to exclude **Brush** and **Draw** items and thus verify their redundancy in the proposed one-factor model. After excluding the Brush and Draw motor tasks, the one-factor model with four indicators showed improvement in fit values (Fig. 8).

Table 4. Fit of the one-factor model without Brush and Draw tasks.

Model	Chi-square	P-value	df	CFI	TLI	RMSEA	WRMR
1-factor	6.58	.25	2	.99	.99	.039	.351

doi:10.1371/journal.pone.0166337.t004

Table 5. One factor model without Brush and Draw tasks.

	Six Items		Four Items	
Items	Factor Loadings	Uniqueness	Factor Loadings	Uniqueness
Draw a leaf according to the model–**Draw**	.96	.08	-	-
Take the bell in one hand and ring it–**Ring**	.90	.019	.91	.17
Take the ball in one hand and throw it at the target–**Throw**	.92	.15	.92	.15
Show how many points you can roll with the dice on three attempts–**Cube**	.94	.12	.93	.13
Demonstrate how you brush your teeth–**Brush**	.98	.04	-	-
Bishop's card reaching task–**Bishop's**	.89	.21	.89	.21
Cronbach's α	.89		.84	

doi:10.1371/journal.pone.0166337.t005

Figure 8. Fit of the one-factor model and factor loadings after removing Brush and Draw hand preference tasks

Adapted from Musalek et al. (2016). Using Bishop's Card Reaching Task to Assess Hand Preference in 8-to 10-Year-Old Czech Children. *PloS one*, *11*(11)

In this abridged model, chi-square did not change significantly from the statistical point of view; however, model significance increased markedly from $p = .08$ to $p = .25$. The reliability, with its lowerbound estimate expressed as Cronbachs α, decreased non-significantly (Fig. 8). We can conclude that the items that are highly dependent on socio-cultural environment like **Brush** and **Draw** can bias the degree of handedness in this study. Therefore, these tasks might be redundant in the presented model. Moreover, the conditional probability that a person who uses one hand for brushing will use the same hand for drawing is enormously high r=0.985. From this perspective, when handedness is not the main aim of a study, researchers sometimes use only one socio-culturally dependent variable, usually which hand a participant uses for writing or drawing. However, as shown above, this approach for identification of human laterality may not be sufficient.

In addition to the sufficient discriminative property and suitability of Bishop's card reaching task within hand preference structure we found that Bishop's card reaching is also sensitive enough for the identification of right-handers and left-handers. Further, we investigated the sensitivity of Bishop's card reaching task in comparison to the composite score achieved by children from the five hand preference used tasks. Children who performed all five tasks with the right hand were described as strong right-handers whereas those who performed all tasks with the left hand were described as strong left-handers: right-handers ($n = 306$) and left-handers ($n = 31$). Results showed that the sensitivity of Bishop's card reaching is sufficient mainly in field testing for identification of both right- and left-handers. In addition, the sensitivity was approximately 7% lower (right-handers = 97.4% and left-handers=90.3%) in identifying left-handers compared to right-handers. Nevertheless, chi-square criterion showed that this difference was not significant.

Summary:

Bishop (2005) argues that her task is a measure of developmental maturity. Groen, Whitehouse, Badcock and Bishop (2013) found in children aged 6-16 a significant association between hemispheric asymmetries during speech production (as measured with functional transcranial Doppler ultrasonography) and handedness determined by reaching card task r=0.40 in contrast to low association r=0.16 in the long version of the Edinburg inventory; and peg moving r=0.13 performance test. Since in assessing of handedness we can talk about visual motor integration in the Bishop's card reaching task, there is one novelty compared to the standard task "throwing, drawing, etc." – the participant must be space-oriented during performance. This connection between visual spatial function and motor executive function along with bigger portion of attempts can provide the Bishop's card reaching task with unique properties in the process of assessing the handedness which was supported in its sensitivity when revealing an abnormal handedness pattern in children with specific language impairment (SLI) or developmental coordination disorder (DCD). These children did not differ in laterality quotient when inventory or unimanual tasks like writing by hand were used. However, when planning and space orientation were added, right-handed children with SLI, DCD, and the younger controls reached predominantly with the right hand to spatial positions located to the right of their body's midline and with the left hand to positions situated to its left. Right-handers in the age-matched control group showed a significantly greater tendency to use their right hand to reach to all spatial positions. The increased tendency of the children with SLI to use the non-preferred hand was particularly striking because it was seen both in those with and without recognised motor difficulties. The QHP task appears to be a sensitive, but non-specific, indicator of developmental disorders. (Hill & Bishop, 1998).

PLOS | ONE

RESEARCH ARTICLE

Using Bishop's Card Reaching Task to Assess Hand Preference in 8- to 10-Year-Old Czech Children

Martin Musalek[1], **Sara Marie Scharoun**[2]*, **Pamela J. Bryden**[3]

1 Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic, **2** School of Physical and Health Education, Nipissing University, North Bay, Ontario, Canada, **3** Department of Kinesiology and Physical Education, Wilfrid Laurier University Waterloo, Ontario, Canada

* saras@nipissingu.ca

CrossMark
click for updates

OPEN ACCESS

Citation: Musalek M, Scharoun SM, Bryden PJ (2016) Using Bishop's Card Reaching Task to Assess Hand Preference in 8- to 10-Year-Old Czech Children. PLoS ONE 11(11): e0166337. doi:10.1371/journal.pone.0166337

Editor: François Tremblay, University of Ottawa, CANADA

Received: September 6, 2016

Accepted: October 26, 2016

Published: November 11, 2016

Data Availability Statement: Due to ethical restrictions regarding patient privacy, data are available through Charles University in Prague. Requests for the data may be sent to musalek.martin@seznam.cz.

Funding: This study was supported by project PRVOUK P39, Social-Sciences Aspects of Human Movement Studies and by the Czech Science Foundation, project No. 14-29358P.

Competing Interests: The authors have declared that no competing interests exist.

Abstract

Hand preference is one of the most apparent functional asymmetry in humans. Under contralateral control, performance is more proficient with the preferred hand; however, the difference between the two hands is greater in right handers, considering left handers generally display less cerebral lateralization. One method of evaluating hand preference is Bishop's card reaching task; however, information regarding validity and sensitivity with children in limited. This study assessed the relationship between Bishop's card reaching task and five hand preference tasks in 8- to 10-year-old typically-developing children from the Czech Republic ($N = 376$). Structural equation modelling identified a one factor model as the most suitable, including Bishop's card reaching task and three hand preference tasks (ringing, throwing, and rolling with dice). The factor validity (.89) and sensitivity of Bishop's card reaching task (90% to 97%) provided a very good identification of hand preference. These results support the suitability of Bishop's card reaching task as a separate test for determining hand preference in children. Accordingly, we suggest that the assessment of handedness, particularly in neurodevelopmental disorders where the proportion of right-handers and left-handers is disrupted (e.g., children with DCD or ADHD), should make use of Bishop's card reaching task alongside other unimanual tasks.

Introduction

Handedness represents the most apparent and studied functional asymmetry in humans [1]. Under contralateral control, the left hemisphere is responsible for right hand function, and the right hemisphere for left hand function [2, 3]. Our understanding of cerebral lateralization dates back to the work of Paul Broca, who observed the effects of left hemisphere lesions in the posterior part of the third frontal convolution in right handers. Broca proposed that cerebral control for speech was specific to one hemisphere, and mirrored an individual's handedness [4, 5]. It has since been observed that the left hemisphere is stereotypically responsible for language and motor skills, and the right hemisphere is responsible for processing visuospatial information. Nevertheless, despite 87–96% of the population displaying left hemisphere lateralization for language, not all are right-handed. Approximately 60–73% of left-handers also fall under this distinction; whereas others display bilateral distribution across hemispheres, or right hemisphere lateralization [6, 7]. The aforementioned distributions have been confirmed using functional transcranial sonography [6, 7], repetitive transcranial magnetic stimulation [8] and functional magnetic resonance imaging (fMRI)[9].

Defined behaviourally in terms of *preference* (i.e., the preferential use of one of the hands) and *performance* (i.e., differentiating based on abilities in a particular task)[10], 90% of the population is right-handed and 10% is left-handed [11, 12]. This distribution has remained relatively consistent for approximately 5000 years [11]. Examining the relationship between preference and performance, it is commonly reported that performance is more proficient with the preferred hand [13]. However, the difference between the two hands is typically greater in right than left handers, considering left handers generally display less functional asymmetry than right handers [14, 15]. In one example, Jäncke et al. [16] have reported, with fMRI, that right handers require an increase in effort to perform with their left hand. As such, right handers display greater activation in the right hemisphere when using the left hand, than in the left hemisphere when using the right hand [16]. Other researchers have similarly identified greater activation in contralateral motor areas [17, 18].

Numerous behavioural tools are available for the evaluation of hand preference. Questionnaires are the most widely used, where participants record their response to a series of unimanual tasks. Questionnaires such as the Edinburgh Handedness Inventory [19], the Waterloo Handedness Questionnaire [20], and the Annett Handedness Questionnaire [13] are commonly used in the literature; however, this method of evaluating hand preference comes with certain limitations. More particularly, limitations include the subjective nature of responses [21] and the consideration that no single questionnaire was explicitly designed to assess children. Therefore, some authors suggest that performance-based measures of preference represent a more objective approach to evaluate hand preference, especially with children [22, 23].

One of these performance-based measures is the Quantification of Hand Preference (QHP) task [24], which assesses hand preference in reaching throughout regions of hemispace. Also assessed in reference to manual midline crossing, it has been suggested that the emergence of such behaviour reflects a shift from extracallosal to callosal control of interhemispheric communication [25] and is thus a prerequisite from developing a skilled preferred hand [26, 27, 28]. The original version of the QHP was limited to one task (i.e., Bishop's card reaching task). Here, seven coloured cards were placed at 30-degree intervals within hemispace. Participants were seated at a table with the task in front of them, and asked to grasp a card of a certain colour and place it into a box located at the midline. The hand used to pick up the card in each region of hemispace was recorded [24]. The QHP displays high homogeneity and test-retest reliability (.78 - .80) [29]. Furthermore, Bishop et al. [24] were able to successfully identify right handers based on degree of hand preference [1]. A reflection of how strongly a person prefers one hand, degree of hand preference is a behavioural reflection of cerebral lateralization for handedness. This has been reported in several studies assessing both structural and functional cortical organization [30, 31, 32]. For example, using resting-state fMRI, Pool et al. [32] identified stronger interhemispheric functional connectivity in right handers. As such, the authors suggested functional connectivity between left primary motor cortex and right dorsolateral premotor cortex may be used as an indicator of handedness [32]. Extending Bishop et al.'s [24] findings, Calvert and Bishop [32] repeated the QHP with right- and left-handers to investigate whether left-handers mirror right-handers, or display less cerebral lateralization. Two additional tasks were added to the QHP (pointing to a letter and placing/posting a marble) to examine the role that skill played in the degree of preference. Overall, the

QHP was sensitive to degree of hand preference both within and between groups of left- and right-handers; however, the pointing and placing tasks proved to be more effective assessments [24, 32]. This finding clearly outlines the need to consider the difficulty of the task when assessing hand preference [32, 33].

More recent investigations have examined the QHP task from a developmental perspective. It is generally reported that the shift from immature to mature motor control strategies at approximately age 10 to 12 may reflect maturation of the corpus callosum [9, 34, 35, 36, 37]. Failure to cross the midline by age 3 to 4 has thus been identified as a marker for potential perceptual-motor difficulties later in life [38]. With respect to the QHP, some [39, 40] have limited inquiries to the card-reaching task, and others [41] have examined all three components (i.e., reaching, pointing and posting). Overall, findings reveal younger children (i.e., 3- to 5-year-olds) have weaker cerebral lateralization, and hand preference tendencies; therefore, are less likely to cross the midline in comparison to older children (i.e., 7- to 12-year-olds) who are strongly lateralized, and thus reliant on their preferred hand. Adults, in comparison, will reach into ipsilateral space with either the preferred or non-preferred hand reflecting acquired motor skills, which decrease complexity [23].

Whereas the aforementioned studies utilized the QHP to investigate hand preference in manual midline crossing, other studies have modified the task to include other objects. In one example, Bryden et al. [42] placed everyday tools (e.g., pen, toothbrush, hammer, paint brush, spoon) at 45-degree angles in peripersonal space. Adult participants were first asked to lift an object and demonstrate the action as if it were a tool. Hand preference was stronger in the tasks that involved demonstration [42]. These findings have been replicated with both adults and children [43]. Overall, results of these studies exemplify the link between hand preference and manual midline crossing over the course of development, where children in the 7- to 10-year-old age range cross the midline significantly more than other age groups (both younger and older) [23, 39, 40, 43].

In summary, the previous literature suggests that the QHP is a suitable measure of human handedness in children and adults. Nevertheless, the quality of the card reaching task (i.e., validity) has not been verified in children. Differences in performance have been shown to reflect changes in cerebral lateralization with age, and midline crossing has been used to infer maturation of the corpus callosum. As such, it is of utmost importance that behavioural measurements tools are both valid and reliable. Therefore, the aim of this study was to examine the factor validity of Bishop's card reaching task. Furthermore, a secondary aim of this study was to assess discriminant and convergent validity between the task, and a selection of five standard assessments of hand preference in 8- to 10-year-old children. It was hypothesized that the task would be identified as a valid assessment for children and be highly correlated ($r > .80$) with other measures of handedness, considering children in this age range are strongly lateralized and thus display consistent hand preference tendencies. The research was focused specifically on describing the defined phenomenon and therefore the study was observational in nature [44].

A threshold of $r > .80$ was selected based on several considerations, including work by Kline [45], descibing convergent validity as a correlation at least of moderate strength. There are several guidelines which can be used to identify a sufficiently high correlation. For example, Cohen [46] and Hendl [47] identify a large effect as >.50 or >.70. Brown [48] discussed sufficient convergent validity in the range of .676 to .749. With respect to reliability, when observing the correlation between the card-reaching task and other validated measures of handedness, this can be expressed similar to internal consistency, where the generally acceptable level is recommended to be greater than .80 [49, 50].

Materials and Methods

Participants

The current study included 376 children (184 boys and 192 girls) between 8 and 10 years of age (M_{age} = 9.2, SD = 0.4). Participants were pupils of state elementary schools of the Capital City of Prague, Czech Republic, and were selected using an intentional selection process. More specifically, participants were selected from schools without art, sport, language or technical specializations. Furthermore, children could not be enrolled in "integrated classes" for children with special needs. Beyond the aforementioned inclusion criteria, other factors which may influence performance (e.g., activities outside of school, including sports, hobbies and activities) were not considered. This was a limitation.

Participants were selected using the following purposefully method of sampling. In cooperation with the Institute of Educational and Psychological Counselling, a complete list of primary schools from each district in the City of Prague was obtained. Only those schools that were attended by at least 50 individuals of the given age were selected, the number of the participants per school was set at 40. Out of these schools, a list was created from which one primary school was randomly selected from each district of Prague. In total, 10 primary schools were selected. The Ethics commission of the Faculty of Physical Education and Sport, at Charles University granted ethics approval. Written parental consent was obtained for all children.

Apparatus and Procedures

Hand preference tasks. To determine hand preference, five unimanual motor tasks were implemented [51]. Assessments have been used in previous studies [13, 19, 52], and have been validated for use with Czech children [51]. The tasks included: (1) draw a leaf according to the model (**Draw**); (2) take the bell in one hand and ring it (**Ring**); (3) take the ball in one hand and throw it at the target (three attempts; **Throw**); (4) show how many points you can roll with the dice (three attempts; **Cube**); and (5) demonstrate how you brush your teeth (**Brush**). Tasks were scored dichotomously, where 0 indicated the task was performed with the left hand and 1 indicated performance with the right hand. Throw, Cube, Cards and Matches tasks included repetition; therefore, scores comprised of a sum of attempts performed with the right hand.

Bishop's card reaching task (Bishop's). Participants were seated on a chair at a desk for the duration of the study. The researcher placed a sheet of paper (42 cm x 29.7 cm; divided in half by a vertical line) on the desk in front of the participant. The paper contained seven rectangular boxes (6 cm × 3 cm) at successive 30 degree intervals forming a semicircle. There were three boxes in left space, one at the midline, and three boxes in right space. Each box was labelled from -3 (far left) to +3 (far right), with the box at the midline labelled 0. The researcher placed a card (all different colors) in each box and asked the participant to turn the card of a designated color using one hand. The card placed at the midline was selected first. If the participant used the right hand, selection progressed in the following order: +2, −2, +3, −3. If the participant used the left hand, selection progressed in the following order: −2, +2, −3, +3. After each trial (i.e., after each card was selected) hand selection was recorded on a score sheet. A value of 0 indicated left hand selection; whereas, a value of 1 indicated right hand selection.

Data Analysis

To analyse the relationship between manifest indicators and latent variables with continuous characters, structural equation modelling (SEM) is recommended [45, 53]. Therefore, SEM

Table 1. Fit of the one-factor model.

Model	Chi-square	P-value	df	CFI	TLI	RMSEA	WRMR
1-factor	21.58	.08	9	.97	.97	.051	.522

doi:10.1371/journal.pone.0166337.t001

was used to assess the relationship between data obtained from the hand preference tasks and Bishop's card reaching task. One SEM approach includes factor analysis, which has been used in previous studies to determine the structure or diagnostic quality of handedness questionnaires [54, 55, 56]. In this study, hand preference was defined as a latent continuous variable with dichotomous (or ordered categorical type) scoring; therefore, categorical confirmatory factor analysis (CCFA) was selected as an appropriate psychometric approach from SEM. This method is sometimes called IRT [57] or item factor analysis (IFA) [58]. It is suitable to test or verify structural theories, and to test the validity of a certain tool [48, 58, 59]. The weighted least-squares (WLSMV) approach was selected as the estimation parameter as recommended in Muthén [60].

The quality of structural models was evaluated according recommended cut-off lines using five fit indices: (1) Chi-square test (Sattora-Bentler scaled chi-square); (2) Comparative fit index (CFI) [61], >.95; (3) Root mean square of approximation (RMSEA) [62], < .06; (4) Tucker-Lewis index (TLI) [63], >.95; and (5) Weighted Root Mean Square Residual (WRMR) [60], < .80. Sensitivity of the QHP Bishop's card reaching task was evaluated using chi-square contingency tables. Data were analyzed in M-plus 6 [64]and NCSS2007 (NCSS, LLC, Kaysville, UT).

Results and Discussion

Six indicators evaluating the latent variable "hand preference" were modeled using CCFA. The proposed uni-dimensional model displayed very good values of fit and high factor loading of all six indicators of hand preference (see Table 1). In this one-factor structure, Bishop's card reaching task proved to be a suitable indicator of hand preference (factor validity = .89; see Table 2); however, high factor loads revealed a possible multicollinearity of some motor tasks (i.e., excessive mutual correlation). A correlation matrix was created to verify the discriminant and convergent validity of individual indicators. Polychoric correlations were used for ordered categorical data, and tetrachoric correlations were used for dichotomously (binary) scored data.

The correlation matrix clearly displays a strong (>.90) correlation between the individual indicators (see Table 3). On average, the weakest correlations (though still at high levels) were in Bishop's card reaching task. Detailed analysis showed that two motor tasks, **Brush** and

Table 2. One-factor model.

	Six items	
Items	Factor Loadings	Uniqueness
Draw a leaf according to the model–**Draw**	.96	.08
Take the bell in one hand and ring it–**Ring**	.90	.19
Take the ball in one hand and throw it at the target–**Throw**	.92	.15
Show how many points you can roll with the dice on three attempts–**Cube**	.98	.04
Demonstrate how you brush your teeth–**Brush**	.94	.12
Bishops' card reading task–**Bishop's**	.89	.21
Cronbach's α	.89	

doi:10.1371/journal.pone.0166337.t002

Table 3. Correlation matric of six motor tasks (including Bishop's card reaching task).

Items	Brush	Throw	Ring	Draw	Bishop's	Cube
Brush						
Throw	.988					
Ring	.956	.968				
Draw	.985	.983	.957			
Bishop's	.921	.896	.859	.868		
Cube	.959	.918	.897	.918	.864	

doi:10.1371/journal.pone.0166337.t003

Table 4. Fit of the one-factor model without Brush and Draw tasks.

Model	Chi-square	P-value	df	CFI	TLI	RMSEA	WRMR
1-factor	6.58	.25	2	.99	.99	.039	.351

doi:10.1371/journal.pone.0166337.t004

Draw, have the strongest correlations with other tasks. Based on the analysis of motor activity and with regard to possible sociocultural pressures on hand preference in these two tasks, we decided to exclude **Brush** and **Draw** items and thus verify their redundancy in the proposed one-factor model (see Table 4).

After excluding the Brush and Draw motor tasks, the one-factor model with four indicators showed a significant improvement in fit values (see Table 5). The most marked proved to be changes in significance of the model ($p = .25$) and chi-square, whose value was considerably lower statistically, at the level $p < .001$, even with the relevant number of degrees of discretion. This improvement in fit in spite of the model restriction (which means a certain loss of information) indicated that the **Brush** and **Draw** tasks were highly redundant in the model.

To evaluate sensitivity of Bishop's card reaching task, participants were divided into two groups based on an absolute preference for the right ($n = 308$) and left ($n = 31$) hand. This division was based on performance of the five hand preference tasks previously standardized for use with Czech children [50]: Draw, Brush, Cube, Ring and Throw. Participants who performed all tasks with the right hand were described as having an absolute preference for the right hand; whereas, those who performed all tasks with the left hand were described as having an absolute preference for the left hand. Chi-square tests with contingency tables revealed the Bishop's card reaching task had sufficient sensitivity for identifying absolute right-handers ($n = 306$) and left-handers ($n = 31$; see Table 6). In addition, these results showed that the

Table 5. One factor model without Brush and Draw tasks.

	Six Items		Four Items	
Items	Factor Loadings	Uniqueness	Factor Loadings	Uniqueness
Draw a leaf according to the model–**Draw**	.96	.08	-	-
Take the bell in one hand and ring it–**Ring**	.90	.019	.91	.17
Take the ball in one hand and throw it at the target–**Throw**	.92	.15	.92	.15
Show how many points you can roll with the dice on three attempts–**Cube**	.94	.12	.93	.13
Demonstrate how you brush your teeth–**Brush**	.98	.04	-	-
Bishop's card reaching task–**Bishop's**	.89	.21	.89	.21
Cronbach's α	.89		.84	

doi:10.1371/journal.pone.0166337.t005

Table 6. Sensitivity of Bishop's card reaching task according to the instructions "turn the cards of the given colour placed on the sheet of paper."

How the task was proved	Right handers	Left handers
All cards were taken by right hand	298	0
All cards were taken by left hand	0	28
At least one card was taken by non-preferred hand	8	3
Total	306	31

doi:10.1371/journal.pone.0166337.t006

sensitivity of Bishop's card reaching task is approximately 7% lower (right-handers = 97.4% and left-handers = 90.3%) in identifying left- handers compared to right-handers. Nevertheless, chi-square criterion showed that this difference was not significant.

The current study aimed to assess the factor validity of Bishop's card reaching task. Furthermore, to examine discriminant and convergent validity between Bishop's card reaching task and a selection of five standard assessments of hand preference in Czech children. Structural equation modeling was used to determine the diagnostic value of Bishop's card reaching task, along with select unimanual indicators, with the defined latent variable "hand preference." Confirming our hypothesis, the factor validity of Bishop's card reaching task indicated it was a suitable indicator of hand preference (.89), and successfully identified hand preference in children. More specifically, assessments of sensitivity revealed identification of 90.3% of left-handers and 97.4% of right-handers. It is important to note that, although sensitivity levels were 7% greater in right-handers, the difference was non-significant. This finding supports previous results that left-handers represent a more heterogeneous population in terms of cerebral lateralization for handedness [65, 66].

Findings of the current study are in agreement with previous reports. In the original study, Bishop et al. [24] used the card-reaching task to distinguish between right-handed young adults based on degree of hand preference. Carlier et al. [39] has used Annett's Questionnaire and Bishop's card reaching task to assess the hand preference of 3- to 10-year-olds (right- and left-handed); however, did not assess the correlation between the two measures. Nevertheless, regardless of the method used to classify hand preference, analysis of the number of midline crossings remained the same for both handedness groups. Using the same methods, Doyen et al. [40] identified a significant, yet low (.23) correlation between measures with right-handed individuals ages 6 to 66, in line with findings from the current study. Likewise, Hill and Khanem [41] reported, "a child's age and peg-moving speed had a significant influence on the likelihood of using their preferred hand to point and reach" (p. 105). The Edinburgh Handedness Questionnaire [19] and an unspecified peg-moving task were used in their study with 4- to 11-year-olds [41]. Taken in light of the current findings, where greater than 90% of participants (90.3% of left-handers and 97.4% of right-handers) were successfully identified according to their hand preference, it can be argued that using Bishop's card reaching task is a suitable and valid method to measure handedness.

That said, although the aforementioned work used Bishop's card reaching task to distinguish between handedness groups, it is important to highlight discrepant findings in the literature as well. In a follow-up to Bishop et al. [24], Calvert and Bishop [33] added two tasks (point, place) to extend the QHP, and assess the relationship with Annett's peg moving task as a traditional assessment. All QHP tasks were significantly correlated with Annett's peg moving task; however, only point and placing were able to separate strong and weak right- and left-handers. For card reaching, there was an evident trend in this direction, where the task was able to differentiate between left-handers based on degree of hand preference, but not right-handers. Doyen and Carlier [29] were also unable to replicate Bishop et al.'s [24] findings. Although homogeneity and test-retest reliability were revealed, the ability to sort participants into subgroups of hand preference was not achieved by Bishop's card reaching test, in particular with left-handers. Doyen and Carlier [29] thus suggested that both preference and performance tasks should be implemented to ensure a complete assessment of handedness, considering differences in cerebral lateralization between right and left handers. Nevertheless, it was also acknowledged that differences are likely attributed to the way in which handedness groups are classified, and the tasks used to divide participants based on degree of handedness [29].

As evidenced in the current study, tasks must be carefully considered when assessing hand preference. Findings revealed that the one factor model which included all five unimanal tasks (see Table 1) showed acceptable fit values (P = .08, RMSEA .051, CFA .97, WRMR .522); however, psychometric problems with strong multicollinearity were also revealed. A correlation matrix was thus created in order to determine the relationship between individual motor tasks in order to identify any potential redundancies. Strong correlations emerged for Brush and Draw tasks (>.90; see Table 3), similar to Komarc and Harbichová [67] who also noted possible redundancy of some motor tasks in their model. These tasks (i.e., Brush and Draw) were thus excluded from further analysis, even though the restriction of the model means a certain loss of information [58]. Despite both of these tasks recognized as most relevant in the handedness literature [11, 19], removing these tasks significantly improved the fit of the unidimensional model (see Table 4). More specifically, chi-square values decreased and the model significance increased (P = .25).

On the basis of these findings, it can be argued that Draw and Brush motor tasks are likely more influenced by sociocultural pressures than other tasks, and consequently were redundant in the model. Cultural influences have been shown to play a role in the development of handedness. In particular, western cultures typically show a higher incidence of left handedness than eastern cultures. For example, comparisons of hand preference in India and North America [68], and Japan and Canada [69] have noted the number of left-handers is considerably lower due to social constraints limiting left hand use [69]. Relevant to the current study, sociocultural pressures have been reported to have primary effects on skilled activities such as writing and eating [69]. As such, it is likely that Draw and Brush tasks may not accurately reflect handedness and cerebral lateralization in everyday settings. Furthermore, these differences may explain why the sensitivity for left-handers was 7% lower than right-handers.

Conclusions

Taken together, findings from the current study revealed that Bishop's card reaching task displayed a significant relationship with the latent variable "hand preference" and previously verified unimanual tasks. Moreover, Bishop's card reaching task was found to have high sensitivity in discriminating between right-handers and left-handers. That said, it is important to notice that Bishop's card reaching task expressed higher sensitivity for right-handers in comparison to left-handers. In summary, these findings support the idea that Bishop's card reaching task is a suitable and valid approach to assess hand preference in 8- to 10-year-old children. Notwithstanding the previous, it is important to acknowledge that the current study assess hand preference in a relatively homogenous narrow age range (i.e., 8 to 10), stereotypically known to display consistent hand preference, indicative of strong cerebral lateralization. Furthermore, participants were recruited using purposeful sampling. It is also important to acknowledge that the unimanual tasks used in the current study was not a fully exhaustive battery; however, do reflect the most commonly used assessments of hand preference in the literature. Future research should thus aim to replicate findings in a broader age range of children, to provide a foundation for examining neurodevelopmental disorders (e.g., Autism Spectrum Disorders, Attention Deficit Hyperactivity Disorders, etc.), where the proportion of right- and left-handers is disrupted in comparison to typically-developing peers. For example, neural deficits characteristics of Autism Spectrum Disorders are stereotypically of left hemisphere functions; therefore, a link between non-right-handedness, learning disability and left hemisphere dysfunction has become prevalent in the literature [10, 70]. In another example, Hill and Bishop [71] used the QHP to compare 7- to 11-year-olds with specific language impairment and developmental coordination disorder to their age-matched peers and younger control group. Findings revealed the ability to be a more sensitive, albeit not specific, indicator of developmental disorder than a traditional handedness questionnaire (i.e., Edinburgh Handedness Questionnaire) [19].

Acknowledgments

This study was supported by project PRVOUK P39, Social-Sciences Aspects of Human Movement Studies and by the Czech Science Foundation, project No. 14-29358P.

Author Contributions

Conceptualization: MM.

Data curation: MM SS.

Formal analysis: SS.

Funding acquisition: MM.

Investigation: MM.

Methodology: MM.

Project administration: MM.

Resources: MM.

Software: MM.

Supervision: MM PB.

Validation: MM SS.

Visualization: MM SS PB.

Writing – original draft: MM SS PB.

Writing – review & editing: MM SS PB.

References

1. Steenhuis RE, Bryden MP. Different dimensions of hand preference that relate to skilled and unskilled activities. Cortex. 1989; 25(2), 289–304. PMID: 2758854
2. Annett M. The right shift theory of handedness and developmental language problems. Bulletin of The Orton Society. 1981; 31, 103–121.
3. Annett M. The genetics of handedness. Trends in Neurosci. 1981, 256–258.
4. Harris LJ. Broca on cerebral control for speech in right-handers and left-handers: a note on translation and some further comments. *Brain and Language*. 1993; 45(1), 108–120. doi: 10.1006/brln.1993.1037 PMID: 8353726

5. Provins KA. Handedness and speech: a critical reappraisal of the role of genetic and environmental factors in the cerebral lateralization of function. Psychological review. 1997; 104(3):554. PMID: 9243964
6. Knecht S, Dreppe M, Dräger B, Bobe L, Lohmann H, Ringelstein EB, et al. Language lateralization in healthy right-handers. Brain. 2000; 123, 74–81. PMID: 10611122
7. Knecht S, Dräger B, Deppe M, Bobe L, Lohmann H, Flöel A, et al. Handedness and hemispheric language dominance in healthy humans. Brain. 2000; 123, 2512–2518. PMID: 11099452
8. Khedr EM, Hamed E, Said A, Basahi J. Handedness and language cerebral lateralization. Euro J Appl Physiol. 2002; 87, 469–473. doi: 10.1007/s00421-002-0652-y
9. Pujol J, Deus J, Losilla JM, Capdevila A. Cerebral lateralization of language in normal left-handed people studied by functional MRI. Neurology. 1999; 52, 1038–1038. doi: 10.1212/WNL.52.5.1038 PMID: 10102425
10. McManus IC, Bryden MP. The genetics of handedness, cerebral dominance, and lateralization. Handb Neuropsychol. 1992; 6, 115–144.
11. Coren S, Porac C. Fifty centuries of right-handedness: the historical record. Science. 1977; 198(4317), 631–632. PMID: 335510
12. Hugdahl K, Westernhausen R. The Two Halves of the Brain: Information Proceesing in the Cerebral Hemispeheres. 2010; Cambridge, Massachussets: MIT Press.
13. Annett M. A classification of hand preference by association analysis. Brit J Psychol. 1970; 61(3), 303–321. doi: 10.1111/j.2044-8295.1970.tb01248.x PMID: 5457503
14. Springer SD, Deutsch G. Left Brain, Right Brain: Perspectives from Cognitive Neuroscience, 5th Edn. 1998; New York: W.H. Freeman.
15. Yahagi S, Kasai T. Motor evoked potentials induced by motor imagery reveal a functional asymmetry of cortical motor control in left- and right-handed human subjects. Neurosci Lett. 1999; 276, 184–188. doi: 10.1016/S0304-3940(99)00823-X
16. Jäncke L, Peters M, Schalug G, Posse S, Steinmetz H, Müller-Gärtner HW. Differential magnetic resonance signal change in human sensorimotor cortex to finger movements of different rate of the dominant and subdominant hand. Cognitive Brain Research. 1998; 6, 279–284. PMID: 9593941
17. Gut M, Urbanik A, Forsberg L, Binder M, Rymarczyk K, Sobiecka B, et al. Brain correlates of right-handedness. Acta Neurobiol Exp. 2007; 67(1), 43.
18. Viviani P, Perani D, Grassi F, Bettinardi V, Fazio F. Hemispheric asymmetries and bimanual asynchrony in left-and right-handers.Exp Brain Research. 1998; 120(4), 531–536. doi: 10.1007/s002210050428
19. Oldfield RC. The assessment and analysis of handedness: the Edinburgh Inventory. Neuropsychologia. 1971; 9, 97–113. doi: 10.1016/0028-3932(71)90067-4 PMID: 5146491
20. Steenhuis RE, Bryden MP, Schwartz M, Lawson S. Reliability of hand preference items and factors. J Clin Exp Neuropsyc. 1990; 12, 921–930. doi: 10.1080/01688639008401031
21. Brown S, Roy E, Rohr L, Bryden P. Using hand performance measures to predict handedness. Laterality, 2006; 11, 1–14. doi: 10.1080/1357650054200000440 PMID: 16414911
22. Bryden PJ, Roy EA, Spence J. An observational method of assessing handedness in children and adults. Dev Neuropsychol. 2007; 32, 825–846. doi: 10.1080/87565640701539667 PMID: 17956184
23. Scharoun SM, Bryden PJ. Hand preference, performance abilities, and hand selection in children. Frontier Psychol, 2014; 5, 82. doi: 10.3389/fpsyg.2014.00082 PMID: 24600414
24. Bishop DV, Ross VA, Daniels MS, Bright P. The measurement of hand preference: a validation study comparing three groups of right-handers. Brit J Psychol, 1996; 87, 269–285. doi: 10.1111/j.2044-8295.1996.tb02590.x PMID: 8673359
25. Liederman J. Mechanisms underlying instability in the development of hand preference, in Manual Specialization and the Developing Brain, eds Young G, Segalworitz SJ, Carter CM, and Trehub SE, 1983;82–85. New York: Academic Press.
26. Provine R, Westerman J. Crossing the midline: Limits of early eye-hand behaviour. Child Dev. 1979; 50, 437–441. doi: 10.2307/1129420 PMID: 487884
27. Ayres AJ. Sensory Integration and Learning Disorders. 1972; Los Angeles: Western Psychological Services.
28. Ayres AJ. Southern California Integration Tests Manual—Revised. 1980; Los Angeles: Western Psychological Services.
29. Doyen AL, Carlier M. Measuring Handedness: a validation study of the Bishop's Card-reaching test. Laterality, 2002; 7, 115–130. doi: 10.1080/13576500143000140 PMID: 15513192

30. Amunts K, Schlaug G, Schleicher A, Steinmetz H, Dabringhaus A, Roland PE, et al. Asymmetry in the human motor cortex and handedness. Neuroimage. 1996; 4, 216–222. PMID: 9345512

31. Hammond G. Correlates of human handedness in primary motor cortex: a review and hypothesis. Neuroscience and Biobehavioral Reviews, 2002; 26, 285–292. PMID: 12034131

32. Pool EM, Rehme AK, Eickhoff SB, Fink GR, Grefkes C. Functional resting-state connectivity of the human motor network: Differences between right-and left-handers. NeuroImage, 2015; 109, 298–306. doi: 10.1016/j.neuroimage.2015.01.034 PMID: 25613438

33. Calvert GA. Bishop DV. Quantifying hand preference using a behavioural continuum. Laterality, 1998; 3 (3), 255–268. PMID: 15513088

34. Finlayson MA, Reitan RM. Handedness in relation to measures of motor and tactile-perceptual functions in normal children. Percept Motor Skills. 1976; 43, 475–481.

35. Dodds AG. Hemispheric differences in tactuo-spatial processing. Neuropsychologia. 1978; 16, 247–250. PMID: 692852

36. O'Leary DS. A developmental study of interhemispheric transfer in children aged five to ten. Child Dev. 1980;743–750. PMID: 7418510

37. Giedd JN, Rumsey JM, Castellanos FX, Rajapakse JC, Kaysen D, Vaituzis AC, et al. A quantitative MRI study of the corpus callosum in children and adolescents. Developmental Brain Research. 1996; 91(2):274–80. doi: 10.1016/0165-3806(95)00193-X PMID: 8852379

38. Michell D, Wood N. An investigation of midline crossing in three-year-old children. Physiotherapy. 1999; 85, 607–615. doi: 10.1016/S0031-9406(05)66041-5

39. Carlier M, Doyen AL, Lamard C. Midline crossing: developmental trends from 3 to 10 years of age in a preferential card-reaching task. Brain Cognition. 2006; 61, 255–261. doi: 10.1016/j.bandc.2006.01.007 PMID: 16513237

40. Doyen AL, Dufour T, Caroff X, Cherfouh A, Carlier M. Hand preference and hand performance: cross-sectional developmental trends and family resemblance in degree of laterality. Laterality, 2008; 13, 179–197. doi: 10.1080/13576500701764124 PMID: 18302059

41. Hill EL, Khanem F. The development of hand preference in children: the effect of task demands and links with manual dexterity. Brain Cognition. 2009; 71, 99–107. doi: 10.1016/j.bandc.2009.04.006 PMID: 19457603

42. Bryden PJ, Roy EA, Mamolo CM. The effects of skill demands and object characteristics on the distribution of preferred hand reaches in working space. Brain Cognition. 2003; 53, 111–112.

43. Bryden PJ, Roy EA. Preferential reaching across regions of hemispace in adults and children. Dev Psychobiol. 2006; 48, 121–132. doi: 10.1002/dev.20120 PMID: 16489592

44. Kerlinger FN, Lee HB. Validity. Foundations of Behavioral Research. (4th ed.) Belmont, California: Cengage, 2000; 665–688.

45. Kline RB. Convergence of structural equation modeling and multilevel modeling. In Williams M & Vogt WP (Eds.), Handbook of methodological innovation (pp. 562–589). 2011; Thousand Oaks, California: Sage.

46. Cohen J. Statistical power analysis for the behavioral sciences. 1988; Hillsdale, N.J: L. Erlbaum Associates.

47. Hendl J. Přehled statistických metod: Analýza a metaanalýza dat. Praha: Portál Translation: Summary of statistical methods: Data analysis and Metha-analysis. 2009; Prague: Portal.

48. Banerjee M, Capozzoli M, McSweeney L, Sinha D. Beyond kappa: A review of interrater agreement measures. The Canadian Journal of Statistics, 1999; 27, 3–23.

49. Krippendorff K. Content analysis: An introduction to its methodology. 1980; Beverly Hills, CA: Sage.

50. Musalek M. Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. Frontier Psychol, 2014; 5, 1513. doi: 10.3389/fpsyg.2014.01513 PMID: 25628579

51. Tapley SM, Bryden MP. A group test for the assessment of performance between the hands. Neuropsychologia, 1985; 23(2), 215–221. PMID: 4000456

52. Hoyle RH. (Ed.). Structural equation modeling: Concepts, issues, and applications. 1995; Thousand Oaks, California: Sage Publications.

53. Dragovic M. Towards an improved measure of the Edinburgh Handedness Inventory: A one-factor congeneric measurement model using confirmatory factor analysis. Laterality. 2004; 9(4), 411–419. doi: 10.1080/13576500342000248 PMID: 15513238

54. Milenkovic S, Dragovic M. Modification of the Edinburgh Handedness Inventory: a replication study. Laterality. 2013; 18(3), 340–348. doi: 10.1080/1357650X.2012.683196 PMID: 22747439

55. McFarland K, Anderson J. Factor stability of the Edinburgh Handedness Inventory as a function of test-retest performance, age and sex. Brit J Psychol. 1980; 71(1), 135–142.

56. Baker FB, Kim SH. Item response theory: Parameter estimation techniques (2nd ed). 2004; CRC Press.

57. McDonald RP. Test theory: A unified treatment. 1999; Mahwah, New Jersey: L. Erlbaum Associates.

58. Brown TA. Confirmatory factor analysis for applied research. 2006; New York: Guilford Press.

59. Vandenberg RJ, Lance CE. A review and synthesis of the measurement invariance literature: Suggestions, practices, and recommendations for organizational research. Organ Res Methods, 2000; 3(1), 4–70.

60. Muthén B. A general structural equation model with dichotomous, ordered categorical, and continuous latent variable indicators. Psychometrika. 1984; 49(1), 115–132.

61. Bentler PM. Comparative fit indexes in structural models. Psychol Bull. 1990; 107(2), 238–246. doi: 10.1037/0033-2909.107.2.238 PMID: 2320703

62. Steiger JH. Structural model evaluation and modification: An interval estimation approach. Multivar Behav Res. 1990; 25(2), 173–180.

63. Tucker LR, Lewis C. A reliability coefficient for maximum likelihood factor analysis. Psychometrika. 1973; 38(1), 1–10.

64. Muthén LK, Muthén BO. Mplus User's Guide: Statistical Analysis with Latent Variables: User's Guide. 2010; Los Angeles, California: Muthén & Muthén.

65. Herron J. Neuropsychology of Left-Handedness. 2012; Burlington: Elsevier Science.

66. Ocklenburg S, Hirnstein M, Beste C, Güntürkün O. Lateralization and cognitive systems. Frontier Psychol. 2014; 5.

67. Komarc M, Harbichová I. Latent structure of the Annett's handedness questionnaire in Czech population. Czech Kinanthropol. 2012; 16(2). 77–87.

68. Singh M, Bryden MP. The factor structure of handedness in India. International J Neurosci. 1994; 74 (1–4), 33–43.

69. Ida Y, Bryden MP. A comparison of hand preference in Japan and Canada. Can J Exp Psychol. 1996; 50(2), 234–239. doi: 10.1037/1196-1961.50.2.234

70. Cornish KM, McManus IC. Hand preference and hand skill in children with autism. J Autism Dev Disord, 1996; 26(6), 597–609. doi: 10.1007/BF02172349 PMID: 8986846

71. Hill EL, Bishop DV. A reaching test reveals weak hand preference in specific language impairment and developmental co-ordination disorder. Laterality. 1998; 3(4), 295–310. doi: 10.1080/713754314 PMID: 15513093

2.2 Highly Complex Tests for Assessing of Footedness – Does It Make Sense?

Motor laterality is, however, not only a question of limb preference. It is important to note that also proficiency and performances tests play a significant role in the process of appropriate determination of the degree of laterality. The above-mentioned diagnosis of preference (previous part) allows only a limited detailed expression of the strength of motor laterality like handedness or footedness. Motor proficiency tests are more time-consuming and therefore generally less attention has been paid to them in literature (Rigal, 1992; Corballis, 2009). In past decades mainly performance tests for upper limb have been created and verified. These tests primarily focus on the differences in speed, precision or correctness of execution between the preferred and non-preferred upper limbs (see more in Scharoun & Bryden, 2014). In both children and adults these aspects of hand proficiency to a significant degree correspond with upper limb preference (Peters, 1976; Rigal, 1992; Cornish & McManus, 1996; Nalcaci et al., 2001). Nevertheless, we have to note that the degree of association between hand preference and hand proficiency highly depends on the type of performance test. In this context Annett (1992) Roy, Kalbfleisch and Elliott (1994) or Sainburg and Kalakanis (2000) emphasize that higher skilfulness of the preferred upper limb is observed primarily in complex motor activities in which higher demands are put on coordination and integration of more segments of the limb involved in the activity (e.g., shoulder and elbow joints).

Although there are different types of peg moving tests, manual dexterity tests and tests of hand-eye coordination, much less attention has been paid to investigating the question of whether also foot performance tests are useful in determining the degree of footedness. Some performance tests for evaluation of different skilfulness of the lower limbs have been created (see Knights & Moule, 1967; Beling et al., 1998). However, their congruency with foot preference showed to be significant only in adult population. One suggested answer to why foot performance shows inconsistencies is that laterality of the upper and lower limbs does not develop in parallel as has been observed particularly in children. Compared to handedness, footedness stabilizes later in life. For instance, Coren, Porac and Duncan (1981) found a significant right-hand preference in preschoolers and selected population of high-school students. Nevertheless, pre-school children had a significantly less distinct lower limb preference. Also Gabbard et al. (1991), Gabbard (1992) and Gentry and Gabbard (1995) found that foot preference in 3- to 5-year-old children is much less consistent than hand preference. In particular, according to Gabbard (1996), who carried out a systematic review focused on the relationship between handedness and footedness in pre-school age, mixed-footedness appears twice as often as mixed-handedness. According to Gentry and Gabbard (1995), significant stabilization of lower limb preference happens later, between 8 and 11 years of age. However, in connection with this finding we have observed that there are not enough studies attempting to verify whether later stabilization of the lower limb preference is also manifested in the results of performance tests for lower limbs that are used to diagnose laterality in the child population. The difference in motor laterality of the upper and lower limb is also explained by the fact that the primary role of the upper limbs is manipulation, whereas the lower limbs' primary function is postural and body transportation Woodburne and Burkel, 1994, p. 87; Christou et al., 2003; Palastanga and Soames, 2011, p. 202). Musálek (2014) investigated the SEM link between foot preference and foot performance/proficiency in middle school age children and adolescence population. The aim was to compare the discriminatory power – factor validity of the same foot proficiency tests for both children and adolescents). These were complex motor activities which integrated more body systems: (1) moving a small object by the lower limb in a limited space and (2) slalom with a tennis ball between obstacles and (3) an activity which focused primarily on speed while performing a simple task – foot tapping. Although in middle school children, foot proficiency tests showed to have poor relation to foot proficiency factor, the same tests fit well into the foot proficiency structure in adolescents. Only simple speedy test foot tapping had acceptable validity λ=0.84 in middle school children. These results suggested that the development of fine motor foot proficiency tests is not particularly important for assessing of footedness.

Together with the hypothesis that laterality of the upper and lower limbs does not develop in parallel, a large body of studies exists which also found significant differences in laterality, particularly consistency, between males and females specifically in handedness. Males are significantly more frequently left-handers and mixed-handers (e.g., Whittington and Richards, 1987; Sommer et al., 2008; Johnston et al., 2009). So there is also the question whether motor laterality preference and proficiency develop in parallel with respect to sex. Research has provided some evidence that from the neurology perspective boys' and girls' brains develop in a slightly different manner. From the point of view of ontogenesis, a very interesting difference between males and females has been revealed in the strength of neural pathways leading into the cerebellum. These pathways which are involved, among other things, in realization of fine motor skills are according to Gurian et al. (2010) significantly stronger in females. Moreover, Amunts et al., (2000) revealed significant differences related to handedness in interhemispheric asymmetry of the central sulcus between males and females. In female brains, the interhemispehric asymmetry between right and left central sulcus was much lower compared to males. These results suggest that anatomical asymmetry might be associated with handedness only in males and not in females. In other words, the authors assume that differences exist between sexes in the cortical organization of hand movements. Another view on brain structural asymmetries was provided by Savic (2014). In this research, the asymmetry of cerebral gray and white matter and structural volumes in relation to sex hormones and chromosomes was assessed. Results showed that the asymmetry in the planum temporale area and the occipital cortex seem related to the processes associated with the male hormone testosterone, whereas the observed cerebellar asymmetries suggest a link with X-chromosome escapee genes.

Based on these findings, the second question studied in this research is whether the level of laterality assessed as a difference in skilfulness between the preferred and the non-preferred limb will differ significantly in males and in females. We suppose that such a difference might be revealed in the form of a different level of relationship factor loadings – in selected performance tests to modelled factors: (1) hand performance, (2) foot performance.

Research question

Based on this information we designed a study to answer two questions: 1) usefulness of motor complex tests assessing the degree of footedness in middle school age children; 2) whether foot proficiency tests modelled in the structure of footedness concept will be sex-dependent.

Since we accepted previous suggestions that laterality of lower limbs is: 1) delayed compared to upper limbs laterality; 2) function of lower limbs is different (also seen in different neural pathways) compared to upper limbs we assumed that in the given category of 8- to 10-year-olds skilled foot performance tests (spiral tracing by small cube, slalom with ball between obstacles) will show fewer differences and more inconsistencies (i.e., weaker lateralization) than complex tests designed for the upper limbs.

A total of 210 typically developing 8- to 10-year-olds (*n* = 107 males and *n* = 103 females; M_{age} = 9.1, SD = ± 0.78) from the Czech Republic whose parents signed an informed consent were recruited for this study. The main reason for the selection of middle age school children aged 8 to 10 was because at this age children's motor skills are harmoniously developed along with stable somatic development and stable coordination patterns (Ljach, 2002). All participants were from three state primary schools in the capital of Prague. The same schools also participated in the validation study of tests and tasks for the determination of motor laterality the results of which were published in Musálek (2014). The following criteria for the selection of participants were used:

- (1) participants were chosen only from schools which had a similar number of pupils in the given age category,
- (2) only schools without any specific specialization (e.g., technical, artistic, sport, or linguistic) were selected,
- (3) schools and classes with integrated children with special needs were not included in the selection.

We decided for this concept of an intentional selection process method in order to ensure a maximum homogeneity of the sample with respect to the findings from Musálek (2014). The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed an informed consent. The data were anonymized.

First, hand and foot preference patterns were assessed by seven observable preference measure tasks. The indicators used for the evaluation of hand preference and foot preference were validated for the Czech child population aged 8–10 in study Musálek (2014). Factor loads of hand preference indicators: λ = 0.85–0.93, generic reliability McDonald ω = 0.95; factor loads of foot preference indicators: λ = 0.66–0.90, generic reliability McDonald ω = 0.81 (Musálek, 2014). The results of the preference observable measure tasks also served to determine the preferred and the non-preferred limb as a necessary precondition for the selected skilled performance tests to be carried out in accordance with the given rules. Six of the seven observable preference measure tasks have already been used in previous research where these indicators were approved as valid and reliable either as questionnaire items or preference tasks (e.g., Annett, 1970; Barnsley & Rabovitch, 1970; Oldfield, 1971; Sharman & Kulhavy, 1976; Tapley

& Bryden, 1985; Rigal, 1992; Coren, 1993; Bishop et al., 1996; Doyen & Carlier, 2002; Mamolo, Roy, Rohr & Bryden, 2006; Musálek & Honsová, 2013).

Preference strength was determined based on laterality quotient calculation, for which equations from previous studies were used (e.g., Humphrey, 1951; Harris, 1958; Bryden, Roy & Spence, 2007; Kalaycıoğlu, Kara, Atbaşoğlu & Nalçacı, 2008). Each execution in preferential tasks was marked 1 when the right limb was used and 0 when the left limb was used.

Laterality quotient for the upper and lower limbs was calculated using the formula

$LQ = (R-L/R+L)*100$

Our selected sample consisted of 136 children who had uncrossed right side lateral preferences (right-handed and right-footed), (65 males and 71 females) LQ = 100, and 18 children who had left side uncrossed lateral preferences (left-handed and left-footed), (10 males and 8 females) LQ = 0. The LQ of the remaining 56 children (32 males and 24 females) ranged within LQ = 31.25–75.

Table 1

Preference tasks for assessing of hand and foot preference

Hand preference tasks	Foot preference tasks
1. Throwing on target	1. Kick to the ball on target
2. Ring by bell	1. Using one foot, tap the rhythm that I am
3. Card reaching task (Bishop task)	2. Perform jumps forward using one leg
4. Erasing	

For assessing the performance/proficiency component of handedness and footedness five validated tests for the Czech child population aged 8–10 years and two new tests (foot proficiency) were used. Five validated tests – four for handedness: (1) spiral tracing, (2) dot-filling, (3) tweezers and beads, (4) twisting box; and one for footedness: foot tapping – had an acceptable level of factor validity with respect to the modelled factors: (1) hand performance λ = 0.58–0.82 and (2) foot performance $\lambda = 0.92$. Generic reliability of the tests modelled only under one factor "performance of locomotive organs" was McDonald $\omega = 0.83$ Musálek (2014).

These five tests have already been replicated in several studies. Scharoun, Bryden, Otipkova, Musalek and Lejcarova, (2013) focused on differences in performance tests between preferred and non-preferred hand in children with ADHD and their neurotypical controls. Musálek, Scharoun and Bryden (2015) investigated relation between cerebellar dominance and hand skilled performance tests in right-handed children (details of this study in the end of this chapter).The results of these studies revealed that all five performance tests are sufficiently sensitive to determine the performance of the preferred hand.

Table 2
Skilled performance tests

Skilled hand performance tests	**Skilled foot performance tests**
1. Spiral tracing	1. Foot tapping
2. Dot-filling	3. While standing, slalom with ball between
3. Moving beads from one box into another	4. Spiral tracing by small cube
4. Turning a box alternately with the front and the rear side on the table	

First, it was necessary to confirm that skilled hand performance tests have sufficient convergent validity with selected hand preference tasks. Correlations between seven hand preference tasks and seven skilled hand performance tests were in the range *r* = 0.56–0.89 (Fig. 9). These results suggested that the differences in performance between the preferred and non-preferred hand in selected hand performance tests are significantly linked to hand preference. This finding supports the assumption that the more complex the motor test, the greater the differences in performance between the preferred and non-preferred hand (Annett, 1992)

Table 1 | Convergent validity between hand preference observable measure and hand performance tests.

Item	Throwing	Ring the bell	Bishop task	Erasing
Spiral tracing	–0.89	–0.84	–0.66	–0.82
Dot-filling	0.70	0.66	0.64	0.63
Twistbox	0.78	0.75	0.64	0.66
Tweezers and beads	0.75	0.70	0.58	0.56

Figure 9. Convergent validity between hand preference tasks and hand performance tests Adapted from Musalek (2015). Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. *Frontiers in psychology*, *5*, 1513.

On the other hand, in the correlation matrix of foot preference and skilled foot performance tests two of the three performance tests (slalom between obstacles and spiral tracing with small cube) did not manifest a satisfactory convergent validity r = 0.25–0.46 (Fig. 10). Only foot tapping was recognised as sufficiently discriminating the performance between the preferred and non-preferred foot. These results suggested that fine motor or complex tests for lower limbs are not sufficiently sensitive to distinguish between the preferred and the non-preferred lower limb in the given age group. It means that the assumption that the more complex the motor test the greater the difference in performance between the preferred and non-preferred limb seems not to be supported for lower limbs.

Table 2 | Convergent validity between foot preference tasks and foot performance tests.

Item	Kicking	Tapp rhytmus	Hop forward
Slalom with ball between obstacles	**−0.46**	**−0.33**	**−0.26**
Spiral tracing by small cube	**−0.39**	**−0.43**	**−0.25**
Foot tapping	0.85	0.74	0.65

Correlations lower than 0.50 are shown in boldface.

Figure 10. Convergent validity between foot preference tasks and foot performance tests Adapted from Musalek, (2015). Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. *Frontiers in psychology*, *5*, 1513.

The lack of sensitivity of skilled foot performance tests was also confirmed when comparing performances of the preferred and non-preferred lower limb. Among skilled foot performance tests, only the “tapping” test showed significant capacity to determine the difference in skilfulness of the preferred and the non-preferred lower limb $p < 0.05$ and *Cohen d* = 1.22. The other two tests, which were of a complex motor character, with the “slalom with a ball between obstacles” test having extra demands on balance, did not confirm the significance of the different performance of the preferred and the non-preferred lower limb *Cohen d* ranging within d = 0.22–0.27, p>0.05. These results together with findings regarding convergent validity for the lower limb (Fig. 10) support the hypothesis that fine motor or complex tests for diagnosing lower limb laterality in children of the given age category are not suitable due to their low discrimination capacity between the preferred and the non-preferred lower limb. It is quite interesting that Kauranen and Vanharanta (1996), who assessed motor performance of upper and lower limbs regarding handedness in adults, found much lower reliability (intraclass correlation coefficient – ICC) of coordination lower limbs tests compared to coordination upper limb tests. In addition, in coordination tests plate tapping for hands and conceptually the same test for feet, participants performed with a significantly higher accuracy in hand coordination test compared to feet. Further, this study showed that significant differences in the reaction time of the preferred hand existed in adults. On the other hand, the speed of movement was significantly higher in feet performance.

In next step we focused our attention on new investigation. Previous research in the area of motor or psychomotor development has mainly looked into whether there are any differences in the degree of gross motor or fine motor skills between boys and girls (e.g., balance, locomotion, coordination, object control etc…).

It is generally accepted that girls perform better in fine motor tasks (Schneck & Henderson, 1990; Blöte & Hamstra-Bletz, 1991; Junaid & Fellowes, 2006; Kokštejn, Musálek, & Tufano, 2017). Neverthless, there is very little information as to whether the used tests have or have not a significantly different discrimination power regarding gender. Information whether tests discriminate equally between males and females is highly necessary when estimating the degree of a certain human trait/property. Several previous studies showed that ignoring the different discrimination power leads to inadequate interpretation of the results (overestimation or underestimation effect) (Burtscher, Furtner, Sachse, & Burtscher, 2011; Komarc & Harbichová, 2015).

A number of previous studies that assessed the difference in handedness revealed that males are significantly less consistent, i.e. there is much higher portion of mixed-handers among males (e.g., Whittington & Richards, 1987; Sommer et al., 2008; Johnston et al., 2009). Moreover, Kauranen and Vanharanta (1996) concluded that the degree of handedness in males and females changes differently during the lifetime. While males were in general faster in non-complex motor tasks foot tapping and finger tapping and achieved higher speed of movement in coordination tests, females were by far more precise. These differences between males and females are generally associated with ontogenesis as well as phylogenesis. For instance, research studies have shown differences in the strength of neural pathways leading to the cerebellum. These neural pathways that, among other things, participate in the performance of motor activities are much stronger in females (Gurian et al., 2010).

Therefore, our second research question was to verify whether the differences in proficiency between the preferred and non-preferred limb will be significantly sex related. We suppose that such difference might be revealed in the form of a different level of relationship factor loadings – in selected performance tests to modelled factors: (1) hand performance, (2) foot performance.

The multigroup two-factor model for females and males revealed only one significant difference in factor load with respect to sex. The "foot tapping" performance test had significantly weaker factor loading in males, $\lambda = 0.56$, compared to females, $\lambda = 0.74$, $p < 0.05$ (Fig. 11). This finding probably has several causes. Firstly, the stabilization of lower limb performance in males may take longer. The differences in foot tapping performances between the preferred and non-preferred lower limb were not so clear. Secondly, the smaller difference in the performance of the right and the left lower limb may be caused by the relationship between the character of the test and a certain environmental factor. Since it is known that boys spend more of their leisure time doing physical activity compared to girls (Trost et al., 2002; Vilhjalmsson & Kristjansdottir, 2003; Marques, Ekelund, & Sardinha, 2016), it is possible that using both lower limbs, for instance, for kicking, hopping, climbing can mean that foot tapping cannot distinguish well between their preferred and non-preferred lower limb.

Table 4 | Factor loadings of the 2-factor model – factors: (1) upper limb performance and (2) lower limb performance.

Factors and used performance tests	Male		Female	
	λ	Uniq	λ	Uniq
Upper limb performance factor				
Spiral tracing	−0.84	0.25	−0.78	0.43
Dot-filling	0.78	0.39	0.87	0.24
Twistbox	0.63	0.56	0.67	0.55
Tweezers and beads	0.47	0.76	0.58	0.67
Lower limb performance factor				
Slalom with ball between obstacles	−0.32	0.86	−0.38	0.74
Spiral tracing by small cube	−0.30	0.89	−0.26	0.92
Tapping foot	0.56*	0.69	0.74*	0.44

*Names of factors are in boldface; λ, factor loading; Uniq, uniqueness - residual variance; *significant difference between factor loadings p < 0.05.*

Figure 11. Factor loadings of hand and foot performance tests in males and females
Adapted from Musalek (2015). Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. *Frontiers in psychology, 5,* 1513.

Summary:

The first important finding was that the difficulty of skilled performance tests for upper and lower limbs was not equal to the degrees of hand or foot preference in middle age school children. In the case of handedness, it was revealed that fine motor or complex tests determine hand preference quite well. This is in line with the conclusions of studies demonstrating that different skilfulness in speed, precision and correctness of execution of the motor activity strongly corresponds with the preferred upper limb in children (e.g., Annett et al., 1979; Rigal, 1992; Carlier, Duyme, Capron, Dumont & Perez-Diaz, 1993; Cornish & McManus, 1996; Nalcaci et al., 2001). On the other hand, lower limb skilled performance tests were poorly linked to foot preference. These results suggest that lower limb lateralization in children is probably not identical in strength with upper limb lateralization.

Interestingly, the lower limb performance test “slalom between obstacles”, which has been validated in the Czech Republic also for the adult population in Musálek (2014), did not reveal similar problems with the detection of the preferred and non-preferred lower limb. This finding is in conformity with studies Knights and Moule (1967) or Beling et al. (1998), which revealed agreement of results of performance tests with determined foot preference solely in the child population. Same like (Coren et al., 1981; Gabbard et al., 1991; Gabbard, 1992; Gentry and Gabbard, 1995; Gabbard, 1996) we assume that the lower limbs undergo a longer process of lateralization as compared to the upper limbs. This longer process of lateralization might be affected by the function of the lower limbs. While the upper limbs are intended for manipulation, the lower limbs are responsible mainly for postural and locomotion functions._In addition, we should not overlook a previous finding to the effect that the spino-cereberllar paths and tracks are different for the upper and lower extremities. Different paths for proprioceptive information for the upper and lower extremity lead from the spine (Chusid, 1982; Kandel, Schwarz, & Jessel, 2000). We see as a concrete application of these findings primarily the assessment of laterality by motor tests. In assessment of laterality of lower limbs we should have taken into account the fact that fine motor or complex lower limbs tests are age dependent.

Results from multigroup modelling showed that the sensitivity of all seven skilled performance tests in a two-factor model for detecting laterality of the upper and lower limbs is quite similar for both genders. This means that the lateralization process for the upper and lower limbs is probably quite similar in females and males at this age. The only difference revealed that was of some significance was related to factor load of the “foot tapping” test in females $r = 0.74$ and males $r = 0.56$ with factor validity coefficient for females being significantly $p < 0.05$ higher in comparison with factor validity of this indicator in males. This difference might be explained by some environmental factors, in males primarily by collective sports where both lower limbs are used (e.g., football). Consequently, the “foot tapping” test might not be sufficiently sensitive to determine the difference between the preferred and the non-preferred lower limb in males. On the other hand, in females who are not affected by these environmental factors, or are affected to a much smaller extent, the “foot tapping” test determines the relation to footedness concept more clearly.

For more details see Musalek (2015).

frontiers in
PSYCHOLOGY

ORIGINAL RESEARCH ARTICLE
published: 12 January 2015
doi: 10.3389/fpsyg.2014.01513

Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10

Martin Musalek*

Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

Edited by:
Claudia L. R. Gonzalez, University of Lethbridge, Canada

Reviewed by:
Leonard James Smart, Miami University, USA
Bernd Strauss, University of Münster, Germany

***Correspondence:**
Martin Musalek, Faculty of Physical Education and Sport, Jose Martiho 31, 162 52 Prague, Czech Republic
e-mail: musalek.martin@seznam.cz

Previous research has shown that hand and foot preferences do not develop in parallel in children and it has been discovered that in children foot preference stabilizes later. Therefore, the aim of this study is to verify whether the differences in stabilization will also be manifested through less consistent results of selected skilled foot performance tests in a comparison with selected skilled hand performance tests. A total of 210 8–10 year old children from elementary schools were recruited for this study. Hand and foot preferences were first tested using hand and foot preference observable measure tasks; consequently, all participants performed four skilled hand performance tests and three foot performance tests. Unlike in complex skilled hand performance tests, which showed a significant convergent validity 0.56–0.89 with hand preference tasks, in complex skilled foot performance tests a very low convergent validity 0.25–0.46 with foot preference tasks was detected. The only skilled foot performance indicator which showed an acceptable convergent validity with foot preference tasks was the "foot tapping" test 0.65–0.85, which represents rather a gross motor activity. Moreover, further results of the tests suggest that complex or fine motor performance tests used for diagnosing laterality of the lower limb that have a manipulative character probably do not represent suitable indicators for children in the given age category. The same trend was revealed in both females and males. This indicates that the level of laterality assessed as difference in skilfulness between the preferred and the non-preferred limb in children in the given age group probably develops in the same way in both genders.

Keywords: handedness, footedness, performance tests, laterality, children, fine motor, gross motor

INTRODUCTION

Numerous studies have in the past been dedicated to human laterality, which represent a multidimensional trait (Corballis, 2010). It is well known, for instance, that in the adult population 90% of people prefer to use their right hand for common manual tasks, whereas about 10% of the population are so called left-handers (Annett, 1994; Raymond et al., 1996; Bryden et al., 1997; McManus, 2002). Another important finding is that throughout human life, the development of laterality is a very active process affected by both genetic and environmental factors (see: Porac et al., 1980; Geschwind and Galaburda, 1987; Halpern and Coren, 1991; Annett, 2002; McManus, 2002).

Research into development of laterality in children has shown that it has different phases with respect to ontogenesis. The authors McManus et al. (1988) suggested that handedness in children is generally defined by one basic factor and begins to become fixed around the age of 3; it becomes stabilized and its level increases between 3 and 7 years of age. According to the authors, stabilization gradually weakens between 7 and 9 years of age (McManus et al., 1988). Studies of Cavill and Bryden (2003) or Whittington and Richards (1987) have proven that the development of handedness (right or left) can be determined in children relatively early; which is not entirely true for strength and consistency of handedness (De Gostini et al., 1992). Development of consistency and the level of preference of upper limbs in children has also been studied by authors using so called reaching tasks (e.g., Bryden and Roy, 2006; Carlier et al., 2006), which focused on whether a child would also manipulate with a tool using the preferred upper limb in the case that the tool was placed counter-laterally to the preferred hand. The conclusions of these studies showed that in this kind of motor activity 6- to 10-year-olds children demonstrate significantly more stable consistency of upper limb preference than younger children (Bryden and Roy, 2006; Carlier et al., 2006). Leconte and Fagard (2004), who also used the reaching task approach, revealed that consistency of handedness in children changes with the complexity of the activity which the child is forced to do with his/her upper limb. The authors also add that development of strength and consistency of handedness in children represents an important dynamic process (Leconte and Fagard, 2004).

In comparison with the number of studies on development of the upper-limb laterality, less research has been done into the development of footedness. Coren et al. (1981) found that 3- to 5-year-olds children, as well as a selected population of high-school students, demonstrated a significant right-hand preference. Their findings at the same time revealed that pre-school children had significantly less distinct lower limb preference (Coren et al., 1981). Studies by Gabbard et al. (1991), Gabbard (1992), and Gentry and Gabbard (1995) also found that foot preference in 3- to 5-year-olds children is much less consistent than hand preference. On average, the agreement of upper and lower limb preference in right-handers was 67% while in left-handers it was only 17%. According to the authors, significant stabilization of lower limb preference happens later, between 8 and 11 years of age (Gabbard, 1992; Gentry and Gabbard, 1995). A review study by Gabbard and Iteya (1996) also revealed that in 3- to 5-year-olds mix-footedness appears with twice as much occurrence as mix-handedness (Gabbard and Iteya, 1996). By contrast, Gudmundsson (1993), who studied conformity between upper and lower limb preference in pre-school and younger school children aged 3–11, found 85 and 87% conformity, respectively (Gudmundsson, 1993).

In the diagnosis of laterality, according to Corballis (2009), for example much less attention is paid to the detailed skilled performance approach (Corballis, 2009). The above-mentioned diagnosis of preference allows only a very limited detailed expression of strength of handedness or footedness. Consequently, in past decades performance tests have been created and verified which primarily focus on the difference between the upper limbs in performing the same motor tests (Scharoun and Bryden, 2014). Research has shown that in both children and adults the different skilfulness in terms of speed, precision or correctness of execution of motor activities strongly corresponds with upper limb preference (Peters, 1976; Annett et al., 1979; Rigal, 1992; Carlier et al., 1993; Cornish and McManus, 1996; Nalcaci et al., 2001). Nevertheless, it has also been found that the level of correspondence between preference and performance depends, to a great extent, on the type of performance test. In this context, Annett (1992) observed that the more the activity is of a fine motor character, the more significant the higher skilfulness of the preferred upper limb (Annett, 1992). The authors Roy et al. (1994) and Sainburg and Kalakanis (2000) later added that this considerably higher skilfulness of the preferred upper limb is observed primarily in motor activities in which higher demands are put on: (1) coordination and (2) integration of more segments of the limb, involved in the activity (e.g., shoulder and elbow joints; Roy et al., 1994; Sainburg and Kalakanis, 2000).

Performance tests to evaluate different skilfulness have also been created for lower limbs (see Knights and Moule, 1967; Beling et al., 1998). However, they showed congruency with the determined foot preference solely in the adult population.

In connection with laterality assessment, Rigal (1992), Steenhuis (1999) and Corey et al. (2001) have suggested that for reliable diagnostics, both preference indicators and performance tests should be used because laterality in humans does not represent a unidimensional trait (Rigal, 1992; Steenhuis, 1999; Corey et al., 2001). Even though previous studies focused on the development of upper and lower limb laterality, they mostly assessed development of handedness and footedness and their stability in the child population. The conclusions of studies focused on the question of consistency of upper and lower limb preference in child population suggest that stabilization of lower limb preference represents in children a longer process than stabilization of hand preference (see Gabbard, 1992; Gentry and Gabbard, 1995; Gabbard and Iteya, 1996). However, in connection with this finding we have observed that there are not enough studies attempting to verify whether later stabilization of the lower limb preference is also manifested in the results of performance tests for lower limbs that are used to diagnose laterality in the child population. The results of our previous research have suggested that primarily complex skilled foot performance tests do not show the differences between the preferred and the non-preferred lower limb with sufficient accuracy in 8- to 10-year-olds. In the monograph Musálek (2013), three identical performance tests (for the lower limb) were modeled using the confirmatory factor analysis for the population of 8- to 10-year-olds and for 17- to 19-year-old adolescents. These were complex motor activities which integrated more systems: (1) moving a small object by the lower limb in a limited space and (2) slalom with a tennis ball between obstacles and (3) an activity which focused primarily on speed while performing a simple task – foot tapping. The revealed results were extremely interesting. While in the adolescent population (17- to 19-year-olds), both complex tests had acceptable factor loadings in range: 0.61–0.72 for the modeled factor "foot performance," in 8- to 10-year-olds factor loadings of the tests significantly lower in a range between 0.38–0.43 with respect to the "foot performance" factor. On the other hand, the foot tapping test showed a strong relationship to the "foot tapping" factor in both children and adolescents with factor loads 0.84 and 0.92, respectively. It was also revealed that loads of both complex skilled foot performance tests used in this study were for both children and adolescent populations significantly lower in comparison with complex fine motor tests for the upper limb ("spiral tracing," "dot-filling"; Musálek, 2013). This result could be found due to the fact that upper limbs are primarily designed for manipulation, whereas lower limbs have primarily a postural function (Woodburne and Burkel, 1994, p. 87; Christou et al., 2003; Palastanga and Soames, 2011, p. 202). Therefore, based on this information we assume that in the given category of 8- to 10-year-olds skilled foot performance tests (spiral tracing by small cube; while standing, slalom with ball between obstacles) will show fewer differences and more inconsistencies (i.e., weaker lateralization) than complex tests designed for the upper limbs.

Moreover, a number of studies have also revealed that significant differences exist between males and females concerning consistency of handedness – it has been revealed that there is a significantly higher number of mixed-handers among males (e.g., Whittington and Richards, 1987; Sommer et al., 2008; Johnston et al., 2009). From the point of view of ontogenesis, a very interesting difference between males and females has been revealed in the strength of neural pathways leading into the cerebellum. These pathways which are involved, among other things, in realization of fine motor skills are according to Gurian et al. (2001) significantly stronger in females. Therefore, the second question studied in this research is whether the level of laterality assessed as difference in skilfulness between the preferred and the non-preferred limb will differ in males and in females. We suppose that such difference might be revealed in the form of a different level of relationship factor loadings – in selected performance tests to modeled factors: (1) hand performance, (2) foot performance.

MATERIALS AND METHODS

PARTICIPANTS

A total of 210 typically developing 8- to 10-year-olds ($n = 107$ males and $n = 103$ females; $M_{age} = 9.1$, SD $= \pm 0.78$) from the Czech Republic were recruited for the current study. All participants were pupils of state primary schools in the capital Prague. The selection of the research file was done using the intentional selection process method. The following criteria for selection of participants were used:

(1) pupils were chosen only from schools which had a similar number of pupils in the given age category,
(2) only schools without any specific specialization (e.g., technical, artistic, sport, or linguistic) were selected,
(3) schools and classes with integrated children with special needs were not included in the selection.

As this study draws on the research (validation of variables for diagnosing of motor manifestations of laterality) performed at these selected schools in 2011 and published in 2013 (Musálek, 2013), all participants were chosen from the same schools, as in the previous research. We decided on this concept of an intentional selection process method in order to ensure maximum homogeneity of the file with respect to the findings of 2011.

The 8–10 age category was selected because at this age children's motor skills are harmoniously developed with stable coordination patterns and this age is called the golden age of skill motor development (Ljach, 2002).

Ethics approval was granted by the Ethics Commission of the Faculty of Physical Education and Sport, Charles University. In addition, parental consent was obtained for all individuals.

APPARATUS

In order to verify whether the selected skill performance tests really detect a difference in performance of the preferred and the non-preferred upper and lower limbs, the results of the seven selected skilled performance tests were first correlated with the results of seven observable preference measure tasks (four for handedness, three for footedness). The indicators used for evaluation of hand preference and foot preference have been validated for the Czech child population aged 8–10. Factor loads of hand preference indicators in a range: $\lambda = 0.85$–0.93, generic reliability McDonald $\omega = 0.95$; factor loads of foot preference indicators in a range: $\lambda = 0.66$–0.90, generic reliability McDonald $\omega = 0.81$ (Musálek, 2013). The results of the preference observable measure tasks also served to determine the preferred and the non-preferred limb as a necessary precondition for the selected skilled performance tests to be carried out in accordance with the given rules. Six of the seven observable preference measure tasks have already been used in previous research where theses indicators were approved as valid and reliable either as questionnaire items or preference tasks (e.g., Annett, 1970; Barnsley and Rabovitch, 1970; Oldfield, 1971; Sharman and Kulhavy, 1976; Tapley and Bryden, 1985; Rigal, 1992; Coren, 1993; Bishop et al., 1996; Doyen and Carlier, 2002; Mamolo et al., 2006).

At the same time, all seven performance tests were validated for the Czech child population aged 8–10 years. Five of them – four for handedness: (1) spiral tracing, (2) dot-filling, (3) tweezers and beads, (4) twisting box; and one for footedness: foot tapping – had an acceptable level of factor validity with respect to the modeled factors: (1) hand performance $\lambda = 0.58$–0.82. and (2) foot performance $\lambda = 0.92$. Subsequently approximated generic reliability of the tests modeled only under one factor "Performance of locomotive organs" had value McDonald $\omega = 0.83$. These five tests have already been replicated in the study Scharoun et al. (2013) for the assessment of different performance of the preferred and the non-preferred upper and lower limbs in children with ADHD and their neurotypical controls. The results of this study revealed that all five performance tests are sufficiently sensitive to determine the performance of the preferred and the non-preferred limb and to detect motor problems in children with ADHD (Scharoun et al., 2013).

Preference strength was determined based on laterality quotient calculation, for which equations from previous studies were used (e.g., Humphrey, 1951; Harris, 1958; Bryden et al., 2007; Kalaycioğlu et al., 2008). Each execution in preferential tasks was marked 1 when right limb was used and 0 when the left limb was used.

Laterality quotient for the upper and lower limbs was calculated using the formula

$$LQ = \frac{R - L}{R + L} * 100$$

Hand preference

Throwing on target. The aim of the participant who sits on chair was to throw the foam ball with 58 mm in diameter using one hand to the target which was placed 2 m from participant. Task was repeated three times.

Ring by bell. The examiner places a (metal) bell on the desk in front of the participant so that there was the same distance to both his/her hands. The aim of the participant was to take the bell in one hand and ring it.

Card reaching task (Bishop task). This task included A3 sheet of paper, divided in half by a vertical line The paper contains seven rectangular boxes with the dimensions of 6 cm × 3 cm forming a semicircle. There were seven cards in total in the boxes on the paper, each card having a different, clearly distinguishable color. Each box had its own description: the first box on the left was marked –3 on the shorter side, the second on the left was marked –2, etc., and the last box on the right was marked +3. The middle box on the axis of the paper was marked 0. The aim of the participant was to turn the card with the required color using one hand. The examiner first chooses the color of the card that s/he placed in the box marked 0. If the participant turned this card using the right hand, the examiner required him/her to turn the colored cards in the boxes marked in the following order: +2, –2, +3, –3. If the participant turned this card using the left hand, the examiner required him/her to turn the colored cards in the boxes marked in the following order: –2, +2, –3, +3. Examinator recorded frequency of using right hand or left hand, respectively.

Erasing. The examiner places an erasing rubber with the dimensions of 4.5 cm × 2.5 cm on the desk in front of the participant so that both hands of the participant were in the same distance. Then the examiner asked the participant to erase the prepared drawn line.

Foot preference

Kick to the ball on target. The aim of the participant was to kick the foam ball with 58 mm in diameter in order to hit the wooden block with an edge length of 40 mm placed 2 m from the ball. The kick was performed three times. After each attempt the examiner returned the ball to its original position.

Using one foot, tap the rhythm that I am clapping. The participant sit on a chair in free space. The examiner claps a simple rhythm with a maximum of five claps. The task of the participant was to tap this rhythm on the floor using one lower limb.

Perform jumps forward using one leg. The task of the participant was to perform jumps forward on one leg from examiner to definite point. It was done twice by participant.

Skilled hand performance tests

Spiral tracing. The score sheet contains pre-drawn white spirals of the same shape and length in two gray square boxes with a side length of 50 mm. The largest diameter of the spirals was 41 mm, the thickness (width) of the spiral being 2 mm. The spiral in the right box is intended for the action of the right hand, and the spiral in the left box for the action of the left hand. The aim of the participant was to draw a spiral in the designated area of the spiral-shaped image, from the outer edge to the center. The position of the score sheet hadn't to be changed during the entire test. An error, penalization 2 s, was noted when the participant left the designated area while drawing. This task was completed by non-preferred and preferred hand. The examiner recorded the final time after each drawing.

Dot-filling. There were two boxes with circles on the inside page of the score sheet. The circles in left box are intended for the action of the left hand, and the circles in the right box are intended for the action of the right hand. Each of the boxes contains 90 identical circles. The diameter of a circle is 2 mm. The aim of the participant was to mark dots in the circles, in order to place the dot within the circle in the specified time of 30 s. Only those marks within the circles were counted toward performance. Task was completed by non-preferred and preferred hand.

Moving beads from one box into another using tweezers. This task included two open matchboxes behind each other and a pair of tweezers with a length of 150 mm on the desk in front of the participant so that there is the same distance between both his/her hands and the closer matchbox; the closer matchbox contains 20 beads with 5 mm in diameter, and the second is empty. The aim of the participant was to move the beads one by one from the full box to the empty box using the tweezers in the specified time of 30 s. The task was completed with the preferred and non-preferred hand, where the number of beads transported in 30 s was recorded.

Turning a box alternately with the front and the rear side on the table. This task included a closed empty matchbox with the front facing upward in front of the participant at the midline. The aim of the participant was to turn the matchbox using one hand by its front and back alternately faces the desk. The matchbox had to always touch the desk with one of its parts, i.e., the matchbox hadn't to be lifted from the desk. The task was completed with the preferred and non-preferred hand, where the number of turns in 30 s was recorded.

Skilled foot performance tests

Foot tapping. For this task, the participant stood next to a desk, with the preferred leg closest to the desk The aim of the participant was to perform tapping in a standing position for 30 s using a lower limb so that the motion is performed in the sagittal plane. The participant taught the ground in front of him/her with the heel and the ground behind him/her with the tip, the range of the motion being the length of one foot of the participant. The task was completed with the preferred and non-preferred foot, where the number of tapps in 30 s was recorded (Musálek, 2013).

Unlike the "foot tapping" test, the following two tests (slalom with a ball between obstacles and spiral tracing by small cube) proved valid for adolescent population of selected students from the Czech Republic; however, this is not true for children aged 8–10 (Musálek, 2013). Also due to the previous equivocal results, we used the following skilled foot performance tests in this study: (1) slalom with a ball between obstacles and (2) spiral tracing by small cube; this test was derived from two tests – spiral tracing test used for hand and moving a cube in the "maze" while standing performed by foot. Both tests underwent multiple content validation with instructions and technical parts (tools) adapted so that different performance of the preferred and the non-preferred lower limb could be assessed.

The content validity of both tests was assessed by six selected experts in: anthropology, kinesiology, psychology, motor development, special pedagogy, and neurology.

While standing, slalom with ball between obstacles. This task included eight cubes on the floor in the line. Distance between each two cubes was 10 cm. In distance 15 cm in front of first cube and 15 cm behind last cube was on the floor attached color line. The aim of the participant was to performed slalom with tennis ball with 65 mm in diameter between cubes. Participant could move ball between obstacles only from top. Each contact of the ball and obstacle is error. This error was counted as 2 s penalty. Participant had to go through whole track from line to line. The task was completed with the preferred and non-preferred foot.

Spiral tracing by small cube. This task included A3 sheet of paper which had a spiral drawn on both sides on the floor. The spiral on each side of the paper was 30 cm in diameter with the thickness (width) of the spiral being 4 cm. The aim of the participant was to use the cube provided with a width of 1.5 cm to copy the spiral path in the designated area of the spiral-shaped image, from the outer edge to the center. The spiral had to be copied only by moving the cube by imposing pressure on the side of the cube; it was therefore forbidden to manipulate the cube by placing the sole of the foot on the top of it. An error, penalization 2 s, was noted when the participant left the designated area while copying. This task is completed by non-preferred and preferred foot. This motor test was carried out without preparation. The examiner recorded the final time after each copying.

STATISTICAL ANALYSIS

In order to determine the level of the relationship between the selected preference measure observable tasks and skilled performance tests, biserial and polyserial correlations were used. Consequently, difference in performance of the preferred and the non-preferred limb for each skilled performance indicator were assessed by a paired t-test with the level of statistical significance $p < 0.05$ and substantive significance Cohen $d > 0.7$ (Cohen, 1988). In order to determine possible differences in the structure of hand and foot performance in females and males, the confirmatory factor analysis multigroup modeling approach was used (Muthén and Muthén, 2010). Robust maximum likelihood (Ferron and Hess, 2007; Muthén and Muthén, 2010) was used as the estimate parameter because in our case the multivariate normality of data condition was not fulfilled. The data analysis was done using the statistical software M-Plus 6 (Muthén and Muthén, 2010) and NCSS2007 (Hintze, 2007).

RESULTS

First we analyzed the number and ratio of those that were pronounced: right-sided children, left-sided children and children who at least once changed limbs while performing the preference tasks (see Methods apparatus). Of the 210 participants, 136 children had uncrossed lateral preferences (right-handed and right-footed), (65 males and 71 females) LQ = 100, and 18 children had uncrossed lateral preferences (left-handed and left-footed), (10 males and 8 females) LQ = 0. The LQ of the remaining 56 children (32 males and 24 females) ranged within LQ = 31.25–75.

The subsequent correlation analysis between preference observable measure and skilled hand performance tests is shown in **Table 1**. The tests which detect different skilfulness of the preferred and the non-preferred upper limb manifest sufficient convergent validity with hand preference observable measure: correlation in a range $r = 0.56$–0.89. It follows that the selected hand performance tests have a sufficient capacity to adequately determine the difference between the preferred and the non-preferred upper limb.

On the other hand, **Table 2**, shows that the correlation analysis between foot preference observable measure and skilled foot performance tests revealed that two of three performance tests (slalom between obstacles and spiral tracing with small cube) do not manifest a satisfactory convergent validity $r = 0.25$–0.46 with foot preference observable measure. This finding suggests that fine motor or complex tests for lower limbs lack sufficient sensitivity to distinguish between the preferred and the non-preferred lower limb in the given age group.

Table 1 | Convergent validity between hand preference observable measure and hand performance tests.

Item	Throwing	Ring the bell	Bishop task	Erasing
Spiral tracing	−0.89	−0.84	−0.66	−0.82
Dot-filling	0.70	0.66	0.64	0.63
Twistbox	0.78	0.75	0.64	0.66
Tweezers and beads	0.75	0.70	0.58	0.56

Table 2 | Convergent validity between foot preference tasks and foot performance tests.

Item	Kicking	Tapp rhytmus	Hop forward
Slalom with ball between obstacles	**−0.46**	**−0.33**	**−0.26**
Spiral tracing by small cube	**−0.39**	**−0.43**	**−0.25**
Foot tapping	0.85	0.74	0.65

Correlations lower than 0.50 are shown in boldface.

Next we assessed the capacity of the seven skilled performance tests to determine preferred and non-preferred upper and lower limb by significance of difference in skilfulness of the preferred and the non-preferred limb.

Table 3 shows that all the skilled hand performance tests used were able to significantly determine the difference between skilfulness of the preferred and the non-preferred upper limb, with the preferred upper limb being significantly more precise and quicker $p < 0.05$, *Cohen d* in the tests $d = 0.84$–2.91. On the contrary, the same cannot be said about the results of the foot performance tests. Among them, only the "tapping" test showed significant capacity to determine the difference in skilfulness of the preferred and the non-preferred lower limb $p < 0.05$ and *Cohen d*, $d = 1.22$. The other two tests, which were of a complex motor character, with the "slalom with a ball between obstacles" test having extra demands on balance, did not confirm the significance of the different performance of the preferred and the non-preferred lower limb *Cohen d* ranging within $d = 0.22$–0.27. These results together with findings regarding convergent validity for the lower limb (see **Table 2**) support the hypothesis that fine motor or complex tests for diagnosing lower limb laterality in children of the given age category are not suitable due to their low discrimination capacity between the preferred and the non-preferred lower limb.

Next, we modeled all skilled performance tests in two-factor structure in order to determine whether the relationship between the individual indicators and defined latent variables upper limb performance and lower limb performance do not differ significantly in females and males.

The multigroup model assessed whether the child's gender in the given age group does not represent a significant factor in the process of lateralization. A two-factor model for females and males shows that factor load does not differ significantly for most items. **Table 4** also shows that most indicators detected laterality (differences in skilfulness of the preferred and the non-preferred limb) between males and females aged 8–10 with approximately the same strength. The "foot tapping" performance test was the only exception, revealing significant difference between factor load in males, $r = 0.56$, and females, $r = 0.74$ at the significance level of $p < 0.05$. There could be two reasons for this result. Firstly, possibly in males stabilization of lower limb performance takes

Table 3 | Differences in performances between preferred and non-preferred hand in skilled hand performance tests.

Item	M NP – limb	SD NP – limb	M P – limb	SD P – limb
Hand performance tests				
Spiral tracing	79.3 s	23.4	44.2* s	13.8
Dot-filling	12.2 dots	5.1	34.3* dots	8.3
Tweezers and beads	7.9 beads	1.7	12.1* beads	2.1
Twistbox	38.4 twists	4.9	43.3* twists	5.1
Foot performance tests				
Slalom with ball between obstacles	53.7 s	17.8	50.9 s	16.6
Spiral tracing by small cube	43.7 s	16.4	42.1 s	15.8
Tapping foot	32.4 tapps	7.1	41.2* tapps	7.3

*NP – limb, non-preferred limb; P – limb, preferred limb; *significant difference between performance of non-preferred and preferred limb $p < 0.05$.*

Table 4 | Factor loadings of the 2-factor model – factors: (1) upper limb performance and (2) lower limb performance.

Factors and used performance tests	Male		Female	
	λ	Uniq	λ	Uniq
Upper limb performance factor				
Spiral tracing	−0.84	0.25	−0.78	0.43
Dot-filling	0.78	0.39	0.87	0.24
Twistbox	0.63	0.56	0.67	0.55
Tweezers and beads	0.47	0.76	0.58	0.67
Lower limb performance factor				
Slalom with ball between obstacles	−0.32	0.86	−0.38	0.74
Spiral tracing by small cube	−0.30	0.89	−0.26	0.92
Tapping foot	0.56*	0.69	0.74*	0.44

*Names of factors are in boldface; λ, factor loading; Uniq, uniqueness - residual variance; *significant difference between factor loadings $p < 0.05$.*

longer. Or secondly, that on the contrary the smaller difference in performance of the right and the left lower limb is caused by the relationship between the character of the test and a certain environmental factor.

DISCUSSION

The aim of the study was to verify in a selected child population whether later stabilization of lower limb preference in comparison to hand preference determined in children (Coren et al., 1981; Gabbard et al., 1991; Gabbard, 1992; Gentry and Gabbard, 1995) is also manifested in lower consistency of performance test results for lower limbs used for the diagnosis of laterality. Within this question we have further studied whether the speed of lateralization diagnosed by selected indicators differs with respect to gender.

First, diagnosis of upper and lower limb preference was carried out using validated measure observable tasks.

Polyserial correlation between all selected skilled hand performance tests and hand measure observable task clearly demonstrated significant convergent validity ranging within $r = 0.56$–0.89. On the other hand, very weak correlations with foot preference ranging within $r = 0.25$–0.46 were determined in polyserial correlation between foot preference tasks and skilled foot performance tests in "slalom between obstacles" and "spiral tracing with small cube" tests. Consequently, convergence was not confirmed for two-foot performance tests and preference tasks, which suggests that lower limb lateralization in children is probably not identical in strength with upper limb lateralization. *t*-test results showed that selected indicators, which have also been validated for the Czech population, assessing upper limb preference in 8- to 10-year olds determine the difference between the preferred and the non-preferred upper limb $p < 0.05$ very well, with the non-preferred upper limb always being slower and less precise. This is in line with the conclusions of studies demonstrating that different skilfulness in speed, precision and correctness of execution of the motor activity strongly corresponds with the preferred upper limb in children (i.e., Annett et al., 1979; Rigal, 1992; Carlier et al., 1993; Cornish and McManus, 1996; Nalcaci et al., 2001). Moreover, these results also correspond with the conclusions of studies (Whittington and Richards, 1987; McManus et al., 1988; Cavill and Bryden, 2003; Bryden and Roy, 2006; Carlier et al., 2006) which show that between 6 and 10 years of age stability of hand preference in children is quite firm. In this respect it was also proved that the finer the motor activity, the bigger the differences between the performance of the preferred and the non-preferred upper limb, which confirms the arguments of Annett (1992). The biggest differences between performance of the preferred and the non-preferred upper limbs were found in complex tests with high demands on coordination ("spiral tracing" and "dot-filling"). This supports hypotheses made by Roy et al. (1994) and Sainburg and Kalakanis (2000) or Scharoun et al. (2013). They claim that significantly higher skilfulness of the preferred upper limb is observed in activities in which more segments of the given limb (e.g., shoulder and elbow joint) are involved at the same time (Roy et al., 1994; Sainburg and Kalakanis, 2000; Scharoun et al., 2013).

However, the results of the performance tests selected for the lower limb did not clearly detect a difference in skilfulness of the preferred and the non-preferred lower limb and thus confirmed problems detected with convergent validity in some skilled foot performance tests. Two out of three tests used ("slalom between obstacles" and "spiral tracing with small cube"), which compared to the tapping test by lower limb are more complex and have a finer motor character, revealed insignificant differences in performance between the preferred and the non-preferred lower limb. It is interesting to note that the "slalom between obstacles test" is validized in the CR for the adult population, in which no problems appeared in detecting difference in performance of the preferred and non-preferred lower limb. These findings are in conformity with studies (Knights and Moule, 1967; Beling et al., 1998) which revealed agreement of results of performance tests with determined foot preference solely in the child population. The revealed low sensitivity of complex and fine motor laterality performance tests for lower limb in children could be related to the detected longer stabilization process of the lower limb preference (Coren et al., 1981; Gabbard et al., 1991; Gabbard, 1992; Gentry and Gabbard, 1995; Gabbard and Iteya, 1996). This shows that lower limb performance in children is limitary. Paradoxically, too fine motor tests or too complex tests with high demands on coordination cannot determine the difference between the preferred and the non-preferred lower limb based on the results. Finally, we verified whether the lateralization process of the upper and lower limbs assessed by performance tests happens differently for females and males at this age. A two-factor model where all seven skilled performance tests were tested showed that the sensitivity of the selected indicators for detecting laterality of the upper and lower limbs is quite similar for both genders. This means that the lateralization process for the upper and lower limbs is probably quite similar in females and males at this age. The only difference of some significance revealed was related to factor load of the "foot tapping" test in females $r = 0.74$ and males $r = 0.56$ with factor validity coefficient for females being significantly $p < 0.05$ higher in comparison with factor validity of this indicator in males. This difference might be explained by some environmental factors, in males primarily by collective sports where both lower limbs are used (e.g., football). Consequently, the "foot tapping" test might not be sensitive enough to determine the difference between the preferred and the non-preferred lower limb in males. On the other hand, in females, who are not affected by these environmental factors, or are affected to a much smaller extent, the "foot tapping" test determined the difference between the preferred and the non-preferred lower limbs very well.

CONCLUSION

It was revealed that in skilled hand performance tests, the more complex and more demanding in terms of coordination the motor activity is, the bigger the differences there are between the preferred and the non-preferred upper limb. However, the same result was not proved in skilled foot performance tests. On the contrary, the more demanding the lower limb tests were, the worse the convergence validity of these tests in connection to preference tasks. This finding in children could be related to a longer stabilization process of the lower limb preference (see Coren et al., 1981; Gabbard et al., 1991; Gabbard, 1992; Gentry and Gabbard, 1995). It is interesting to note that the lateralization process assessed by difference in performance in skilled performance tests happens in parallel in both genders.

ACKNOWLEDGMENT

This work was supported by project PRVOUK39, Social-Sciences Aspects of Human Movement Studies.

REFERENCES

Annett, J., Annett, M., Hudson, P. T., and Turner, A. (1979). The control of movement in the preferred and non-preferred hands. *Q. J. Exp. Psychol.* 31, 641–652. doi: 10.1080/14640747908400755

Annett, M. (1970). A classification of hand preference by association analysis. *Br. J. Psychol.* 61, 303–321. doi: 10.1111/j.2044-8295.1970.tb01248.x

Annett, M. (1992). Five tests of hand skill. *Cortex* 28, 583–600.

Annett, M. (1994). Handedness as a continuous variable with dextral shift: sex, generation, and family handedness in subgroups of left- and right-handers. *Behav. Genet.* 24, 51–63. doi: 10.1007/BF01067928

Annett, M. (2002). *Handedness and Brain Asymmetry: The Right Shift Theory.* Hove: Psychology Press.

Barnsley, R. H., and Rabovitch, S. (1970). Handedness: Proficiency versus state preference. *Percept. Mot. Skills* 30, 343–362. doi: 10.2466/pms.1970.30.2.343

Beling, J., Wolfe, G. A., Allen, K. A., and Boyle, J. M. (1998). Lower extremity preference during gross and fine motor skills performed in sitting and standing postures. *J. Orthop. Sports Phys. Ther.* 28, 400–404. doi: 10.2519/jospt.1998.28.6.400

Bishop, D. V. M., Ross, V., Daniels, M. S., and Bright, P. (1996). The measurement of hand preference: a validation study comparing three groups of right-handers. *Br. J. Psychol.* 87, 269–285. doi: 10.1111/j.2044-8295.1996.tb02590.x

Bryden, M. P., Roy, E. A., Mcmanus, I. C., and Bulman-Fleming, M. B. (1997). On the genetics and measurement of human handedness. *Laterality* 2, 317–336. doi: 10.1080/713754269

Bryden, P. J., and Roy, E. A. (2006). Preferential reaching across regions of hemispace in adults and children. *Dev. Psychobiol.* 48, 121–132. doi: 10.1002/dev.20120

Bryden, P. J., Roy, E. A., and Spence, J. (2007). An observational method of assessing handedness in children and adults. *Dev. Neuropsychol.* 32, 825–846. doi: 10.1080/87565640701539667

Carlier, M., Doyen, A.-L., and Lamard, C. (2006). Midline crossing: developmental trend from 3 to 10 years of age in a preferential card-reaching task. *Brain Cogn.* 61, 255–261. doi: 10.1016/j.bandc.2006.01.007

Carlier, M., Duyme, M., Capron, C., Dumont, A. M., and Perez-Diaz, F. (1993). Is a dot-filling group test a good tool for assessing manual performance in children? *Neuropsychologia* 31, 233–240. doi: 10.1016/0028-3932(93)90087-G

Cavill, S., and Bryden, P. (2003). Development of handedness: comparison of questionnaire and performance-based measures of preference. *Brain Cogn.* 53, 149–151. doi: 10.1016/S0278-2626(03)00098-8

Christou, E. A., Zelent, M., and Carlton, L. G. (2003). Force control is greater in the upper compared with the lower extremity. *J. Mot. Behav.* 35, 322–324. doi: 10.1080/00222890309603153

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* Hillsdale, NJ: L. Erlbaum Associates.

Corballis, M. C. (2009). The evolution and genetics of cerebral asymmetry. *Philos. Trans. R. Soc. B Biol. Sci.* 364, 867–879. doi: 10.1098/rstb.2008.0232

Corballis, M. C. (2010). "Handedness and cerebral asymmetry," in *The Two Halves of the Brain: Information Processing in the Cerebral Hemispeheres*, eds K. Hugdahl, and R. Westernhausen (Cambridge, MA: MIT Press), 65–88. doi: 10.7551/mitpress/9780262014137.003.0063

Coren, S. (1993). The lateral preference inventory for measurement of handedness, footedness, eyedness and earedness: norms for young adults. *Bull. Psychon. Soc.* 31, 1–3. doi: 10.3758/BF03334122

Coren, S., Porac, C., and Duncan, P. (1981). Lateral preference behaviors in preschool children and young adults. *Child Dev.* 52, 443–450. doi: 10.2307/1129160

Corey, D., Hurley, M., and Foundas, A. L. M. (2001). Right and left handedness defined: a multivariate approach using hand preference and hand performance measures. *Neuropsychiatry Neuropsychol. Behav. Neurol.* 14, 144–152.

Cornish, K. M., and McManus, I. C. (1996). Hand preference and hand skill in children with autism. *J. Autism. Dev. Disord.* 26, 597–609. doi: 10.1007/BF02172349

De Gostini, M., Pareé, C., Goudot, D., and Dellatolas, G. (1992). Manual preference and skill development in preschool children. *Dev. Neuropsychol.* 8, 41–57. doi: 10.1080/87565649209540514
Doyen, A. L., and Carlier, M. (2002). Measuring handedness: a validation study of Bishop's reaching card test. *Laterality* 7, 115–130. doi: 10.1080/13576500143000140
Ferron, J. M., and Hess, M. R. (2007). Estimation in SEM: a concrete example. *J. Educ. Behav. Stat.* 32, 110–120. doi: 10.3102/1076998606298025
Gabbard, C. (1992). Associations between hand and foot preference in 3- to 5-year-olds. *Cortex* 28, 497–502. doi: 10.1016/S0010-9452(13)80158-X
Gabbard, C., Dean, M., and Haensly, P. (1991). Foot preference behavior during early childhood. *J. Appl. Dev. Psychol.* 12, 131–137. doi: 10.1016/0193-3973(91)90036-4
Gabbard, C., and Iteya, M. (1996). Foot laterality in children, adolescents, and adults. *Laterality* 1, 199–205. doi: 10.1080/713754236
Gentry, V., and Gabbard, C. (1995). Foot-preference behavior: a developmental perspective. *J. Gen. Psychol.* 122, 37–45. doi: 10.1080/00221309.1995.9921220
Geschwind, N., and Galaburda, A. (1987). *Cerebral Lateralization: Biological Mechanisms Associations and Patology.* Cambridge, MA: MIT Press.
Gudmundsson, E. (1993). Lateral preference of preschool and primary school children. *Percept. Mot. Skills* 77, 819–828. doi: 10.2466/pms.1993.77.3.819
Gurian, M., Henley, P., and Trueman, T. (2001). *Boys and Girls Learn Differently: A Guide for Teachers and Parents.* San Francisco, CA: Jossey-Bass.
Halpern, D. F., and Coren, S. (1991). Handedness and life span. *N. Engl. J. Med.* 324, 998. doi: 10.1056/NEJM199104043241418
Harris, A. J. (1958). *Harris Tests of Lateral Dominance, Manual of Direction for Administration and Interpretation*, 3rd Edn. New York: The Psychological Corporation.
Hintze, J. (2007). *NCSS 2007. NCSS, LLC.* Kaysville, UT. Available at: www.ncss.com
Humphrey, M. (1951). *Handedness and Cerebral Dominance.* B.Sc, thesis, Oxford University, Oxford.
Johnston, D. W., Nicholls, M. E. R., Shah, M., and Shields, M. A. (2009). Nature's experiment?: handedness and early childhood development. *Demography* 46, 281–301. doi: 10.1353/dem.0.0053
Kalaycioğlu, C., Kara, C., Atbaşoğlu, C., and Nalçaci, E. (2008). Aspects of foot preference: differential relationships of skilled and unskilled foot movements with motor asymmetry. *Laterality* 13, 124–142. doi: 10.1080/13576500701701704
Knights, R. M., and Moule, A. D. (1967). Normative and reliability data on finger and foot tapping in children. *Percept. Mot. Skills* 25, 717–720. doi: 10.2466/pms.1967.25.3.717
Leconte, P., and Fagard, J. (2004). Influence of object spatial location and task complexity on children's use of their preferred hand depending on their handedness consistency. *Dev. Psychobiol.* 45, 51–58. doi: 10.1002/dev.20019
Ljach, W. (2002). The effect of genetic and Environmental Factors on the Development of Motor Coordination Abilities in Children Aged 7-10 Years. *Physic. Educ. Sport* 46, 267–276.
Mamolo, C., Roy, E., Rohr, L., and Bryden, P. J. (2006). Reaching patterns across working space: the effects of handedness, task demands, and comfort levels. *Laterality* 11, 465–492. doi: 10.1080/13576500600775692
McManus, C. (2002). *Right Hand Left Hand: The Origins of Asymmetry in Brains, Bodies, Atoms and Culture.* Cambridge, MA: Harvard University Press.
McManus, I. C., Sik, G., Cole, D. R., Mellon, A. F., Wong, J., and Kloss, J. (1988). The development of handedness in children. *Br. J. Dev. Psychol.* 6, 257–273. doi: 10.1111/j.2044-835X.1988.tb01099.x
Musálek, M. (2013). *Development of Test Batteries for Diagnostics of Motor Laterality Manifestation – Link between Cerebellar Dominance and Hand Performance.* Praha: Karolinum.
Muthén, L. K., and Muthén, B. O. (2010). *Mplus: Statistical Analysis with Latent Variables: User's Guide.* Los Angeles, CA: Muthén & Muthén.
Nalcaci, E., Kalaycioglu, C., Cicek, M., and Genc, Y. (2001). The relationship between handedness and fine motor performance. *Cortex* 37, 493–500. doi: 10.1016/S0010-9452(08)70589-6
Oldfield, R. C. (1971). The assessment and analysis of handeness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113. doi: 10.1016/0028-3932(71)90067-4
Palastanga, N., and Soames, R. (2011). *Anatomy and Human Movement: Structure and Function.* Edinburgh: Churchill Livingstone.
Peters, M. (1976). Prolonged practise of a simple motor task by preferred and non-preferred hands. *Percept. Mot. Skills* 43, 447–450. doi: 10.2466/pms.1976.43.2.447
Porac, C., Coren, S., and Duncan, P. (1980). Life-span age trends in laterality. *J. Gerontol.* 35, 715–721. doi: 10.1093/geronj/35.5.715
Raymond, M., Pontier, D., Dufour, A.-B., and Moller, A. P. (1996). Frequency-dependent maintenance of left handedness in humans. *Proc. R. Soc. B Biol. Sci.* 263, 1627–1633. doi: 10.1098/rspb.1996.0238
Rigal, R. A. (1992). Which handedness: preference or performance? *Percept. Mot. Skills* 75, 851–866. doi: 10.2466/pms.1992.75.3.851
Roy, E. A., Kalbfleisch, L., and Elliott, D. (1994). Kinematic analyses of manual asymmetries in visual aiming movements. *Brain Cogn.* 24, 289–295. doi: 10.1006/brcg.1994.1017
Sainburg, R. L., and Kalakanis, D. (2000). Differences in control of limb dynamics during dominant and nondominant arm reaching. *J. Neurophysiol.* 83, 2661–2675.
Scharoun, S. M., and Bryden, P. J. (2014). Hand preference, performance abilities, and hand selection in children. *Front. Psychol.* 5:82. doi: 10.3389/fpsyg.2014.00082
Scharoun, S., Bryden, P., Otipkova, Z., Musalek, M., and Lejcarova, A. (2013). Motor skills in Czech children with attention-deficit/hyperactivity disorder and their neurotypical counterparts. *Res. Dev. Disabil.* 43, 4142–4153. doi: 10.1016/j.ridd.2013.08.011
Sharman, J. L., and Kulhavy, R. W. (1976). The assessment of cerebral laterality: the Sharman-Kulhavy laterality assessment inventory: some validaton data. *Percept. Mot. Skill* 42:1314. doi: 10.2466/pms.1976.42.3c.1314
Sommer, I. E., Somers, M., Boks, M. P., Kahn, R. S., and Aleman, A. (2008). Sex differences in handedness, asymmetry of the planum temporale and functional language lateralization. *Brain Res.* 1206, 76–88. doi: 10.1016/j.brainres.2008.01.003
Steenhuis, R. E. (1999). The relation between hand preference and hand performance: what you get depends on what you measure. *Laterality* 4, 3–26. doi: 10.1080/713754324
Tapley, S. M., and Bryden, M. P. (1985). A group test for the assessment of performance between the hands. *Neuropsychologia* 23, 215–221. doi: 10.1016/0028-3932(85)90105-8
Whittington, J., and Richards, P. N. (1987). The stability of children's laterality prevalences and their relationship to measures of performance. *Br. J. Educ. Psychol.* 57, 45–55. doi: 10.1111/j.2044-8279.1987.tb03060.x
Woodburne, R. T., and Burkel, W. E. (1994). *Essentials of Human Anatomy.* New York: Oxford University Press.

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 30 September 2014; accepted: 08 December 2014; published online: 12 January 2015.
Citation: Musalek M (2015) Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. Front. Psychol. 5:1513. doi: 10.3389/fpsyg.2014.01513
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology.

Chapter 2

References:

Amunts, K., Jäncke, L., Mohlberg, H., Steinmetz, H., & Zilles, K. (2000). Interhemispheric asymmetry of the human motor cortex related to handedness and gender. *Neuropsychologia*, *38*(3), 304-312.

Annett, M. (1985). *Left, right, hand and brain: The right shift theory*. Psychology Press (UK).

Annett, M. (1992). Five tests of hand skill. *Cortex*, *28*(4), 583-600.

Annett, M. (2002). *Handedness and Brain Asymmetry*. London: Psychology Press. Associates

Annett, J., Annett, M., Hudson, P. T. W., & Turner, A. (1979). The control of movement in the preferred and non-preferred hands. *The Quarterly journal of experimental psychology*, *31*(4), 641-652.

Ayres, A. J. (1980). *Southern California sensory integration tests manual*. Western psychological services,

Barnsley, R. H., & Rabinovitch, M. S. (1970). Handedness: Proficiency versus stated preference. *Perceptual and Motor Skills*, *30*(2), 343-362.

Beling, J., Wolfe, G. A., Allen, K. A., & Boyle, J. M. (1998). Lower extremity preference during gross and fine motor skills performed in sitting and standing postures. *Journal of Orthopaedic & Sports Physical Therapy*, *28*(6), 400-404.

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological bulletin*, *107*(2), 238-246.

Bishop, D. V. (2005). Handedness and specific language impairment: A study of 6-year-old twins. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology*, *46*(4), 362-369.

Bishop, D. V. M., Ross, V. A., Daniels, M. S., & Bright, P. (1996). The measurement of hand preference: A validation study comparing three groups of right-handers. *British journal of psychology*, *87*(2), 269-285.

Blöte, A. W., & Hamstra-Bletz, L. (1991). A longitudinal study on the structure of handwriting. *Perceptual and motor skills*, *72*(3), 983-994.

Bochner, S. (1978). Ayres, sensory integration and learning disorders: A question of theory and practice. *Australian Journal of Mental Retardation*, *5*(2), 41-45.

Bollen, K. A. (2002). Latent variables in psychology and the social sciences. *Annual review of psychology*, *53*(1), 605-634.

Brown, M. B., & Benedetti, J. K. (1977). On the mean and variance of the tetrachoric correlation coefficient. *Psychometrika*, *42*(3), 347-355.

Brown, T. A. (2006). *Confirmatory factor analysis for applied research*. New York: Guilford Press

Bryden, M. P. (1977). Measuring handedness with questionnaires. Neuropsychologia, 15(4–5), 617-624.

Bryden, M. P., Ardila, A., & Ardila, O. (1993). Handedness in native Amazonians. *Neuropsychologia*, *31*(3), 301-308.

Bryden, P. J., & Roy, E. A. (2006). Preferential reaching across regions of hemispace in adults and children. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology*, *48*(2), 121-132.

Bryden, P. J., Roy, E. A., & Spence, J. (2007). An observational method of assessing handedness in children and adults. *Developmental Neuropsychology*, *32*(3), 825-846.

Burtscher, J., Furtner, M., Sachse, P., & Burtscher, M. (2011). Validation of a German version of the Sport Motivation Scale (SMS28) and motivation analysis in competitive mountain runners. *Perceptual and motor skills*, *112*(3), 807-820.

Calvert, G. A. (1998). Quantifying hand preference using a behavioural continuum. *Laterality: Asymmetries of Body, Brain and Cognition*, *3*(3), 255-268.

Carlier, M., Doyen, A. L., & Lamard, C. (2006). Midline crossing: developmental trend from 3 to 10 years of age in a preferential card-reaching task. *Brain and Cognition*, *61*(3), 255-261.

Carlier, M., Duyme, M., Capron, C., Dumont, A. M., & Perez-Diaz, F. (1993). Is a dot-filling group test a good tool for assessing manual performance in children?. *Neuropsychologia*, *31*(3), 233-240.

Cavill, S., & Bryden, P. (2003). Development of handedness: comparison of questionnaire and performance-based measures of preference. *Brain and cognition*, *53*(2), 149-151.

Cermak, S. A., Quintero, E. J., & Cohen, P. M. (1980). Developmental age trends in crossing the body midline in normal children. *American Journal of Occupational Therapy*, *34*(5), 313-319.

Christou, E. A., Zelent, M., & Carlton, L. G. (2003). Force control is greater in the upper compared with the lower extremity. *Journal of motor behavior*, *35*(4), 322-324.

Chusid, J. G. (1982). *Correlative Neuroanatomy and Functional Neurology*. 18th ed. Los Altos, California: Lange Medical Publication

Corballis, M. C. (2008). The evolution and genetics of cerebral asymmetry. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1519), 867-879.

Coren, S. (1993). The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms for young adults. *Bulletin of the Psychonomic Society*, *31*(1), 1-3.

Coren, S., Porac, C., & Duncan, P. (1981). Lateral preference behaviors in preschool children and young adults. *Child Development*, 443-450.

Corey, D. M., Hurley, M. M., & Foundas, A. L. (2001). Right and left handedness defined: a multivariate approach using hand preference and hand performance measures. *Cognitive and Behavioral Neurology*, *14*(3), 144-152.

Cornish, K. M., & McManus, I. C. (1996). Hand preference and hand skill in children with autism. *Journal of Autism and Developmental Disorders*, *26*(6), 597-609.

Costello, A. B., & Osborne, J. W. (2005). Best practices in exploratory factor analysis: Four recommendations for getting the most from your analysis. *Practical assessment, research & evaluation*, *10*(7), 1-9.

Crovitz, H. F., & Zener, K. (1962). A group-test for assessing hand-and eye-dominance. *The American journal of psychology*, *75*(2), 271-276.

Divgi, D. R. (1979). Calculation of the tetrachoric correlation coefficient. *Psychometrika*, *44*(2), 169-172.

Domellöf, E., Johansson, A. M., & Rönnqvist, L. (2011). Handedness in preterm born children: a systematic review and a meta-analysis. *Neuropsychologia*, *49*(9), 2299-2310.

Doyen, A. L., & Carlier, M. (2002). Measuring handedness: A validation study of Bishop's reaching card test. *Laterality: Asymmetries of Body, Brain and Cognition*, *7*(2), 115-130.

Dragovic, M. (2004). Towards an improved measure of the Edinburgh Handedness Inventory: A one-factor congeneric measurement model using confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition*, *9*(4), 411-419.

Dragovic, M., Milenkovic, S., & Hammond, G. (2008). The distribution of hand preference is discrete: a taxometric examination. *British Journal of Psychology*, *99*(4), 445-459.

Fride, E., & Weinstock, M. (1989). Alterations in behavioral and striatal dopamine asymmetries induced by prenatal stress. *Pharmacology Biochemistry and Behavior*, *32*(2), 425-430.

Gabbard, C. (1996). Foot laterality in children, adolescents, and adults. *Laterality: Asymmetries of Body, Brain and Cognition*, *1*(3), 199-206.

Gabbard, C., Dean, M., & Haensly, P. (1991). Foot preference behavior during early childhood. *Journal of Applied Developmental Psychology*, *12*(1), 131-137.

Gentry, V., & Gabbard, C. (1995). Foot-preference behavior: a developmental perspective. *The Journal of General Psychology*, *122*(1), 37-45.

Geschwind, N., & Galaburda, A. M. (1987). *Cerebral lateralization: Biological mechanisms, associations, and pathology*. MIT press.

Groen, M. A., Whitehouse, A. J., Badcock, N. A., & Bishop, D. V. (2013). Associations between handedness and cerebral lateralisation for language: a comparison of three measures in children. *PLoS One*, *8*(5), e64876.

Gurian, M. (2010). *Boys and girls learn differently! A guide for teachers and parents: Revised 10th anniversary edition*. John Wiley & Sons.

Harris A. J. (1958). *Harris Tests of Lateral Dominance, Manual of Direction for Administration and Interpretation* 3rd Edn. New York: The Psychological Corporation.

Harris, L. J. (1990). Cultural influences on handedness: Historical and contemporary theory and evidence. In *Advances in psychology* (Vol. 67, pp. 195-258). North-Holland.

Healey, J. M., Liederman, J., & Geschwind, N. (1986). Handedness is not a unidimensional trait. *Cortex*, *22*(1), 33-53.

Hill, E., & Bishop, D. V. (1998). A reaching test reveals weak hand preference in specific language impairment and developmental co-ordination disorder. *Laterality: Asymmetries of Body, Brain and Cognition*, *3*(4), 295-310.

Humphrey M. (1951). *Handedness and Cerebral Dominance.* B.Sc, thesis, Oxford University; Oxford

Johnston, D. W., Nicholls, M. E., Shah, M., & Shields, M. A. (2009). Nature's experiment? Handedness and early childhood development. *Demography*, *46*(2), 281-301.

Jöreskog, K. G. (1994). On the estimation of polychoric correlations and their asymptotic covariance matrix. *Psychometrika*, *59*(3), 381-389.

Jöreskog, K. G., Sörbom, D., & Du Toit, S. H. C. (2001). *LISREL 8: New statistical features*. Scientific Software International.

Junaid, K. A., & Fellowes, S. (2006). Gender differences in the attainment of motor skills on the movement assessment battery for children. *Physical & Occupational Therapy in Pediatrics*, *26*(1-2), 5-11.

Kalaycıoğlu, C., Kara, C., Atbaşoğlu, C., & Nalçacı, E. (2008). Aspects of foot preference: Differential relationships of skilled and unskilled foot movements with motor asymmetry. *Laterality*, *13*(2), 124-142.

Kandel, E. R., Schwarz, J. H., Jessell, T. M. (2000). *Principles of neural science*. 4th ed. New York: McGraw Hill.

Kang, Y., & Harris, L. J. (2000). Handedness and footedness in Korean college students. *Brain and cognition*, *43*(1-3), 268-274.

Kauranen, K., & Vanharanta, H. (1996). Influences of aging, gender, and handedness on motor performance of upper and lower extremities. *Perceptual and motor skills*, *82*(2), 515-525.

Kline, R. B. (2011). *Principles and practice of structural equation* (3rd ed.). New York: Guildford Press.

Knights, R. M., & Moule, A. D. (1967). Normative and reliability data on finger and foot tapping in children. *Perceptual and motor skills*, *25*(3), 717-720.

Kokštejn, J., Musálek, M., & Tufano, J. J. (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

Komarc, M., Harbichová, I. (2015). Analýza meziskupinových rozdílů pomocí strukturálního modelování: možnosti využití v pedagogickém a psychologickém výzkumu, [Analysis of between-group differences using structural equation modeling: potential use in pedagogical and psychological research], *Česká kinantropologie, 19*(4), 15-22.

Lane, S., Raymond, M. R., & Haladyna, T. M. (Eds.). (2015). *Handbook of test development*. Routledge.

Leconte, P., & Fagard, J. (2004). Influence of object spatial location and task complexity on children's use of their preferred hand depending on their handedness consistency. *Developmental Psychobiology*, *45*(2), 51-58.

Leonard, M. T. (1960). *An analysis of the relationship of selected eye-hand factors to success in eye-hand skill* (Doctoral dissertation, Boston University).

Liederman, J. (1983). Mechanisms underlying instability in the development of hand preference. In *Manual specialization and the developing brain* (pp. 71-92). Academic Press.

Liederman, J., & Healey, J. M. (1986). Independent dimensions of hand preference: Reliability of the factor structure and the handedness inventory. *Archives of Clinical Neuropsychology*, *1*(4), 371-386.

Ljach, W. (2002). The Effects Of Genetic and Environmental Factors on the Development of Motor Coordination Abilities in Children Aged 7-10 Years. *Wychowanie Fizyczne I Sport*, *46*(2), 267-276.

Mamolo, C. M., Roy, E. A., Rohr, L. E., & Bryden, P. J. (2006). Reaching patterns across working space: the effects of handedness, task demands, and comfort levels. *Laterality*, *11*(5), 465-492.

Marques, A., Ekelund, U., & Sardinha, L. B. (2016). Associations between organized sports participation and objectively measured physical activity, sedentary time and weight status in youth. *Journal of Science and Medicine in Sport*, *19*(2), 154-157.

McDonald, R. *P. Faktorová analýza a příbuzné metody v psychologii. 1. vyd., Praha: Academia, 1991, 256 s*. ISBN 80-200-0081-X. Translation Blahuš, P. from original: *Factor Analysis and Related Methods*

McDonald, R. P. (1999). *Test theory: A unified treatment*. Mahwah, N. J: L. Erlbaum

McFarland, K., & Anderson, J. (1980). Factor stability of the Edinburgh Handedness Inventory as a function of test-retest performance, age and sex. *British Journal of Psychology*, *71*(1), 135-142.

McManus, C. (2004). *Right hand, left hand: The origins of asymmetry in brains, bodies, atoms and cultures*. Harvard University Press.

McManus, I. C. (1991, February). The inheritance of left-handedness. In *Ciba Found Symp* (Vol. 162, No. 251281.8).

McManus, I. C., Sik, G., Cole, D. R., Mellon, A. F., Wong, J., & Kloss, J. (1988). The development of handedness in children. *British Jounral of Developmental Psychology.* 6, 257–273.doi: 10.1111/j.2044-835X.1988.tb01099.x

Medland, S. E., Perelle, I., De Monte, V., & Ehrman, L. (2004). Effects of culture, sex, and age on the distribution of handedness: An evaluation of the sensitivity of three measures of handedness. *Laterality: Asymmetries of Body, Brain and Cognition*, *9*(3), 287-297.

Musalek, M. (2015). Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. *Frontiers in psychology*, *5*, 1513.

Musálek, M., Scharoun, S., & Bryden, P. J. (2015). The link between cerebellar dominance and skilled hand performance in 8- to 10-year-old right- handed children. *Journal of Motor Behavior. 47*(5), 386–396.

Musálek. M. (2012). Dimensionality of indicators in questionnaire for diagnostics of hand and foot preference – adult population. *Acta Universitatis Carolinae Kinanthropologica, 48*(2), 27-36.

Muthén, B. (1984). A general structural equation model with dichotomous, ordered categorical, and continuous latent variable indicators. *Psychometrika*, *49*(1), 115-132.

Muthén, B., & Hofacker, C. (1988). Testing the assumptions underlying tetrachoric correlations. *Psychometrika*, *53*(4), 563-577.

Muthén, L. K., & Muthén, B. O. (2010). *Mplus user's guide: Statistical analysis with latent variables: User'ss guide*. Muthén & Muthén.

Nalcaci, E., Kalaycioğlu, C., Çiçek, M., & Genç, Y. (2001). The relationship between handedness and fine motor performance. *Cortex*, *37*(4), 493-500.

Nicholls, M. E., Thomas, N. A., Loetscher, T., & Grimshaw, G. M. (2013). The Flinders Handedness survey (FLANDERS): a brief measure of skilled hand preference. *Cortex*, *49*(10), 2914-2926.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113.

Palastanga, N., & Soames, R. (2011). *Anatomy and human movement, structure and function with PAGEBURST access, 6: anatomy and human movement*. Elsevier Health Sciences.

Peters, M. (1976). Prolonged practice of a simple motor task by preferred and nonpreferred hands. *Perceptual and Motor Skills*, *43*(2), 447-450.

Peters, M., & Murphy, K. (1993). Factor analyses of pooled hand questionnaire data are of questionable value. *Cortex*, *29*(2), 305-314.

Pool, E. M., Rehme, A. K., Eickhoff, S. B., Fink, G. R., & Grefkes, C. (2015). Functional resting-state connectivity of the human motor network: differences between right-and left-handers. *NeuroImage*, *109*, 298-306.

Powls, A., Botting, N., Cooke, R. W., & Marlow, N. (1996). Handedness in very-low-birthweight (VLBW) children at 12 years of age: relation to perinatal and outcome variables. *Developmental Medicine & Child Neurology*, *38*(7), 594-602.

Provine, R. R., & Westerman, J. A. (1979). Crossing the midline: Limits of early eye-hand behavior. *Child Development*, 437-441.

Reissland, N., Aydin, E., Francis, B., & Exley, K. (2015). Laterality of foetal self-touch in relation to maternal stress. *Laterality: Asymmetries of Body, Brain and Cognition*, *20*(1), 82-94.

Rigal, R. A. (1992). Which handedness: preference or performance?. *Perceptual and motor skills*, *75*(3), 851-866.

Richardson, J. T. (1978). A factor analysis of self-reported handedness. *Neuropsychologia, 16*, 747-748.

Ross, G., Lipper, E. G., & Auld, P. A. (1987). Hand preference of four-year-old children: its relationship to premature birth and neurodevelopmental outcome. *Developmental Medicine & Child Neurology*, *29*(5), 615-622.

Roszkowski, M. J., Snelbecker, G. E., & Sacks, R. (1981). Children's, adolescents', and adults' reports of hand preference: Homogeneity and discriminating power of selected tasks. *Journal of Clinical and Experimental Neuropsychology*, *3*(3), 199-213.

Roy, E. A., Kalbfleisch, L., & Elliott, D. (1994). Kinematic analyses of manual asymmetries in visual aiming movements. *Brain and cognition*, *24*(2), 289-295.

Sainburg, R. L., & Kalakanis, D. (2000). Differences in control of limb dynamics during dominant and nondominant arm reaching. *Journal of neurophysiology*, *83*(5), 2661-2675.

Savic, I. (2014). Asymmetry of cerebral gray and white matter and structural volumes in relation to sex hormones and chromosomes. *Frontiers in neuroscience*, *8*, 329.

Sharman J. L. & Kulhavy, R. (1976). The assessment of cerebral laterality: the Sharman-Kulhavy laterality assessment inventory: some validaton data. *Technical report No. 4*. Arizona State University, Department of Educational Psychology, 33 pages.

Scharoun, S. M., & Bryden, P. J. (2014). Hand preference, performance abilities, and hand selection in children. *Frontiers in psychology*, *5*, 82.

Scharoun, S. M., Bryden, P. J., Otipkova, Z., Musalek, M., & Lejcarova, A. (2013). Motor skills in Czech children with attention-deficit/hyperactivity disorder and their neurotypical counterparts. *Research in developmental disabilities*, *34*(11), 4142-4153.

Schneck, C. M., & Henderson, A. (1990). Descriptive analysis of the developmental progression of grip position for pencil and crayon control in nondysfunctional children. *American Journal of Occupational Therapy*, *44*(10), 893-900.

Schofield, W. N. (1976). Hand movements which cross the body midline: Findings relating age differences to handedness. *Perceptual and Motor Skills*, *42*(2), 643-646.

Schwartz, M. (1988). Handedness, prenatal stress and pregnancy complications. *Neuropsychologia*, *26*(6), 925-929.

Singh, M., & Bryden, M. P. (1994). The factor structure of handedness in India. *International Journal of Neuroscience*, *74*(1-4), 33-43.

Smith, B. B. (1950). Part II: An Evaluation of Factor Analysis from the Point of View of a Psychologist. *Journal of the Royal Statistical Society. Series B (Methodological)*, *12*(1), 73-94.

Sommer, I. E., Aleman, A., Somers, M., Boks, M. P., & Kahn, R. S. (2008). Sex differences in handedness, asymmetry of the planum temporale and functional language lateralization. *Brain research*, *1206*, 76-88.

Steenhuis, R. E., & Bryden, M. P. (1989). Difference dimensions of handedness that relate to skilled and unskilled activities. *Cortex, 25*(2), 289-304.

Steenhuis, R. E., Bryden, M. P., Schwartz, M., & Lawson, S. (1990). Reliability of hand preference items and factors. *Journal of Clinical and Experimental Neuropsychology*, *12*(6), 921-930.

Steiger, J. H. (1990). Structural model evaluation and modification: An interval estimation approach. *Multivariate behavioral research*, *25*(2), 173-180.

Stilwell, J. M. (1987). The development of manual midline crossing in 2-to 6-year-old children. *American Journal of Occupational Therapy*, *41*(12), 783-789.

Štochl, J., & Musálek, M. (2009). A practical guide to pilot standardization of tests. *Acta Universitatis Carolinae*, *45*(2), 5-15.

Talge, N. M., Neal, C., Glover, V., & Early Stress, Translational Research and Prevention Science Network: Fetal and Neonatal Experience on Child and Adolescent Mental Health. (2007). Antenatal maternal stress and long-term effects on child neurodevelopment: how and why?. *Journal of Child Psychology and Psychiatry*, *48*(3-4), 245-261.

Tapley, S. M., & Bryden, M. P. (1985). A group test for the assessment of performance between the hands. *Neuropsychologia*, *23*(2), 215-221.

Trost, S. G., Pate, R. R., Sallis, J. F., Freedson, P. S., Taylor, W. C., Dowda, M., & Sirard, J. (2002). Age and gender differences in objectively measured physical activity in youth. *Medicine & Science in Sports & Exercise*, *34*(2), 350-355.

Tucker, L. R., & Lewis, C. (1973). A reliability coefficient for maximum likelihood factor analysis. *Psychometrika*, *38*(1), 1-10.

van Strien, J. J. (2003). The Dutch handedness questionnaire. *Journal of Clinical and Experimental Neuropsychology* DOI: 10.1037/t00463-000

Vilhjalmsson, R., & Kristjansdottir, G. (2003). Gender differences in physical activity in older children and adolescents: the central role of organized sport. *Social science & medicine*, *56*(2), 363-374.

White, K., & Ashton, R. (1976). Handedness assessment inventory. *Neuropsychologia*, *14*(2), 261-264.

Whittington, J. E., & Richards, P. N. (1987). The stability of children's laterality prevalences and their relationship to measures of performance. *British Journal of Educational Psychology*, *57*(1), 45-55.

Williams, S. M. (1986). Factor analysis of the Edinburgh Handedness Inventory. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*.

Woodburne R. T., Burkel W. E. (1994). *Essentials of Human Anatomy.* New York: Oxford University Press.

Zverev, Y. P. (2006). Cultural and environmental pressure against left-hand preference in urban and semi-urban Malawi. *Brain and Cognition*, *60*(3), 295-303.

3. GROSS AND FINE MOTOR PERFORMANCE IN CHILDREN WITH ADHD IN CONTEXT OF SEX AND STRENGTH OF LATERALITY

We should realize that human laterality and its assessing are an important source of information about brain development, its disorders or diseases. For instance, a large body of studies found an unusual handedness pattern specifically in sense of higher frequency of left- and mixed-handers in schizophrenia patients, people with developmental coordination disorders, children with the Attention Deficit Hyperactivity Disorder (ADHD) syndrome, or children with developmental learning and reading challenges (e.g., Gur, 1977; Wheeler, Watkins, & McLaughlin, 1977; Roussounis, Gaussen, & Stratton, 1987; Shaw & Brown, 1991; Sommer, Aleman, Ramsey, Bouma, & Kahn, 2001; Dragovic & Hammond, 2005; Rasmussen & Levander, 2009; Rodriguez et al., 2010).

Therefore, assessing of motor laterality allows us not only to derive the degree of handedness but it could also be seen as a suitable tool which can help us find the answer to the question whether non-standard laterality patterns (like cross laterality preference or small differences in performance between the dominant and non-dominant extremity in certain tests) are a consequence of impaired or decreased brain lateralization.

The Attention Deficit Hyperactivity Disorder (ADHD) syndrome is one of the research areas where motor performance in fine and gross activities along with motor laterality patterns or laterality profile have been heavily investigated in the last few decades.

The Attention Deficit Hyperactivity Disorder (ADHD) is a neurobehavioural disorder characterized by a disruption of inattention and/or hyperactivity-impulsivity (Weiss & Hechtman, 1993; Hinshaw, 1994; Barkley, 1997; APA, 2013; Glozman, 2013). ADHD affects approximately 5% of children, although in literature the range varies from 3% to 20% (Swanson et al., 1998; Polanczyk & Jensen, 2008; Romanchuk, 2010). It is also important to realize that ADHD is a neurobehavioural disorder persistent to adulthood even though its prevalence varies with age. For example, Willcutt (2012) reports 11.4% in 6- to 12-year-olds, 8% in 13- to 18-year-olds, and 5%

in individuals aged 19 and older. The prevalence is ten times higher in children with learning disabilities (Glozman, 2013) and three times higher in male children compared to female children (Arcia & Conners, 1998; Nøvik et al., 2006; Rasmussen & Levander, 2009; Willcutt, 2012). Although the ratio decreases with age, the difference is still evident in adults aged 19 and older (Willcutt, 2012).

Many previous studies have shown that individuals with ADHD face common challenges with fine and gross motor activities in upper and lower limbs (e.g., Wade, 1976; Pitcher, Piek & Hay, 2003; Harvey et al. 2007; Pan, Tsai & Chu, 2009). It is generally accepted that between 30% and 50% of children with ADHD have motor impairments, which can undoubtedly affect their daily life (Hartsough & Lambert, 1985; Barkley, DuPaul & McMurray, 1990; Piek, Pitcher & Hay, 1999; Pitcher, Piek & Hay, 2003; Visser, 2003; Fliers et al., 2010). Pitcher et al. (2003), who assessed the degree of fundamental motor skills (Movement Assessment Battery for Children (MABC)) and fine motor skill (Purdue Pegboard) of male children with ADHD and their neurotypical counterparts, found significantly higher prevalence of movement impairments in all three subtypes of children with ADHD: ADHD-PI (58%), ADHD-HI (49%) and ADHD-C (47%), consistent with developmental coordination disorder (DCD). The characteristics and presence of ADHD motor difficulties and the probability of the diagnosis have been linked to possible brain anomalies and to non-standard cerebral lateralization of motor function (e.g., Ludors et al., 2010; Gilliam et al., 2011). The large systematic review by Siedeman, Valera and Makris (2005) concluded that the most replicated alterations in ADHD in childhood include significantly smaller volumes in the dorsolateral prefrontal cortex, caudate, pallidum, corpus callosum, and cerebellum. Mostofsky et al. (2006) found decreased activation in primary motor cortex during simple tapping test in ADHD children compared to controls.

Neuroimaging data have revealed aberrant cerebral connectivity in individuals with ADHD, which manifests itself in difficulties with internal timing mechanisms (Rubia, Noorloos, Smith, Gunning & Sergeant, 2003). As a result, movement programming is altered in individuals with ADHD, thus leading to poor fine and gross motor skills. In addition, ADHD syndrome was related to a lower increase of dopamine on the periphery and a reduced lactate response to exercise (Wigal et al., 2003). In the area of associations between ADHD and human laterality, non-right and/or mixed-handedness or footedness have been linked to some characteristic of ADHD:

mixed/handedness and inattention (Rodriguez et al., 2010; Lin & Tsuang, 2018); impulsivity and direction and consistency of handedness (Simoes, Carvalho & Schmidt, 2017; Schmidt, Carvalho, & Simoes, 2017) an increased risk of depression and impaired psychosocial functioning in children with ADHD who demonstrated a non-right motor preference (Beiderman et al., 1994); mixed-footedness and probability of ADHD and high impulsivity scores and left-; and mixed footedness (Tran & Voracek, 2018). A different brain structure, poorer brain lateralization or different biochemical responses of ADHD individuals compared to neurotypical peers have been perceived as possible causes of higher probability of motor difficulties in ADHD. It has been suggested that motor impairments in ADHD can be explained by poor attention. However, recent investigations have identified motor impairments as a separate entity from attention deficit (Miyahara, Piek, & Barrett, 2006; Fliers et al., 2008). Approximately 41% of children with ADHD displayed atypical motor skills, which could result from a cortical maturation delay in prefrontal regions (see Shaw et al., 2007). Overall, the aforementioned studies highlight that children with ADHD may possess an inherent risk for developmental delays in motor skill performance.

It became a little complicated to generalize the above information on ADHD population when investigations brought very inconsistent results in motor performance of ADHD males and ADHD females. Whereas some studies have demonstrated differences in ADHD functional impairment between males and females (Biederman et al., 2002; Cole, Mostofsky, Larson, Denckla, & Mahone, 2008) others have revealed no difference (e.g., Gaub & Carlson, 1997; Nøvik et al., 2006; Fliers et al., 2008). It is thus unclear whether motor characteristics (gross and fine motor manifestation) of ADHD are the same in both sexes. Some light into this area was brought by Dirlikov et al. (2010), who, by neuroimaginary approach, revealed structural deficits in different investigated brain regions between ADHD boys and ADHD girls. Girls had overall reductions in total prefrontal cortex (dorsolateral, left inferior lateral, right medial, orbitofrontal and left anterior cingulate). These areas play an important role in planning, decision-making, and synthesis of information from other brain regions. On the other hand, boys with ADHD showed an overall reduction in total premotor cortex. Premotor cortex is greatly involved in complex motor activities.

Further, due to higher prevalence of ADHD in males (1:3-5) compared to females there are much fewer studies with a balanced sample of ADHD males and ADHD females.

Although research has been done that aimed to shed light on the causes of motor impairment in ADHD, which is also related to human laterality, still many questions remain open. Castellanos and Proal (2012), who summarized functional and structural anomalies/differences in brain regions and networks of ADHD individuals compared to controls, emphasised that these networks (visual, motor, fronto-parietal and default) cannot be exhaustively or equally relevant to all individuals with ADHD, but they provide a straightforward framework for converging attempts to parse the pertinent dimensions of symptoms and constructs (Castellanos & Proal, 2012, p.22)

Taking into account previous findings and suggestions, we carried out a study in which we tested differences in motor performance between ADHD children and neurotypical controls in specific fine and gross motor tests. The core of the study was to use tests in which we assessed the activity of different brain regions (indirectly). This specificity was built on motor or planning requirements, whether test contained continuous movement with high demand on hand-eye coordination or discontinued movement with high demand on hand-eye coordination (with or without subject transportation); whether movement had rotation (pronation and supination) or a swing arm (two types of plate tapping) character.

We were interested to learn whether:

1) motor impairment in fine and gross motor performances will be the same in middle school age ADHD boys and ADHD girls
2) ADHD boys and ADHD girls will differ significantly and equally in specific fine (generally stronger cerebro-cerebellar neuropathways) and specific gross motor performances from neurotypical peers
3) ADHD boys and ADHD girls will display significantly smaller differences in fine and gross motor performances between the dominant and non-dominant upper and lower limb compared to neurotypical peers.

First, we had to prepare a test bank which contained items/tests sufficiently reflecting the finding that ADHD individuals have difficulties with internal timing mechanisms. Implications of these difficulties have been shown in children with ADHD or children at risk of ADHD, including lower accuracy and higher variability within hand-eye tracking and pursuit tasks (e.g., copying of shape; threading beads, drawing a line) compared to neurotypical peers (Kalff et al., 2003; Rommelse et al. 2007; Lavasani & Stagnitti, 2011). We also worked with the assumption that items with higher demands on motor coordination (complex motor activities in which higher demands are put on coordination and integration of more segments of the limb involved in the activity) (Annett, 1992; Roy et al., 1994; Sainburg & Kalakanis, 2000) should show the biggest differences in performance between the preferred and non-preferred hand. When considering these theoretical outcomes, we selected seven motor tests from gross motor to higher fine motor character using the content validity process (Table 3).

Table 3
Fine and gross motor tests

Fine motor tests	**Gross motor tests**
1. Spiral tracing	4. Turning a box alternately with the front and the rear side on the table
2. Dot-filling	5. Small plate finger tapping
3. Moving beads from one box into another	6. Big plate finger tapping
	7. Foot tapping

Research sample:

First we had to determine the age category of children. Since the middle school age is considered a very stable period in motor and somatic development (Ljach, 2002), we selected children aged 9 to 11. The second requirement in this study was to obtain a balanced sample in terms of gender of ADHD children. Children with ADHD were recruited from the National Institute of Pedagogy and Psychology (IPPP) database of neurobehavioural disorders. These children were enrolled in a special state school in Prague for children with ADHD who were first diagnosed with ADHD when they were 5 or 6 years old, and who are re-tested on a yearly basis to confirm the accurate diagnosis. For more details about the diagnostic process see Scharoun et al. (2013). In the end, the research sample of ADHD children contained 58 participants (males=29; females=29) and 58 neurotypical controls (males=29; females=29). All ADHD children passed the tests without any medication such as ritalin. Neurotypical children were selected from schools without any specific specialization (e.g., technical, artistic, sport, or linguistic). Ethics approval was granted by the Ethics Commission of the Faculty of

Physical Education and Sport, Charles University. In addition, parental consent was obtained for all individuals.

Procedure:

Hand preference:

Hand preference was determined based on results from three specific tests contained in a battery validated for Czech children Musálek (2012):

1) throwing at a target; 2) ringing a bell; 3) cutting with a knife.

Eleven of the participants were identified as left-handed. This included three neurotypical children (two males and one female) and eight children with ADHD (two males and six females).

For more details see Scharoun et al. (2013)

Results:

Our finding can be seen from three perspectives

1) Performance by preferred and non-preferred hand:
    a. Firstly, in all tests regardless of character (fine, gross) or its specificity, the preferred hand achieved a better performance compared to the non-preferred hand in both ADHD children and neurotypical controls.
    b. Secondly, the degree of difference in performance between the preferred and non-preferred hand was similar (non-significantly different) in ADHD children and neurotypical peers.
2) Differences in motor performance between ADHD children and neurotypical controls
    a. ADHD children performed significantly worse in high complex fine motor tests with high demands on hand-eye coordination (spiral tracing, dot filling, tweezers and beads) regardless whether it was a movement

continuous or a movement discontinuous test. Nevertheless, children with ADHD were significantly worse only in the performance of the preferred hand compared to neurotypical peers. Further, it is interesting to note that in a specific foot tapping test where participants had to change heel toe part of the foot during the test – which means high coordination demands on acral part of the lower limb – ADHD children also performed much worse compared to neurotypical controls.

b. On the other hand, in gross motor “speedy” tests where the level of motor accuracy was not included, no significant differences were found between ADHD and controls regardless whether the movement had a rotation or swing character.

3) Differences in motor performance in interaction – ADHD vs. controls vs. gender

a. Gender effect was revealed only in spiral tracing test which had a character of a complex continuous movement test with high demand on hand-eye coordination. ADHD girls were significantly faster than ADHD boys. Still, ADHD girls were significantly worse in spiral tracing performance by the preferred hand compared to neurotypical girls. In addition, boys with ADHD were significantly worse in spiral tracing performance by the non-preferred hand compared to nerotypical boys. In speedy rotation test twist box, a major effect of gender was also revealed. Boys did significantly more twists than girls but ADHD children and neurotypical controls did not differ in performance. In swing arm gross motor tests 1) small plate tapping and 2) big plate taping no effect regarding group ADHD vs. neurotypical peers or gender was found. Although this study showed that highly complex tests with high demand on hand-eye coordination or foot coordination caused the biggest differences in motor performance between ADHD children and their neurotypical peers and also suggested variability in performance even within ADHD children considering gender we realized several limitations of this study. Our first plan in this investigation was to do precise motor and sensoric laterality evaluation; however, we were not able to fulfil this aim. Due to the very specific work with ADHD children and the many compromises we had to make during testing, we were not able to acquire objective information about possible cross laterality of ADHD children (hand-eye, foot-eye). Since previous research showed that higher evidence of hand-eye cross laterality exists in ADHD population, we perceive the absence of this information as the main deficiency of the study.

Summary:

Although in this study the motor laterality profile was limited only to handedness of the participants, its results support previous findings that non-right handedness is more common in ADHD population. In addition, it was found that highly complex motor tasks emphasising hand-eye or foot coordination showed significant motor impairment in ADHD children compared to neurotypical controls. In these tests, ADHD children's performance was worse by about 11–16%. These results are in conformity with previous studies focused on – hand-eye coordination. Lavasani and Stagnitti (2011) have observed poorer performance in children with ADHD when placing dots in a grid pattern and drawing lines. Meyer and Sagvolden (2006) revealed significant impairment in children with ADHD within a Maze Coordination task. In addition, many studies also revealed poor handwriting in ADHD children, which is highly coordination demanded (e.g. Barkley, 1998; Flapper et al., 2006; Racine et al., 2008) Since previous studies suggested that ADHD syndrome in associated with higher prevalence of mixed handedness (Beiderman et al., 1994; Rodriguez et al., 2010; Lin & Tsuang, 2018) as a possible result of poorer brain lateralization, we would expect a much lower difference in motor performance between the preferred and non-preferred hand in ADHD children. The unpublished data available in Appendix 1 shows that mix-handedness was higher in the ADHD sample (24%) compared to neurotypical peers (18%). Also the degree of right-handedness calculated as laterality quotient (LQ) from hand preference tasks was stronger in neurotypical children 91.7% compared to ADHD children 84.7%. Interestingly, lower LQ was found in ADHD girls (83.1%) than in ADHD boys (86.1%) even though it was hypothesised that male population would manifest generally lower right side lateralization (Whittington and Richards, 1987; McManus, 2004; Sommer et al., 2008).

Although we had some evidence that the ADHD sample in our study expressed higher variability and lower lateralization of upper limb, when we compared the data distribution and performances of the preferred and non-preferred limb, we found non-significant differences between ADHD individuals and neurotypical peers. ADHD children as well as their neurotypical peers displayed a similar degree of performance (from 58 to 67%) of the preferred limb in the highly complex test where the differences between the preferred and non-preferred limb were the greatest (Scharoun et al., 2013). It means that ADHD children were (according to our laterality assessment, restricted only to the upper limb) less lateralized and showed systematically worse performance by the preferred and non-preferred limb in highly complex tests demanding coordination and place or timing accuracy compared to neurotypical peers. Impairment of coordination in fine motor activities could be explained by decreased level of catecholamines in brain of ADHD individual especially in prefrontal cortex (Carter, Krener, Chaderjian, Northcutt & Wolfe, 1995; Arnsten & Li, 2005; Arnsten & Pliszka, 2011) or on the periphery which has been documented by Hanna, Ornitz and Hariharan (1996) or Wigal et al. (2003).

We can understand the motor difficulties of ADHD children in fine motor tests also when taking into account the evidence of structural anomalies in connections between and within specific brain regions and reduction of volume in certain brain regions which has been well documented in ADHD individuals (e.g. Siedeman et al., 2005; Mostofsky et al., 2006; Rubia et al., 2003). When it comes to the question whether motor difficulties in ADHD boys and ADHD girl are different, we have to conclude that they seem to be of a similar extent. The only test where ADHD girls performed significantly better was fine motor continuous movement test spiral tracing. These results, however, are in contrast with the findings of Meyer and Sagvolden (2006), who noted that female children with ADHD perform the maze coordination task and the grooved pegboard task significantly slower than male children with ADHD. In our study, ADHD girls were significantly worse than ADHD boys in foot tapping. It has to be noted, though, that in this test also neurotypical girls performed significantly worse than neurotypical boys. It can thus be suggested that sex differences in fine motor skills are limited. This is in line with Gaub and Carlson's (1997) meta-analysis and critical review, where no sex differences in ADHD were revealed. When observing gross motor skills, similar to Fliers et al. (2008), female children with ADHD displayed similar motor coordination problems as male children with ADHD. What we perceive as a major challenge for further research is to consider, in addition to lateral preference, also cross laterality patterns which have not been commonly studied in ADHD in relation to motor difficulties even though especially the connection between visual and motor network has been documented by neuroimagery studies as significantly impaired in individuals with ADHD.

References:

American Psychiatric Association. (2013). *Diagnostic and Statistical Manual of Mental Disorders. (5th ed.).* Washington, D. C.: American Psychiatric Association

Annett, M. (1992). Five tests of hand skill. *Cortex*, *28*(4), 583-600.

Arcia, E., & Conners, C. K. (1998). Gender differences in ADHD?. *Journal of Developmental and Behavioral Pediatrics*.

Arnsten, A. F., & Li, B. M. (2005). Neurobiology of executive functions: catecholamine influences on prefrontal cortical functions. *Biological psychiatry*, *57*(11), 1377-1384.

Arnsten, A. F., & Pliszka, S. R. (2011). Catecholamine influences on prefrontal cortical function: relevance to treatment of attention deficit/hyperactivity disorder and related disorders. *Pharmacology Biochemistry and Behavior*, *99*(2), 211-216.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: constructing a unifyingtheoryof ADHD. *Psychological Bulletin, 121*(1), 65–94.

Barkley, R. A., DuPaul, G. J., & McMurray, M. B. (1990). Comprehensive evaluation of attention deficit disorder with and without hyperactivity as defined by research criteria. *Journal of consulting and clinical psychology*, *58*(6), 775-789.

Barkley, R.A. (1998). *Attention-deficit hyperactivity disorder: a handbook for diagnosis and treatment (2nd ed.).* NewYork, NY: The Guilford Press.

Beiderman, J., Lapey, K. A., Milberger, S., Faraone, S. V., Reed, E. D., & Seidman, L. J. (1994). Motor preference, major depression and psychosocial dysfunction among children with attention deficit hyperaktivity disorder. *Journal of Psychiatric Research, 28*(2), 171–184.

Biederman, J., Mick, E., Faraone, S. V., Braaten, E., Doyle, A., Spencer, T., ... & Johnson, M. A. (2002). Influence of gender on attention deficit hyperactivity disorder in children referred to a psychiatric clinic. *American Journal of Psychiatry*, *159*(1), 36-42.

Carter, C. S., Krener, P., Chaderjian, M., Northcutt, C., & Wolfe, V. (1995). Asymmetrical visual-spatial attentional performance in ADHD: evidence for a right hemispheric deficit. *Biological Psychiatry*, *37*(11), 789-797.

Castellanos, F. X., & Proal, E. (2012). Large-scale brain systems in ADHD: beyond the prefrontal–striatal model. *Trends in cognitive sciences*, *16*(1), 17-26.

Cole, W. R., Mostofsky, S. H., Larson, J. G., Denckla, M. B., & Mahone, E. M. (2008). Age-related changes in motor subtle signs among girls and boys with ADHD. *Neurology*, *71*(19), 1514-1520.

Dirlikov, B., Rosch, K. S., Crocetti, D., Denckla, M. B., Mahone, E. M., & Mostofsky, S. H. (2015). Distinct frontal lobe morphology in girls and boys with ADHD. *Neuroimage: Clinical*, *7*, 222-229.

Dragovic, M., & Hammond, G. (2005). Handedness in schizophrenia: a quantitative review of evidence. *Acta Psychiatrica Scandinavica*, *111*(6), 410-419.

Flapper, B. C. T., Houwen, S., & Schoemaker, M. M. (2006). Fine motor skills and affects of methylphenidate in children with attention deficit/hyperactivity disorder. *Journal of Developmental Medicine and Child Neurology, 48,* 165–169.

Fliers, E. A., Franke, B., Lambregts-Rommelse, N. N., Altink, M. E., Buschgens, C. J., Nijhuis-van der Sanden, M. W., ... & Buitelaar, J. K. (2010). Undertreatment of motor problems in children with ADHD. *Child and adolescent mental health*, *15*(2), 85-90.

Fliers, E., Rommelse, N., Vermeulen, S. H. H. M., Altink, M., Buschgens, C. J. M., Faraone, S. V., ... & Buitelaar, J. K. (2008). Motor coordination problems in children and adolescents with ADHD rated by parents and teachers: effects of age and gender. *Journal of neural transmission*, *115*(2), 211-220.

Gaub, M., & Carlson, C. L. (1997). Gender differences in ADHD: a meta-analysis and critical review. *Journal of the American Academy of Child & Adolescent Psychiatry*, *36*(8), 1036-1045.

Glozman J. M. (2013) *Developmental neuropsychology*. London - New York: Routledge, Taylor and Francis group.

Gur, R. E. (1977). Motoric laterality imbalance in schizophrenia: A possible concomitant of left hemisphere dysfunction. *Archives of General Psychiatry*, *34*(1), 33-37.

Hanna, G. L., Ornitz, E. M., & Hariharan, M. (1996). Urinary catecholamine excretion and behavioral differences in ADHD and normal boys. *Journal of child and adolescent psychopharmacology*, *6*(1), 63-73.

Hartsough, C. S., & Lambert, N. M. (1985). Medical factors in hyperactive and normal children: Prenatal, developmental, and health history findings. *American Journal of Orthopsychiatry*, *55*(2), 190-201.

Harvey, W. J., & Reid, G. (2003). Attention-deficit/hyperactivity disorder: A review of research on movement skill performance and physical fitness. *Adapted Physical Activity Quarterly*, *20*(1), 1-25.

Hinshaw, S. P. (1994). *Attention deficits and hyperactivity in children*. Thousand Oaks: Sage

Kalff, A. C., de, S. L. M. J., Hurks, P. P. M., Hendriksen, J. G. M., Kroes, M., Feron, F. J. M., Steyaert, J., ... Jolles, J. (2003). Low- and high-level controlled processing in executive motor control tasks in 5-6-year-old children at risk of ADHD. *Journal of Child Psychology and Psychiatry, 44*(7), 1049–1057.

Lavasani, N. M., & Stagnitti, K. (2011). A study on fine motor skills of Iranian children with attention deficit/hyper activity disorder aged from 6 to 11 years. *Occupational therapy international*, *18*(2), 106-114.

Lin, H. L., & Tsuang, H. C. (2018). Handedness and Attention Deficit/Hyperactivity Disorder Symptoms in College Students. *Psychiatric Quarterly*, *89*(1), 103-110.

Luders, E., Cherbuin, N., Thompson, P. M., Gutman, B., Anstey, K. J., Sachdev, P., & Toga, A. W. (2010). When more is less: associations between corpus callosum size and handedness lateralization. *Neuroimage*, *52*(1), 43-49.

Meyer, A., & Sagvolden, T. (2006). Fine motor skills in South African children with symptoms of ADHD: influence of subtype, gender, age, and hand dominance. *Behavioral and Brain Functions: Bbf, 2.*

Miyahara, M., Piek, J., & Barrett, N. (2006). Accuracy of drawing in a dual-task and resistance-to-distraction study: Motor or attention deficit?. *Human Movement Science*, *25*(1), 100-109.

Mostofsky, S. H., Rimrodt, S. L., Schafer, J. G., Boyce, A., Goldberg, M. C., Pekar, J. J., & Denckla, M. B. (2006). Atypical motor and sensory cortex activation in attention-deficit/hyperactivity disorder: a functional magnetic resonance imaging study of simple sequential finger tapping. *Biological psychiatry*, *59*(1), 48-56.

Musálek, M. (2012). Development of Test Batteries for Diagnostics of Motor Laterality Manifestation-Link between Cerebellar Dominance and Hand Performance. Dissertation thesis - unpublished

Nøvik, T. S., Hervas, A., Ralston, S. J., Dalsgaard, S., Pereira, R. R., Lorenzo, M. J., & ADORE Study Group. (2006). Influence of gender on attention-deficit/hyperactivity disorder in Europe–ADORE. *European Child & Adolescent Psychiatry*, *15*(1), i15-i24.

Pan, C. Y., Tsai, C. L., & Chu, C. H. (2009). Fundamental movement skills in children diagnosed with autism spectrum disorders and attention deficit hyperactivity disorder. *Journal of Autism and Developmental Disorders, 39(*12), 1694-1705.

Piek, J. P., Pitcher, T. M., & Hay, D. A. (1999). Motor coordination and kinaesthesis in boys with attention deficit–hyperactivity disorder. *Developmental medicine and child neurology*, *41*(3), 159-165.

Pitcher, T. M., Piek, J. P., & Hay, D. A. (2003). Fine and gross motor ability in males with ADHD. *Developmental medicine and child neurology*, *45*(8), 525-535.

Polanczyk, G., & Jensen, P. (2008). Epidemiologic Considerations in Attention Deficit Hyperactivity Disorder: A Review and Update. *Child and Adolescent Psychiatric Clinics of North America, 17*(2), 245-260.

Racine, M. B., Majenemer, A., Shevell, M., & Snider, L. (2008). Handwriting performance in children with attention deficit hyperactivity disorder. *Journal of Child Neurology, 23(4)*, 399-406.

Rasmussen, K., & Levander, S. (2009). Untreated ADHD in adults: are there sex differences in symptoms, comorbidity, and impairment?. *Journal of Attention Disorders*, *12*(4), 353-360.

Rodriguez, A., Kaakinen, M., Moilanen, I., Taanila, A., McGough, J. J., Loo, S., & Järvelin, M. R. (2010). Mixed-handedness is linked to mental health problems in children and adolescents. *Pediatrics, 125*(2), 340-348.

Romanchuk, O. I. (2010). Attention deficit and hyperactivity disorder in children. *Moscow: Genesis*.

Rommelse, N. N., Altink, M. E., Oosterlaan, J., Buschgens, C. J., Buitelaar, J., De Sonneville, L. M., & Sergeant, J. A. (2007). Motor control in children with ADHD and non-affected siblings: deficits most pronounced using the left hand. *Journal of Child Psychology and Psychiatry*, *48*(11), 1071-1079.

Roussounis, S. H., Gaussen, T. H., & Stratton, P. (1987). A 2-year follow-up study of children with motor coordination problems identified at school entry age. *Child: Care, Health and Development, 13*(6), 377-391

Roy, E. A., Kalbfleisch, L., & Elliott, D. I. G. B. Y. (1994). Kinematic analyses of manual asymmetries in visual aiming movements. *Brain and cognition*, *24*(2), 289-295.

Rubia, K., Noorloos, J., Smith, A., Gunning, B., & Sergeant, J. (2003). Motor timing deficits in community and clinical boys with hyperactive behavior: the effect of methylphenidate on motor timing. *Journal of abnormal child psychology*, *31*(3), 301-313.

Sainburg, R. L., & Kalakanis, D. (2000). Differences in control of limb dynamics during dominant and nondominant arm reaching. *Journal of neurophysiology*, *83*(5), 2661-2675.

Seidman, L. J., Valera, E. M., & Makris, N. (2005). Structural brain imaging of attention-deficit/hyperactivity disorder. *Biological psychiatry*, *57*(11), 1263-1272.

Shaw, G. A., & Brown, G. (1991). Laterality, implicit memory and attention disorder. *Educational Studies*, *17*(1), 15-23.

Shaw, P., Lerch, J., Greenstein, D., Sharp, W., Clasen, L., Evans, A., ... & Rapoport, J. (2006). Longitudinal mapping of cortical thickness and clinical outcome in children and adolescents with attention-deficit/hyperactivity disorder. *Archives of general psychiatry*, *63*(5), 540-549.

Schmidt, S. L., Carvalho, A. L. N., & Simoes, E. N. (2017). Effect of handedness on auditory attentional performance in ADHD students. *Neuropsychiatric Disease and Treatment*, *13*, 2921-2924.

Sommer, I., Aleman, A., Ramsey, N., Bouma, A., & Kahn, R. (2001). Handedness, language lateralisation and anatomical asymmetry in schizophrenia: meta-analysis. *The British Journal of Psychiatry*, *178*(4), 344-351.

Swanson, J. M., Sergeant, J. A., Taylor, E., Sonuga-Barke, E. J., Jensen, P. S., & Cantwell, D. P. (1998). Attention-deficit hyperactivity disorder and hyperkinetic disorder. *Lancet, 351*(9100), 429-433.

Visser, J. (2003). Developmental coordination disorder: a review of research on subtypes and comorbidities. *Human movement science*, *22*(4-5), 479-493.

Wade, M. G. (1976). Effects of Methylphenidate on Motor Skill Acquisition of Hyperactive Children. *Journal of Learning Disabilities, 9*(7), 443-447.

Weiss, G., & Hechtman, L. T. (1993). *Hyperactive children grown up: ADHD in children, adolescents, and adults*. New York: Guilford Press.

Wheeler, T. J., Watkins, E. J., & McLaughlin, S. P. (1977). Reading retardation and cross-laterality in relation to short-term information processing tasks. *The British Journal of Educational Psychology, 47(*2), 126–131.

Wigal, S. B., Nemet, D., Swanson, J. M., Regino, R., Trampush, J., Ziegler, M. G., & Cooper, D. M. (2003). Catecholamine response to exercise in children with attention deficit hyperactivity disorder. *Pediatric research*, *53*(5), 756-761.

Willcutt, E. G. (2012). The prevalence of DSM-IV attention-deficit/hyperactivity disorder: a meta-analytic review. *Neurotherapeutics*, *9*(3), 490-499.

Research in Developmental Disabilities 34 (2013) 4142–4153

Contents lists available at ScienceDirect

Research in Developmental Disabilities

Motor skills in Czech children with attention-deficit/hyperactivity disorder and their neurotypical counterparts

S.M. Scharoun [a,*], P.J. Bryden [b], Z. Otipkova [c], M. Musalek [c], A. Lejcarova [c]

[a] Department of Kinesiology, University of Waterloo, 200 University Avenue West, Waterloo, ON, Canada N2L 3G1
[b] Department of Kinesiology & Physical Education, Wilfrid Laurier University, 75 University Avenue West, Waterloo, ON, Canada N2L 3C5
[c] Faculty of Physical Education and Sport, Charles University, José Martího 31, 6-Veleslavín, Praha 162 52, Czech Republic

ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form 6 August 2013
Accepted 6 August 2013
Available online

Keywords:
Attention-deficit/hyperactivity disorder (ADHD)
Fine motor skills
Gross motor skills
Children

ABSTRACT

Attention-deficit/hyperactivity disorder (ADHD) is the most commonly diagnosed neurobehavioural disorder. Characterized by recurring problems with impulsiveness and inattention in combination with hyperactivity, motor impairments have also been well documented in the literature. The aim of this study was to compare the fine and gross motor skills of male and female children with ADHD and their neurotypical counterparts within seven skill assessments. This included three fine motor tasks: (1) spiral tracing, (2) dot filling, (3) tweezers and beads; and four gross motor tasks: (1) twistbox, (2) foot tapping, (3) small plate finger tapping, and (4) large plate finger tapping. It was hypothesized that children with ADHD would display poorer motor skills in comparison to neurotypical controls in both fine and gross motor assessments. However, statistically significant differences between the groups only emerged in four of the seven tasks (spiral tracing, dot filling, tweezers and beads and foot tapping). In line with previous findings, the complexity underlying upper limb tasks solidified the divide in performance between children with ADHD and their neurotypical counterparts. In light of similar research, impairments in lower limb motor skill were also observed. Future research is required to further delineate trends in motor difficulties in ADHD, while further investigating the underlying mechanisms of impairment.

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD; also referred to as hyperkinetic disorder by the World Health Organization, 1993) is the most commonly diagnosed neurobehavioural disorder. Affecting approximately 3% to 6% of school aged children (Banerjee, Middlerton, & Faraone, 2007; Brown et al., 2008; Polanczyk, Lima, Horta, Biederman, & Rhode, 2007), prevalence rates are estimated at 5.29% worldwide. Occurrence of ADHD is greater in male children, where estimates indicate boys out-represent girls by 2:1 to 9:1 (Rucklidge, 2010). Individuals with ADHD typically present with co-morbidities, such as other neurological and psychiatric diseases (Barkley, 2003; Polanczyk et al., 2007). The most commonly reported co-morbidities include oppositional defiant disorder, conduct disorder, affective and anxiety disorders (American Psychiatric Association, 2000; Kadesjö & Gillberg, 2001; Melnick & Hinshaw, 2000). Nevertheless, researchers have also

* Corresponding author. Tel.: +1 519 888 4567x32972.
E-mail addresses: sscharou@uwaterloo.ca, sara.scharoun@gmail.com (S.M. Scharoun), pbryden@wlu.ca (P.J. Bryden), z.otipkova@seznam.cz (Z. Otipkova), musalek.martin@seznam.cz (M. Musalek), lejcarova@ftvs.cuni.cz (A. Lejcarova).

0891-4222/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ridd.2013.08.011

noted reading disabilities, developmental coordination disorder and immature moral development in ADHD (e.g., Hinshaw, Herbsman, Melnick, Nigg, & Simmel, 1993; Kadesjö & Gillberg, 2001; Visser, 2003).

ADHD has been described by numerous authors during the last 200 years (see Goldstein & Morewitz, 2011; Lange, Reichl, Lange, Tucha, & Tucha, 2010). A diagnosis of ADHD according to the diagnostic and statistical manual of mental disorders (DSM-IV-TR) requires six or more symptoms of inattention or hyperactivity-impulsivity, which have persisted for at least 6 months (American Psychiatric Association, 2000; Biederman & Faraone, 2005; Lange, Reichl, Lange, Tucha, & Tucha, 2010). Based on these criteria, three specific subtypes can be identified: Predominantly inattentive (ADHD-PI), predominantly hyperactive-impulsive (ADHD-HI) and the combined type (ADHD-C), which is more prevalent and results in greater impairment (American Psychiatric Association, 2000; Rohde & Halpern, 2004).

In comparison to the DSM-IV-TR, the World Health Organization (1993) uses hyperkinetic disorder (HD) to describe a full set of symptoms in the domains of inattention, hyperactivity and impulsivity in the International Classification of Diseases (ICD). The primary difference between the two means of diagnosis include DSM-IV-TR (ADHD) criteria recognizing three subtypes of ADHD, whereas ICD-10 criteria requires a full set of symptoms in all three domains; there is a narrower category. Nonetheless, it is suggested that nearly all children diagnosed with hyperkinetic disorder should also be included within the ADHD classification (Taylor et al., 2004), where it is postulated that an ICD-10 diagnosis of HD is the most congruent with the DSM-IV-TR diagnosis of ADHD-C (Döpfner, Breuer, Wille, Erhart, & Ravens-Sieberer, 2008). Children in the current study were diagnosed according to ICD criteria.

In addition to the above mentioned behavioural manifestations (i.e., inattention, hyperactivity and impulsivity) which are used for diagnostic purposes, motor impairments associated with ADHD have been well documented in the literature (e.g., Harvey & Reid, 1997; Harvey et al., 2007; Pitcher, Piek, & Hay, 2003). A review of 49 studies published between 1949 and 2002 (Harvey & Reid, 1997) concluded that impaired movement skills are more likely to manifest in children with ADHD in comparison to neurotypical peers. It is generally accepted that between 30% and 50% of children with ADHD have motor impairments, which can undoubtedly affect daily life (Barkley, DuPaul, & McMurray, 1990; Fliers et al., 2010; Hartsough & Lambert, 1985; Piek, Pitcher & Hay, 1999; Pitcher et al., 2003; Visser, 2003). In light of these observations, children with ADHD are typically described as 'clumsy' (Tervo, Azuma, Fogas, & Flechtner, 2002). More specifically, children with ADHD lag behind their neurotypical peers with respect to the development of speed and timing, balance, and suppression of contralateral overflow movements—all key components in the overall development of motor control skills (Denckla & Rudel, 1978). As such, Scandinavia countries have implemented the term Deficits of Attention and Motor Perception (DAMP) to describe children with a combination of ADHD and motor impairments (Fliers et al., 2008).

A plethora of studies have incorporated different assessments to measure motor skills in children with ADHD. For example, the Physical and Neurological Examination for Subtle Signs (PANESS: Denckla, 1985) has been used to differentiate children with ADHD from their neurotypical counterparts (Cole, Mostofsky, Larson, Denckla, & Mahone, 2008; Schuerholz, Cutting, Mazzacco, Singer, & Denckla, 1997). Harvey and colleagues (Harvey and Reid, 1997; Harvey et al., 2007) used the Test of Gross Motor Development (TGMD; Ulrich, 1985; TGMD-2; Ulrich, 2000) to examine gross motor skills in children with ADHD. The authors observed significant differences between children with ADHD and their neurotypical counterparts; such that below average performance was observed in children with ADHD (Harvey & Reid, 1997; Harvey et al., 2007).

Harvey and Reid (1997) observed that children with ADHD demonstrated fewer performance criteria on locomotor skills (slide, horizontal jump, skip, lead, hop, gallop and run) and object control skills (overhand throw, kick, catch, stationary bounce, and two-hand strike). These results were replicated by Pan, Tsai, and Chu (2009), thus highlighting impaired gross motor development, locomotor control and object control. In a similar study, Pitcher et al. (2003) used the Movement Assessment Battery for Children (MABC; Henderson & Sugden, 1992) and the Purdue Pegboard (Tiffin & Asher, 1948; Tiffin, 1968) to investigate both fine and gross motor abilities of male children with ADHD and their neurotypical counterparts. The authors observed an increased prevalence of movement impairments in all three subtypes of children with ADHD: ADHD-PI (58%), ADHD-HI (49%) and ADHD-C (47%), consistent with developmental coordination disorder (DCD).

A very recent study (Goulardins, Marques, Casella, Nascimento, & Oliveira, 2013) used the Motor Development Scale (MDS; Rosa Neto, 2002, cf. Goulardins et al., 2013) to assess the motor profile of children with ADHD-C. Results revealed that the general motor quotients in all areas investigated were significantly lower in children with ADHD in comparison to neurotypical controls; however, in most cases, these values were still in the normal range. Consistent with previous clinical and epidemiological studies (e.g., Fliers et al., 2008; Pitcher et al., 2003) 41% of children with ADHD displayed atypical motor skills, which the authors suggested to result from cortical maturation delay in prefrontal regions (see Shaw et al., 2007). Overall, the aforementioned studies highlight that children with ADHD may possess an inherent risk for developmental delays in motor skill performance.

In addition to studies which have incorporated general assessments of fine and gross motor skills, researchers have investigated specific motor skills of children with ADHD as well. In North America, writing performance has been anecdotally observed in ADHD (Barkley, 1998), such that a review from 1966 to 2006 revealed impaired performance in this population (Racine, Majehemer, Shevall, & Snider, 2008). It has also been noted that children with ADHD show impairments in learning and motor skills (e.g., typing; Karatekin et al., 2002), which is further exaggerated in complex tasks (Barkley, 1998).

In other parts of the world, similar findings have been observed. For example, Pitcher et al. (2003) observed children with ADHD had significantly impaired gross and fine motor abilities in comparison to neurotypical controls. That said the motor performance of numerous children with ADHD paralleled that seen in developmental coordination disorder (DCD). Flapper, Houwen, and Schoemaker (2006) reported that children with ADHD displayed poor manual dexterity, had poor handwriting performance, and drew less accurately. That said, when prescribed methylphenidate, these motor skills improved significantly. Kalff et al. (2003) revealed that children at risk of ADHD were less accurate and more variable within both tracking (tracing in between a fixed outer and inner circle with a mouse cursor on a computer display) and pursuit tasks (following a randomly moving target across the computer screen with a mouse cursor), in comparison to children with other neurodevelopmental disorders, and their neurotypical counterparts. Rommelse et al. (2007) observed children with ADHD were less precise and stable than neurotypical controls in both pursuit and tracking tasks, where impairments were most pronounced when performing with the left hand. Finally, a recent article surrounding fine motor skills of Iranian children (Lavasani & Stagnitti, 2011) revealed that children with ADHD have poorer fine motor skills that their neurotypical counterparts, with respect to cutting, placing dots in a grip pattern, threading beads, drawing a line, finger movements and the Purdue pegboard.

Based on the aforementioned ADHD literature, it is well understood that children with ADHD display impaired motor skills. These results have been replicated in various countries around the world, using a variety of motor assessments. That said, it remains inconclusive which mechanisms play a role in the origin of co-occurrence of ADHD and motor impairment (Fliers et al., 2008). It has been suggested that motor impairments in ADHD can be explained by poor attention. However, recent investigations have identified motor impairments as a separate entity from attention deficit (Miyahara, Piek, & Barrett, 2006; Fliers et al., 2008). Furthermore, findings are inconsistent in how the association between ADHD and motor impairment applies to the various aspects of movement (Fliers et al., 2008). Most researchers implicate fine motor control processes as the most impaired in ADHD, whereas others implicate gross motor problems (Fliers et al., 2008; Pitcher et al., 2003; Visser, 2003; Tseng, Henderson, Chow, & Yao, 2004). Consequently, despite the breadth of knowledge that currently exists, it is suggested that more research with larger sample sizes, including control groups, is required to fully understand anomalies in motor skills that manifest in children with ADHD (Lavasani & Stignitti, 2011).

Taking the aforementioned into consideration, literature to date has primarily focused on male children with ADHD (e.g., Flapper et al., 2006; Gershon, 2002; Goulardins et al., 2013; Harvey & Reid, 1997; Harvey et al., 2007), as ADHD is more prevalent in males than females (Biederman et al., 2002). However, it is suggested that ADHD is more similar than different when comparing males and females (Rucklidge, 2010). Research involving females with ADHD has revealed they are as affected as males with ADHD (Seidman et al., 2005; Biederman et al., 2006). More specifically, females with ADHD typically have lower ratings of primary symptoms, such as hyperactivity, inattention, impulsivity and externalizing problems. However, intellectual impairments and problems with internalizing are typically greater in females with ADHD (Gershon, 2002). As such, in a recent paper investigating age-related improvement in motor speed and subtle signs, Cole et al. (2008) emphasized that "when considering developmental patterns of executive and motor control in ADHD, boys and girls should be studied separately and at younger ages for a fuller understanding of the female-specific patterns of deficit" (p. 1518).

Summarizing previous findings, which focused specifically on motor skills, a meta-analysis and critical review (Gaub & Carlson, 1997) did not reveal any sex differences in fine motor skills in ADHD. More recent investigations have revealed conflicting results, such that Meyer and Sagvolden (2006) observed female children with ADHD perform a maze coordination task and complete the grooved pegboard task significantly slower than male children with ADHD. However this study was limited to analysis of fine motor skills. In comparison, Fliers et al. (2008) noted female children with ADHD displayed similar motor coordination problems as males with ADHD. That said, within this study, motor functioning was assessed via the Developmental Coordination Disorder Questionnaire (DCD-Q), completed by parents, and the 'Groningen Motoriek Observatieschaal' (Groningen Motor Observation Scale, GMO) completed by teachers. No performance assessment was included.

To our knowledge, no literature to date has included the same ratio of male to female children with ADHD and neurotypical controls when investigating motor functioning via motor skill performance. As previous research has revealed specific male- and female-specific patterns of deficit (e.g., Cole et al., 2008) in ADHD, this undoubtedly limits the ability of researchers to generalize current findings to females with ADHD (e.g., Gershon, 2002). A lack of information has led to difficulties with the identification and treatment of females with ADHD (Gershon, 2002), thus highlighting the significance of research in this domain. Taking the aforementioned into consideration, the aim of the study was to compare motor skill performance of an equal number of male and female children with ADHD and their neurotypical counterparts living in the Capital City of Prague. Based on previous observations, it was hypothesized that children with ADHD would display poorer fine and gross motor skills in comparison to neurotypical controls.

2. Methods

2.1. Participants

One hundred and sixteen 9- to 11-year-old children (58 males and 58 females, mean age = 10.1 years) participated in the current study. Of these children half ($n = 58$) were diagnosed with ADHD, and half were included as neurotypical controls ($n = 58$). Eleven of all participants were identified as left-handed. This included three neurotypical children (two male and one female) and eight children with ADHD (two male and six female). Hand preference was determined based on observation of several unimanual tasks, including throwing at a target, ringing a bell, cutting with a knife.

Participants were students of state primary schools of the Capital City of Prague, and were selected using purposeful sampling. Within the educational sector of the Czech Republic government, the National Institute of Pedagogy and

Psychology (IPPP) employs a team of professional psychiatrists, psychologists, neurologist and pedagogists (all certified according to government standards) to diagnose children with neurobehavioural disorders using standard scales. This includes the International Statistical Classification of Diseases and Related Health Problems (ICD-10), translated to Czech (MKN-10) (World Health Organization, 1993), the Wechsler Intelligence Scale and Wechsler Memory Working Scale translated and standardized in Czech (Havlůj, 2002) and The Strengths and Difficulties Questionnaire (Goodman, 1997).

In the current study, children with ADHD were recruited from the IPPP database of neurobehavioural disorders, which organizes children according to diagnosis, but is limited, as researchers do not have access to scores computes from the aforementioned standard scales. The researchers were informed that, having received their first diagnoses of ADHD when they were 5- or 6-years-old, all children were enrolled at a special school in Prague for children with ADHD, where re-testing occurs on a yearly basis to confirm an accurate diagnosis. Neurotypical children were selected from schools without any specific specialization (e.g., technical, artistic, sport, or linguistic). Ethics approval was granted by the Ethics Commission of the Faculty of Physical Education and Sport, at Charles University. In addition, parental consent was obtained for all individuals.

2.2. Procedure

Participants completed seven motor skill assessments (see Fig. 1). This included three fine motor tasks: (1) spiral tracing, (2) dot filling, (3) tweezers and beads; and four gross motor tasks: (1) twistbox, (2) foot tapping, (3) small plate finger tapping, and (4) large plate finger tapping. Each of these measures has proven to be valid and reliable assessments of skilled motor performance (e.g., Barnsley & Rabinovitch, 1970; Musálek, 2012; Rigal, 1992; Tapley & Bryden, 1985). All children completed the tasks in the same order (i.e., spiral tracing, dot filling, tweezers and beads, twist box, foot tapping, small plate finger tapping and large plate finger tapping), as the ranking of tasks was strictly determined based on a progression from fine to gross motor skills (Musálek, 2012).

2.2.1. Fine motor skills

Spiral tracing: This task included two side-by-side white spirals of the same shape and length embedded in grey square boxes (50 mm × 50 mm). The largest diameter of the spirals was 41 mm, with the width of the spiral measuring 2 mm. The

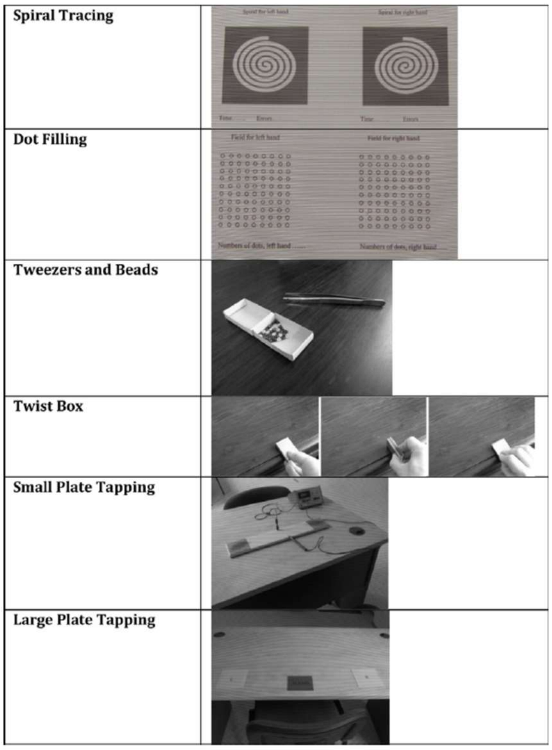


Fig. 1. Upper limb motor skill assessments.

spiral in the right box was intended for right-hand performance, and subsequently, the spiral in the left-box was meant for the left-hand. The aim of the task was to navigate through the spiral in one movement, from the outer edge to the centre, as quickly as possible, without moving the position of the score sheet. An error (penalized with 2 s) was noted when the participant left the designated area while drawing. The task was completed with the preferred and non-preferred hand.

Dot filling: This task included two boxes, each containing 90 identical circles (diameter 2 mm). Similar to the spiral tracing task, the right box was intended for right-hand hand performance, and subsequently, the left box was meant for the left-hand. The aim of the task was to place a mark in as many of the circles as possible, in 30 s. Only those marks within the circles were counted towards performance. The task was completed with the preferred and non-preferred hand.

Tweezers and beads: This task included two open matchboxes (one behind the other) and a pair of tweezers, place 150 mm on the desk directly in front of the participant, at the midline. The matchbox closest to the participant was filled with 20 beads (5 mm diameter), whereas the second was empty. The aim of the task was to move the beads one at a time from the starting position to the empty box, using the tweezers. The participant had 30 s to move as many beads as possible. If one of the beads was dropped during transport, the participant was instructed to take a new bead from the box. The task was completed with the preferred and non-preferred hand, where the number of beads transported in 30 s was recorded.

2.2.2. Gross motor skills

Twistbox: This task included a closed, empty matchbox, directly in front of the participant at the midline. The aim of the task was to overturn the matchbox, without lifting the matchbox from the desk. The task was completed with the preferred and non-preferred hand, where the number of times the matchbox was overturned in 30 s was recorded.

Foot tapping: For this task, the participant stood next to a desk, with the preferred leg closest to the desk. The aim of the task was to tap the ground in a standing position, for 30 s. During the task, the participant was able to hold onto the desk for stability. The task was completed with the preferred and non-preferred foot, where the number of taps completed in 30 s was recorded.

Small plate finger tapping: This task included an electronic plate (30 cm wide), with two embedded metal tapping surfaces (6 cm; one on right, and one on left). The plate was connected to a counting machine, where a metal tapping instrument was also connected via wire to the counting machine. Participants were asked to tap the metal tapping surfaces with the tapping instrument, alternating between the left- and right-surface. This task was completed with the preferred and non-preferred hand, where the number of taps completed in 30 s was recorded.

Big plate finger tapping: This task included a platform (70 cm wide) in front of the participant with two plates (paper, plastic; 15 cm diameter) embedded within. Participants were asked to tap each plate, alternating between the left and right plate. The task was completed with the preferred and non-preferred hand, where the number of taps completed in 30 s was recorded.

2.3. Statistical analysis

IBM® SPSS® statistics software (version 20) was used to complete statistical analysis. For each task, a 2 (group: ADHD × neurotypical) × 2 (sex: male × female) × 2 (limb used: preferred × non-preferred) factorial analysis of variance (ANOVA) was conducted.

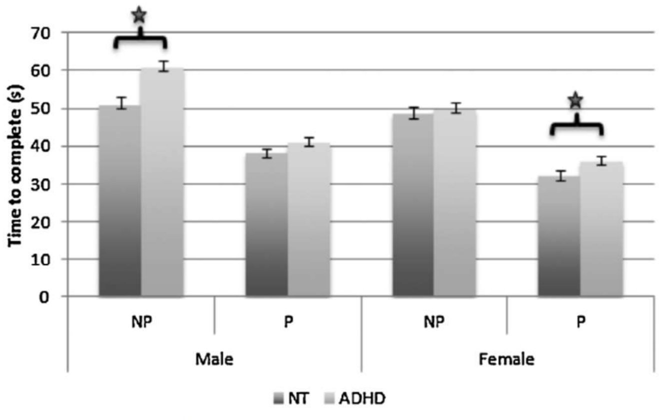


Fig. 2. In the spiral tracing task, both groups performed faster with the preferred hand. In comparison, participants with ADHD were significantly slower than neurotypical controls. For male participants, this was particularly true when performing with the non-preferred hand; however, for female participants, when performing with the preferred hand.

3. Results

Mean and standard error values are reported for all main effects and interactions which were statistically significant.

3.1. Fine motor tasks

3.1.1. Spiral tracing

A main effect of hand used to complete the task was revealed ($F(1, 112) = 270.89$, $p < .001$), such that participants completed the task significantly faster with their preferred hand ($\bar{x} = 36.76 \pm 0.68$) in comparison to their non-preferred hand ($\bar{x} = 52.45 \pm 0.97$). In addition, a main effect of sex was observed ($F(1, 112) = 20.24$, $p < .001$), such that female participants ($\bar{x} = 41.50 \pm 0.98$) were significantly faster than male participants ($\bar{x} = 47.71 \pm 0.98$). Finally, a main effect of group was revealed ($F(1, 112) = 10.80$, $p < .01$), such that participants with ADHD ($\bar{x} = 46.81 \pm 0.98$) were significantly slower than their neurotypical counterparts ($\bar{x} = 42.34 \pm 0.98$). Taking the above main effects into consideration, a significant interaction was revealed between hand used to complete the task, sex and group ($F(1, 112) = 5.96$, $p < .05$; see Fig. 2). With respect to participants with ADHD, during both preferred and non-preferred hand performance, females were significantly faster than males. That said, in neurotypical controls, females were only faster than males when using the preferred hand. Observing male participants, participants with ADHD were significantly slower than neurotypical controls when performing with the non-preferred hand. In comparison, female participants with ADHD were significantly slower than their neurotypical counterparts, when performing with the preferred hand. Overall, regardless of sex or group, participants were significantly faster with the preferred hand.

3.1.2. Dot filling

A main effect of hand used to complete the task was revealed ($F(1, 112) = 307.70$, $p < .001$), such that significantly more dots were made in 30 s with the preferred hand ($\bar{x} = 27.62 \pm 0.53$) in comparison to the non-preferred hand ($\bar{x} = 16.91 \pm 0.40$). A main effect of group was also observed ($F(1, 112) = 14.43$, $p < .001$), such that participants with ADHD ($\bar{x} = 20.93 \pm 0.50$) placed significantly fewer dots in 30 s in comparison to their neurotypical counterparts ($\bar{x} = 23.60 \pm 0.50$). Finally, a significant interaction between hand used to complete the task and group was noted ($F(1, 112) = 4.49$, $p < .05$; see Fig. 3). Overall, both groups completed significantly more dots in 30 s with their preferred hand; however, when contrasting the two groups, participants with ADHD placed significantly fewer dots in 30 s than neurotypical controls when using the preferred hand. No differences emerged between the groups during non-preferred hand performance. Finally, no differences were revealed between male and female children

3.1.3. Tweezers and beads

This task revealed a main effect of hand used to complete the task ($F(1, 112) = 608.55$, $p < .001$), such that participants transported significantly more beads (in 30 s) with their preferred hand ($\bar{x} = 18.45 \pm 0.19$) in comparison to their non-preferred hand ($\bar{x} = 13.00 \pm 0.25$). A main effect of group was also noted ($F(1, 112) = 15.87$, $p < .001$), where participants with ADHD transported significantly fewer beads ($\bar{x} = 14.99 \pm 0.27$) than their neurotypical counterparts ($\bar{x} = 16.50 \pm 0.27$). No significant effect of sex was revealed. No differences between male and female children were revealed.

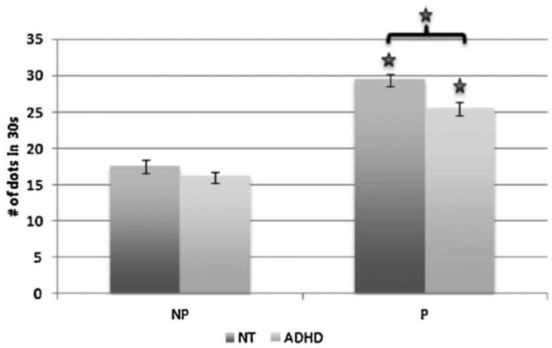


Fig. 3. In the dot filling task, both groups placed significantly more dots in 30 s with their preferred hand. However, when using the preferred hand, participants with ADHD placed significantly less dots in 30 s than neurotypical controls.

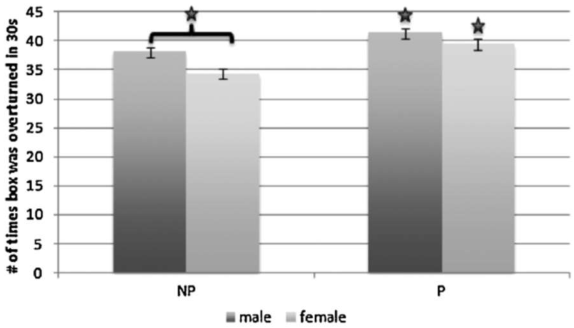


Fig. 4. In the twistbox task, both male and female participants performed better with the preferred hand. However, when completing the task with the non-preferred hand, male participants overturned the box significantly more times than female participants.

3.2. Gross motor tasks

3.2.1. Twistbox

A main effect of hand used to complete the task was revealed ($F(1, 112) = 97.90$, $p < .001$), such that participants overturned the match box more times (in 30 s) with the preferred hand ($\bar{x} = 40.50 \pm 0.62$) in comparison to the non-preferred hand ($\bar{x} = 36.29 \pm 0.55$). A main effect of sex was also noted ($F(1, 112) = 6.74$, $p < .05$), where male participants ($\bar{x} = 39.82 \pm 0.78$) overturned the match box more times than female participants ($\bar{x} = 36.97 \pm 0.78$). Taking the aforementioned into consideration, a significant interaction between hand used to complete the task and sex emerged ($F(1, 112) = 4.62$, $p < .05$; see Fig. 4). Overall, both male and female participants overturned the match box more times with their preferred hand. However, when using the non-preferred hand, male participants overturned the match box more times than female participants in 30 s. No effect of group was revealed, thus suggesting that children with ADHD and neurotypical controls performed similarly within this task.

3.2.2. Foot tapping

In the foot-tapping task, a main effect of foot used to complete the task was revealed ($F(1, 112) = 29.16$, $p < .001$), where significantly more taps were completed in 30 s with the preferred foot ($\bar{x} = 50.63 \pm 1.15$) in comparison to the non-preferred foot ($\bar{x} = 47.21 \pm 1.02$). Additionally, a main effect of group was revealed ($F(1, 112) = 4.65$, $p < .05$), where participants with ADHD performed significantly fewer taps ($\bar{x} = 46.68 \pm 1.47$) than their neurotypical counterparts ($\bar{x} = 51.16 \pm 1.57$) in 30 s. No differences between male and female children were revealed.

3.2.3. Small plate finger tapping

In this task, a main effect of hand used to complete the task was revealed ($F(1, 112) = 277.49$, $p < .001$), such that participants completed significantly more taps in 30 s with their non-preferred hand ($\bar{x} = 162.37 \pm 1.50$) in comparison to their preferred hand ($\bar{x} = 141.34 \pm 1.31$). A main effect of group was approaching significance ($F(1, 112) = 2.99$, $p = 0.086$), such that the data highlighted weak evidence for differences between children with ADHD ($\bar{x} = 149.68 \pm 1.78$) and their neurotypical peers ($\bar{x} = 154.03 \pm 1.78$). No differences emerged between male and female children.

3.2.4. Big plate finger tapping

Similar to the small plate finger tapping task, in the large plate finger tapping task, a main effect of hand used to complete the task was revealed ($F(1, 112) = 190.20$, $p < .001$), where participants completed significantly more taps in 30 s with their preferred hand ($\bar{x} = 74.99 \pm 0.93$) in comparison to their non preferred hand ($\bar{x} = 66.30 \pm 0.77$). Similar to the small plate finger tapping task, a main effect of group was approaching significance ($F(1, 112) = 3.75$, $p = 0.055$), where analysis revealed weak evidence for a difference between children with ADHD ($\bar{x} = 69.11 \pm 1.12$) and neurotypical controls ($\bar{x} = 72.18 \pm 1.12$). No differences emerged between male and female children.

4. Discussion

The aim of this study was to compare motor skills of an equal number of male and female children with ADHD and their neurotypical peers with respect to seven assessments. This included three fine motor tasks: (1) spiral tracing, (2) dot filling, (3) tweezers and beads; and four gross motor tasks: (1) twistbox, (2) foot tapping, (3) small plate finger tapping, and (4) large plate finger tapping. Based on previous reports in the literature, it was originally hypothesized that children with ADHD would display poorer motor skill performance in comparison to neurotypical controls. This was observed in all three of the upper limb fine motor skill assessments: spiral tracing, dot filling, tweezers and beads, and the lower limb gross motor skill assessment: foot tapping. No differences between groups emerged for the one upper limb gross motor assessments (twistbox), where the difference between children with ADHD and neurotypical controls was approaching significance for the other two upper limb gross motor assessments (small plate finger tapping, and large plate finger tapping). It can be suggested that the element of complexity inherent to the aforementioned tasks influenced the divide in performance that emerged between children with ADHD and their neurotypical counterparts. More specifically, the twistbox, small and large plate finger tapping tasks were simply measures of gross motor speed, therefore, no statistically significant differences emerged, as the tasks did not involve complex coordination or goal-directed movements (e.g., Meyer & Sagvolden, 2006). The following section will discuss each of the fine and gross motor skills assessed, in light of the current ADHD literature.

4.1. Upper limb tasks

Observing differences that emerged within upper limb tasks, children with ADHD displayed poorer performance in the spiral tracing, dot filling and tweezers and beads tasks (fine upper limb motor skills). The spiral tracing and dot filling tasks were similar in nature, as they both required a stylus (writing utensil) to complete. That said, the spiral tracing task required participants to navigate through a spiral as quickly as possible, whereas the dot filling task asked participants to place a mark in as many circles as possible in 30 s. Similar to the spiral tracing and dot filling tasks, the tweezers and bead task required participants to manipulate an instrument as an extension of the hand. In this case, tweezers were used to transport beads from a small matchbox to another. As such, each of these skills required a great amount of hand eye coordination to complete. Within all three tasks, children with ADHD performed poorer than their neurotypical counterparts. That said, both groups of children performed better with their preferred hand.

Although, to our knowledge, the spiral tracing and tweezers and bead tasks have not been used specifically to assess fine motor functioning, Lavasani and Stagnitti (2011) have observed poorer performance in children with ADHD when placing dots in a grid pattern. In addition, Meyer and Sagvolden (2006) revealed significant impairment in children with ADHD within a Maze Coordination task. Observations of handwriting (Barkley, 1998; Flapper et al., 2006; Racine et al., 2008) and drawing lines (Lavasani & Stagnitti, 2011), which both require a stylus, have also revealed impairments in ADHD. Regarding the tweezers and bead tasks, a plethora of studies have reported that children with ADHD display poor manual dexterity and are typically more variable, less stable and less accurate (Flapper et al., 2006; Kalff et al., 2003; Lavasani & Stagnitti, 2011; Rommelse et al., 2007). This provides support to the notion that impairments in ADHD are heightened in complex tasks (Barkley, 1998), as was observed in the current study. Rommelse et al. (2007) observed that motor skill impairments were most pronounced with the left hand, where 90% of participants were right-handed. As such, it can be argued that motor skill impairments were more apparent in the non-preferred hand. With respect to current results, analyses of all tasks (with the exception of big plate finger tapping) revealed main effects of hand used to complete the task, such that superior performance was seen with the preferred hand. This was expected, as it is commonly observed that performance increases with the preferred hand (Annett, 1970). More specifically, Jäncke et al. (1998) have demonstrated that right-handed individuals show more activation in the right hemisphere when using the left-hand, than in the left hemisphere when using the right hand; therefore suggesting that there is an increase in effort necessary for right-handers to perform with their left-hand.

Interestingly, within the spiral tracing task, the interaction between hand used to complete the task, sex and group revealed that, in male children with ADHD, the greatest difference was in non-preferred hand performance. However, when comparing female children with ADHD to their neurotypical counterparts, the greatest difference was observed in preferred hand performance. A meta-analysis and critical review (Gaub, & Carlson, 1997) did not find any sex differences in fine motor skills in ADHD. However, a more recent investigation (Meyer & Sagvolden, 2006) revealed female children with ADHD performed a maze coordination task and completed the grooved pegboard task significantly slower than male children with ADHD. That said, only slight differences in performance emerged between the preferred and non-preferred hands (Meyer & Sagvolden, 2006).

A significant interaction was also revealed between hand used to complete the task and group within the dot filling task. As expected, both groups performed better with the preferred hand. Interestingly, this interaction revealed that differences between children with ADHD and neurotypical controls were only evident during performance with the preferred hand. These results conflict with Rommelse et al. (2007) findings, where the authors noted motor deficits were more pronounced during left-hand performance. Ninety percent of their population was right-handed; therefore, left-hand performance was representative of non-preferred hand performance in the majority of participants. Looking specifically at the degree to which an individual uses their preferred hand, it is well known that left-handers show less functional asymmetry than right-handers (e.g., Springer & Deutsch, 1998; Yahagi & Kasai, 1999). Therefore, the degree to which they use their preferred hand is significantly less than that of right-handers. It is suggested that left- and mixed-handedness are linked to ADHD (e.g., Niederhofer, 2005; Rodriguez et al., 2010). Therefore, it is possible that performance difference between the hands were smaller for children with ADHD, thus motor impairments were highlighted in preferred hand performance, but conserved in non-preferred hand performance. Future research is required to confirm these hypotheses.

In comparison to the spiral tracing, dot filling, tweezers and bead and foot tapping tasks, no statistically significant differences emerged between children with ADHD and neurotypical controls for the twistbox, small and large plate finger tapping tasks. Nonetheless, it is important to highlight that differences between groups were approaching significance for the small and large plate finger tapping tasks, thus providing weak evidence for an effect. These results are in line with previous investigations (e.g., Meyer & Sagvolden, 2006; Seidman, Biederman, Faraone, Weber, & Ouellette, 1997), which have reported that impairments in motor control in ADHD are more prevalent in complex motor tasks (Kalff et al., 2003). Therefore, motor performance did not differ statistically between groups in these tasks because each was a simple assessment of motor speed, and, therefore, did not include complex coordination or goal-directed movements, as was seen in the other upper limb tasks (Meyer & Sagvolden, 2006). More specifically, the spiral tracing, dot filling and tweezers and bead tasks all required a high degree of manual dexterity. In order to complete the desired movement, it was necessary that small muscle movements of the hands and fingers were coordinated with those of the eyes. In comparison, the twistbox, small and large plate finger tapping tasks required less fine motor control to complete.

4.2. Lower limb tasks

In comparison to the aforementioned assessments, the foot-tapping task was unique, as it was the only assessment of lower limb performance included within this study. That said, children with ADHD performed significantly fewer taps in comparison to neurotypical controls. To date, a paucity of research surrounding lower limb motor control has been reported in the literature (e.g., Harvey & Reid, 2003), despite the suggestion that lower limb reaction time tests may be more appropriate than upper limb tests, to assess motor deficiencies (Peters, 1990, 1988). Observing static and dynamic balance (Piek et al., 1999; Shum & Pang, 2009; Wade, 1976; Wang, Wang, & Ren, 2003; Zang, Gu, Qian, & Wang, 2002), studies have observed poorer performance in children with ADHD in comparison to neurotypical controls. However, a more recent investigation revealed that children with ADHD do not display deficits in static balance in comparison to neurotypical controls (Schlee, Neubert, Worenz, & Milani, 2012).

More relevant to the current study, Pedersen, Heath, and Surburg (2007) incorporated a lower limb goal-directed aiming task to assess reaction time in children with ADHD. Results revealed slower reaction and movement times in children with ADHD, in comparison to neurotypical controls. Analogous to this report, the current study highlighted lower limb motor difficulties in children with ADHD. More specifically, significantly fewer taps were performed in the allotted 30 s, in comparison to neurotypical controls. Similarly, participants performed significantly better with their preferred foot (e.g., Pedersen et al., 2007). To date, most findings support the notion that children with ADHD show deficits in lower limb motor skills. However, as Schlee et al. (2012) recently observed no difference in static balance, further investigation is warranted to delineate trends in lower limb motor control in ADHD.

5. Conclusions

Numerous researchers have assessed motor skills in ADHD, where it is generally understood that impairments are present in this population. Nevertheless, despite the breadth of knowledge that currently exists, some researchers implicate primary deficits in fine motor processes, whereas other implicate gross motor problems (Fliers et al., 2008; Pitcher et al., 2003; Visser, 2003; Tseng et al., 2004). Furthermore, despite suggestions that ADHD manifests differently in male and female children, most research to date focuses on male children. Recent investigations surrounding sex differences provide inconclusive results (e.g., Fliers et al., 2008; Meyer & Sagvolden, 2006). As such, the overall aim of this study was to compare motor skill performance in an equal number of male and female children with ADHD to their neurotypical counterparts with seven assessments: (1) spiral tracing, (2) dot filling, (3) tweezers and beads, (4) twistbox, (5) foot tapping, (6) small plate finger tapping, and (7) large plate finger tapping. Based on previous reports in the literature, it was originally hypothesized that children with ADHD would demonstrate poorer performance in comparison to their neurotypical counterparts. However, in light of previous findings, impairments were observed in tasks requiring more complex motor skill (spiral tracing, dot filling, tweezers and beads, foot tapping), where performance was similar in less complex tasks (twistbox, small and large plate finger tapping). It is thus suggested that the complexity underlying the tasks solidified the divide, where motor impairments in ADHD were highlighted in more complex tasks.

Some researchers (e.g., Barkley, 1998; Leung & Connolly, 1998) implicate deficits in higher-order cognitive processing inherent to complex motor tasks (e.g., planning and organizing). However, others (e.g., Johansen, Aase, Meyer, & Sagvolden, 2002; Sagvolden, Johansen, Aase, & Russell, 2005) hypothesize that "the neurobiological basis is predicted to be a hypofunctioning nigro-striatal dopaminergic system" (Meyer & Sagvolden, 2006, p. 10). Overall, future work is required to further delineate trends in motor difficulties in children with ADHD and their underlying mechanisms.

Finally, addressing sex differences in ADHD, female children were faster than male children in the spiral tracing task. However, performance was similar for the remaining motor skills assessments, as no other significant interactions between sex and group were revealed. These results contrast the findings of Meyer and Sagvolden (2006), who noted female children with ADHD perform a maze coordination task and the grooved pegboard task significantly slower than male children with ADHD. However, in line with results of the current study, Meyer and Sagvolden (2006) did not see any sex differences in the finger tapping task. It can thus be suggested that sex differences in fine motor skills are limited. This offers support to Gaub and Carlson's (1997) meta-analysis and critical review, where no sex differences in ADHD were revealed. Observing gross motor skills, similar to Fliers et al. (2008), female children with ADHD displayed similar motor coordination problems as male children with ADHD.

5.1. Strengths and possible limitations of the study

Results of the current study should be interpreted in the context of the strengths and possible limitations of the study. Strengths include a large sample with an equal number of male and female children with ADHD and their neurotypical peers, thus enabling comparison based on sex. This is of utmost importance, given literature to date has primarily focused on male children with ADHD (e.g., Flapper et al., 2006; Gershon, 2002; Goulardins et al., 2013; Harvey & Reid (1997); Harvey et al. 2007). That said, referral bias continues to constrain and confound the ability to make good hypotheses about how the sexes may differ (Gershon, 2002; Rucklidge, 2010). As ADHD is under identified in females, due to lower ratings of primary symptoms, intellectual impairments are typically greater in females with ADHD (Gershon, 2002). As such, results of this study may not be completely representative of differences that exist between male and female children with ADHD.

As mentioned in the methods section, all children completed the tasks in the same order (i.e., spiral tracing, dot filling, tweezers and beads, twist box, foot tapping, small plate finger tapping and large plate finger tapping), as the ranking of tasks was strictly determined based on a progression from fine to gross motor skills (Musálek, 2012). Considering the order was not counterbalanced, it is likely that children performed poorer on the later tasks due to fatigue). This can be considered a limitation of the current study.

5.2. Implications and future directions

A recent investigation (Fliers et al., 2010) reports that "the frequent co-occurrence of both motor problems and Attention Deficit Hyperactivity Disorder (ADHD) has received relatively little attention in research" (p. 85). Furthermore, screening for ADHD does not typically included assessment of motor skills; therefore, attention to motor impairments is typically excluded from intervention (Gillberg et al., 2004; Sergeant, Piek, & Oosterlaan, 2006). Motor deficits occur in 30% to 50% of children with ADHD (Fliers et al., 2008; Visser, 2003), thus having a significant impact on children's daily life. More specifically, motor impairments have been linked to low self-esteem, higher levels of anxiety and poor social functioning (Skinner & Piek, 2001; Cummins, Piek, & Dyck, 2005). Furthermore, poor motor performance has been linked to childhood obesity (e.g., Morano, Colella, Roazza, Bortoli, & Capranica, 2011), where recent reports suggest an association between proneness to obesity and ADHD (Cortese & Vincenzi, 2012; Riverin & Tremblay, 2009).

Further research is required, not only to better our understanding of motor skills in ADHD, but to improve assessment and intervention methods. Researchers investigating developmental patterns of executive and motor control suggest "boys and girls should be studied separately and at younger ages for a fuller understanding of the female-specific patterns of deficit" (Cole et al., 2008, p. 1518). Subsequently, Rucklidge (2010) highlights the need to develop sex-appropriate diagnostic criteria and diagnostic tools as current assessments are limited in analysis of sex differences in ADHD. For example, Ohan and Johnston (2005) identified that DSM-IV items are more appropriate to describe ADHD in boys than in girls (Ohan & Johnston, 2005). Overall, although ADHD appears to be more similar than different in males and females, our understanding of the female-specific pattern of deficit is currently limited. A lack of information has led to difficulties with the identification and treatment of females with ADHD (Gershon, 2002). Recent clinical and experimental evidence implicates motor factors playing a greater role in ADHD than was originally believed (Fliers et al., 2008), thus highlighting significance of future research in the domain of sex differences in ADHD as they pertain to motor skill performance.

Acknowledgement

This study was supported by project PRVOUK P039.

References

American Psychiatric Association. Task Force on DSM-IV. (2000). *Diagnostic and statistical manual of mental disorders: DSM-IV-TR.* Washington, DC: American Psychiatric Association.

Annett, M. (1970). The growth of manual preference and speed. *British Journal of Psychology, 61*(4), 545–558.

Banerjee, T. D., Middleton, F., & Faraone, S. V. (2007). Environmental risk factors for attention-deficit hyperactivity disorder. *Acta Paediatrica, 96*(9), 1269–1274.

Barkley, R. A. (1998). *Attention-deficit hyperactivity disorder: a hand book for diagnosis and treatment* (2nd ed.). New York, NY: The Guilford Press.

Barkley, R. A. (2003). Issues in the diagnosis of attention-deficit/hyperactivity disorder in children. *Brain and Development, 25*(2), 77–83.

Barkley, R. A., DuPaul, G. J., & McMurray, M. B. (1990). Comprehensive evaluation of attention deficit disorder with and without hyperactivity as defined by research criteria. *Journal of Consulting and Clinical Psychology, 58*(6), 775–789.

Barnsley, R. H., & Rabinovitch, S. (1970). Handedness: Proficiency versus state preference. *Perceptual and Motor Skills, 30*(2), 343–362.

Biederman, J., & Faraone, S. (2005). Attention deficit hyperactivity disorder (abstract). *Lancet, 366*(9481), 237–248.

Biederman, J., Mick, E., Faraone, S. V., Braaten, E., Doyle, A., Spencer, T., & Johnson, M. A. (2002). Influence of gender on attention deficit hyperactivity disorder in children referred to a psychiatric clinic. *American Journal of Psychiatry, 159*(1), 36–42.

Biederman, J., Monuteaux, M. C., Mick, E., Spencer, T., Wilens, T. E., Klein, K. L., & Faraone, S. V. (2006). Psychopathology in females with attention-deficit/hyperactivity disorder: A controlled, five-year prospective study. *Biological Psychiatry, 60*(10), 1098–1105.

Brown, R. T., Antonuccio, D. O., DuPaul, G. J., Fristad, M. A., King, C. A., Leslie, L. K., & Vitiello, B. (2008). *Childhood mental health disorders: evidence base and contextual factors for psychosocial, psychopharmacological, and combined interventions.* Washington, DC: American Psychological Association.

Cole, W. R., Mostofsky, S. H., Larson, J. C., Denckla, M. B., & Mahone, E. M. (2008). Age-related changes in motor subtle signs among girls and boys with ADHD. *Neurology, 71*, 1514–1520.

Cortese, S., & Vincenzi, B. (2012). Obesity and ADHD: clinical and neurobiological implications. *Behavioral neuroscience of attention deficit hyperactivity disorder and its treatment* (pp. 199–218). Berlin, Heidelberg: Springer.

Cummins, A., Piek, J. P., & Dyck, M. J. (2005). Motor coordination, empathy, and social behaviour in school-aged children. *Developmental Medicine & Child Neurology, 47*, 437–442.
Denckla, M. B. (1985). Revised neurological examination for subtle signs. *Psychopharmacology Bulletin, 21*, 773–800.
Denckla, M. B., & Rudel, R. G. (1978). Anomalies of motor development in hyperactive boys. *Annals of Neurology, 3*, 231–233.
Döpfner, M., Breuer, D., Wille, D. P. N., Erhart, M., & Ravens-Sieberer, U. (2008). How often do children meet ICD-10/DSM-IV criteria of attention deficit-/hyperactivity disorder and hyperkinetic disorder? Parent-based prevalence rates in a national sample-results of the BELLA study. *European Child & Adolescent Psychiatry, 17*(1), 59–70.
Flapper, B. C. T., Houwen, S., & Schoemaker, M. M. (2006). Fine motor skills and affects of methylphenidate in children with attention deficit/hyperactivity disorder. *Journal of Developmental Medicine and Child Neurology, 48*, 165–169.
Fliers, E. A., Franke, B., Lambregts-Rommelse, N. N., Altink, M. E., Buschgens, C. J., Nijhuis-van der Sanden, M. W., & Buitelaar, J. K. (2010). Undertreatment of motor problems in children with ADHD? *Child and Adolescent Mental Health, 15*(2), 85–90.
Fliers, E., Rommelse, N., Vermeulen, S. H. H. M. , Altink, M., Buschgens, C. J. M., Faraone, S. V., & Buitelaar, J. K. (2008). Motor coordination problems in children and adolescents with ADHD rated by parents and teachers: Effects of age and gender. *Journal of Neural Transmission, 115*(2), 211–220.
Gaub, M., & Carlson, C. L. (1997). Gender differences in ADHD: A meta-analysis and critical review. *Journal of the American Academy of Child & Adolescent Psychiatry, 36*(8), 1036–1045.
Gershon, J. (2002). A meta-analytic review of gender differences in ADHD. *Journal of Attention Disorders, 5*(3), 143–154.
Gillberg, C., Gillberg, I. C., Rasmussen, P., Kadesjö, B., Söderström, H., Råstam, M., & Niklasson, L. (2004). Co-existing disorders in ADHD—Implications for diagnosis and intervention. *European Child & Adolescent Psychiatry, 13*, 80–92.
Goldstein, M. L., & Morewitz, S. (2011). Attention-deficit hyperactivity disorder. *Chronic disorders in children and adolescents* (pp. 99–123). New York: Springer.
Goodman, R. (1997). The strengths and difficulties questionnaire: A research note. *Journal of Child Psychology and Psychiatry, 38*, 581–586.
Goulardins, J. B., Marques, J. C. B., Casella, E. B., Nascimento, R. O., & Oliveira, J. A. (2013). Motor profile of children with attention deficit hyperactivity disorder, combined type. *Research in Developmental Disabilities, 34*, 40–45.
Havlůj, J. (2002). *Wechsler intelligence scale for children III*. Praha: Testcentrum.
Hartsough, C. S., & Lambert, N. M. (1985). Medical factors in hyperactive and normal children: Prenatal, developmental, and health history findings. *American Journal of Orthopsychiatry, 55*(2), 190–201.
Harvey, W. J., & Reid, G. (2003). Attention-deficit/hyperactivity disorder: A review of research on movement skill performance and physical fitness. *Adapted Physical Activity Quarterly, 20*, 1–25.
Harvey, W. J., & Reid, G. (1997). Motor performance of children with attention-deficit hyperactivity disorder: A preliminary investigation. *Adapted Physical Activity Quarterly, 14*, 189–202.
Harvey, W. J., Reid, G., Grizenko, N., Mbekou, V., Ter-Stepanian, M., & Joober, R. (2007). Fundamental movement skills and children with attention-deficit hyperactivity disorder: Peer comparisons and stimulant effects. *Journal of Abnormal Child Psychology, 35*, 871–882.
Henderson, S. E., & Sugden, D. A. (1992). *Movement assessment battery for children*. London, UK: The Psychological Corporation.
Hinshaw, S. P., Herbsman, C., Melnick, S., Nigg, J., & Simmel, C. (1993). Psychological and familial processes in ADHD: Continuous or discontinuous with those in normal comparison children. *Annual meeting of the International Society for Research in Child and Adolescent Psychopathology*.
Jäncke, L., Peters, M., Schalug, G., Posse, S., Steinmetz, H., & Müller-Gärtner, H. W. (1998). Differential magnetic resonance signal change in human sensorimotor cortex to finger movements of different rate of the dominant and subdominant hand. *Cognitive Brain Research, 6*, 279–284.
Johansen, E. B., Aase, H., Meyer, A., & Sagvolden, T. (2002). Attention-deficit/hyperactivity disorder (ADHD) behaviour explained by dysfunctioning reinforcement and extinction processes. *Behavioral Brain Research, 130*, 37–45.
Kadesjö, B., & Gillberg, C. (2001). The comorbidity of ADHD in the general population of Swedish school-age children. *Journal of Child Psychology and Psychiatry, 42*(4), 487–492.
Kalff, A., Sonneville, L., Hurks, P., Hendriksen, J., Kroes, M., Feron, F., Steyaert, J., Zeban, T., Vles, J., & Jolles, J. (2003). Low and high level controlled processing in executive motor control tasks in 5–6-year-old children at risk of ADHD. *Journal of Child Psychology and Psychiatry, 44*, 1049–1057.
Karatekin, C., Makiecz, S., & Siegal, M. (2002). A preliminary study of motor problems in children with attention deficit hyper activity disorder. *Perceptual and Motor Skills, 97*, 1267–1280.
Lange, K. W., Reichl, S., Lange, K. M., Tucha, L., & Tucha, O. (2010). The history of attention deficit hyperactivity disorder. *ADHD Attention Deficit and Hyperactivity Disorders, 2*(4), 241–255.
Lavasani, N. M., & Stagnitti, K. (2011). A study on fine motor skills of Iranian children with attention deficit/hyper activity disorder aged from 6 to 11 years. *Occupational Therapy International, 18*, 106–114.
Leung, P. W., & Connolly, K. J. (1998). Do hyperactive children have motor organization and/or execution deficits? *Developmental Medicine & Child Neurology, 40*(9), 600–607.
Melnick, S. M., & Hinshaw, S. P. (2000). Emotion regulation and parenting in AD/HD and comparison boys: Linkages with social behaviors and peer preference. *Journal of Abnormal Child Psychology, 28*(1), 73–86.
Meyer, A., & Sagvolden, T. (2006). Fine motor skills in South African children with symptoms of ADHD: Influence of subtype, gender, age, and hand dominance. *Behavioral and Brain Functions, 2*(1), 33.
Miyahara, M., Piek, J., & Barrett, N. (2006). Accuracy of drawing in a dual-task and resistance-to distraction study: Motor or attention deficit? *Human Movement Science, 25*, 100–109.
Morano, M., Colella, D., Robazza, C., Bortoli, L., & Capranica, L. (2011). Physical self-perception and motor performance in normal-weight, overweight and obese children. *Scandinavian Journal of Medicine & Science in Sports, 21*(3), 465–473.
Musálek, M. (2012). Development of test batteries for diagnostic of motor laterality lanifestation: link between cerebellar dominance and hand performance. *Dissertation Thesis*, Prague: Charles University.
Niederhofer, H. (2005). Hand preference in attention deficit hyperactivity disorder. *Perceptual and Motor Skills, 101*(3), 808–810.
Ohan, J. L., & Johnston, C. (2005). Gender appropriateness of symptom criteria for attention-deficit/hyperactivity disorder, oppositional-defiant disorder, and conduct disorder. *Child Psychiatry and Human Development, 35*(4), 359–381.
Pan, C. Y., Tsai, C. L., & Chu, C. H. (2009). Fundamental movement skills in children diagnosed with autism spectrum disorders and attention deficit hyperactivity disorder. *Journal of Autism and Developmental Disorders, 39*(12), 1694–1705.
Pedersen, S. J., Heath, M., & Surburg, P. R. (2007). Lower extremity response time performance in boys with ADHD. *Journal of Attention Disorders, 10*(4), 343–349.
Peters, M. (1988). Footedness: Asymmetries in foot preference and skill and neuropsychological assessment of foot movement. *Psychological Bulletin, 103*, 179–192.
Peters, M. (1990). Neuropsychological identification of motor problems: Can we learn something from the feet and legs that hand and arms will not tell us. *Neuropsychology Review, 1*, 165–183.
Piek, J. P., Pitcher, T. M., & Hay, D. A. (1999). Motor coordination and kinaesthesis in boys with attention deficit–hyperactivity disorder. *Developmental Medicine & Child Neurology, 41*(3), 159–165.
Pitcher, T. M., Piek, J. P., & Hay, D. A. (2003). Fine and gross motor ability in males with ADHD. *Developmental Medicine and Child Neurology, 45*, 525–535.
Polanczyk, G., Lima, M. S., Horta, B. L., Biederman, J., & Rohde, L. A. (2007). The worldwide prevalence of ADHD: A systematic review and metaregression analysis. *American Journal of Psychiatry, 164*, 942–948.
Racine, M. B., Majenemer, A., Shevell, M., & Snider, L. (2008). Handwriting performance in children with attention deficit hyper activity disorder. *Journal of Child Neurology, 23*(4), 399–406.
Rigal, R. A. (1992). Which handedness: Preference or performance. *Perceptual and Motor Skills, 75*(3), 851–866.
Riverin, M., & Tremblay, A. (2009). Obesity and ADHD. *International Journal of Obesity, 33*(8), 945.

Rodriguez, A., Kaakinen, M., Moilanen, I., Taanila, A., McGough, J. J., Loo, S., & Järvelin, M. R. (2010). Mixed-handedness is linked to mental health problems in children and adolescents. *Pediatrics, 125*(2), e340–e348.
Rohde, L. A., & Halpern, R. (2004). Recent advances on attention deficit/hyperactivity disorder. *Jornal de Pediatria, 80*(2), 61–70.
Rommelse, N. N., Altink, M. E., Oosterlaan, J., Buschgens, C. J., Buitelaar, J., De Sonneville, L. M., & Sergeant, J. A. (2007). Motor control in children with ADHD and non-affected siblings: Deficits most pronounced using the left hand. *Journal of Child Psychology and Psychiatry, 48*(11), 1071–1079.
Rosa Neto, F. (2002). *Manual de avaliação motora*. Porto Alegre: Artmed.
Rucklidge, J. J. (2010). Gender differences in attention-deficit/hyperactivity disorder. *The Psychiatric Clinics of North America, 33*(2), 357.
Sagvolden, T., Johansen, E. B., Aase, H., & Russell, V. A. (2005). A dynamic developmental theory of attention-deficit/hyperactivity disorder (ADHD) predominantly hyperactive/impulsive and combined subtypes. *Behavioral Brain Science, 28*, 397–419.
Schlee, G., Neubert, T., Worenz, A., & Milani, T. L. (2012). Children with ADHD show no deficits in plantar foot sensitivity and static balance compared to healthy controls. *Research in Developmental Disabilities, 33*(6), 1957–1963.
Schuerholz, L. J., Cutting, L., Mazzocco, M. M., Singer, H. S., & Denckla, M. B. (1997). Neuromotor functioning in children with Tourette syndrome with and without attention deficit hyperactivity disorder. *Journal of Child Neurology, 12*, 438–442.
Seidman, L. J., Biederman, J., Faraone, S. V., Weber, W., & Ouellette, C. (1997). Toward defining a neuropsychology of attention deficit hyperactivity disorder: Performance of children and adolescents from a large clinically referred sample. *Journal of Consulting and Clinical Psychology, 65*(1), 150–160.
Seidman, L. J., Biederman, J., Monuteaux, M. C., Valera, E., Doyle, A. E., & Faraone, S. V. (2005). Impact of gender and age on executive functioning: Do girls and boys with and without attention deficit hyperactivity disorder differ neuropsychologically in preteen and teenage years? *Developmental Neuropsychology, 27*(1), 79–105.
Sergeant, J. A., Piek, J. P., & Oosterlaan, J. (2006). ADHD and DCD: A relationship in need of research. *Human Movement Science, 25*(1), 76–89.
Shaw, P., Eckstrand, K., Sharp, W., Blumenthal, J., Lerch, J. P., Greenstein, D., et al. (2007). Attention-deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proceedings of the National Academy of Sciences, 104*(49), 19649–19654.
Shum, S., & Pang, M. Y. (2009). Children with attention deficit hyperactivity disorder have impaired balance function: Involvement of somatosensory, visual, and vestibular systems. *The Journal of Pediatrics, 155*(2), 245–249.
Skinner, R. A., & Piek, J. P. (2001). Psychosocial implications of poor motor coordination in children and adolescents. *Human Movement Science, 20*(1), 73–94.
Springer, S. P., & Deutsch, G. (1998). *Left brain, right brain* (5th ed.). San Francisco, CA: Freeman.
Tapley, S. M., & Bryden, M. P. (1985). A group test for the assessment of performance between the hands. *Neuropsychologia, 23*(2), 215–221.
Taylor, E., Döpfner, M., Sergeant, J., Asherson, P., Banaschewski, T., Buitelaar, J., & Zuddas, A. A. (2004). European clinical guidelines for hyperkinetic disorder—First upgrade. *European Child & Adolescent Psychiatry, 13*(1), i7–i30.
Tervo, R. C., Azuma, S., Fogas, B., & Fiechtner, H. (2002). Children with ADHD and motor dysfunction compared with children with ADHD only. *Developmental Medicine & Child Neurology, 44*, 383–390.
Tiffin, J. (1968). *Purdue Pegboard: examiner manual*. Chicago: Science Research Associates.
Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard: Norms and studies of reliability and validity. *Journal of Applied Psychology, 32*, 234–247.
Tseng, M. H., Henderson, A., Chow, S. M., & Yao, G. (2004). Relationship between motor proficiency, attention, impulse, and activity in children with ADHD. *Developmental Medicine & Child Neurology, 46*, 381–388.
Ulrich, D. A. (1985). *Test of gross motor development*. Austin, TX: Pro-Ed.
Ulrich, D. A. (2000). *Test of gross motor development: examiner's manual* (2nd ed.). Austin, TX: Pro-Ed.
Visser, J. (2003). Developmental coordination disorder: A review of research on subtypes and comorbidities. *Human Movement Science, 22*, 479–493.
Wade, M. (1976). Effects of methylphenidate on motor skill acquisition of hyperactive children. *Journal of Learning Disabilities, 9*, 48–52.
Wang, J., Wang, Y., & Ren, Y. (2003). A case-control study on balance function of attention deficit hyperactivity disorder (ADHD) children. *Beijing da xue xue bao. Yi xue ban,* Journal of Peking University. Health sciences35(3), 280.
World Health Organization. (1993). *ICD-10: International Statistical Classification of Diseases and Related Health Problems*. Geneva: World Health Organization.
Yahagi, S., & Kasai, T. (1999). Motor evoked potentials induced by motor imagery reveal a functional asymmetry of cortical motor control in left-and right-handed human subjects. *Neuroscience Letters, 276*(3), 185–188.
Zang, Y., Gu, B., Qian, Q., & Wang, Y. (2002). Objective measurement of the balance dysfunction in attention deficit hyperactivity disorder children. *Chinese Journal of Clinical Rehabilitation, 6*(9), 1372.

4. LINK BETWEEN HANDEDNESS AND CEREBELLAR DOMINANCE

As described in the first chapter, handedness in humans can be perceived as the most transparent functional asymmetry since 90% of people are right-handers and 10% are left-handers (e.g., Annett, 2002; McManus, 2004; Hugdahl & Westerhausen, 2010). Here I would like to emphasize that previous research determined that handedness is a behavioural property which reflects the structural and functional lateralization of the human brain (see Geschwind & Levitsky, 1968; LeMay, 1976; Pujol, Deus, Losilla & Capdevila, 1999; McManus, 2004; Takao, Hayashi & Ohtomo, 2013; Annett, 2013; James et al., 2015). The origin and deviations of this functional brain lateralization have been investigated from a genetic perspective – genetic models of handedness inheritance (Annett, 1985, 2002; Gangestad & Yeo,1994; Levy & Nagylak, 1972; McManus, 1984, 1985, 2002) as well as from an environmental perspective where it was found that factors like premature birth (Ross, Lipper, & Auld, 1987; Saigal, Rosenbaum, Szatmari & Hoult, 1992; Domellöf, Johansson, & Rönnqvist, 2011), prenatal level of testosterone (Geschwind & Galaburda, 1985; Tan, 1990; Beking, Geuze, van Faassen, Kema, Kreukels & Groothuis, 2018); birth stress (Bakan, 1977; Van Strien, Bouma, & Bakker, 1987; Coren, 1995) can influence brain lateralization with relations to handedness and limb motor performance. However, most of these and other studies have been focused mainly on structural (like lobes or gyri and sulci) and functional (pathways) lateralization of the cerebral right and left hemispheres.

A large body of research has verified that movements of the preferred hand are controlled by the contralateral cerebral hemisphere, which also exhibits a higher brain activity and involves an extensive area of the motor brain map compared to the ipsilateral cerebral hemisphere, (e.g., Amunts et al., 1996; Viviani, Perani, Grassi, Bettinardi & Fazio, 1998; Volkmann, Schnitzler, Witte, & Freund, 1998; Gut et al., 2007). However, movement manifestation is not just a question of the cerebral hemispheres function. A voluntary movement is possible only when a complex of occurrences takes place in the brain network involving many regions. For instance, neuroimaginery studies revealed that basal ganglia, which are connected with cerebral cortex, play an indisputable role in voluntary movement. In addition, functional as well as structural asymmetries in certain parts of basal ganglia related to handedness were found during movements (e.g., Scholz et al., 2000; Klöppel, Mangin, Vongerichten, Frackowiak & Siebner, 2010). In addition to basal ganglia and limbic system, which will not be part of the current study, it is important to realize that other brain structures, like cerebellum, are involved in the performance of movement. Therefore, in the following part I will outline the cerebellar function and its possible connection to human laterality. In particular, cerebellum could be described as a fantastic computer involved in both motor actions (sensomotor control, information about position, balance control and muscle tension control) (Ito, Yoshida, & Obata, 1964; Keele & Ivry, 1990; Nicholls et al., 2001; Ito, 2002; Stoodley & Schmahmann, 2010) and cognition (Schmahmann,1997; Nixon & Passingham, 2000; Stoodley, 2012).

Previous research has repeatedly shown that the cerebral hemispheres are contralaterally connected to the cerebellar hemispheres. The connection of these two structures creates a cerebrocerebellar communication loop (Kelly & Strict, 2003; Jissendi, Baudry & Baleriaux, 2008; Stoodley & Schmahmann, 2009; Salmi et al., 2010). An increase in blood oxygen flow in the contralateral region of motor cortex and ipsilateral cerebellar cortex was observed in unimanual motor activities (Nair, Purcott, Fuchs, Steinberg, & Kelso, 2003; Hu, Shen & Zhou, 2008). From this we can conclude that each of the cerebellar hemispheres participates in motor control on the ipsilateral side of the body (e.g., Eccles, 1967; Chollet et al., 1991; Cui et al., 2000; Yan et al., 2006; Ito, 2012). Since, from the point of motor control, cerebellum is believed to play an important role in particular in the timing of movement, the discovery of the cerebrocerebellar loop led to a better understanding of the involvement of cerebellum in its responsibility for motor coordination of the motion (Miall & Reckess, 2002; Gowen & Miall, 2007). For instance, the neuroimage study of Snyder et al. (1995) revealed in right-handers a significant relation between the hand preference and the cerebellar torque (Spearman correlation $r = .52$). Further, Gao et al. (1996) and Grafton, Arbib, Fadiga & Rizzolatti (1996) found a stronger blood flow in the right cerebellar hemisphere in right-handers when performing a reach and grasp activity. Very important findings were provided by He et al. (2006). These authors revealed handedness-related functional connections in cerebellar-prefrontal, cerebellar-parietal, cerebellar-temporal and cerebellar-limbic connectivity which support the assumption of a significant role of cerebellum in the concept of handedness. In addition, Begliomini, Nelini, Castiello, Caria and Grodd (2008) found that cerebellar and cortical activation is related in grip and handedness. According to them, this might indicate a possible involvement of the cerebellum in the process of adaptation and precision of the shape of the hand intended for grip and manipulation (Begliomini et al., 2008). Although some authors (e.g., Rosch, Ronan, Cherkas, & Gurd, 2010) consider the research in the field of functional cerebellar asymmetry an essential complement to cortical studies in the understanding of human laterality, primarily in the field of the concept of thedevelopment of hemispheric specialization, the question of functional lateralization of the two cerebellar hemispheres and their relationship to handedness is still an open issue.

Understanding the connection between human laterality and cerebellar function could be helpful in many fields (pedagogical, psychological, sport) to improve or increase the effectiveness of motor learning (explicit versus implicit approach) for acquiring of fundamental or specific motor skills (Veraksa, Aires, Leonov & Musálek, 2018).

Prof. Kamil Henner, a leading Czechoslovak neurologist, was among the first to obtain results from investigating the association between handedness and cerebellar function during clinical testing of muscle tone. Henner revealed that the right-handed adult population exhibited a significant level of hypotonia, a higher articular flexibility in the non-preferred, i.e. left upper limb, observed as synkinesis during walking (Henner, 1927, 1936). Since cerebellum is also composed of two hemispheres, Henner (1936) defined the revealed asymmetry as a physiological extinction syndrome or manifestation of cerebellar dominance. Henner’s followers, Tichy and Belacek (2008, 2009), confirmed that asymmetric cerebellar hypotonia is well detectable in joint junctions, for instance during walking (see also Plate, Sedunko, Pelykh, Schlick, Ilmberger & Bötzel, 2015), or in controlled parallel falls of the upper or lower limbs, when it takes the form of a significantly larger extent of motion of the non-preferred limb. Tichy and Belacek (2008) were also first to find, using clinical evaluation (by aspection and palpation) of muscle tone and articularis passivity that Henner’s hypothesis of cerebellar dominance on the non-preferred hand works also in right-handed children. On the other hand, a follow-up study Tichý, Běláček, Nykl and Kaspříková (2012), conducted on healthy adults (n=26 right-handers and n=35 left-handers), revealed that cerebellum dominance does not manifest itself with the same specificity regarding handedness of participants. Hypotonia, which was again evaluated (by aspection and palpation) as a difference in the number of swings in the wrist, shoulder, elbow, knee joints and in the ankle during controlled free falls proved to be significantly detectable in the non-preferred limb exclusively in the right-hand population. Left-handers showed significant variability that did not correspond to the specified principles of cerebellar dominance (Tichý et al., 2012).

Even though the aforementioned clinical studies by Henner (1927, 1936) and Tichy et al. (2008 – 2012) showed with a lot of consistency a greater hypotonia on the non-preferred limb in right-handed children and adults, it must be still taken into account that these studies evaluated primarily the relationship between laterality and cerebellar dominance by clinical methods (aspection, palpation). This may have a significant impact on the quality of the acquired data. Further, there has not been any evidence showing that motor performance of the preferred and non-preferred hand will also support the suggested link between hand preference and cerebellar dominance.

Therefore, in our research we aimed to extend the approach to include the assessment of a certain manifestation of cerebellar dominance (so-called physiological extinction syndrome) in the upper limb in middle age school right-handed children. At the same time, we aimed to reveal whether the performance of the preferred and non-preferred limb in right-handers might be connected to a different muscle tone, which is significantly influenced by right and left cerebellar hemispheres. In other words, whether a higher muscle tone implies or may imply a better control. Since, unlike in the previous studies, we designed and used a novel photoscopic method of assessment of a selected manifestation of cerebellar dominance (articular passivity), it was first necessary to verify the test- retest reliability of the assessment of articular joint passivity in a selected joint connection (wrist), where it was assumed that consistent results would be obtained. At the same time, this study aimed to assess the relationship between handedness performance measures and the assessment of the joint passivity of the wrist, which might show that the cerebellum controls the dominant and the non-dominant limb in a different way.

It was hypothesized that a significant relationship between the difference in the performance of the preferred and non-preferred hand would be observed. Acquiring such information will allow a deeper insight into the questions of cerebro-cerebellar asymmetries in humans and it can open additional research areas targeting motor learning process and also by presenting new possibilities in the diagnosis of laterality.

Research sample:

In line with the approach used in previous studies to find a homogenous sample of children in the age range when the human body expresses quite stable patterns of motor behaviour including motor laterality of the upper limb, we focused our selective attention on middle age school children (age 8 to 10 years). Children were recruited from public elementary schools in the Capital City of Prague and they were selected using an intentional selection process. More specifically, schools and pupils without any specific specialization (e.g., technical, artistic, sport, or linguistic) were selected. We used a list of schools from each Prague district (there are 10 main districts) and selected one school from each district. All selected schools had to have a similar number of children in age category 8-10 and classes with integrated children were excluded, so as not to bias the results. In the Czech education system, it means that our sample consisted of children from 2nd to 4th grade. Ethics approval was granted by the Ethics Commission of Faculty of Physical Education and Sport, Charles University. In addition, a parental consent was obtained for all individuals.

A total of 193 typically developing 8–10-year-olds from Czech primary schools without previous injury of upper limbs were selected for the present study. Since it proved to be too difficult to get a proportional sample of right- and left-handed children, we limited our investigation only to right-handed children. Results of hand preference tasks from test battery Musalek (2013) validated for Czech children confirmed that 157 of the children were pure right-handers (71 boys and 86 girls; Mage = 9.2 years, SD= ±0.75 years), n=18 were pure left-handers and n=18 were mixed-handers.

Procedure:

Four difference motor tests were used to assess hand performance: spiral tracing, dot filling, tweezers and beads, twisting box. These tests were validated for Czech children by Musalek (2014). The applicability of these tests was previously verified for children of the same age in studies Scharoun et al. (2013), Musalek (2015). A detailed characteristic of these tests from the methodology and motor perspective is given in publications: Scharoun et al. (2013), Musalek (2014), Musalek (2015), Musalek, Scharoun and Bryden (2015).

Developing a maximally objective tool that could be used in field testing conditions presented a new challenge for the assessment of articularis passivity as replications of a previous suggestion about manifestation of cerebellar dominance. In the first step, it was necessary to determine a sufficiently sensitive joint in which suggested hypotonia could be assessed. Since human hands are adapted for manipulation and transportation, we decided to measure the differences in articularis passivity in the left and right wrists. In the next step, the unilateral immobilizer was made using the technology of shaping thermoplastic on a gypsum model (for more detail, see Figure 1 and the description of the developing process in Musalek at al., 2015).

Methodology for the use of the portable immobilizer:

In each participant the following anatomical markers were found: centre of the humerus capitulum, the lateral epicondyle of the humerus, styloid process of the ulna, and the distal end of the fifth metacarpal. All these markers were labelled by a tip pen. Then the height of the immobilizer was adjusted for each participant to a comfortable position. The arm fixed in the immobilizer was locked to ensure that the participant's elbow remained at a 75° angle. The accuracy of the fixed joint angle was checked by the cross line laser. The participant was then asked to relax the wrist (see Figure 2. in Musalek et al., 2015). While the participant maintained the fixed position, the researcher took a photograph of the preferred and non-preferred arm and hand using a digital camera attached on tripod and kept at a fixed distance of 150 cm from the immobilizer throughout the duration of the study. All participants went through the measurement procedure twice (test-retest) with a 90-min break between assessments. The angle of the right or left wrist at the end of the test was calculated from connected anatomical markers in Dartfish program.

Before we started to analyze all collected data, we had verified the reliability (time stability) of the portable immobilizer developed for assessing of articularis passivity. The reliability of left- and right-wrist joint angles, as assessed by correlating measurements of articular joint passivity in the first and second assessment ($r = 0.97$), showed that our photoscopic method was highly stable across 90 min (see Table 2 in Musalek et al., 2015).

Results:

In all hand performance tests participants achieved a significantly better performance by the preferred hand (see Table 1 in Musalek et al., 2015). Further, it was

found that the non-preferred upper limb (left) in the research group of right-handed children demonstrated significant hypotonia $p < .01$ (i.e., higher articular joint passivity; see Figure 4 in Musalek et al., 2015). Nevertheless, a detailed analysis revealed that the increased passivity in the left wrist assessed in a static relaxed position using a photoscopic method was found in 95% of cases; eight right-handed children demonstrated a reverse result (i.e., hypotonia being detected in the preferred [right] upper limb). Further, significant correlations between articular passivity in the wrist as the manifestation of cerebellum dominance and hand performance tests $r = 0.36 – 0.59$ were revealed (see Table 3 in Musalek et al., 2015).
For more details see Musalek et al. (2015)

Summary:

Unlike in previous studies Tichy and Belacek, (2008, 2009), a new photoscopic method was used to determine neocerebellar extinction syndrome as a manifestation of cerebellar dominance. The test-retest verification of reliability showed that in the defined conditions (repetition of tests after 90 min) the measurement of articular passivity was highly stable ($r = 0.97$). Our results considering greater hypotonia on the non-preferred hand are in line with conclusion of Tichy and Belacek (2008). A subsequent correlation analysis of articular joint passivity which revealed a significant relationship with hand performance tests ($p < .001$) adds important information to the existing literature (e.g., Beaton, 2003; Beaton & Mariën, 2010; Jäncke, Specht, Mirzazade & Peters, 1999; McManus & Cornish, 1997; Peters, 1995; Snyder et al.,1995), which suggests that cerebellar dominance plays a unique role in handedness. Our finding represents possible supplementary information to the common understanding of the statement that the preferred hand is usually also more skilful in hand performance tasks. Therefore, we suggest that a higher muscle tone could be a prerequisite for a better performance. More specifically, the correlation between articular joint passivity and motor performance tests for the upper limb, which has always worked with the given tool grasped by fingers in a certain way, support the findings of the study Begliomini et al. (2008), in which a correlation between cerebellum activation, handedness and grasp-related core areas was observed. In addition, in this study hand performance tests were used in which the final test result was affected by the level of precision and speed, which can also be formulated as the ability of time synchronization of movements where muscle tone control plays an important role (Keele & Ivry, 1990; Miall, Reckess, & Imamizu, 2001; Miall & Reckess, 2002;Gowen & Miall, 2007).

Therefore, based on our results we suggest that the indirect manifestation of cerebellar dominance observed as different articularis passivity in the preferred and non-preferred hand might show that the preferred and non-preferred upper limb is controlled differently by each cerebellar hemisphere.

Recently it has been observed in several sports that left-handers have a certain advantage – in tennis, table tennis, fencing, at least from the space perspective. The information about cerebellar dominance could be used in situations when the coach is not sure about the child's handedness or in situations when parents want to change a child's natural handedness (mostly from right-hander to left-hander) with the aim to increase the child's chance to succeed in a sport discipline (tennis player Rafael Nadal). In addition, we assume that the information about cerebellar dominance could represent a novel supplementary approach in the assessment of handedness which could overcome socially dependent preference items and tasks. Acquiring such information will allow a deeper insight into the questions of cerebro-cerebellar asymmetries in humans and it can open additional research areas targeting motor learning process and also by presenting new possibilities in the diagnosis of laterality.

References:

Annett, M. (1985). *Left, right, hand and brain: The right shift theory*. Psychology Press (UK).

Annett, M. (2002). *Handedness and Brain Asymmetry*. London: Psychology Press.

Annett, M. (2013). *Handedness and brain asymmetry: The right shift theory*. Psychology Press.

Bakan, P. (1977). Left handedness and birth order revisited. *Neuropsychologia*, *15*(6), 837-839.

Beaton, A. V. (2003). The nature and determinants of handedness. In K. Hugdahl & R. J. Davidson (Eds.), *The asymmetrical brain* (pp. 105-158). Cambridge, MA, US: MIT Press.

Beaton, A., & Mariën, P. (2010). Language, cognition and the cerebellum: grappling with an enigma. *Cortex*, *46*(7), 811-820.

Begliomini, C., Nelini, C., Caria, A., Grodd, W., & Castiello, U. (2008). Cortical activations in humans grasp-related areas depend on hand used and handedness. *PLoS One*, *3*(10), e3388.

Beking, T., Geuze, R. H., Van Faassen, M., Kema, I. P., Kreukels, B. P. C., & Groothuis, T. G. G. (2018). Prenatal and pubertal testosterone affect brain lateralization *Psychoneuroendocrinology*, *88*, 78-91.

Chollet, F., DiPiero, V., Wise, R. J. S., Brooks, D. J., Dolan, R. J., & Frackowiak, R. S. J. (1991). The functional anatomy of motor recovery after stroke in humans: a study with positron emission tomography. *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, *29*(1), 63-71.

Coren, S. (1995). Family patterns in handedness: Evidence for indirect inheritance mediated by birth stress. *Behavior Genetics*, *25*(6), 517-524.

Cui, S. Z., Li, E. Z., Zang, Y. F., Weng, X. C., Ivry, R., & Wang, J. J. (2000). Both sides of human cerebellum involved in preparation and execution of sequential movements. *Neuroreport*, *11*(17), 3849-3853.

Domellöf, E., Johansson, A. M., & Rönnqvist, L. (2011). Handedness in preterm born children: a systematic review and a meta-analysis. *Neuropsychologia*, *49*(9), 2299-2310.

Eccles, J. C. (1967). Circuits in the cerebellar control of movement. *Proceedings of the National Academy of Sciences of the United States of America*, *58*(1), 336-343.

Gangestad, S. W., & Yeo, R. A. (1994). Parental handedness and relative hand skill: A test of the developmental instability hypothesis. *Neuropsychology*, *8*(4), 572-578.

Gao, J. H., Parsons, L. M., Bower, J. M., Xiong, J., Li, J., & Fox, P. T. (1996). Cerebellum implicated in sensory acquisition and discrimination rather than motor control. *Science*, *272*(5261), 545-547.

Geschwind, N., & Galaburda, A. M. (1985). Cerebral lateralization: Biological mechanisms, associations, and pathology: I. A hypothesis and a program for research. *Archives of neurology*, *42*(5), 428-459.

Geschwind, N., & Levitsky, W. (1968). Human brain: left-right asymmetries in temporal speech region. *Science*, *161*(3837), 186-187.

Gowen, E., & Miall, R. C. (2007). The cerebellum and motor dysfunction in neuropsychiatric disorders. *The Cerebellum*, *6*(3), 268-279.

Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography. *Experimental brain research*, *112*(1), 103-111.

Gut, M., Urbanik, A., Forsberg, L., Binder, M., Rymarczyk, K., Sobiecka, B., ... & Grabowska, A. (2007). Brain correlates of right-handedness. *Acta neurobiologiae experimentalis*, *67*(1), 43-51.

He, Y., Zang, Y., Jiang, T., Gong, G., Xie, S., & Xiao, J. (2006). Handedness-related functional connectivity using low-frequency blood oxygenation level-dependent fluctuations. *Neuroreport*, *17*(1), 5-8.

Henner, K. (1927). *Příznaky vznikající z nadměrné činnosti mozečku*. Praha: Kamil

Henner, K. (1936). *Všeobecná diagnostika chorob mozečkových*. Praha: Bursík & Henner.

Hu, D., Shen, H., & Zhou, Z. (2008). Functional asymmetry in the cerebellum: a brief review. *The Cerebellum*, *7*(3), 304-313.

Hugdahl, K., & Westerhausen, R. (Eds.). (2010). *The two halves of the brain: information processing in the cerebral hemispheres*. MIT press.

Ito, M. (2002). Historical review of the significance of the cerebellum and the role of Purkinje cells in motor learning. *Annals of the New York Academy of Sciences*, *978*(1), 273-288.

Ito, M. (2012). *The cerebellum: brain for an implicit self*. FT press.

Ito, M., Yoshida, M., & Obata, K. (1964). Monosynaptic inhibition of the intracerebellar nuclei induced from the cerebellar cortex. *Cellular and Molecular Life Sciences*, *20*(10), 575-576.

James, J. S., Kumari, S. R., Sreedharan, R. M., Thomas, B., Radhkrishnan, A., & Kesavadas, C. (2015). Analyzing functional, structural, and anatomical correlation of hemispheric language lateralization in healthy subjects using functional MRI, diffusion tensor imaging, and voxel-based morphometry. *Neurology India*, *63*(1), 49-57.

Jäncke, L., Specht, K., Mirzazade, S., & Peters, M. (1999). The effect of finger-movement speed of the dominant and the subdominant hand on cerebellar activation: a functional magnetic resonance imaging study. *Neuroimage*, *9*(5), 497-507.

Jissendi, P., Baudry, S., & Baleriaux, D. (2008). Diffusion tensor imaging (DTI) and tractography of the cerebellar projections to prefrontal and posterior parietal cortices: a study at 3T. *Journal of Neuroradiology*, *35*(1), 42-50.

Keele, S. W., & Ivry, R. (1990). Does the cerebellum provide a common computation for diverse tasks? A timing hypothesisa. *Annals of the New York Academy of Sciences*, *608*(1), 179-211.

Kelly, R. M., & Strick, P. L. (2003). Cerebellar loops with motor cortex and prefrontal cortex of a nonhuman primate. *Journal of neuroscience*, *23*(23), 8432-8444.

Klöppel, S., Mangin, J. F., Vongerichten, A., Frackowiak, R. S., & Siebner, H. R. (2010). Nurture versus nature: long-term impact of forced right-handedness on structure of pericentral cortex and basal ganglia. *Journal of Neuroscience*, *30*(9), 3271-3275.

LeMay, M. (1976). Morphological cerebral asymmetries of modern man, fossil man, and nonhuman primate. *Annals of the New York Academy of Sciences*, *280*(1), 349-366.

Levy, J., & Nagylaki, T. (1972). A model for the genetics of handedness. *Genetics*, *72*(1), 117-128.

McManus, C. (2004). *Right hand, left hand: The origins of asymmetry in brains, bodies, atoms and cultures*. Harvard University Press.

McManus, I. C. (1984). Genetics of handedness in relation to language disorder. *Advances in neurology*, *42*, 125-138.

McManus, I. C. (1985). Handedness, language dominance and aphasia: A genetic model. *Psychological Medicine Monograph Supplement*, *8*, 3-40.

McManus, I. C., & Cornish, K. M. (1997). Commentary Fractionating Handedness in Mental Retardation: What is the Role of the Cerebellum?. *Laterality: Asymmetries of Body, Brain and Cognition*, *2*(2), 81-90.

Miall, R. C., & Reckess, G. Z. (2002). The cerebellum and the timing of coordinated eye and hand tracking. *Brain and cognition*, *48*(1), 212-226.

Miall, R. C., Reckess, G. Z., & Imamizu, H. (2001). The cerebellum coordinates eye and hand tracking movements. *Nature neuroscience*, *4*(6), 638-644.

Musálek, M. (2014). *Development of Test Baterries for Diagnostics of Motor Laterality Manifestation: Link Between Cerebellar Dominance and Hand Performance*. Karolinum Press.

Musalek, M. (2015). Skilled performance tests and their use in diagnosing handedness and footedness at children of lower school age 8–10. *Frontiers in psychology*, *5*, 1513.

Musálek, M., Scharoun, S., & Bryden, P. J. (2015). The link between cerebellar dominance and skilled hand performance in 8- to 10-year-old right- handed children. *Journal of Motor Behavior. 47*(5), 386-396.

Nair, D. G., Purcott, K. L., Fuchs, A., Steinberg, F., & Kelso, J. S. (2003). Cortical and cerebellar activity of the human brain during imagined and executed unimanual and bimanual action sequences: a functional MRI study. *Cognitive brain research*, *15*(3), 250-260.

Nixon, P. D., & Passingham, R. E. (2000). The cerebellum and cognition: cerebellar lesions impair sequence learning but not conditional visuomotor learning in monkeys. *Neuropsychologia*, *38*(7), 1054-1072.

Peters, M. (1995). Handedness and its relation to other indices of cerebral lateralization. In: Davidson RJ, Hugdahl K (eds) *Brain asymmetry* (pp 183-214). MIT, Cambridge,.

Plate, A., Sedunko, D., Pelykh, O., Schlick, C., Ilmberger, J. R., & Bötzel, K. (2015). Normative data for arm swing asymmetry: How (a) symmetrical are we?. *Gait & posture*, *41*(1), 13-18.

Pujol, J., Deus, J., Losilla, J. M., & Capdevila, A. (1999). Cerebral lateralization of language in normal left-handed people studied by functional MRI. *Neurology*, *52*(5), 1038-1038.

Rosch, R. E., Ronan, L., Cherkas, L., & Gurd, J. M. (2010). Cerebellar asymmetry in a pair of monozygotic handedness-discordant twins. *Journal of anatomy*, *217*(1), 38-47.

Ross, G., Lipper, E. G., & Auld, P. A. (1987). Hand preference of four-year-old children: its relationship to premature birth and neurodevelopmental outcome. *Developmental Medicine & Child Neurology*, *29*(5), 615-622.

Saigal, S., Rosenbaum, P., Szatmari, P., & Hoult, L. (1992). Non-right handedness among ELBW and term children at eight years in relation to cognitive function and school performance. *Developmental Medicine & Child Neurology*, *34*(5), 425-433.

Salmi, J., Pallesen, K. J., Neuvonen, T., Brattico, E., Korvenoja, A., Salonen, O., & Carlson, S. (2010). Cognitive and motor loops of the human cerebro-cerebellar system. *Journal of cognitive neuroscience*, *22*(11), 2663-2676.

Scharoun, S. M., Bryden, P. J., Otipkova, Z., Musalek, M., & Lejcarova, A. (2013). Motor skills in Czech children with attention-deficit/hyperactivity disorder and their neurotypical counterparts. *Research in developmental disabilities*, *34*(11), 4142-4153.

Schmahmann, J. D. (1997). *The cerebellum and cognition* (Vol. 41). Academic Press.

Scholz, V. H., Flaherty, A. W., Kraft, E., Keltner, J. R., Kwong, K. K., Chen, Y. I., ... & Jenkins, B. G. (2000). Laterality, somatotopy and reproducibility of the basal ganglia and motor cortex during motor tasks1. *Brain research*, *879*(1-2), 204-215.

Snyder, P. J., Bilder, R. M., Wu, H., Bogerts, B., & Lieberman, J. A. (1995). Cerebellar volume asymmetries are related to handedness: a quantitative MRI study. *Neuropsychologia*. 33, 407–419.

Stoodley, C. J. (2012). The cerebellum and cognition: evidence from functional imaging studies. *The Cerebellum*, *11*(2), 352-365.

Stoodley, C. J., & Schmahmann, J. D. (2009). Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. *Neuroimage*, *44*(2), 489-501.

Stoodley, C. J., & Schmahmann, J. D. (2010). Evidence for topographic organization in the cerebellum of motor control versus cognitive and affective processing. *Cortex*, *46*(7), 831-844.

Takao, H., Hayashi, N., & Ohtomo, K. (2013). White matter microstructure asymmetry: effects of volume asymmetry on fractional anisotropy asymmetry. *Neuroscience*, *231*, 1-12.

Tan, Ü. (1990). Testosterone and hand skill in right-handed men and women. *International Journal of Neuroscience*, *53*(2-4), 179-189.

Tichy, J., & Belacek, J. (2008). Right-lefthandedness and crossed foot preference. Testing of laterality and cerebellar dominance. *Ceska a Slovenska neurologie a neurochirurgie*, *71*(5), 552-558.

Tichy, J., & Belacek, J. (2009). Laterality in children: cerebellar dominance, handedness, footedness and hair whorl. *Act. Nerv. Super. Rediviva*, *51*(1-2), 9-20.

Tichý, J., Běláček, J., Nykl, M., & Kaspříková, N. (2012). Stanovení mozečkové dominance podle asymetrie svalového tonu končetin. *Čes Slov Neurol*, (2012), 75. Determination of cerebellar dominance by asymmetry of muscle tone on limbs

Van Strien, J. W., Bouma, A., & Bakker, D. J. (1987). Birth stress, autoimmune diseases, and handedness. *Journal of Clinical and Experimental Neuropsychology*, *9*(6), 775-780.

Veraksa, A., Aires, J. Q., Leonov, S., & Musálek, M. (2018). The Vygotskian Approach in Physical Education for Early Years. In N. Veraksa, & S. Sheridan, (Eds.). (2018). *Vygotsky's Theory in Early Childhood Education and Research: Russian and Western Values* (pp 179 – 190). Routledge.

Viviani, P., Perani, D., Grassi, F., Bettinardi, V., & Fazio, F. (1998). Hemispheric asymmetries and bimanual asynchrony in left-and right-handers. *Experimental Brain Research*, *120*(4), 531-536.

Volkmann, J., Schnitzler, A., Witte, O. W., & Freund, H. J. (1998). Handedness and asymmetry of hand representation in human motor cortex. *Journal of neurophysiology*, *79*(4), 2149-2154.

Journal of Motor Behavior, Vol. 47, No. 5, 2015

RESEARCH ARTICLE

The Link Between Cerebellar Dominance and Skilled Hand Performance in 8–10-Year-Old Right-Handed Children

Martin Musalek[1], Sara M. Scharoun[2], Pamela J. Bryden[3]
[1]Department of Kinanthropology and Humanities, Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic. [2]Department of Kinesiology, University of Waterloo, Ontario, Canada. [3]Department of Kinesiology & Physical Education, Wilfrid Laurier University, Waterloo, Ontario, Canada.

ABSTRACT. Although literature surrounding handedness and cerebellar asymmetry is limited, many researchers have suggested that a relationship exists (e.g., A. A. Beaton, 2003; L. Jäncke, K. Specht, S. Mirzazade, & M. Peters, 1999; I. C. McManus & K. M. Cornish, 1997; M. Peters, 1995; P. J. Snyder, R. M. Bilder, H. Wu, B. Bogerts, & J. A. Lieberman, 1995). For example, J. Tichy and J. Belacek (2008, 2009) identified a link between cerebellar dominance and hand preference. The authors aimed to assess the relationship between cerebellar dominance and handedness, in 8–10-year-olds (N = 157 right-handers) as assessed with hand performance tests. Articular joint passivity in the wrist and performance differences between the hands were used as a means of assessing cerebellar dominance, where a link to skilled hand performance tests was revealed. Specifically, significant correlations between articular joint passivity and all measurements of handedness ($p < .001$) were observed. Greater hypotonia was seen in the left wrist of 95% of right-handers. This result supports the assumption that the preferred and nonpreferred hand could be controlled by the cerebellum in a different ways.

Keywords: handedness, cerebellar dominance, performance tests, muscle tension

Handedness is typically defined as the hand an individual prefers to use to complete various unimanual tasks (M. Annett, 1970), where research has demonstrated that handedness is a multidimensional trait defined by preference and performance (Bryden, MacRae, & Steenhuis, 1991; McManus & Bryden, 1992; Reiss & Reiss 1999). Hand preference, which is measured on a continuum from extreme left to extreme right, determines the preferred hand for completing an activity. In comparison, performance delineates between left- and right-hand abilities in a specific task. Both constructs must therefore be taken into consideration during the assessment of handedness (Brown, Roy, Rohr, Snider, & Bryden, 2004; Corey, Hurley, & Foundas, 2001; Steenhuis & Bryden, 1989).

An excess of studies have examined human handedness in relation to hemispheric asymmetry (e.g., M. Annett, 1981a, 1981b; Knecht et al., 2000a, 2000b). However, literature surrounding the link between measures of handedness (both preference and performance) and the cerebellum is limited. In fact, according to Peters (1995), "in the literature on handedness, the cerebellum does not normally enter the discussion. However, there are good reasons to focus some attention on this structure" (p. 194). Many researchers to date have suggested that handedness is undoubtedly linked to the functions of the cerebellum (e.g., Beaton, 2003, 2004; Beaton & Mariën, 2010; Jäncke, Specht, Mirzazade, & Peters, 1999; McManus & Cornish, 1997; Peters, 1995; Snyder, Bilder, Wu, Bogert, & Lieberman, 1995). This hypothesis is driven by the fact that damage to the cerebellum leads to impaired skilled finger movements (Glickstein, Waller, Baizer, Brown, & Timmann, 2005). Furthermore, left- and right-handers differ with regards to steadiness (J. Annett, Annett, Hudson, & Turner, 1979; Simon, 1964), or lack of exaggerated movement within fine motor tasks, where both are linked with activation of the cerebellum (Jäncke et al., 1999).

The cerebellum, which, according to some, evolved in vertebrates as an enlargement of vestibular nuclei during evolution (Nieuwenhuys, Donkelaar, & Nicholson, 1998), has long been implicated in both motor and cognitive tasks (see Ito, 1984; Kornhuber, 1971, 1974; Levisohn, Cronin-Golomb, & Schmahmann, 2000; Nicholls, Martin, Wallace, & Fuchs, 2001; Smith, Dugas, Fortier, Kalaska, & Picard, 1993; Stoodley, & Schmahmann, 2009) resultant from connections to other core brain areas (i.e., frontal, parietal, and temporal lobes; Ito, 2012; Middleton & Strick, 1998, 2000). Regarding the control of movement, it is established that the cerebellum is involved primarily in balance, position, muscle tone and sensorimotor control (Hallett, Shahani, & Young, 1975; Ito, 2002; Stoodley & Schmahmann, 2010) and that each cerebellar hemisphere controls the ipsilateral side of the body (Eccles, 1967). As such, the primary role of the cerebellum in movement is attributed to the coordination and timing of movement (e.g., Keele & Ivry, 1990). This hypothesis has been confirmed in neuroimaging studies, which have observed a significant increase in blood oxygen signaling in the cerebellum during eye and hand tracking movements (Gowen & Miall, 2007; Miall & Reckess, 2002; Miall, Reckess, & Imamizu, 2001).

McManus and Cornish (1997) suggested that investigating neurological disorders may help unravel the neural underpinnings of handedness and the link to cerebellar function. For example, neural tube deficits in children with spina bifida result in atypical posterior fossa—the Arnold-Chiari malformation (McManus & Cornish, 1997). These

Correspondence address: Martin Musalek, Department of Kinanthropology and Humanities, Faculty of Physical Education and Sport, Charles University, Jose Martiho 31, Praha 6-Veleslavin, 162 52, Czech Republic. e-mail: musalek.martin@seznam.cz

children also show an increased prevalence of left-handedness (e.g., Wassing, Siebelink, & Luyendijk, 1993). That said, the link between the cerebellum and handedness has been reported directly by Snyder et al. (1995) through magnetic resonance imaging (MRI) of left and right cerebellar hemisphere volume asymmetry. Furthermore, Gao et al. (1996) observed greater blood flow in the right dentate nucleus in right-handers. However, a more recent MRI study, focusing on the anatomic assessment of cerebellar asymmetry in monozygotic handedness-discordant twins did not confirm the relationship between anatomic cerebellar asymmetry and hand preference (Rosch, Ronan, Cherkas, & Gurd, 2010).

In another example, He et al. (2006) used functional connectivity MRI analysis to investigate the relationship between handedness and cerebellar connectivity patterns in left- and right-handers. Li's Handedness Inventory (Li, 1983), a 10-item self-report questionnaire, was used to assess handedness. The authors found handedness-related functional connections in cerebellar-prefrontal, cerebellar-parietal, cerebellar-temporal, and cerebellar-limbic connectivity; thus suggesting that "cerebellar involvement in higher function may be related to handedness" (He et al., 2006, p. 7). This hypothesis was also supported by Begliomini, Nelini, Castiello, Caria, and Grodd (2008), who identified a relationship between cerebellar activation in grasp-related core areas and handedness using functional MRI. Overall, this research indicates possible involvement of the cerebellum in adjustment and refinement of hand shape for grasp and manipulation (Begliomini et al., 2008). Interestingly, Cantalupo and Hopkins' (2010) work with chimpanzees identified that handedness (or armedness) for throwing is related to asymmetry in volume of the cerebellum.

The work of Henner (1927) has also helped to delineate the connection between the cerebellum and motor lateralization, enabling detailed clinical diagnosis of paleocerebellar regulatory extinction functions and the neocerebellar extinction syndrome (Tichy & Belacek, 2009). A result of cerebellar hypotonia, neocerebellar extinction syndrome is characterized by increased muscle hypotonia, passivity, and increased joint flexibility. According to Henner and Tichy and Belacek (2009), cerebellar hypotonia manifests itself in humans during standing and walking, characterized by noticeable movement in the nonpreferred limb. Henner (1936) also suggested that the neocerebellar syndrome is easily detected in joints.

Based on Henner's (1927, 1936) work, Tichy and Belacek (2008) provided support for the relationship between cerebellar dominance and upper limb preference in their work with 9–11-year-old children. Synkinesis of nonpreferred shoulder during walking, number of swings in elbow and inspection of the wrist revealed significantly greater passivity in the nonpreferred arm ($p < .05$). However, the results did not positively confirm greater passivity in the nonpreferred lower limb in knee and ankle during parallel free falls. A follow up study (Tichy & Belacek, 2009) investigated laterality in 9–11-year-old children via handedness, footedness and hair whorl. Cerebellar dominance was "ascertained clinically by means of palpation and inspection; by the presence of physiological muscle hypotonia in the extremities contra lateral to the dominant upper extremity" (Tichy & Belacek, 2009, p. 9). Results provided further support for the link between neocerebellar dominance and hand dominance.

Previous investigations by Tichy and Belacek (2008, 2009) have successfully identified a link between cerebellar dominance and hand preference in 9–11-year-old children. Nevertheless, assessments of handedness have been limited to self-report questionnaires. The Edinburgh Handedness Inventory is one of the most commonly reference handedness inventories, which has been shown to be both a valid and reliable tool for assessing hand preference (McMeekan & Lishman, 1975; Ransil & Schachter, 1994; Reib, Reib, & Freye, 1998). However, several problems exist when relying solely on self-report questionnaires. First, numerous hand preference questionnaires are presently in use; therefore, the choice of questionnaire may influence the results (Williams, 1991). More specifically, research has demonstrated that depending on the questionnaire, and how handedness is classified, different patterns of results can ultimately emerge (e.g., Peters, 1998). Finally, hand preference measures possess inherent subjectivity, such that questions posed are open to the reader's interpretation. As such, limitations make use of hand preference questionnaires with children difficult, and not necessarily valid.

Considering the multidimensional nature of handedness (Corey et al., 2001; Kertesz, Polk, Black, & Howell, 1990; Rigal, 1992), hand performance tests offer another means suitable for assessment of handedness (Corey et al., 2001; Rigal, 1992). These hand performance tests, sometimes referred to as skilled performance or fine motor tests (Steenhuis & Bryden, 1999), compare the performance and quality of the two hands, where the preferred hand is typically more efficient than the nonpreferred hand (J. Annett et al., 1979; McManus & Cornish, 1997; Peters, 1976). For the aforementioned reasons, performance measures have been implemented to account for the limitations of preference measures.

With Tichy and Belacek's (2008, 2009) work as a foundation, in the present study we aimed to assess the relationship between cerebellar dominance (as assessed by the difference in joint passivity between the right and left wrist) and measures of hand performance—(one component of handedness) in typically developing right-handed 8–10-year-olds. This age group was selected, in part as means of comparison to Tichy and Belacek's (2008, 2009) work, which implemented a hand preference assessment, but also in consideration of developmental factors, both in handedness (preference and performance), and also the cerebellum. Regarding the handedness literature, it is generally understood that handedness emerges early in infancy (e.g., Butterworth & Hopkins, 1993); however, the age at which adult-like handedness is attained is debated. It has been suggested that direction (i.e., right- or left-handed) of hand preference is adult-like by age 3 years, where the degree (i.e., strength) continues to increase until age 9 years (e.g., Archer, Campbell, & Segalowitz, 1988). That said, a recent review (see Scharoun & Bryden, 2014) argued that hand preference is adult-like when the reliance on the preferred hand drops, which is approximately at age 10–12 years. As such, the 8–10-year-olds included in this study have, arguably, established and display stable hand preference tendencies.

With respect to the development of the cerebellum, a study by Saksena et al. (2008) showed that maturation of cerebral and cerebellar white matter is not the same during human (child) development. By means of diffusion tensor imaging the authors observed that a major increase in cerebellar white matter in children occurs before 36 months compared to an equally progressive increase in cerebral white matter, which happens only until 24 months (Saksena et al., 2008). That said, Diamond (2000) observed that the cerebellum, together with prefrontal cortex, matures in humans at approximately 6 years old. Nevertheless, by the age of 8 years, structural and functional maturation of the cerebellum is arguably adult-like, where hand preference has reached a stable level.

Overall, the previously mentioned studies describing cerebellar functions have stressed the fundamental role of the cerebellum, together with contralateral core brain areas, in motion initiation. From this point of view, then, according to some authors (e.g., Rosch et al., 2010), functional cerebellar asymmetry is an essential complement to cortical studies in the understanding of laterality with regards to the development of hemispheric specialization. Presently only a few studies have sought to assess the relationship between functional asymmetry of the cerebellar hemispheres at the body periphery and handedness by means of a clinical approach (see Tichy & Belacek, 2008, 2009). However, these works concentrated only on upper limp preference.

Therefore, in our research we aimed to extend the approach to assessment of a certain manifestation of cerebellar dominance (extinction syndrome) in a selected body segment. At the same time we aimed to reveal whether performance of the preferred and nonpreferred limb in right-handers might be connected to different muscle tone control by right and left cerebellar hemispheres. In other words, whether higher muscle tone implies or may imply a better control. Because, unlike in the previous studies, we designed and used a novel photoscopic method of assessment of a selected manifestation of cerebellar dominance (articular passivity), it was first necessary to verify the test–retest reliability of assessment of articular joint passivity in selected joint connection (wrist), where it was assumed that consistent results would be obtained. At the same time, this study aimed to assess the relationship between handedness performance measures and the assessment of joint passivity of the wrist, which might show that the cerebellum controls the dominant and the subdominant limb in a different way. It was hypothesized that a significant relationship would be observed.

Method

Participants

A total of 193 typically developing 8–10-year-olds from Czech primary schools without previous injury of upper limbs were selected for the present study. Children in this age group were selected considering structural maturation of the cerebellum and the notion of a stable hand preference (e.g., Ljach, 2002). In order to determine the handedness of participants, two hand preference tasks and four motor performance tests were used (see Apparatus). Results confirmed that 157 of the children were right-handed (71 boys and 86 girls; $M_{age} = 9.2$ years, $SD = 0.75$ years). Participants were pupils in the Capital City of Prague, and were selected using an intentional selection process. More specifically, schools and students without any specific specialization (e.g., technical, artistic, sport, linguistic) were selected. Furthermore, classes where children with special needs were integrated were excluded, so as to not bias the results. Ethics approval was granted by the Ethics Commission of the Faculty of Physical Education and Sport at Charles University. In addition, parental consent was obtained for all individuals.

Apparatus

Four skilled hand performance tests were selected (i.e., tracing a spiral, dot filling, moving beads with tweezers, turning a box; described in procedures) based on a previous study, which validated these tasks as strong measures of handedness in Czech children from the same age group (8–10-year-olds; $N = 200$). Validity of the selected tests with regard to the modeled construct of handedness ranged between $r = .63$ and $r = .82$ (Musalek, 2013). All skilled hand performance tests were selected in accordance with the finding that if during the performance of a motor activity by an upper limb more segments are activated (e.g., shoulder or elbow joints), the performance of the preferred upper limb is significantly better than the performance of the nonpreferred upper limb (Bagesteiro & Sainburg, 2002; Roy, Kalbfleisch, & Elliott, 1994; Sainburg & Kalakanis, 2000). Bryden and Roy (2005) added that significant differences in performance between preferred and nonpreferred upper limbs are pronounced in tests with high complexity and higher demands on precision. Another important aspect is the level of subtle motor movements, which are required due to precision of the performed movement. The more subtle motor character of the activity, the more evident the differences between the preferred and the nonpreferred limb (e.g., in speed and quality of execution of the given activity; M. Annett, 1992). Furthermore, each of these tasks has been documented in previous studies as a reliable assessment of skilled hand performance (Barnsley & Rabinovitch, 1970; Rigal, 1992; Tapley & Bryden, 1985). Evaluation of cerebellar dominance was done through measurement of articular joint passivity in both wrists (e.g., Tichy & Belacek, 2008).

Procedure

The hand preference of each participant was initially assessed by means of two valid and reliable repetitive tasks, which have been previously validated in 8–10-year-old Czech children (Musalek, 2013): (a) ringing a bell, in which participants were asked to take a bell in one hand and ring it two times—before and after performing the second task; and (b) throwing a ball, in which participants were asked to take a ball in one hand and throw it at a target, three times. The hand used to complete each task was recorded. These items have been used previously within hand preference questionnaires (M. Annett, 1970; Bryden, 1977; Coren & Porac 1978; Oldfield, 1971; Sharman & Kulhavy, 1976) and in unimanual tasks (Harris, 1958). Because some traditionally used preference tasks (e.g., cutting with scissors, cleaning the teeth, writing) are variables that may be affected by social environment we used tasks thought to be free from environmental bias. Participants then completed the following four skilled hand performance tasks to gain a full understanding of the individual's handedness in the order in which the tests are described.

Spiral tracing. This task included two side-by-side white spirals of the same shape and length embedded in grey square boxes (50 mm × 50 mm). The largest diameter of the spirals was 41mm, with the thickness (width) of the spiral measuring 2 mm. The spiral in the right box was intended for right-hand performance, and subsequently, the spiral in the left box was meant for left-hand performance. The aim of the task was to navigate through the spiral in one movement, from the outer edge to the center, as quickly as possible, without moving the position of the score sheet. An error (penalized with 2 s) was documented when the participant's movement path went outside the designated area while drawing. The task was completed with the left and right hand, where time to completion was measured.

Dot-filling. This task included two boxes, each containing 90 identical circles (diameter 2mm). The right box was intended for right-hand performance, and subsequently, the left box was meant for left-hand performance. The aim of the task was to place a mark in as many of the circles as possible, in 30 s. Only those marks within the circles were counted toward performance. The task was completed with the left and right hand, where the number of dots marked in 30 s was recorded.

Tweezers and beads. This task included two open matchboxes (one behind the other) and a pair of tweezers, placed 150 mm on the desk directly in front of the participant, at the midline. The matchbox closest to the participant was filled with 20 beads (5 mm diameter), whereas the second was empty. The aim of the task was to move the beads one at a time from the starting position to the empty box, using the tweezers. The participant had 30 s to move as many beads as possible. If one of the beads was dropped during transport, the participant was instructed to take a new bead from the box. The task was completed with the left and right hand, where the number of beads transported in 30 s was recorded.

Twistbox. This task included a closed, empty matchbox, directly in front of the participant at the midline. The aim of the task was to overturn the matchbox, without lifting it from the desk. The task was completed with the left and right hand, where the number of times the matchbox was overturned in 30 s was recorded.

Articular joint passivity. In addition to the aforementioned skilled hand performance tests, one of the manifestations of cerebellar dominance (i.e., neocerebellar extinction syndrome; Henner, 1927) was assessed by means of articular joint passivity (as an indicator of hypotonia in the wrist), where the angle of both wrists was assessed using a photoscopic method and a unilateral immobilizer on a movable stand.

The unilateral immobilizer was made using the technology of shaping thermoplastic on a gypsum model (see Figure 1). This is a common method used to create the majority of individual braces. A 4 mm strong polyethylene SOA-111P17 of the Simona mark in white color, which has been certified for medical use and is commonly used in manufacturing braces, was used. The gypsum model was constructed on the basis of length and width standards for 8–10-year-old children stipulated in the latest anthropological research made in the Czech Republic (Bláha et al., 2005) in order to enable elbow joint bend.

The thermic processing was carried out in standard technological conditions at the temperature of 180°C, which leave the plastic flexible and firm. Leather strings were fixed to the body of the brace, which enable immobilization in the given angle of 75°. This angle was determined following an on site preclinical study carried out in 8–10-year-old children ($n = 10$). This angle enables sufficient detection of different wrist joint passivity. At the same time this sharp angle ensures a natural vertical position of the humerus and acceptable comfort for the participants. In order to eliminate deformation of soft tissue the brace was placed on a separate rack, which enables fixation of the defined angle. The brace was made in cooperation with the medical facility Protetika s.r.o. registered in accordance with laws of the Czech Republic.

FIGURE 1. Development of unilateral immobilizer.

First, anatomical points were marked on both the left and right limb with a felt-tip pen. These included the center of the humerus capitulum, the lateral epicondyle of the humerus, styloid process of the ulna, and the distal end of fifth metacarpal. The participant's preferred arm was then fixed in an immobilizer, which was mounted on a movable stand. The height of the immobilizer was adjusted for each participant to a comfortable position to prevent shoulder elevation or depression and the arm fixed in the immobilizer was locked to ensure the participant's elbow remained at a 75° angle. The accuracy of the fixed joint angle was checked by the cross line laser. The participant was then asked to relax the wrist (see Figure 2). While maintaining the fixed position, the researcher took a photograph (using a digital camera, Olympus SP-560, Olympus America Inc., Center Valley, PA) for each measurement, at the height of the participants elbow. The camera was attached on tripod and remained at a fixed distance of 150 cm from the immobilizer throughout the duration of the study. The same procedures were repeated for the nonpreferred arm. All participants went through the measurement procedure twice (test-retest) with a 90-min break between assessments. Each coded picture was imported to Dartfish program version 4.5.2.0 (Dartfish HQ, Fribourg, Switzerland). In this program the anatomical markers (lateral epicondyle of the humerus, process styloid of the ulna, and the distal end of fifth metacarpal) were connected and the joint angle was computed. The joint angle of the left wrist was subtracted from the joint angle of the right wrist. This measure was compared to results of the performance tests.

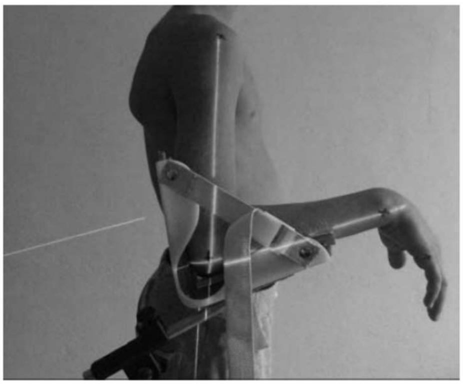


FIGURE 2. Measurement of articular passivity, final position with fixed angle of 75° in elbow joint.

Statistical Analysis

In order to analyze the data we used the difference in gross scores of the preferred and nonpreferred limb obtained from four hand performance tests (time needed for tracing the spiral, number of correctly marked dots, number of transported beads and number of times the matchbox was twisted) and recorded angles in the wrist (articular passivity). The data were continuous in nature, therefore, Pearson correlation coefficients were used to examine the relationship between handedness measures and cerebellar dominance. In order to determine significance of the difference between the preferred and the nonpreferred hand performance in four performance tests and in recorded articular joint passivity angles, a t test with the level of statistical significance at $p < .01$ and effect size (Cohen's d) > 0.8 (see Cohen, 1988) was used. Reliability (i.e., consistency) of the articular joint passivity measures was tested using test retest procedures. NCSS2007 statistical software (NCSS, LLC, Kaysville, UT) was used to complete statistical analysis.

Results

As we have already noted in the Participants section, of 193 individuals, 157 were diagnosed as right-handers. These participants performed all trials of the two selected motor preference tasks (ringing and throwing) with their right upper limb. Results of the hand performance tests (see Table 1 and Figure 3), which followed the preference tasks showed that the nonpreferred (left) upper limb in right-handers was in all four motor tests significantly slower and less precise than the preferred (right) upper limb $p < .01$

TABLE 1. Results of Hand Performance Tests at Right-Handers

Item	*M* left hand	*SD* left hand	*M* right hand	*SD* right hand
Spiral tracing	82.7 s	25.35 s	44.9 s	14.01 s
Dot-filling	11.13 dots	4.93 dots	33 dots	8.48 dots
Tweezers and beads	8 beads	1.72 beads	12 beads	2.06 beads
Twistbox	38.07 turns	4.91 turns	42.54 turns	5.09 turns

*$p < .01$.

and Cohen's *d* in the range 0.89–2.96. Detailed analysis confirmed that none of the 157 right-handers demonstrated reverse performance of upper limbs (i.e., they did not achieve better results with the nonpreferred [left] upper limb).

First, we analyzed the reliability of each measurement tool, using test retest procedures. Table 2 outlines differences in variance between first and second assessment. The reliability of left- and right-wrist joint angles, as assessed by correlating measurements of articular joint passivity in the first and second assessment ($r = .97$) showed that our photoscopic method was highly stable across 90 min. Subsequent correlation matrices display, in more detail, the relationship between the articular joint passivity task and the other tests used to evaluate handedness.

In both cases results of measured differences in articular joint passivity showed that the nonpreferred upper limb (left) in the research group of right-handed children demonstrates significant hypotonia $p < .01$ (i.e., higher articular joint passivity; see Figure 4). Detailed analysis showed that eight children demonstrated a reverse result (i.e., hypotonia being detected in the preferred [right] upper limb). The average difference in recorded angles of the preferred minus nonpreferred upper limb in these participants was 4.7°.

From Table 3, it is clear that articular joint passivity and the four skilled performance tests used for assessing

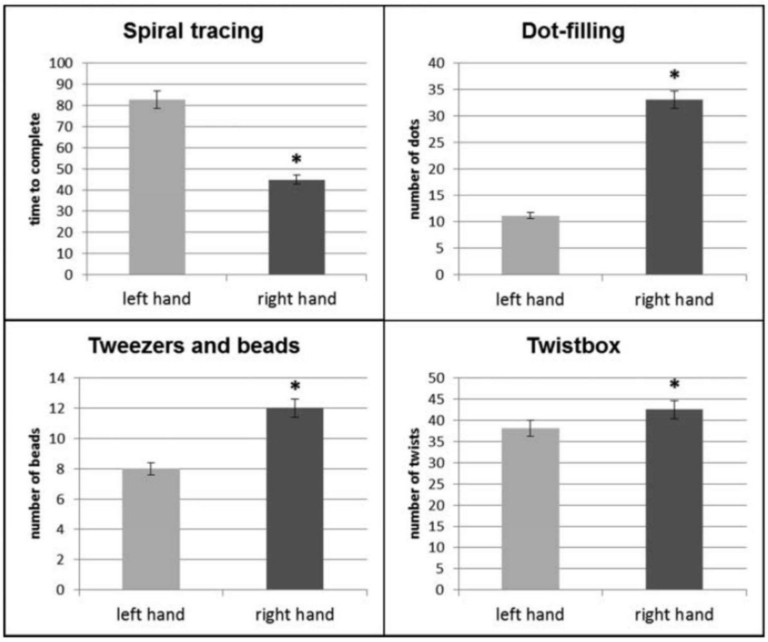


FIGURE 3. Differences in performance between left, (nonpreferred) hand and right, (preferred) hand at right-handers.

TABLE 2. Descriptive Statistics of the Right and Left Hand in the First and Second Assessment of Right-Handers

Hand	*M* 1	Variance 1	*SD* 1	*M* 2	Variance 2	*SD* 2
Right hand (preferred hand)	71.18	44.01	6.63	70.98	43.90	6.62
Left hand (nonpreferred hand)	76.06	46.19	6.79	75.93	46.45	6.81

$^{*}p < .01$.

handedness (i.e., spiral tracing, dot-filling, tweezers and beads, and twistbox) display significant correlations. The weakest however still significant correlation ($r = .356$, $p < .01$) was found between articular joint passivity and dot-filling tasks.

Discussion

In the present study we aimed to examine (a) the test–retest reliability of articular joint passivity measurements (indicative of cerebellar dominance) and (b) the relationship between articular joint passivity, and skilled hand performance measures (i.e., spiral tracing, dot-filling, tweezers and beads, and twistbox tasks) in a sample of 8–10-year-old right-handed children ($N = 157$). It was originally hypothesized that measurements of articular joint passivity would display consistent results, and that statistically significant relationships between tasks would be revealed.

Unlike in previous studies (Tichy & Belacek, 2008, 2009), a new photoscopic method was used to determine neocerebellar extinction syndrome as a manifestation of cerebellar dominance. The test retest verification of reliability showed that in the defined conditions (repetition of tests after 90 min) measurement of articular passivity was highly stable ($r = .97$). That said, the question remains as to what extent the articular passivity as a demonstration of neocerebellar extinction syndrome changes in longer periods of time for the preferred and nonpreferred upper limbs, also with respect to the performed activity.

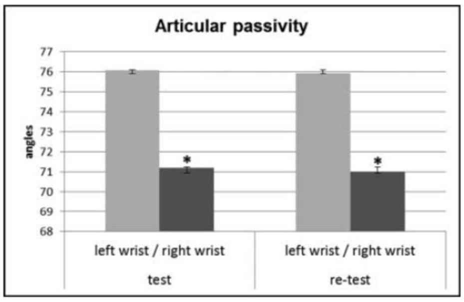


FIGURE 4. Differences of articular passivity between left and right wrist at right-handers in test–retest procedure.

Subsequent correlation analysis of articular joint passivity revealed a significant relationship with hand performance tests ($p < .001$). This finding is in line with the results of Tichy and Belacek (2008). More specifically, Tichy and Belacek observed significantly greater articular joint passivity in the nonpreferred arm ($p < .05$) as assessed with the Edinburgh handedness questionnaire. The same results were displayed in the present study, when assessing handedness using performance measures. As noted in the introduction, questionnaires are the most commonly referenced tools to assess handedness and have proven both valid and reliable (McMeekan & Lishman, 1975; Ransil & Schachter, 1994; Reib et al., 1998). Nevertheless, different patterns of results may emerge depending on the questionnaire used and how handedness is classified (Williams, 1991). It is also generally understood that hand preference measures are limited by their inherent subjectivity. In particular, given the large verbal component requirement and the inability to distinguish how familiar children may be with particular tasks, investigating handedness in children possesses unique challenges. As such, identifying parallel results with performance measures as when using a handendess inventory (e.g., Tichy & Belacek, 2008) adds to our understanding of the relationship between cerebellar dominance and handedness.

Findings also add to the previous literature (e.g., Beaton, 2003, 2004; Beaton & Mariën, 2010; Jäncke et al., 1999; McManus & Cornish, 1997; Peters, 1995; Snyder et al., 1995), which suggests that cerebellar dominance plays a unique role in handedness.

More specifically, the correlation between articular joint passivity and motor performance tests for the upper limb, which has always worked with the given tool grasped by fingers in a certain way, support the findings of the study Begliomini et al. (2008), in which a correlation between cerebellum activation, handedness and grasp-related core areas was observed. In addition, in this study hand performance tests were used in which the final test result was affected by the level of precision and speed, which can also be formulated as the ability of time synchronization of movements where muscle tonus control plays an important role (Gowen & Miall, 2007; Keele & Ivry, 1990; Miall & Reckess, 2002; Miall et al., 2001). Performance results in all performance tests showed that precision (movement

TABLE 3. Correlation Matrix of Whole Used Indicators With Emphasis on Relation Between Articular Joint Passivity and Handedness Performance Tests of Right-Handers

Variable	Spiral tracing	Dot-filling	Tweezers and beads	Twist box	Articular joint passivity
Spiral tracing	—				
Dot-filling	−.413	—			
Tweezers and beads	−.584	.363	—		
Twist box	−.432	.291	.563	—	
Articular joint passivity	**−.453*****	**.356***	**.586*****	.432*	—

Note. Variable in boldface, Articular joint passivity, represent manifestation of cerebellar dominance.
*$p < .01$. ***$p < .001$.

synchronization) and speed of movement are significantly lower ($p < .01$) for the nonpreferred upper limb in all tested children. Thus the finding is in line with previous studies (Bagesteiro, & Sainburg, 2002; Bryden & Roy, 2005; Roy et al., 1994; Sainburg & Kalakanis, 2000), which established that if more segments of the limb are involved in the movement, or the activity is of a subtle motor character (M. Annett, 1992; i.e., more demands are laid on movement synchronization), the difference between the performance of the preferred and the nonpreferred hands is greater.

Eccles (1967) demonstrated that the cerebellar hemispheres are involved in motor control of the ipsilateral body side. In line with this, significant correlations between articular passivity and hand performance tests in this study suggest that each cerebellar hemisphere controls muscular tone differently for the preferred and the nonpreferred limbs. He et al. (2006) revealed in their study that a significant relationship exists between handedness and functional connections between the cerebellum, core brain areas and the limbic area. This complex connection of cerebellar hemispheres with contralateral motor brain areas, in particular, could thus be the reason of different muscle tone for the preferred and the nonpreferred upper limb. This manifests as more precise timing and thus in better movement coordination in the preferred upper limb. The question that remains to be answered is why eight participants in the present research group showed hypotonia in the preferred upper limb.

Notwithstanding the determined correlation between hand performance tests and articular passivity, it was revealed that the dot-filling task test expressed the weakest relationship ($p < .01$) in comparison to the rest of the correlation pairs. At the same time, in this test the paired t test results clearly showed statistically ($p < .01$) as well as factually (Cohen's $d = 2.96$) a significant difference in performance of the preferred and the nonpreferred limb. In the previous validation study by Musalek (2013) this indicator verified for 8–10-year-old children with the same criteria for selection of participants revealed a close correlation ($r = .80$) with the measures of handedness. It has been suggested that the relationship between hand preference and performance is dependent on the tool in which handedness is assessed (Steenhuis & Bryden, 1999). For example, Steenhuis and Bryden identified a subgroup of mixed-handers, who wrote with their left hand and were self-proclaimed left-handers. Using performance measures to confirm handedness, these participants were more skilled with their left hand in a dot-filling task; however, when completing other performance tasks (e.g., peg-moving, dart-throwing) appeared right-handed. It is thus clear that handedness is multidimensional trait, where the skill required to complete a task must be considered during assessment (Steenhuis, 1996; Steenhuis & Bryden, 1999). Carlier, Duyme, Capron, Dumont, and Perez-Diaz (1993) suggested the dot-filling task it not the best tool for assessing handedness in children. More specifically, they have proposed that the dot-filling task is likely too sensitive to the practice effect and testing condition. Overall, it is clear that handedness is multidimensional trait, where, in this context it is likely that cerebellar dominance is only weakly related to handedness as assessed in a dot-filling task.

Based on previous results the question remains how strong the relationship between cerebellar dominance and hand performance tests would be if a sufficient sample of left-handers was also tested. Another question is whether the strength of the discovered correlations is typical only for child population, which is not affected by environmental factors to such an extent, or if it is a stable feature traceable in adults as well. Handedness is often understood as a human trait of continuum character, the strength of which can be expressed using a wide range of indicators that measure different dimensions of handedness (e.g., M. Annett, 1992; Büsch, Hagemann, & Bender, 2010; Dragovic & Hammond, 2007; Steenhuis & Bryden, 1989). However, by definition all of these indicators represent a voluntary motor movement. By contrast, assessment of articular joint passivity could be labeled as an unconscious physiological function of the organism. In this regard, a question arises as to whether the strength of handedness would to a significantly imply the manifestation of cerebellar dominance that we have diagnosed. We strongly believe that such information would be fundamental in revealing what place, suitability and importance should be ascribed to this variable in the multidimensional structure of handedness itself.

Conclusion

It is generally understood that the cerebellum plays a key role in the voluntary control of movement, especially in timing of movements and controlling muscle tension (Gowen & Miall, 2007; Keele & Ivry, 1990; Miall & Reckess, 2002; Miall et al., 2001). Previous research has suggested that asymmetries in muscle tension, observed in upper and lower limbs could be associated with lateralization of motor behavior (e.g., Beaton, 2003, 2004; Beaton & Mariën, 2010; Jäncke et al., 1999; McManus & Cornish, 1997; Peters, 1995; Snyder et al., 1995; Tichy & Belacek, 2009). In the present study asymmetries of muscle tension, assessed by means of articular joint passivity, were used as a means of quantifying cerebellar dominance. Not only did assessment of articular joint passivity reveal consistent test retest reliability, but a significant relationship was revealed between articular joint passivity and skilled hand performance tests was also revealed. This evidence provides support for the link between handedness and cerebellar dominance, which suggests that preferred and the nonpreferred hand could be controlled by cerebellum in different way. However questions still remain, whether the revealed hypotonia in the preferred upper limb represents an across lifespan permanent feature, or whether we deal with a dynamic process which, like the level of lateralization, is a subject to environmental factors.

Limitations

We do realize that neocerebellar extinction syndrome diagnostics as a manifestation of cerebellar dominance, which we have detected by means of articular joint passivity in the wrist is not a verified method. In connection with long-term stability of this parameter we are not able to answer the question how and to what extent the articular joint passivity can change for the preferred and the nonpreferred limbs during the day and depending on the activity performed. Therefore, results of this study, which revealed relation between articularis passivity and handedness in right-handers may not be completely representative.

FUNDING

This research was supported by the scientific branch development program PRVOUK P39 Social-Sciences Aspects of Human Movement Studies.

REFERENCES

Annett, J., Annett, M., Hudson, P. T., & Turner, A. (1979). The control of movement in the preferred and non-preferred hands. *The Quarterly Journal of Experimental Psychology*, *31*, 641–652.

Annett, M. (1970). A classification of hand preference by association analysis. *British Journal of Psychology*, *61*, 303–321.

Annett, M. (1981a). The right shift theory of handedness and developmental language problems. *Bulletin of The Orton Society*, *31*, 103–121.

Annett, M. (1981b). The genetics of handedness. *Trends in Neuroscience*, *3*(4), 256–258.

Annett, M. (1992). Five tests of hand skill. *Cortex*, *28*, 583–600.

Archer, L. A., Campbell, D., & Segalowitz, S. J. (1988). A prospective study of hand preference and language development in18- to 30-month-olds: I. hand preference. *Developmental Neuropsychology*, *4*, 85–92.

Bagesteiro, L. B., & Sainburg, R. L. (2002). Handedness: Dominant arm advantages in control of limb dynamics. *Journal of Neurophysiology*, *88*, 2408–2421.

Barnsley, R. H., & Rabinovitch, S. (1970). Handedness: Proficiency versus state preference. *Perceptual and Motor Skills*, *30*, 343–362.

Beaton, A. A. (2003). The determinants of handedness. In K. Hugdahl & R. J. Davidson (Eds.), *Brain asymmetry* (2nd ed., pp. 105–158). Cambridge, MA: MIT Press.

Beaton, A. A. (2004). Anatomy of manual skill. *Cortex*, *40*, 228–229.

Beaton, A. A., & Mariën, P. (2010). Language, cognition and the cerebellum: Grappling with an enigma. *Cortex*, *46*, 811–820.

Begliomini, C., Nelini, C., Castiello, U., Caria, A., & Grodd, W. (2008). Cortical activations in humans grasp-related areas depend on hand used and handedness. *PLoS One*, *3*, 10.

Bláha, P., Vignerová, J., Riedlová, J., Kobzová, J., Krejčovský, L., & Brabec, M. (2005). Nationwide anthropological research of children and youth 2001, Czech Republic—basic physical characteristics . Charles University in Prague, Faculty of Science + National Institute of Public Health in Prague.

Brown, S. G., Roy, E. A., Rohr, L. E., Snider, B. R., & Bryden, P. J. (2004). Preference and performance measures of handedness. *Brain and Cognition*, *55*, 283–285.

Bryden, M. P. (1977). Measuring handedness with questionnaires. *Neuropsychologia*, *15*, 617–624.

Bryden, M. P., MacRae, L., & Steenhuis, R. E. (1991). Hand preference in school children. *Developmental Neuropsychology*, *7*, 477–486.

Bryden, P. J., & Roy, E. A. (2005). Unimanual performance across the age span. *Brain and Cognition*, *57*, 1, 26–29.

Büsch, D., Hagemann, N., & Bender, N. (2010). The dimensionality of the Edinburgh Handedness Inventory: An analysis with models of the item response theory. *Laterality*, *15*, 610–628.

Butterworth, G., & Hopkins, B. (1993). Origins of handedness in human infants. *Developmental Medicine & Child Neurology*, *35*, 177–184.

Cantalupo, C., & Hopkins, W. (2010). The cerebellum and its contribution to complex tasks in higher primates: A comparative perspective. *Cortex*, *46*, 821–830.

Carlier, M., Duyme, M., Capron, C., Dumont, A. M., & Perez-Diaz, F. (1993). Is a dot-filling group test a good tool for assessing manual performance in children? *Neuropsychologia*, *31*, 233–240.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.

Coren, S., & Porac, C. (1978). The validity and reliability of self-report items for the measurement of lateral preference. *British Journal of Psychology*, *69*, 207–211.

Corey, D., Hurley, M., & Foundas, A. L. M. (2001). Right and left handedness defined: A multivariate approach using hand preference and hand performance measures. *Neuropsychiatry, Neuropsychology, & Behavioral Neurology*, *14*, 144–152.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*, 44–56.

Dragovic, M., & Hammond, G. (2007). A classification of handedness using the Annett Hand Preference Questionnaire. *British Journal of Psychology*, *98*, 375–387.

Eccles, J. C. (1967). Circuits in the cerebellar control of movement. *Proceedings of the National Academy of Sciences of the United States of America*, *58*, 336–343.

Gao, J., Parson, L. M., Bower, J. M., Xiong, J., Li, J., & Fox, P. T. (1996). Cerebellum implicated in sensory acquisition and discrimination rather than motor control. *Science*, *272*, 545–547.

Glickstein, M., Waller, J., Baizer, J. S., Brown, B., & Timmann, D. (2005). Cerebellum lesions and finger use. *The Cerebellum*, *4*, 189–197.

Gowen, E., & Miall, R. C. (2007). The cerebellum and motor dysfunction in neuropsychiatric disorders. *Cerebellum*, *6*, 268–279.

Hallett, M., Shahani, B. T., & Young, R. R. (1975). EMG analysis of patients with cerebellar deficits. *Journal of Neurology, Neurosurgery & Psychiatry*, *38*, 1163–1169.

Harris, A. J. (1958). *Harris tests of lateral dominance, manual of direction for administration and interpretation* (3rd ed.). New York, NY: The Psychological Corporation.

He, Y., Zang, Y., Jiang, T., Gong, G., Xie, S., & Xiao, J. (2006). Handedness-related functional connectivity using low-frequency blood oxygenation level-dependent fluctuations. *NeuroReport*, *17*, 5–8.

Henner, K. (1927). *Symptoms arising from increased cerebellar activity*. Prague: Kamil Henner.

Henner, K. (1936). *General diagnostics of cerebellar conditions*. Prague: Bursík & Kohout.

Ito, M. (1984). *The cerebellum and neural control*. New York, NY: Raven Press.

Ito, M. (2002). Historical review of the significance of the cerebellum and the role of Purkinje cells in motor learning. *Annals of the New York Academy of Sciences*, *978*, 273–288.

Ito, M. (2012). *The cerebellum: Brain for an implicit self*. Upper Saddle River, NJ: FT Press.

Jäncke, L., Specht, K., Mirzazade, S., & Peters, M. (1999). The effect of finger-movement speed of the dominant and the subdominant hand on cerebellar activation: A functional magnetic resonance imaging study. *NeuroImage*, *9*, 497–507.

Johnson, M. H. (2005). *Developmental cognitive neuroscience* (2nd ed.). Victoria, Australia: Blackwell.

Keele, S. W., & Ivry, R. (1990). Does the cerebellum provide a common computation for diverse tasks? A timing hypothesis. *Annals of the New York Academy of Sciences*, *608*, 179–207.

Kertesz, A., Polk, M., Black, S. E., & Howell, J. (1990). Sex, handedness, and the morphometry of cerebral asymmetries on magnetic resonance imaging. *Brain Research*, *530*, 40–48.

Knecht, S., Dräger, B., Deppe, M., Bobe, L., Lohmann, H., Flöel, A., Ringelstein, E.-B., & Henningsen, H. (2000a). Handedness and hemisphereic language dominance in healthy humans. *Brain*, *123*, 2512–2518.

Knecht, S., Dreppe, M., Dräger, B., Bobe, L., Lohmann, H., Ringelstein, E.-B., & Benningsen, H. (2000b). Language lateralization in healthy right-handers. *Brain*, *123*, 74–81.

Kornhuber, H. H. (1971). Motor functions of cerebellum and basal ganglia: The cerebellocortical saccadic (ballistic) clock, the cerebellonuclear hold regulator, and the basal ganglia ramp (voluntary speed smooth movement) generator. *Kybernetik*, *8*, 157–162.

Kornhuber, H. H. (1974). Cerebral cortex, cerebellum and basal ganglia: An introduction to their motor functions. In F. O. Schmitt & F. G. Worden (Eds.), *The neuroscience third study program* (pp. 267–280). Cambridge, MA: MIT Press.

Levisohn, L., Cronin-Golomb, A., & Schmahmann, J. D. (2000). Neuropsychological consequences of cerebellar tumour resection in children: Cerebellar cognitive affective syndrome in a paediatric population. *Brain*, *123*, 1041–1050.

Li, X. T. (1983). The distribution of left and right handedness in Chinese people. *Acta Psychologica Sinica*, *3*, 68–76.

Ljach, W. (2002). The effects of genetic and environmental factors on the development of motor coordination abilities in children aged 7–10 years. *Wychowanie Fizyczne I Sport*, *46*, 267–276.

McManus, I. C., & Bryden, M. P. (1992). The genetics of handedness, cerebral dominance and lateralization. In I. Rapin & S. J. Segalowitz (Eds.), *Handbook of neuropsychology: Vol. 6. Child neuropsychology* (pp. 115–142). Amsterdam, the Netherlands: Elsevier.

McManus, I. C., & Cornish, K. M. (1997). Commentary fractionating handedness in mental retardation: What is the role of the cerebellum? *Laterality*, *2*, 81–90.

McMeekan, E. R. L., & Lishman, W. A. (1975). Retest reliabilities and interrelationship of the Annett Hand Preference Questionnaire and the Edinburgh Handedness Inventory. In M. Annett (Ed.), *Left right, hand and brain: The right shift theory* (pp. 194–195). London, England: Erlbaum.

Miall, R. C., & Reckess, G. Z. (2002). The cerebellum and the timing of coordinated eye and hand tracking. *Brain and Cognition*, *48*, 212–226.

Miall, R. C., Reckess, G. Z., & Imamizu, H. (2001). The cerebellum coordinates eye and hand tracking movements. *Nature Neuroscience*, *4*, 638–644.

Middleton, F. A., & Strick, P. L. (1998). Cerebellar output: Motor and cognitive channels. *Trends in Cognitive Sciences*, *2*, 348–354.

Middleton, F. A., & Strick, P. L. (2000). Basal ganglia and cerebellar loops: motor and cognitive circuits. *Brain Research Reviews*, *31*, 236–250.

Musalek, M. (2013). *Development of test batteries for diagnostic of motor laterality manifestation – Link between cerebellar dominance and hand performance*. Prague, Czech Republic: Karolinum.

Nicholls, J. G., Martin, A. R., Wallace, B. G., & Fuchs, P. A. (2001). *From neuron to brain*. Sunderland, MA: Sinauer Associates Inc.

Nieuwenhuys, R., Donkelaar, H. J., & Nicholson, C. (1998). *The central nervous system of vertebrates*. Berlin, Germany: Springer.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Peters, M. (1976). Prolonged practise of a simple motor task by preferred and non-preferred hands. *Perceptual and Motor Skills*, *43*, 447–450.

Peters, M. (1995). Handedness and its relation to other indices of cerebral lateralization. In R. J. Davidson & K. Hugdahl (Eds.), *Brain asymmetry* (pp. 183–214). Cambridge, MA: MIT Press.

Peters, M. (1998). Description and validation of a flexible and broadly usable handedness questionnaire. *Laterality*, *3*, 77–96.

Ransil, B. J., & Schachter, S. C. (1994). Test–retest reliability of the Edinburgh Handedness Inventory and global handedness preference measurements, and their correlation. *Perceptual and Motor Skills*, *79*, 1355–1372.

Reib, M., Reib, G., & Freye, H. (1998). Some aspects of self-reported hand preference. *Perceptual and Motor Skills*, *86*, 953–954.

Reiss, M., & Reiss, G. (1999). Earedness and handedness: Distribution in a German sample with some family data. *Cortex*, *35*, 403–412.
Rigal, R. A. (1992). Which handedness: Preference or performance. *Perceptual and Motor Skills*, *75*, 851–866.
Rosch, R. E., Ronan, L., Cherkas, L., & Gurd, J. M. (2010). Cerebellar asymmetry in a pair of monozygotic handedness-discordant twins. *Journal of Anatomy*, *217*, 38–47.
Roy, E. A., Kalbfleisch, L., & Elliott, D. (1994). Kinematic analyses of manual asymmetries in visual aiming movements. *Brain and Cognition*, *24*, 289.
Sainburg, R. L., & Kalakanis, D. (2000). Differences in control of limb dynamics during dominant and nondominant arm reaching. *Journal of Neurophysiology*, *83*, 2661–2675.
Saksena, S., Husain, N., Malik, G., Trivedi, R., Sarma, M., Rathore, R., ... Gupta, R. (2008). Comparative evaluation of the cerebral and cerebellar white matter development in pediatric age group using quantitative diffusion tensor imaging. *The Cerebellum*, *7*, 392–400.
Scharoun, S. M., & Bryden, P. J. (2014). Hand preference, performance abilities and hand selection in children. *Frontiers in Psychology*, *5*(82), 1–15.
Sharman, J. L., & Kulhavy, R. W. (1976). The assessment of cerebral laterality: The Sharman-Kulhavy Laterality Assessment Inventory: Some validation data. *Perceptual and Motor Skill*, *42*, 1314.
Simon, J. R. (1964). Steadiness, handedness, and hand preference. *Perceptual and Motor Skills*, *18*, 203–206.
Smith, A. M., Dugas, C., Fortier, P., Kalaska, J., & Picard, N. (1993). Comparing cerebellar and motor cortical activity in reaching and grasping. *The Canadian Journal of Neurological Sciences/Le Journal Canadien des Sciences Neurologiques*, *20*, 53–61.
Snyder, P. J., Bilder, R. M., Wu, H., Bogerts, B., & Lieberman, J. A. (1995). Cerebellar volume asymmetries are related to handedness: A quantitative MRI study. *Neuropsychologia*, *33*, 407–419.
Steenhuis, R. E. (1996). Hand preference and performance in skilled and unskilled activities. In D. Elliot & E. A. Roy (Eds.), *Manual asymmetries in motor performance* (pp. 123–142). New York, NY: CRC Press.
Steenhuis, R. E., & Bryden, M. P. (1989). A different dimensions of hand preference that relate to skilled and unskilled activities. *Cortex*, *25*, 289–304.
Steenhuis, R. E., & Bryden, M. P. (1999). The relation between hand preference and hand performance: What you get depends on what you measure. *Laterality*, *4*, 3–26.
Stoodley, C. J., & Schmahmann, J. D. (2009). Functional topography in the human cerebellum: A meta-analysis of neuroimaging studies. *Neuroimage*, *44*, 489–501.
Tapley, S. M., & Bryden, M. P. (1985). A group test for the assessment of performance between the hands. *Neuropsychologia*, *23*, 215–221.
Tichy, J., & Belacek, J. (2008). Right-lefthandedness and crossed foot preference. Testing of laterality and cerebellar dominance. *Ceska a Slovenska neurologie a neurochirurgie*, *71*, 552–558.
Tichy, J., & Belacek, J. (2009). Laterality in children: Cerebellar dominance, handedness, footedness and hair whorl. *Activitas Nervosa Superior Rediviva*, *51*(1–2), 9–20.
Wassing, H. E., Siebelink, B. M., & Luyendijk, W. (1993). Handedness and progressive hydrocephalus in spina bifida patients. *Developmental Medicine and Child Neurology*, *35*, 788–797.
Williams, S. M. (1991). Handedness inventories: Edinburgh versus Annett. *Neuropschology*, *5*, 43–48.

Received May 18, 2014
Revised December 13, 2014
Accepted December 20, 2014

5. FUNDAMENTAL MOTOR SKILLS – ITS ESSENCE

The majority of our research devoted to laterality contained a fine motor performance component. We have used at least three fine motor complex tests (spiral tracing, dot-filling, tweezers and beads). These tests can be also perceived as tests of manual dexterity. The term dexterity as it is currently accepted was defined by Latash and Turrey (1996), who built on Berstein's theory of motor control as "harmony in movements" (p. 20). In humans, manual dexterity represents a multidimensional trait with at least five factors (Fleishman & Hempel, 1954) and is mostly described as the ability to perform precisely (accuracy, speed, fluency) fine motor movements (Rosenblum & Josman, 2003) respecting children's developmental age (Kohlmeyer, 1998; Jenkinson, Hyde, & Ahmad, 2008) and it belongs to a more general concept called "motor competences". However, we should point out that the term "motor competences" (MC) seems to be developed as a universal term. For instance, Robinson et al. (2015) stated that *"contemporary use of the term motor competence "...reflect[s] various terminologies that have been used in previous literature (i.e., motor proficiency, motor performance, fundamental movement/motor skill, motor ability, and motor coordination)"* (Robinson et al., 2015 p. 1274).

Motor competence can be conceptualized as a person's ability to execute different motor acts, including coordination of both fine and gross motor skills in physical activities and specific sports (Henderson & Sugden 1992; Corbin, Pangrazi, & Franks, 2000).

One of the terms within the motor competence domain in called fundamental motor skills. Fundamental motor skills (FMS) as a concept were first described by Wickstrom (1977, p. 3) who explained them *as ". . .a common motor activity with a general goal"* which represent *"the basis for more advanced and highly specific motor activities"*. However, it does not mean that before 1977 the term FMS did not exist. A variety of studies investigated: 1) relations between FMS and physical growth or development in children (Johnson, 1962; Halverson, 1966); 2) how FMS influence acquiring of rhythmic skills (Beisman, 1967); 3) learning/acquiring of FMS in a population with lower motor ability (Lafuze, 1951); or 4) studies which tried to detect the structure of FMS (Jones, 1935). Generally, a lot of questions have been asked mostly regarding the role of FMS in human motor development.

FMS are clearly defined types of movements so we can also find in literature the term "fundamental movement skills" (Logan, Ross, Chee, Stodden, & Robinson, 2018) and they are considered as building blocks of more advanced movements, for instance, for developing of physical fitness components (strength, speed, coordination) or acquiring of sports-specific skills (Clark & Metcalfe, 2002; Robinson & Goodway, 2009; Payne & Isaacs, 2017). FMS are most often divided into three parts a) locomotion – involving run, jump, hop, leap, slide, gallop; b) object control skills – manipulation – involving catching, throwing, kicking, and balance (changes of positions and movements during standing and while moving, standing on one leg, walking on tip-toes, etc.), (Stodden et al., 2008; Haywood & Getchell, 2009; Gallahue, Goodway & Ozmun, 2012).

Fundamental motor skills (FMS) are developed through human ontogeny as a higher function of verticalization whose aim is locomotion in upright position and manipulation. Evidence of a significant relation between verticalization, locomotion and manipulation has been provided especially by physiotherapy and pediatric neurologists (e.g., Twitchell, 1951; Stockmeyer, 1967; Bobath & Bobath, 1972; Case-Smith et al., 1989;).

The verticalization process in every human starts immediately after birth (we will not include the reflex period) and is firstly driven mainly by sequences of reflexive and rudimentary movements of children. In the following parts we will not discuss infants' reflexes (author's note). These rudimentary movements have an evolutionary perspective, which includes a certain amount of stages necessary for a full sensory motor control (Shirley, 1933; Bayley, 1935; Gesell, 1945). These stages are, for instance: turning from back to tummy, crawling, creeping, sitting, quadrupedal walking, staying and walking (Gallahue, Goodway, & Ozmun, 2012; Blythe, 2014). One field of physiotherapy called "developmental kinesiology" investigates the presence or absence of certain reflexes in infants and tries to correct, mostly using reflexology approaches like Vojta approach, rudimentary movements and their continuity (Kobesova & Kolar, 2014). Starting at about 4 months of age, rudimentary movements are combined with first voluntary movements, which are involved in the verticalization of walking as an energetically very efficient kind of transportation (Lieberman, 2014) and free hand manipulation. Therefore, rudimentary movements could be perceived as platform stages for developing of higher brain centres involved in more complex voluntary movements like transportation plus manipulation (if a child wants a toy which is out of reach then the child first has to transport itself to the toy and then it can move or manipulate – observing, playing, etc.). At this point it is important to emphasise that in the early stages of child development, children learn mainly through movement (Houston-Wilson, 2015, p.12).

Nevertheless, rudimentary movements should not be seen as only maturationally based because then they would lack voluntary developmental control like it was suggested by Heldebrandt, Rareik, Glassow and Carns (1961). The subsequent developing the locomotion, manipulation skills and balance can, under certain concepts, be determined as a process of developing and improving of FMS.

In literature, the term FMS often overlaps with other terms like gross motor. Gross motor refers to processes in which large muscles are usually involved that are responsible for moving the body in space. It includes, for instance, trunk movements, orientation or balance (Carlson, Rowe, & Curby, 2013; Cameron, Cottone, Murrah & Grissmer, 2016). When we look back at the structure of FMS, we can see that human gross motor is partly reflected in each defined sub-concept of FMS (Veldman, Okely, & Jones, 2015). Thus, locomotion definitely contains gross motor as well as balance; otherwise we would not be able to walk. Further, object control is also involved in gross motor, which is observed, for instance, in certain types of throwing. Moreover, throwing on distance or on target is generally considered as part of the concept called manipulation and object control. One kind of manipulation skills that is highly developed in human is manual dexterity. Manual dexterity in simplification represents conception of fine motor performance (very deep and detail description of Dexterity as complex psychophysical phenomenon provides Latash and Turvey (1996)). Nevertheless, it is important to realize that no fine motor activities could be carried without gross motor. These concepts of human motor skills are joined vessels (Seashore, 1942; Case-Smith et al., 1989; Case-Smith & Bigsby, 1993). When someone wants to perform a very accurate, precise fine motor movement, the main role of gross motor is to adjust the angles in our joints to the most effective position, which consequently enables us to perform the fine motor movement by acral parts (fingers) as accurately as possible (Skinner, 1979; Véle, 2006). Therefore, efficient co-operation of gross and fine motor is essential for learning of new skills (Jenkinson et al., 2008).

From this perspective, the conjunction of gross motor and FMS, according to Logan et al. (2018), leads to misunderstanding of the basic principles that FMS is a superordinate construct to each of its subconstructs, including gross motor.

5.1 Fundamental Motor Skills: Review

We consider it crucial to at least briefly note that before FMS concept was established, research had published conclusions that explained only certain natural relations in motor development. In the field of physical fitness it was found that different aspects of physical fitness from preschool age are age and sex dependent. Older children perform better than younger ones and boys perform better than girls except for flexibility (e.g., Phillips, 1955; Adams, Linde, & Miyake, 1961; Pařízková, 1973, 1977; Milne, Seefeldt, & Reuschlein, 1976). Even though the concept of FMS was not known, the studies that looked into the development of motor skills (no unified consensus existed between categories used or assessed skills) pointed out that the acquisition or the level of motor skills are also age dependent – younger children performed worse compared to older ones. Further, it was revealed that the level or improvement in different motor skills is significantly related to the content of the assessed motor skill. Boys outperformed girls in catching and throwing but girls performed better in balance, fine motor tests and in motor skills where anticipation was necessary (e.g., Dusenberry, 1952; Sapir, 1966; Connolly, Brown, & Bassett, 1968; Denckla, 1973; Dunham, 1977; Halverson, Roberton, & Langendorfer, 1982).

Investigations into FMS which developed from the FMS concept defined by Wickstrom (1977) have been under way for approximately 40 years. If we look back at these four decades, we can observe interesting break points in research. Studies focused on FMS in the late 1970s and in the 1980s found that the degree of FMS is age and sex dependent during preschool age and elementary-school age and that its degree is significantly related to children's physical activity (e.g., Martinek, Cheffers, & Zaichkowsky, 1978; Morris, Williams, Atwater, & Wilmore, 1982; Toriola & Igbokwe, 1986). Researchers also identified factors which influence the development of FMS including genotype, environmental factors and own motor development from birth (Haubenstricker & Seefeldt, 1986; Pohlman & Isaacs, 1990). Particular attention was devoted to the role of family and especially to parents, who seemed to be important drivers for children in developing of FMS (Halverson, et al., 1982; Morris et al., 1982; Thomas & French, 1985). In addition, next to what we can call internal environment – family, further research verified that the development of FMS can be successfully improved in external education environment (kindergarten, schools) by application of special education programmes (Masser, 1987; Kelly, Dagger & Walkley, 1989).

Additional direction to which a lot of attention has been devoted is assessing of FMS. Generally in the 1970s, there were several batteries for assessing of psychomotor development in children (Seashore, 1930; Ozeretsky, 1948; Bruininks, 1978) as well as batteries which tried to identify children with a motor skills impairment. Among them was also the Test of Motor Impairment (TOMI) by Stott, Moyes and Henderson, (1972). The TOMI was later revised in 1984 and called TOMI-H (Stott, Moyes & Henderson, 1984). Other instruments that could be adopted for measuring of some parts of FMS included, for instance, Koordinations Test fur Kinder (KTK) (Schilling & Kiphard, 1974), which assessed body control (walking backwards, hopping for height, jumping and moving sideways), Ohio State University, Scale for Intra-Gross Motor Assessment (OSUSIGMA) (Loovis & Ersing, 1979) or a very comprehensive Peabody Developmental Motor Scale (PDMS) containing 244 items assessing concepts of Reflexes, Stationary, Locomotion, Object Manipulation, Grasping, Visual-Motor Integration (Folio & Fewell, 1983). From a different perspective, what was quite interesting was assessing of kinaesthetic sensitivity which showed that kinaesthetic perception and memory – the position of a body segment or speed of segment is significantly correlated with fine manual control as well as with co-ordinated gross body movements (Bairstow & Laszlo, 1981).

In our opinion, the first truly worldwide accepted instrument was developed in the beginning of the 1980s by Ulrich and colleagues (Ulrich, 1984; Ulrich & Ulrich, 1984; Ulrich & Wise, 1984). These authors developed an instrument with a qualitative assessment protocol called the Test of Gross Motor Development (TGMD) (Ulrich, 1985) covering the gross motor sub-concept of FMS. This qualitative approach met the demand for an instrument which would take into consideration the fact that motor development and FMS do not contain only a product (quantitative) oriented component but also a process (qualitative) oriented component. Immediately in the second half of the 1980s, research studies interested in motor development started to point out the worsening of manipulation skills in children. Graham (1987), who was focused on the “goal of physical education programme”, presented a very important finding that children from 3rd to 7th grade had very poor throwing, catching and kicking skills with definite differences regarding sex (girls performed worse than boys). Several of these findings led to the question as to whether there might be some rational cut off which would distinguish between motor difficulties caused by neurology deficits and others with environmental causes.

In the middle of the 1980, researchers and professional and general public were already familiar, at least in the western world, with the term "Developmental Coordination Disorder" (DCD) (Dare & Gordon, 1970). This diagnosis is explained as the presence of severe motor difficulties or clumsiness manifested also in daily activities which have a neurological background and are often associated with another comorbidities like Attention Deficit Hyperactivity Disorder (ADHD), reading or learning disorders, or dyslexia (e.g., Tarver & Hallahan, 1974; Henderson & Hall, 1982; Cermak, Ward & Ward, 1986; Visser, 2003; Pieters, Roeyers, Rosseel, Van Waelvelde & Desoete, 2015; Biotteau et al., 2017). However, in the 1980s there was only little evidence as to what is the proportion of these children in the population and whether the worsening manipulation, found for instance by Graham (1987), might not be associated with the growing amount of children with motor difficulties or children with diagnosis of DCD.

Hence, during the 1985–1992 period, we can notice something like the first wave of development of diagnostic instruments that tried to identify, using field testing methods, the degree of motor difficulties in FMS (TGMD, Ulrich 1985; Component Developmental Sequences (DevSeq), Haubenstricker & Seefeldt, 1986; Motoriktest fur Vier- bis Sechsjahrige Kinder (MOT 4–6), Zimmer & Volkamer, 1987; Fundamental Motor Skills (FMS) Test package in Eurofit test, Adam et al., 1988; Movement assessment battery for children, Henderson & Sugden, 1992; In. Logan et al., 2018). The Movement Assessment Battery for Children (MABC), developed by Henderson and Sugden (1992), contained centile scale with two important cut-off points (16th and 5th). A child scoring under or equal the 15th centile was considered to have severe motor difficulties and a child scoring under or equal the 5th centile was considered to have a high probability of DCD. This approach was very helpful and widely used because it provided examiners with information that was important for deciding to what extent the measured motor difficulties were related to a possible neurology impairment of motor coordination. The following period 1993–2000 could be labelled as the second wave of instrument development focusing on the identification of motor difficulties in FMS sub-concepts. During that period, some previous instruments were re-validated and improved (TGMD-2, Ulrich, 2000; KTK, Schilling & Kiphard, 2000) and others were developed (Motor Skill Checklist, State of Victoria, Department of Education, 1996; Assessment of Perceptual and Fundamental Motor Skills (APM) Inventory, Numminen, 1995; Get Skilled Get Active (GSGA), NSW Department of Education and Training, 2000; In Logan et al., 2018).

During the last wave that took place between 2000 and 2012, two widely used instruments were re-validated: 1) Bruininks Ozeretksky test battery of motor proficiency BOTMP-2, (Bruininks & Bruininks, 2005), and 2) the MABC-2, (Henderson, Sugden, & Barnett, 2007). In addition, Furtado-Gallagher Computerized Observational Movement Pattern Assessment System (FGCOMPASS) (Furtado, 2009; Furtado & Gallagher, 2012) or Fundamental Movement Skill (FMS) Polygon for 8-year-old children (Zuvela, Bozanic, & Miletic, 2011) were developed; however, the replication and verification of the diagnostic quality and applicability of these tools is still in process.

In our opinion, the development of the aforementioned test batteries, particularly in the first two waves, was very important for the determination of FMS in human motor development. Questions related to human motor development are closely connected with the term “motor behaviour”. For instance, studies by Ellson (1949) or Fitts (1954) presented a possible understanding of human motor behaviour as a certain change, though mostly explained as an immediate reaction to a definite stimulus. Gallahue (1982) pointed out that a vast amount of instruments used for assessing of motor development in children are product oriented which means that they are descriptive and *“establish a standard of performance based on certain expectations for each chronological age”* (Gallahue, 1982, p. 247). In addition, in that period much less attention was given to the development of process orientated tests and batteries which could provide more information about the developmental progression of movement skill acquisition (Gallahue, 1982, p. 247). Another perspective regarding the importance of FMS in motor development, was introduced by

Seefeld (1984) focused on when to start with systematic development of FMS in children. In conclusion Seefeld propose that FMS and its developemtn as well as degree is probably closely linked with physical fitness of children. Specifically, he assigned FMS an irreplaceable role in increasing physical fitness from early childhood (Seefeld, 1984). Further, Schmidt and Young (1987), who worked on the transfer of learning (the transfer of motor control into process of acquiring of motor skill) suggested that motor behaviour is a process in which the primary determinants are: how an individual controls certain body segments during movement (timing, precise patterning, muscle force). Therefore, motor behaviour is a situation when humans have to determine the way to solve it rather than how to solve it (Schmidt & Yang, 1987). Even though it might seem that the conclusions from previous studies only emphasized the necessity: 1) to develop other kinds of tools for assessing of motor development; 2) to pay attention to FMS development or 3) how to understand acquiring of motor skills in the domain of motor behaviour, we perceive these conclusions and suggestions as important connections to another study Clark and Whitall (1989), which dealt with the difficult question: What is motor development, and how it is connected with the field of FMS. The biggest challenge which remains, by the way, still open to a certain extent, in assessing of FMS was to show whether motor development is a product or a process. If we consider motor development as product then motor development could be seen as a "*change over time in motor behavior. On the other hand, when considering motor development as process then emphasis is on the underlying mechanisms of change"* (Clark & Whitall, 1989, p. 194). This conclusion showed not only that motor development contains both product and process and that none of them should be given priority but it also defined new perspectives of research in the area of FMS. Even though shortly after Clark and Whitall (1989) some studies, like Higgins (1991), concluded that *"Factors that influence the individual's level of skill are fully explored, along with the implications for functional behavior"* (Higgins, 1991, p. 123), many other investigations were conducted in several dominant areas.

We consider most important those studies that verified the importance of FMS development during childhood within educational process. In his theoretical paper, Gabbard (1988) saw FMS as one of the key mechanism for motor as well as cognitive development and underlined that FMS development must be an integral part of physical education. In addition, Ignico (1994), who focused on preschool children, emphasized the irreplaceable role of teacher for developing of FMS. Moreover, this author pointed out that the right guidance of children in FMS development also means looking for positive association of children to physical activities which persist to adulthood. This was also supported by 20-year longitudinal study carried out by Lloyd, Saunders, Bremer and Tremblay (2014). In addition, it was found out that certain aspects of academic achievement (math, reading, information processing skills) are positively and significantly related to the amount of physical activity (Goldstein & Britt, 1994; Shephard, 1997). Following research showed that social or cognitive skills significantly correlate with FMS in preschool children (Connor-Kuntz & Dummer, 1996; Goodway

& Rudisill, 1996; Payne & Isaacs, 1998) and especially agility and balance seemed to have a significant impact on working memory capacity and visual perceptual ability (Alloway, 2007; Niederer et al., 2011). On the other hand, poor level of FMS was found to be a significant predictor for lower self-concept (Gallahue & Ozmun, 1998). Later (more recent) research focused on the relation between academic achievement and FMS found that children with better FMS achieved better results in math and language skills (Ericsson, 2008) and that mastery of FMS may contribute to better student achievement (Sortor & Kulp, 2003; Jelle Vuijk, Hartman, Mombarg, Scherder & Visscher, 2011; Jaakkola, Hillman, Kalaja & Liukkonen, 2015;). A very interesting study was carried out by Rigoli, Piek, Kane and Oosterlaan (2012), who found, using structural equation modelling (on a small sample of n=93 adolescents) that motor coordination (aiming and catching) has significant indirect effect on academic achievement via working memory what could have an important impact specifically on the assessment of treatment of motor and learning difficulties. One of many factors which can affect/delay the degree of cognitive and executive skills is related to low gestanional age because the central nervous system is not generally well matured. Research showed that very preterm children have significantly poorer degree of FMS with higher probability of DCD and worse cognitive skills as well as academic performance (Foulder-Hughes & Cooke, 2003; Davis, Ford, Anderson, Doyle & Victorian Infant Collaborative Study Group, 2007; Wocadlo & Rieger, 2008) and significantly higher prevalence of DCD (Goyen & Lui, 2009).

References:

Adam, C., Council of Europe, & Council of Europe. (1988). *Eurofit: Handbook for the Eurofit tests of physical fitness*. Rome: Italian National Olympic Committee, Central Direction for Sport’s Technical Activities Documentation and Information Division.

Adams, F. H., Linde, L. M., & Miyake, H. (1961). The physical working capacity of normal school children: I. California. *Pediatrics*, *28*(1), 55-64.

Alloway, T. P. (2007). Working memory, reading, and mathematical skills in children with developmental coordination disorder. *Journal of experimental child psychology*, *96*(1), 20-36.

Bairstow, P. J., & Laszlo, J. I. (1981). Kinaesthetic sensitivity to passive movements and its relationship to motor development and motor control. *Developmental Medicine & Child Neurology*, *23*(6), 606-616.

Bayley, N. (1935). The development of motor abilities during the first three years: A study of sixty-one infants tested repeatedly. *Monographs of the Society for Research in Child Development*, *1*(1), 1-26.

Beisman, G. L. (1967). Effect of rhythmic accompaniment upon learning of fundamental motor skills. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *38*(2), 172-176.

Biotteau, M., Péran, P., Vayssière, N., Tallet, J., Albaret, J. M., & Chaix, Y. (2017). Neural changes associated to procedural learning and automatization process in developmental coordination disorder and/or developmental dyslexia. *european journal of paediatric neurology*, *21*(2), 286-299.

Blythe, S. G. (2014). *Well Balanced Child: Movement and Early Learning*. Hawthorn Press.

Bobath, K., & Bobath, B. (1972). The neurodevelopmental approach to treatment. *Physical therapy services in the developmental disabilities*, 114-185.

Bruininks, R. H. (1978). Bruininhs—Oseretsky test of motor proficiency. *Circle Pines, MN: American Guidance Service*.

Bruininks, R. H., & Bruininks, B. D. (2005). *Test of motor proficiency (2nd ed.).* Manual. Circle Pines, MN: AGS Publishing

Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement?. *Child Development Perspectives*, *10*(2), 93-98.

Carlson, A. G., Rowe, E., & Curby, T. W. (2013). Disentangling fine motor skills' relations to academic achievement: The relative contributions of visual-spatial integration and visual-motor coordination. *The Journal of genetic psychology*, *174*(5), 514-533.

Case-Smith, J., Fisher, A. G., & Bauer, D. (1989). An analysis of the relationship between proximal and distal motor control. *American Journal of Occupational Therapy*, *43*(10), 657-662.

Case-Smith, & Bigsby, R. (1993). *Posture and fine motor assessment of infants.* Unpublished document. Columbus, OH: The Ohio State University.

Cermak, S. A., Ward, E. A., & Ward, L. M. (1986). The relationship between articulation disorders and motor coordination in children. *American Journal of Occupational Therapy*, *40*(8), 546-550.

Clark, J. E., & Metcalfe, J. S. (2002). The mountain of motor development: A metaphor. In J.E. Clark & J.H. Humphrey (Eds.), *Motor development: Research and reviews* (Vol. 2, pp. 163–190). Reston, VA: National Association of Sport and Physical Education.

Clark, J. E., & Whitall, J. (1989). What is motor development? The lessons of history. *Quest*, *41*(3), 183-202.

Connolly, K., Brown, K., & Bassett, E. (1968). Developmental changes in some components of a motor skill. *British journal of Psychology*, *59*(3), 305-314.

Connor-Kuntz, F. J., & Dummer, G. M. (1996). Teaching across the curriculum: Language-enriched physical education for preschool children. *Adapted Physical Activity Quarterly*, *13*(3), 302-315.

Corbin, C. B., Pangrazi, R. P., & Franks, B. D. (2000). Definitions: Health, fitness, and physical activity. *President's Council on Physical Fitness and Sports Research Digest*.

Dare, M. T., & Gordon, N. (1970). Clumsy children: a disorder of perception and motor organisation. *Developmental Medicine & Child Neurology*, *12*(2), 178-185.

Davis, N. M., Ford, G. W., Anderson, P. J., Doyle, L. W., & Victorian Infant Collaborative Study Group. (2007). Developmental coordination disorder at 8 years of age in a regional cohort of extremely-low-birthweight or very preterm infants. *Developmental Medicine & Child Neurology*, *49*(5), 325-330.

Denckla, M. B. (1973). Development of speed in repetitive and successive finger-movements in normal children. *Developmental Medicine & Child Neurology*, *15*(5), 635-645.

Dunham Jr, P. (1977). Age, sex, speed, and practice in coincidence-anticipation performance of children. *Perceptual and Motor Skills*, *45*(1), 187-193.

Dusenberry, L. (1952). A study of the effects of training in ball throwing by children ages three to seven. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *23*(1), 9-14.

Ellson, D. G. (1949). The application of operational analysis to human motor behavior. *Psychological review*, *56*(1), 9-17.

Ericsson, I. (2008). Motor skills, attention and academic achievements. An intervention study in school years 1–3. *British Educational Research Journal*, *34*(3), 301-313.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, *47*(6), 381-391.

Folio, M. R., & Fewell, R. R. (1983). *Peabody developmental motor scales and activity cards.* Allen, TX: DLM Teachers Resources.

Foulder-Hughes, L. A., & Cooke, R. W. I. (2003). Motor, cognitive, and behavioural disorders in children born very preterm. *Developmental medicine and child neurology*, *45*(2), 97-103.

Furtado Jr, O., & Gallagher, J. D. (2012). The reliability of classification decisions for the Furtado-Gallagher computerized observational movement pattern assessment system - FG-COMPASS. *Research quarterly for exercise and sport*, *83*(3), 383-390.

Furtado, O., Jr. (2009). Development and initial validation of Furado-Galla computerized observational movement pattern assessment system – FGCOMPASS (Unpublished doctoral dissertation). University of Pittsburgh. Retrieved from http://d-scholarship.pitt.edu/8917/

Gabbard, C. (1988). Early childhood physical education: The essential elements. *Journal of Physical Education, Recreation & Dance*, *59*(7), 65-69.

Gallahue, D. L. (1982). Assessing motor development in young children. *Studies in Educational Evaluation*, *8*(3), 247-252.

Gallahue, D. L., & Ozmun, J. C. (1998). Childhood perception and perceptual motor development. *DL Gallahue, JC Ozmun. Understanding motor development infants, children, adolescents, adults. Singapore: McGraw-Hill*, 297-316.

Gallahue, D. L., Goodway, J. D., & Ozmun, J. C. (2012). *Understanding motor development:* Infants, children, adolescents, adults. Boston: McGraw-Hill

Gesell, A., & Amatruda, C. S. (1945). *The embryology of behavior*. New York: Mcmilan

Goldstein, D. J., & Britt Jr, T. W. (1994). Visual-motor coordination and intelligence as predictors of reading, mathematics, and written language ability. *Perceptual and motor skills*, *78*(3), 819-823.

Goodway, J. D., & Rudisill, M. E. (1996). Influence of a motor skill intervention program on perceived competence of at-risk African American preschoolers. *Adapted Physical Activity Quarterly*, *13*(3), 288-301.

Goyen, T. A., & Lui, K. (2009). Developmental coordination disorder in “apparently normal” schoolchildren born extremely preterm. *Archives of disease in childhood*, *94*(4), 298-302.

Graham, G. (1987). Motor skill acquisition–an essential goal of physical education programs. *Journal of Physical Education, Recreation & Dance*, *58*(7), 44-48.

Halverson, L. E. (1966). Development of motor patterns in young children. *Quest*, *6*(1), 44-53.

Halverson, L. E., Roberton, M. A., & Langendorfer, S. (1982). Development of the overarm throw: Movement and ball velocity changes by seventh grade. *Research Quarterly for Exercise and Sport*, *53*(3), 198-205.

Haubenstricker, J., & Seefeldt, V. (1986). Acquisition of motor skills during childhood. In V. Seefeldt *Physical activity and well-being*, (pp. 41-102). American Alliance for Health, Physical Education, Recreation and Dance Publications, Waldorf, MD 20601.

Haywood, K. M., & Getchell, N. (2009). *Lifespan motor development (5th ed.)* Champaign, IL: Human Kinetics.

Heldebrandt, F. A., Rareik, G. L., Glassow, R., & Carns, M. L. (1961). Physiological analysis of basic motor skills. *American Journal of Physical Medicine*, *40*, 14-25.

Henderson, S. E., & Hall, D. (1982). Concomitants of clumsiness in young schoolchildren. *Developmental Medicine & Child Neurology*, *24*(5), 448-460.

Henderson, S. E., & Sugden, D. A. (1992). *Movement assessment battery for children*. Sidcup: Therapy skill builders.

Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *Movement assessment battery for children – 2 examiner’s manual*. London: Harcourt Assessment.

Higgins, S. (1991). Motor skill acquisition. *Physical therapy*, *71*(2), 123-139.

Houston-Wilson, C. (2015). Early Childhood Development. In Aiello, R. *Sports, Fitness, and Motor Activities for Children with Disabilities: A Comprehensive Resource Guide for Parents and Educators*, (Eds.) (pp. 12), Rowman & Littlefield:Maryland

Ignico, A. (1994). Early childhood physical education: Providing the foundation. *Journal of Physical Education, Recreation & Dance*, *65*(6), 28-30.

Jaakkola, T., Hillman, C., Kalaja, S., & Liukkonen, J. (2015). The associations among fundamental movement skills, self-reported physical activity and academic performance during junior high school in Finland. *Journal of sports sciences*, *33*(16), 1719-1729.

Jelle Vuijk, P., Hartman, E., Mombarg, R., Scherder, E., & Visscher, C. (2011). Associations between academic and motor performance in a heterogeneous sample of children with learning disabilities. *Journal of learning disabilities*, *44*(3), 276-282.

Jenkinson, J., Hyde, T., & Ahmad, S. (2008). *Building blocks for learning occupational therapy approaches: practical strategies for the inclusion of special needs in primary school*. John Wiley & Sons.

Johnson, R. D. (1962). Measurements of achievement in fundamental skills of elementary school children. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *33*(1), 94-103.

Jones, L. M. (1935). *A factorial analysis of ability in fundamental motor skills* (No. 665). Teachers College, Columbia University.

Kelly, L. E., Dagger, J., & Walkley, J. (1989). The effects of an assessment-based physical education program on motor skill development in preschool children. *Education and Treatment of Children*, 152-164.

Kobesova, A., & Kolar, P. (2014). Developmental kinesiology: three levels of motor control in the assessment and treatment of the motor system. *Journal of bodywork and movement therapies*, *18*(1), 23-33.

Kohlmeyer, K. (1998). Evaluation of performance components. In: E. Neistadt, Willard & *Spackman's Occupational Therapy*(pp. 582-607). N. Y: Lippincott Williams & Wilkins.

Lafuze, M. (1951). A study of the learning of fundamental skills by college freshman women of low motor ability. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *22*(2), 149-157.

Latash, M. L. W. & Turvey, M. T. (1996). *Dexterity and its development*. NJ: Lawrence Erlbaum Associates

Lieberman, D. (2014). *The story of the human body: evolution, health, and disease*. Vintage.

Lloyd, M., Saunders, T. J., Bremer, E., & Tremblay, M. S. (2014). Long-term importance of fundamental motor skills: A 20-year follow-up study. *Adapted physical activity quarterly*, *31*(1), 67-78.

Logan, S. W., Ross, S. M., Chee, K., Stodden, D. F., & Robinson, L. E. (2018). Fundamental motor skills: A systematic review of terminology. *Journal of sports sciences*, *36*(7), 781-796.

Loovis, M. E., & Ersing, W. F. (1979). Assessing and programming gross motor development for children (2nd ed.). Bloomington, IN: College Town Press. (Out of print). Retrieved from http://engagedscholarship.csuohio.edu/edhperd_bks/1/

Martinek, T. J., Cheffers, J. T., & Zaichkowsky, L. D. (1978). Physical activity, motor development and self-concept: race and age differences. *Perceptual and Motor Skills*, *46*(1), 147-154.

Masser, L. (1987). The effect of refinement on student achievement in a fundamental motor skill in grades K through 6. *Journal of Teaching in Physical Education*, *6*(2), 174-182.

Milne, C., Seefeldt, V., & Reuschlein, P. (1976). Relationship between grade, sex, race, and motor performance in young children. *Research Quarterly. American Alliance for Health, Physical Education and Recreation*, *47*(4), 726-730.

Morris, A. M., Williams, J. M., Atwater, A. E., & Wilmore, J. H. (1982). Age and sex differences in motor performance of 3 through 6 year old children. *Research Quarterly for Exercise and Sport*, *53*(3), 214-221.

Niederer, I., Kriemler, S., Gut, J., Hartmann, T., Schindler, C., Barral, J., & Puder, J. J. (2011). Relationship of aerobic fitness and motor skills with memory and attention in preschoolers (Ballabeina): a cross-sectional and longitudinal study. *BMC pediatrics*, *11*(1), 34.

NSW Department of Education and Training. (2000). *Get skilled: Get active. A K-6 resource to support the teaching of fundament skills.* Ryde: NSW Department of Education and Training.

Numminen, P. (1995). *Alle kouluikäisten lasten psykomotorisia ja motorisia perustaitoja mittaavan APM-testistön käsikirja [APM-inventory*: Manual test booklet for assessing preschool children's perceptual and fundamental motor skills]. Jyväskylä: LIKES

Ozeretsky, N. (1948). A metric scale for studying the motor capacity of children in Rusia. *Journal of Clinical Psychology*, *12*, 37-47.

Pařízková, J. (1973). Body composition and lipid metabolism. *The Proceedings of the Nutrition Society*, *32*(3), 181-186.

Pařízková, J. (1977). Body fat and physical fitness: Body composition and lipid metabolism in different regimes of physical activity. *The Hague: Nijhoff/Medical Division*.

Payne, G., & Isaacs, L. (1998). *Human motor development: A* lifespan approach. California: Mayfield Publishing Company.

Payne, V. G., & Isaacs, L. D. (2017). *Human motor development: A lifespan approach*. Routledge.

Phillips, M., Bookwalter, C., Denman, C., McAuley, J., Sherwin, H., Summers, D., & Yeakel, H. (1955). Analysis of results from the Kraus-Weber test of minimum muscular fitness in children. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *26*(3), 314-323.

Pieters, S., Roeyers, H., Rosseel, Y., Van Waelvelde, H., & Desoete, A. (2015). Identifying subtypes among children with developmental coordination disorder and mathematical learning disabilities, using model-based clustering. *Journal of learning disabilities*, *48*(1), 83-95.

Pohlman, R. L., & Isaacs, L. D. (1990). The previously low birth weight infant: Fundamental motor skill outcomes in the 5-to 9-year-old. *Pediatric Exercise Science*, *2*(3), 263-271.

Rigoli, D., Piek, J. P., Kane, R., & Oosterlaan, J. (2012). Motor coordination, working memory, and academic achievement in a normative adolescent sample: Testing a mediation model. *Archives of clinical neuropsychology*, *27*(7), 766-780.

Robinson, L. E., & Goodway, J. D. (2009). Instructional climates in preschool children who are at risk. Part I: object-control skill development. *Research quarterly for exercise and sport*, *80*(3), 533-542.

Robinson, L. E., Stodden, D. F., Barnett, L. M., Lopes, V. P., Logan, S. W., Rodrigues, L. P., & D’Hondt, E. (2015). Motor competence and its effect on positive developmental trajectories of health. *Sports medicine*, *45*(9), 1273-1284.

Rosenblum, S., & Josman, N. (2003). The relationship between postural control and fine manual dexterity. *Physical & occupational therapy in pediatrics*, *23*(4), 47-60.

Sapir, S. G. (1966). Sex differences in perceptual motor development. *Perceptual and motor skills*, *22*(3), 987-992.

Seashore, H. G. (1942). Some relationships of fine and gross motor abilities. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *13*(3), 259-274.

Seashore, R. H. (1930). Individual differences in motor skills. *The Journal of General Psychology*, *3*(1), 38-66.

Seefeldt, V. (1984). Physical fitness in preschool and elementary school-aged children. *Journal of Physical Education, Recreation & Dance*, *55*(9), 33-40.

Shephard, R. J. (1997). Curricular physical activity and academic performance. *Pediatric exercise science*, *9*(2), 113-126.

Shirley, M. M. (1933). *The first two years: A study of twenty-five babies, 1. Postural and Locomotor Developmen*t. Minneapolis, MN: University of Minnesota Press.

Schilling, F., & Kiphard, E. J. (1974). *Körperkoordinationstest für kinder: KTK*. Beltz.

Schilling, F., & Kiphard, E. J. (2000). *Körperkoordinationstest für kinder Manual.* Göttingen: Beltz Test GmbH.

Schmidt, R. A., & Young, D. E. (1987). Transfer of movement control in motor skill learning. In *Transfer of learning: Contemporary research and applications* (pp. 47-79).

Skinner, L. (1979). *Motor development in the preschool years*. Charles C. Thomas.

Sortor, J. M., & Kulp, M. T. (2003). Are the results of the Beery-Buktenica Developmental Test of Visual-Motor Integration and its subtests related to achievement test scores?. *Optometry and vision science*, *80*(11), 758-763.

State of Victoria, Department of Education. (1996). *Fundamental motor skills: A manual for classroom teachers.* Melbourne: Community Information Service, Department of Education

Stockmeyer, S. A. (1967). An interpretation of the approach of Rood to the treatment of neuromuscular dysfunction. *American journal of physical medicine & rehabilitation*, *46*(1), 900-956.

Stodden, D. F., Goodway, J. D., Langendorfer, S. J., Roberton, M. A., Rudisill, M. E., Garcia, C., & Garcia, L. E. (2008). A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest*, *60*(2), 290-306.

Stott D. H., Moyes F. A., Henderson S. E. (1972). *Test of motor impairment***.** Department of Psychology, University of Guelph, Ontario, Guelph, Ontario

Stott, D. H., Moyes, F., & Henderson, S. E. (1984). *Test of motor impairment: Manual*. Brook Educational Pub..

Tarver, S. G., & Hallahan, D. P. (1974). Attention deficits in children with learning disabilities: A review. *Journal of Learning Disabilities*, *7*(9), 560-569.

Thomas, J. R., & French, K. E. (1985). Gender differences across age in motor performance: A meta-analysis. *Psychological bulletin*, *98*(2), 260-282.

Toriola, A. L., & Igbokwe, N. U. (1986). Age and sex differences in motor performance of pre-school Nigerian children. *Journal of Sports Sciences*, *4*(3), 219-227.

Twitchell, T. E. (1951). The restoration of motor function following hemiplegia in man. *Brain*, *74*(4), 443-480.

Ulrich, D. A. (1984). The reliability of classification decisions made with the objectives-based motor skill assessment instrument. *Adapted Physical Activity Quarterly*, *1*(1), 52-60.

Ulrich, D. A. (1985). *TGMD, test of gross motor development*. Pro-Ed.

Ulrich, D. A., & Ulrich, B. D. (1984). The Objectives-Based motor-skill assessment instrument: Validation of instructional sensitivity. *Perceptual and motor skills*, *59*(1), 175-179.

Ulrich, D. A., & Wise, S. L. (1984). Reliability of scores obtained with the objectives-based motor skill assessment instrument. *Adapted Physical Activity Quarterly*, *1*(3), 230-239.

Veldman, S. L., Okely, A. D., & Jones, R. A. (2015). Promoting gross motor skills in toddlers: the active beginnings pilot cluster randomized trial. *Perceptual and motor skills*, *121*(3), 857-872.

Véle, F. (2006). *Kineziologie*, Triton ISBN 80-7254-837-9, Translation: Véle, F. (2006). *Kinesiology*

Visser, J. (2003). Developmental coordination disorder: a review of research on subtypes and comorbidities. *Human movement science*, *22*(4-5), 479-493.

Wickstrom, R. L. (1977). *Fundamental motor patterns. (2nd ed.*). Philadelphia, PA: Lea & Febiger.

Wocadlo, C., & Rieger, I. (2008). Motor impairment and low achievement in very preterm children at eight years of age. *Early human development*, *84*(11), 769-776.

Zimmer, R., & Volkamer, M. (1987). Motoriktest für vier-bis sechsjärige Kinder (manual).

Zuvela, F., Bozanic, A., & Miletic, D. (2011). POLYGON-A new fundamental movement skills test for 8 year old children: Construction and validation. *Journal of sports science & medicine*, *10*(1), 157-163.

6. ARE SEX DIFFERENCES IN FUNDAMENTAL MOTOR SKILLS UNIFORM THROUGHOUT THE ENTIRE PRESCHOOL PERIOD?

In parallel with research devoted to benefits of FMS or how it could possibly be affected by definite factors, differences in FMS performance related to gender were also investigated. Gender differences in tests involved in the FMS concept had already been found in studies from the 1950s and 1960s. In relative conformity these investigations concluded that girls were better in balance, fine motor tests and in motor skills where anticipation was necessary and boys outperformed girls mainly in catching and throwing (e.g., Dusenberry, 1952; Govatos, 1959; Sapir, 1966; Connolly, Brown & Bassett, 1968;). In contrast to these findings, in their comprehensive meta-analysis Thomas & French (1985) found that balance did not differ in boys and girls till the age of 12 when boys start to perform better. In addition, according to some studies, gender differences in pre-pubescent age might be more dependent on social and environmental conditions (Garcia, 1994) than on biological factors. Since the development of FMS was often associated with preschool age period, intensive research started to investigate FMS structure and differences using standardized FMS batteries (KKT, MABC, MABC-2, TGMD and others) in preschoolers. Subsequent findings were mostly in conformity with the results of studies conducted in the 1950s and 1960s. In samples including children from preschool age to the end of pre-pubescence, girls were better in balance and fine motor and boys were better in overhead throwing (Schneck & Henderson, 1990; Butterfield & Loovis, 1993; Loovis & Butterfield, 1993; Raudsepp & Pääsuke, 1995; Junaid & Fellowes, 2006; Olesen, Kristensen, Ried-Larsen, Grøntved & Froberg, 2014). On the other hand, we must not forget studies that did not find any gender differences in the FMS degree particularly in preschoolers (e.g., Van Waelvelde, Peersman, Lenoir, Engelsman, & Henderson, 2008; Shala, 2009; Venetsanou & Kambas, 2011; LeGear et al., 2012; Spessato, Gabbard, Valentini, & Rudisill, 2013; Foulkes et al., 2015)

When we studied the methodology applied in the aforementioned research focused on gender differences in preschool age, we concluded that the inconsistency of results could be explained by a number of factors. We consider as highly significant the two following aspects: 1) not including children from the entire preschool period (3±6 years old); 2) researchers sometimes created two age categories by combining 3- and 4-year-olds and 5- and 6-year-olds together. Our subsequent search showed that only few studies compared the degree of FMS of boys and girls against each other according to individual age. One of these studies was conducted by Morris, Williams, Atwater & Wilmore (1982), where sex differences were present for locomotor and balance skills, but object control and fine motor skills were not investigated. We consider the information about the combination of sex age-specific in FMS vitally important in order to optimally develop FMS in modern day preschoolers whose conditions and social environment has significantly changed compared to the time of Morris et al. (1982) study.

Therefore, the aim of our following research was to compare FMS scores of preschool boys and girls for each age group across the entire preschool period. Based on the incongruous findings of the research discussed above, it was hypothesized that sex differences would occur in different types of FMS (manipulative, locomotor and balance), but would not be uniform between boys and girls in each age group across the entire preschool period. Since we were not able to carry out repeated measurements, our research design was a cross sectional type of study.

Research sample:

For the purpose of this study, seven randomly chosen preschools in two regions (Prague and Central Bohemia) of the Czech Republic were selected. Parents were informed of the purpose, procedures and benefits of the study. The study was approved by the Ethics Committee of the Faculty of Physical Education and Sport at Charles University, and an informed consent was required from the children's parents or legal guardians. Children who had been diagnosed with mental or other clinically diagnosed impairments (such as ADHD, DCD, developmental dysphasia, etc.) and children from special needs classes were not included in the study.

In the end, we received an informed consent from parents of n=325 children (162 boys and 163 girls; see Fig. 12) aged 3 to 6 years (4.9 ± 1.1yrs).

Age		Boys	Girls
3 years	N	32	33
	Age (M±SD)	3.4±0.3	3.4±0.3
4 years	N	48	48
	Age (M±SD)	4.4±0.3	4.4±0.3
5 years	N	44	46
	Age (M±SD)	5.4±0.3	5.3±0.3
6 years	N	38	36
	Age (M±SD)	6.3±0.3	6.4±0.3

https://doi.org/10.1371/journal.pone.0176556.t001

Figure 12. Frequency of children considering age and sex
Adapted from Kokštejn, Musálek, & Tufano, (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

Procedure:

We recognized that if we wanted to assess FMS in whole preschool age spectrum which is, according to Czech legislative, between the age of 3 and 6, we should focus our attention on the Movement Assessment Battery for Children – second edition (MABC-2) (Henderson et al., 2007), specifically on MABC-2 Age Band 1 (AB1), which was designed for assessing of FMS in preschool children. The MABC-2 was translated to Czech environment by modified direct translation method (Behling & Law, 2000) and validated on Czech population of children (Psotta, 2014).

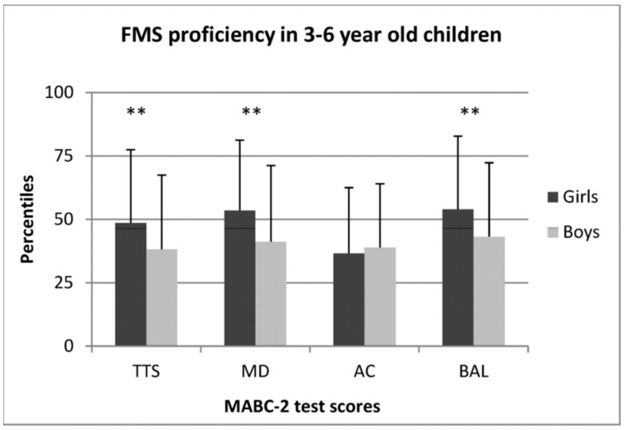
The MABC-2 test AB1 contains eight test items which assess FMS in three basic motor domains: manual dexterity (MD), aiming and catching (AC), and balance (BAL) The four motor tasks have different conditions between younger (3- and 4-year old) and older (5- and 6-year old) children. For instance, younger children must post six coins and thread six beads whereas older children must complete 12 of each. Younger children can use the entire body when catching a beanbag; older children must only use their hands.

Further, the MABC manual allocates normative values for 5- and 6-year olds independently, while norms for 3- and 4-year olds are divided into two groups per age using 6-month categories, yielding four groups in total (3 y 0 months to 3 y 6 months; 3 y 6 months to 4 y 0 months, etc.). For simplicity and clarity, these half-year categories were combined into a single score for each age, and the same was done in case of 5- and 6-year olds. Data were collected by one trained research team. For more detail, see Kokštejn et al. (2017) at the end of this chapter.

Results:

In the first step we analysed "as usual" whether any differences exist in FMS between boys and girls in preschool age. We compared the degree of FMS in each assessed sub-concept (manual dexterity – MD; aiming and catching – AC; balancing – BAL) between boys and girls regardless to which specific age category they belonged to.

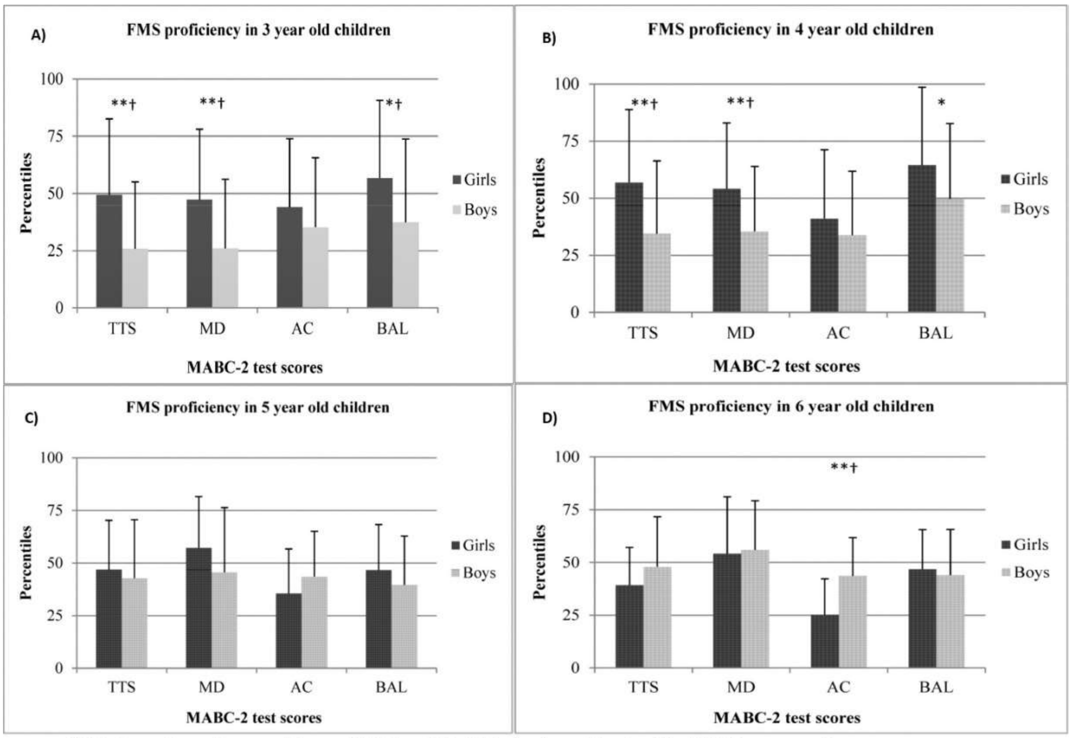
From fig. XX it is evident that not only the total test score (TTS), which is a composite score of results of each sub-concept, but also performances in two sub-concepts were significantly different for boys and girls. Girls achieved better results in MD and BAL compared to boys. On the other hand, AC did not prove to be sex dependent (Fig. 13).



Note: FMS = fundamental motor skills; MABC-2 = Movement Assessment Battery for Children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; ** p < .01.

Figure 13. FMS proficiency in 3- to 6-year-old children
Adapted from Kokštejn et al. (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

To verify whether the assumed changes in the development of FMS during preschool period between boys and girls exist, we split the results from the MABC-2 to age categories of 3-year-old, 4-year-old, 5-year-old and 6-year-old children.



FMS in 3-year, 4-year, 5-year and 6-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; ** p < .01; ² medium effect size

Figure. 14 FMS in 3-year, 4-year, 5-year and 6-year old children
Adapted from Kokštejn et al., (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

The results received by splitting children into four age categories with respect to sex showed that the differences between boys and girls in FMS and its sub-concepts are not uniform during whole preschool age. We can see that girls achieved better TTS only at the age of 3 and 4 years. A detailed investigation of changes in TTS also revealed that while each age group of boys achieved better results in the MABC-2 from the 25th centile at the age of three (Fig. 14A) to the 48th centile at the age of six, (Fig. 14D) girls showed quite a different pattern. The group of 3-year-old girls achieved the 50th centile (Fig. 14A) and the group of 4-year-old girls achieved the 56th centile, an even better result (Fig. 14B). However, 5- and 6-year-old girls worsened their performance to the 48th and the 40th centile respectively (Fig. 14C and Fig. 14D). In addition, MD, which is closely related to fine motor and which, it has been frequently stated, is generally superior in girls compared to boys, seemed not to be different with regards to sex at the end of preschool age (Fig. 14D). Very similar changes are also visible in BAL, which negatively and rapidly changed between the age of 4 and 5 in girls (Fig. 14B and Fig. 14C). The last sub-concept, AC, could be also divided into two periods. At the age of 3-

4, girls performed better in AC even though the difference was not significant. However, at the age of 5, the position between boys and girls in AC clearly changed. Boys start to outperform girls in AC and this outperformance was at its maximum in the last age category of 6-year-old children when boys achieved significantly better results in AC compared to girls (Fig. 14C and Fig. 14D).

Summary:

It was shown that FMS development probably does not occur in preschool age boys and girls in parallel way. Our results from each age category matched with conclusions of previous studies to the effect that girls aged 3–5 outperform boys in MD (Sigmundsson & Rostoft, 2003; Livesey, Coleman, & Piek, 2007; Kourtessis et al., 2008) and TTS and BAL; (Sigmundsson & Rostoft, 2003; Livesey et al., 2007). In addition, our finding that boys are significantly better at AC at the end of preschool age (6-year-old boys) was also in line with results of Vandaele, Cools, de Decker and de Martelaer (2011) or Spessato et al. (2013). However, it must be said that in our study differences in AC skills did not occur between sexes in 3-, 4-, or 5-year-olds. Based on these findings, we support the suggestions that preschool boys and girls should not be compared to each other, but should be compared only to children of the same age and sex. In relation to the used instrument it has been previously suggested that unisex norms in the MABC-2 should be separated for boys and girls Livesey et al. (2007). To support this idea, it is plausible that differences in FMS proficiency between sexes exist during early childhood and can be credited to a complex interaction of environmental, socio-cultural and biological factors (Thomas & French, 1985; Cools, De Martelaer, Samaey & Andries, 2009). Specifically, it has been indicated that motor development during infancy is different, with a note that in some areas of motor development girls are faster/more advanced compared to boys (Hutt, 1972). This suggestion concerned the different tempo in motor development, which has been related to different maturation of the brain structure between sexes during infancy, childhood and adolescence age (De Bellis et al., 2001; Piek, Gasson, Barrett & Case, 2002). In particular, the study of De Bellis et al. (2001) found, on a sample of boys and girls in the age range 6-17 years, an age-related decrease of gray matter volume in boys along with an increase of white matter volume and corpus callosum area compared to girls. Here, it is also quite important to remind that research conducted in the 1990s proved that cerebral gray matter volumes decrease progressively after age 4 (Jernigan & Tallal, 1990; Pfefferbaum et al., 1994), which could be seen in our study as a break point for significant changes in the FMS profile regarding sex (Fig. 14, A-D). Studies focused on changes in white matter volume in relation to motor skills showed that increasing volume of white matter in primary motor cortex was significantly related to improving of motor skills in children (Barnea-Goraly et al., 2005; Mostofsky, Burgess & Gidley Larson, 2007). On the other hand, reduced volume of white matter or smaller development of white matter is related to neurodevelopmental problems (Dyet et al., 2006), including motor difficulties manifestation (Bos, Van Braeckel, Hitzert, Tanis & Roze, 2013). Differences in the degree of FMS during preschool period between boys and girls could be also explained from neurology perspective. In preschool age children, an increase in white matter volume has been observed, which has been linked to the improvement of motor skills. Further, this increase which is more evident after fourth year is greater in motor cortex areas in boys compared to girls. Nevertheless, we must not forget another aspect, namely that changes in the CNS system usually occur as a result of interaction with the environment (Malina, 2004).

According to Malina (2004), the sex differences in FMS might be explained by social and cultural diversity and appropriateness of motor skills that involve these motor patterns (Malina, 2004). Interaction of socio-environmental factor along with biology maturation involving maturation of CNS was partially presented by Seefeldt and Haubenstricker (1982), who developed 5 stages from immature to fully mature performance in specific eight motor skills (jump, hop, catch, strike, kick, run, skip, overhead throw). During early childhood period till the age of seven boys dominated in overhead throw and kick. It was also found that the range of differences between boys and girls is age-related in these tests. On the other hand, girls were better at catching and hoping. Nevertheless, only better results in catching showed to be age-related.

Aforementioned information about the specifics of brain maturation and changes and its interaction with environmental factors could suggest that 3- to 4-year-old boys may need more time to develop fine motor skills and should not be compared to girls of the same age, which is supported by the seemingly sub-par performance of younger boys in nearly all FMS skills. As the present study utilized a cross-sectional design, meaning that age groups could not be compared to each other and patterns of FMS development could not be determined from the data, a longitudinal follow-up of children may allow for more accurate explanation as to why boys begin to outperform

girls in object control skills as they get older. Lastly, the data presented should not be viewed as novel normative values, but instead they indicate that preschool children of all ages and both sexes should not be compared to one another in the Czech Republic.
For more details see Kokštejn et al. (2017).

References:

Barnea-Goraly, N., Menon, V., Eckert, M., Tamm, L., Bammer, R., Karchemskiy, A., ... & Reiss, A. L. (2005). White matter development during childhood and adolescence: a cross-sectional diffusion tensor imaging study. *Cerebral cortex*, *15*(12), 1848-1854.

Behling, O., & Law, K. S. (2000). *Translating questionnaires and other research instruments: Problems and solutions* (Vol. 133). Sage.

Bos, A. F., Van Braeckel, K. N., Hitzert, M. M., Tanis, J. C., & Roze, E. (2013). Development of fine motor skills in preterm infants. *Developmental Medicine & Child Neurology*, *55*, 1-4.

Butterfield, S. A., & Loovis, E. M. (1993). Influence of age, sex, balance, and sport participation on development of throwing by children in grades K-8. *Perceptual and motor skills*, *76*(2), 459-464.

Cools, W., De Martelaer, K., Samaey, C., & Andries, C. (2009). Movement skill assessment of typically developing preschool children: A review of seven movement skill assessment tools. *Journal of sports science & medicine*, *8*(2), 154-168.

De Bellis, M. D., Keshavan, M. S., Beers, S. R., Hall, J., Frustaci, K., Masalehdan, A., ... & Boring, A. M. (2001). Sex differences in brain maturation during childhood and adolescence. *Cerebral cortex*, *11*(6), 552-557.

Foulkes, J. D., Knowles, Z., Fairclough, S. J., Stratton, G., O'dwyer, M., Ridgers, N. D., & Foweather, L. (2015). Fundamental movement skills of preschool children in Northwest England. *Perceptual and motor skills*, *121*(1), 260-283.

Garcia, C. (1994). Gender differences in young children's interactions when learning fundamental motor skills. *Research Quarterly for Exercise and Sport*, *65*(3), 213-225.

Govatos, L. A. (1959). Relationships and age differences in growth measures and motor skills. *Child development*, 333-340.

Hutt, C. (1972). Sex differences in human development. *Human Development*, *15*(3), 153-170.

Jernigan, T. L., & Tallal, P. (1990). Late childhood changes in brain morphology observable with MRI. *Developmental Medicine & Child Neurology*, *32*(5), 379-385.

Junaid, K. A., & Fellowes, S. (2006). Gender differences in the attainment of motor skills on the movement assessment battery for children. *Physical & Occupational Therapy in Pediatrics*, *26*(1-2), 5-11.

Kokštejn, J., Musálek, M., & Tufano, J. J. (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

Kourtessis, T., Tsougou, E., Maheridou, M., Tsigilis, N., Psalti, M., & Kioumourtzoglou, E. (2008). Developmental coordination disorder in early childhood: A preliminary epidemiological study in Greek schools. *The International Journal of Medicine*, *1*(2), 95-99.

LeGear, M., Greyling, L., Sloan, E., Bell, R. I., Williams, B. L., Naylor, P. J., & Temple, V. A. (2012). A window of opportunity? Motor skills and perceptions of competence of children in kindergarten. *International Journal of Behavioral Nutrition and Physical Activity*, *9*(1), 29.

Livesey, D., Coleman, R., & Piek, J. (2007). Performance on the Movement Assessment Battery for Children by Australian 3-to 5-year-old children. *Child: care, health and development*, *33*(6), 713-719.

Loovis, E. M., & Butterfield, S. A. (1993). Influence of age, sex, balance, and sport participation on development of catching by children grades K-8. *Perceptual and motor skills*, *77*(3_suppl), 1267-1273.

Malina, R. M. (2004). Motor development during infancy and early childhood: Overview and suggested directions for research. *International journal of sport and health science*, *2*, 50-66.

Morris, A. M., Williams, J. M., Atwater, A. E., & Wilmore, J. H. (1982). Age and sex differences in motor performance of 3 through 6 year old children. *Research Quarterly for Exercise and Sport*, *53*(3), 214-221.

Mostofsky, S. H., Burgess, M. P., & Gidley Larson, J. C. (2007). Increased motor cortex white matter volume predicts motor impairment in autism. *Brain*, *130*(8), 2117-2122.

Olesen, L. G., Kristensen, P. L., Ried-Larsen, M., Grøntved, A., & Froberg, K. (2014). Physical activity and motor skills in children attending 43 preschools: a cross-sectional study. *BMC Pediatrics*, *14*(1), 229.

Pfefferbaum, A., Mathalon, D. H., Sullivan, E. V., Rawles, J. M., Zipursky, R. B., & Lim, K. O. (1994). A quantitative magnetic resonance imaging study of changes in brain morphology from infancy to late adulthood. *Archives of neurology*, *51*(9), 874-887.

Piek, J. P., Gasson, N., Barrett, N., & Case, I. (2002). Limb and gender differences in the development of coordination in early infancy. *Human movement science*, *21*(5-6), 621-639.

Psotta, R. (2014). MABC-2: Test motoriky pro děti (1. českévydání)[The Movement Assessment Battery for Children-2 Test (1st Czech edition)]. *Praha, Czech Republic: Hogrefe-Testcentrum*.

Raudsepp, L., & Pääsuke, M. (1995). Gender differences in fundamental movement patterns, motor performances, and strength measurements of prepubertal children. *Pediatric Exercise Science*, *7*(3), 294-304.

Seefeldt, V., & Haubenstricker, J. (1982). Patterns, phase, or stages: An analytical model for the study of developmental movement. In J. A. S. Kelso, & J. E. Clark (Eds.), The development of movement control and coordination (pp. 309-318). New York, NY: John Wiley & Sons, Ltd.

Shala, M. (2009). Assessing gross motor skills of Kosovar preschool children. *Early Child Development and Care*, *179*(7), 969-976.

Schneck, C. M., & Henderson, A. (1990). Descriptive analysis of the developmental progression of grip position for pencil and crayon control in nondysfunctional children. *American Journal of Occupational Therapy*, *44*(10), 893-900.

Sigmundsson, H., & Rostoft, M. S. (2003). Motor development: Exploring the motor competence of 4-year-old Norwegian children. *Scandinavian Journal of Educational Research*, *47*(4), 451-459.

Spessato, B. C., Gabbard, C., Valentini, N., & Rudisill, M. (2013). Gender differences in Brazilian children's fundamental movement skill performance. *Early Child Development and Care*, *183*(7), 916-923.

Van Waelvelde, H., Peersman, W., Lenoir, M., Engelsman, B. C. S., & Henderson, S. E. (2008). The movement assessment battery for children: similarities and differences between 4-and 5-year-old children from Flanders and the United States. *Pediatric Physical Therapy*, *20*(1), 30-38.

Vandaele, B., Cools, W., de Decker, S., & de Martelaer, K. (2011). Mastery of fundamental movement skills among 6-year-old Flemish pre-school children. *European Physical Education Review*, *17*(1), 3-17.

Venetsanou, F., & Kambas, A. (2011). The effects of age and gender on balance skills in preschool children. *Facta universitatis-series: Physical Education and Sport*, *9*(1), 81-90.

PLOS ONE

RESEARCH ARTICLE

Are sex differences in fundamental motor skills uniform throughout the entire preschool period?

Jakub Kokštejn[©], **Martin Musálek**[©], **James J. Tufano***[©]

Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

© These authors contributed equally to this work.
* james.j.tufano@gmail.com

Check for updates

OPEN ACCESS

Citation: Kokštejn J, Musálek M, Tufano JJ (2017) Are sex differences in fundamental motor skills uniform throughout the entire preschool period? PLoS ONE 12(4): e0176556. https://doi.org/10.1371/journal.pone.0176556

Editor: Christos Papadelis, Boston Children's Hospital / Harvard Medical School, UNITED STATES

Received: December 16, 2016

Accepted: April 12, 2017

Published: April 27, 2017

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The study was supported by the Czech Science Foundation project no. 14-29358P and program Progress Q19 Social-Sciences Aspects Of Human Movement Studies II. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

The aim of this study was to assess differences in fundamental motor skills (FMS) proficiency between boys and girls of each age group, independently, across the entire preschool period. Using the Movement Assessment Battery for Children–second edition, FMS proficiency was tested in 325 preschoolers (4.9 ± 1.1 y, range 3–6) using a cross-sectional design. Compared to boys of the same age, 3- and 4-year-old girls had greater total ($p < .01$), fine motor skill ($p < .01$), and balance scores ($p < .05$). There were no sex differences for total test or balance scores in 5- and 6-year-olds, but 6-year-old boys outperformed girls in aiming and catching ($p < .001$). These data not only agree with previous research in that sex differences in FMS proficiency exist in preschool children, but the data also show that differences may not be uniform throughout the whole preschool period when analyzing by age. To avoid under- or overestimating FMS proficiency and subsequently prescribing inaccurate motor intervention programs, FMS proficiency normative values should be age- and sex-specific throughout the entire preschool period.

Introduction

During early childhood, children begin to learn and acquire many fundamental motor skills (FMS), which are commonly grouped into the functional skill categories of locomotor (e.g. running, hopping), balance (e.g. twisting, standing on one leg), and manipulative skills [1, 2]. Manipulative FMS are further divided into: 1) object control skills (e.g. catching, throwing, kicking) and 2) fine motor skills (e.g. sewing, cutting, and self-helping) that involve intricate use of the hand and wrist muscles [2].

Adequate acquisition and command of FMS at the end of early childhood (around the age of six) have been considered as crucial elements in the development of specialized and more complex motor skills in later years [1, 2, 3]. These are particularly important for children, not only for mastering habitual daily activities, but also for successful participation in both organized and non-organized sports and recreational activities [3].

Previous studies have shown that higher levels of FMS proficiency correlate with more physical activity [4–7] and greater physical fitness performance in preschool and school-aged

Competing interests: The authors have declared that no competing interests exist.

children [8–10]. At the opposite end of the spectrum, poor FMS proficiency has been linked to delayed participation in physical activity, thus resulting in suboptimal levels of physical activity and fitness [10, 11]. Therefore, it is important to properly identify children who display FMS deficiencies in order to prescribe appropriate motor skill interventions to increase the likelihood of physical activity during adolescence.

Currently, FMS normative values include both sexes across four age categories for 3- and 4-year-olds (four six-month categories) as well as individual categories for 5- and 6-year-olds independently [12, 13]. Although a lack of sex-defining phenotypic gender characteristics often allow preschoolers of both sexes to be combined when describing physical development during early childhood, sex has been shown to play a role in acquiring and mastering FMS [14–17], sometimes as early as about three years of age [14].

Although preschool boys and girls generally do not differ in terms of total FMS test scores [18–20], object control skills have been shown to be similar between sexes [19, 20, 21], but have also been shown to be better in boys [16, 18, 22–25]. Locomotor skills have been shown to be similar between sexes [16, 19, 20, 22], better in girls [6, 18, 26], and better in boys [23]. Balance skills have shown to be similar between sexes [20, 27, 28] and better in girls [25, 29, 30]. Similarly, fine motor skills have been shown to be similar between sexes [20] and better in girls [17, 25, 29, 31]. Although the research process aims to reveal patterns that are repeatedly observed within a population in order to provide conclusive statements about a topic, the inconsistencies of the aforementioned body of literature do not allow for conclusive statements regarding FMS in preschool children.

Such discrepancies within the data can most likely be explained by a number of possibilities including: 1) studies not including children from the entire preschool period (3–6 years old); 2) studies often combining children of both sexes together; or 3) researchers creating two age group categories by combining 3- and 4-year-olds and 5- and 6-year-olds together. In fact, to the authors' knowledge, boys and girls have not been compared against each other according to individual age groups since 1982 [32] where sex differences were present for locomotor and balance skills, but object control and fine motor skills were not investigated. Therefore, a detailed and up-to-date analysis of sex-specific FMS proficiency is needed in order to optimally develop FMS in modern day preschoolers.

To address this issue, the aim of this study was to compare FMS scores of preschool boys and girls for each age group across the entire preschool period. Based on the incongruous findings of the research discussed above, it was hypothesized that sex differences would occur in different types of FMS (manipulative, locomotor, and balance), but would not be uniform between boys and girls in each age group across the entire preschool period.

Materials and methods

Participants

Preschool children (n = 325: 162 boys and 163 girls; see Table 1) aged 3 to 6 years (4.9 ± 1.1 yrs) from seven randomly chosen preschools in two regions (Prague and central Bohemia) of the Czech Republic participated in the study. In cooperation with the management of the preschools, parents were informed of the purpose, procedures, and benefits of the study. The study was approved by the Ethics Committee of the Faculty of Physical Education and Sport at Charles University, Prague, and informed consent was required from the children's parents or legal guardians. Children who had been diagnosed with mental or other clinically diagnosed impairments (such as ADHD, DCD, developmental dysphasia, etc.) and children from special needs classes were not included in the study.

Table 1. Numerical data of participants (N = 325).

Age		Boys	Girls
3 years	N	32	33
	Age (M±SD)	3.4±0.3	3.4±0.3
4 years	N	48	48
	Age (M±SD)	4.4±0.3	4.4±0.3
5 years	N	44	46
	Age (M±SD)	5.4±0.3	5.3±0.3
6 years	N	38	36
	Age (M±SD)	6.3±0.3	6.4±0.3

https://doi.org/10.1371/journal.pone.0176556.t001

Measures and procedures

The MABC-2 test AB1 (Movement Assessment Battery for Children-2 test Age Band 1) [12, 13] for preschool children assessed the level of FMS proficiency. The test contains eight test items which assess FMS proficiency in three basic motor domains: manual dexterity (MD), aiming and catching (AC), and balance (BAL) (Table 2).

A team of 4–6 trained research assistants (with Master's degrees in Physical Education and Sport, Adapted Physical Education, Physiotherapy) tested children using the MABC-2 test AB 1. Before official testing and under the supervision of three MABC-2 certified testers, all examiners completed the user's training program, which focused on understanding the theoretical issues and practical administration and scoring of the test. Research assistants performed the same tests for all children, meaning that there were no inter-rater testing procedures. Therefore, all children were scored by the same tester using the same guidelines.

Briefly, all testing occurred in a quiet kindergarten classroom during morning class time, and children were tested in small groups (2–3 children per group). The order of all eight tests was randomized and were performed on the same day. Children were familiarized with each test and performed two practice attempts for each. Then, children completed a single formal attempt, and the score of that attempt was used for data analysis.

The four motor tasks have different conditions between the younger (3- and 4-year old) and older (5- and 6-year old) children. For example, younger children must post six coins and thread six beads whereas older children must complete 12 of each. Younger children can use the entire body when catching a beanbag, but the older children must only use their hands. Lastly, young children can pause while jumping on mats, but older children are instructed to jump consecutively without pausing.

Table 2. MABC-2 test for preschool children (version AB1).

MABC-2 test components	Task	Test Criterion
Manual dexterity (fine motor skills)	Posting Coins	Number of seconds
	Threading Beads	Number of seconds
	Drawing Trail	Number of errors
Aiming and Catching (gross motor skills)	Catching Beanbag	Number of correctly executed catches
	Throwing a Beanbag onto a Mat	Number of successful hits
Balance	One-Leg Balance	Number of seconds
	Walking Heels Raised	Number of correct consecutive steps
	Jumping on Mats	Number of correct consecutive jumps

https://doi.org/10.1371/journal.pone.0176556.t002

Data analysis

Since raw scores from the MABC-2 test cannot and should not be compared between younger and older children due to the differences in testing protocols mentioned above, raw scores from each of the eight tests were converted to standard scores and percentiles in accordance with age-specific normative values for the Czech population [13]. The MABC manual allocates normative values for 5- and 6-year olds independently, while norms for 3- and 4-year olds are divided into two groups per age using 6-month categories, yielding four groups total (3 y 0 months to 3 y 6 months; 3 y 6 months to 4 y 0 months, etc.). For simplicity and clarity, these half-year categories were combined into a single score for each age, like the 5- and 6-year olds. The overall level of FMS was calculated by totaling the standard scores in the individual tests, and stated as the total test score (TTS) using percentile scores [13]. Scores for MD, AC and BAL were calculated in the same way. All data can be found in the S1 Dataset supplement file.

Percentile scores were used to interpret sex differences in TTS, MD, AC, and BAL for each age group (three to six years). Data normality was rejected, so the Mann-Whitney U test ($p < .05$) was used to determine statistical significance and the r coefficient was used to interpret effect size (ES), which can be interpreted as: $r < 0.3$ = small effect, r 0.3–0.5 = medium effect, and $r > 0.5$ = large effect [33]. Statistical analyses were conducted using the IBM SPSS Statistics 22 program.

Results

The sex differences between preschool boys and girls for TTS, MD, AC, and BAL are shown in Figs 1–5. When collapsed across age, girls had greater TTS (U = 10357.5 $p < .01$), MD (U = 9940 $p < .01$), and BAL (U = 23657 $p < .01$) scores compared to boys, but there were no differences in AC (Fig 1). At the age of 3, girls had greater TTS (U = 297.0 $p < .01$ ES = .38), MD (U = 306 $p < .01$; ES = .36), and BAL (U = 340.5 $p < .05$; ES = .31) scores than boys, but there were no differences in AC (Fig 2). At the age of 4, girls also scored higher than in TTS (U = 711.0 $p < .01$; ES = .33), MD (U = 738.0 $p < .01$; $r = .31$) and BAL (U = 861.5 $p < .05$), with no

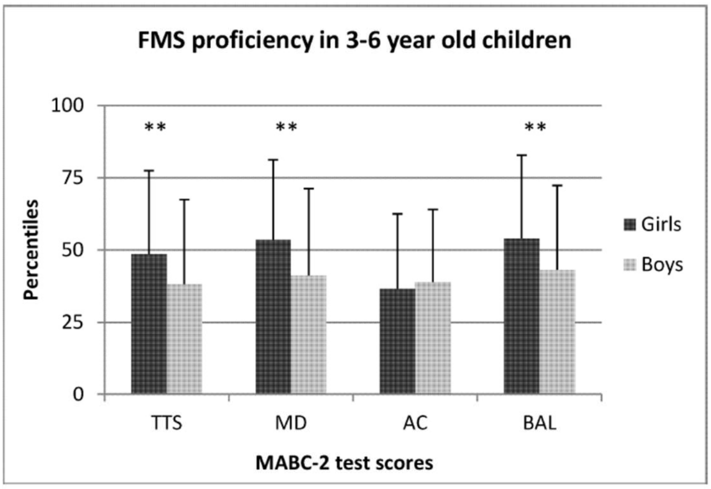


Fig 1. FMS proficiency in 3- to 6-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; ** p < .01.

https://doi.org/10.1371/journal.pone.0176556.g001

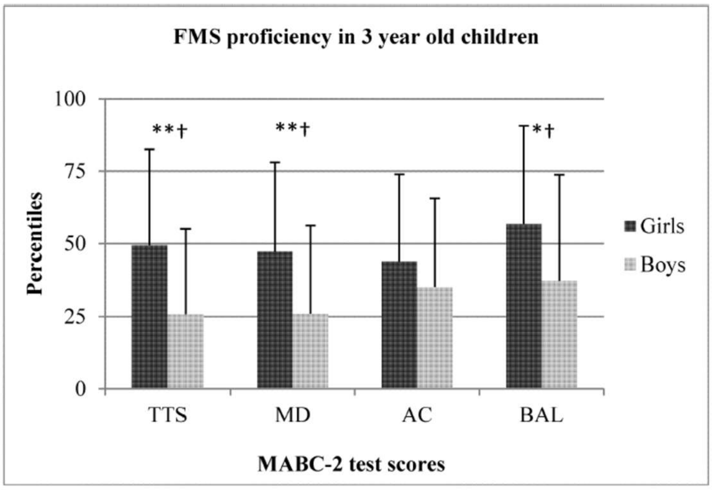


Fig 2. FMS proficiency in 3-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; ** p < .01; † medium effect size.

https://doi.org/10.1371/journal.pone.0176556.g002

differences in AC (Fig 3). At the age of 5, there were no differences between sexes for any test (Fig 4). At the age of 6, there was also no difference in TTS, MD, and BAL between girls and boys, however, boys performed significantly better in the AC subtest of MABC-2 test (U = 306.5 $p < .01$; $r = 0.48$) (Fig 5). Small ES were not reported.

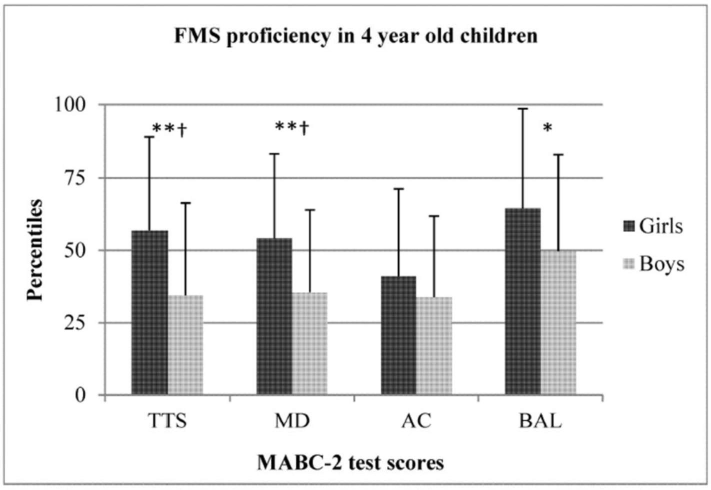


Fig 3. FMS proficiency in 4-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; ** p < .01; † medium effect size.

https://doi.org/10.1371/journal.pone.0176556.g003

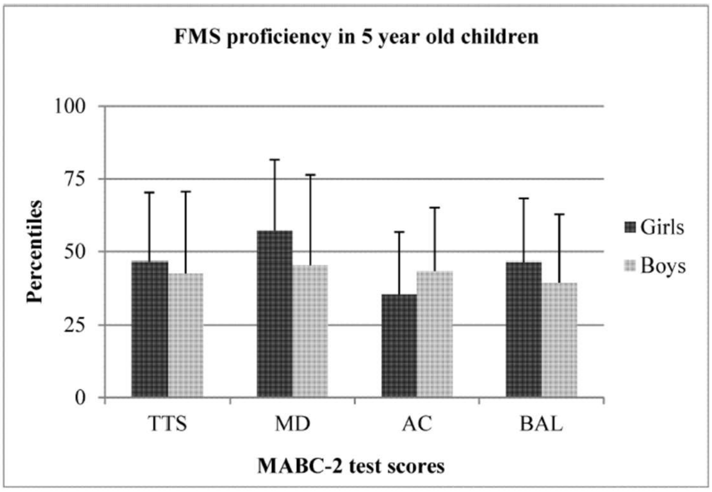


Fig 4. FMS proficiency in 5-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance.

https://doi.org/10.1371/journal.pone.0176556.g004

Discussion

Generally, the results of previous studies do not allow practitioners to identify sex differences in FMS proficiency throughout the whole preschool period because studies either did not account for age [16, 19, 23, 24, 27], did not collect data on all age groups within the preschool

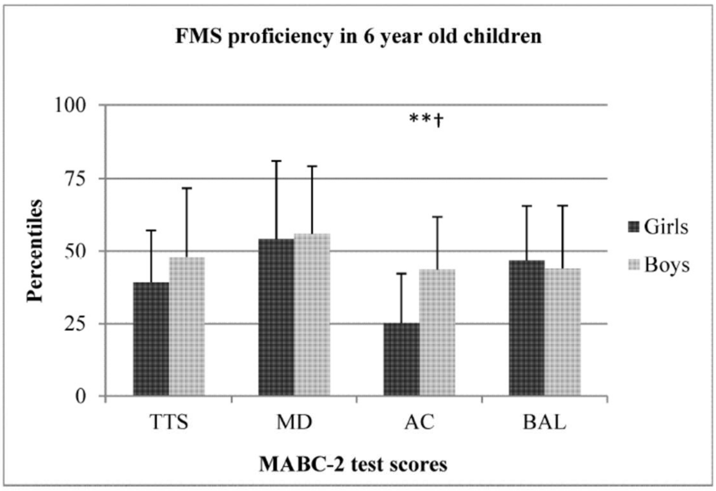


Fig 5. FMS proficiency in 6-year old children. Note: FMS = fundamental motor skills; MABC-2 = movement assessment battery for children-2; TTS = total test score; MD = manual dexterity; AC = aiming and catching; BAL = balance; *** p < .001; † medium effect size.

https://doi.org/10.1371/journal.pone.0176556.g005

period [4, 17, 18, 20, 21, 25, 27, 29–31, 34] or combined age groups together by comparing younger (3- and 4-year olds) and older (5- and 6-year olds) children [17, 22]. Therefore, an under- or overestimation of FMS competency in preschool children may be possible, resulting in inappropriate motor intervention programs. No study since 1982 [32] has investigated differences in FMS proficiency across the entire preschool period while also accounting for sex. To shed light on the FMS proficiency of modern-day children, the main aim of this study was to assess sex differences in FMS proficiency between boys and girls of all preschool ages. As hypothesized, there were significant sex differences in FMS proficiency in different motor domains, but the differences were not uniform throughout the entire preschool period when analyzed by age.

In the present study, younger girls (3–4 years old) outperformed boys in TTS, MD, and BAL, but no differences in AC were observed. In older children (5–6 years old), there were no differences in TTS, MD, and BAL, but 6-year old boys outperformed girls in AC. These data show that girls generally have better FMS scores than boys at a younger age and that these differences disappear toward the end of the preschool period. Perhaps more importantly, the average TTS and MD scores of 3-year old boys and AC score of 6-year old girls placed them all around the 25th percentile in their respective age groups [13]. Although speculative, it is unlikely that entire groups of children from preschools across an entire region performed worse than 75% of their peers. Rather, these data may suggest that there are maturational differences between sexes in preschoolers and that preschool boys and girls should not be compared to each other, but should be compared only to children of the same age and sex.

Previous studies using preschoolers of different cultural backgrounds have also noted that girls generally perform better than boys in TTS, MD, and BAL [25, 29, 34]. These results are in line with the results of Sigmundsson & Rostoff [29], who showed that 4-year old girls outperformed boys on TTS, MD, and BAL skills. However, their research sample only included 4-year olds, meaning that information about FMS proficiency in other preschool age categories was missing. Including children of all ages but not accounting for age, Kourtessis et al. [34] noted that girls outperformed boys in MD, and when using the same strategy, we also observed that girls performed better during MD tests (Fig 1). However, when assessing children according to sex and age, we found that only younger girls (3- and 4-year olds) scored better on MD tests than younger boys, but no sex differences were present in 5 or 6 year olds (Figs 4 and 5). Also accounting for sex and age, Livesey et al. [25] also showed that girls scored better on MD and BAL skills in 3- to 5-year old preschool children in Australia, leading the authors to state that it may be wise to create sex- and age-specific normative values for the MABC test. Additionally, our results agreed with previous studies in that 6-year old boys performed better than girls on AC [22, 35], but differences in AC skills did not exist between sexes in 3-, 4-, or 5-year olds. Based on our results, we support the idea of Livesey et al. [25] of separated norms for boys and girls on MABC-2 test, especially for younger preschool age children (3- and 4-year old).

To support this idea, it is plausible that differences in FMS proficiency between sexes exist during early childhood and can be credited to a complex interaction of environmental, sociocultural, and biological factors [15, 36]. Specifically, it has been indicated that brain structure and development differs between sexes during infancy [37, 38], which may have residual effects during the toddler years, evidenced by enhanced development of the brain's left hemisphere, which is mainly related to enhanced language acquisition, fine motor skills, and social cognition in young preschool girls compared to boys [39]. Thus, different sex-specific rhythms in brain maturation could suggest that 3- to 4-year old boys may need more time to develop fine motor skills and should not be compared to girls of the same age, supported by the seemingly sub-par performance of younger boys in nearly all FMS skills (Figs 2 and 3).

It is difficult to determine why 6-year old boys performed better than girls at throwing and catching in the present study. It has been hypothesized [15, 40–42] that environmental and socio-cultural factors may partly explain why preschool boys generally outperform girls at object control skills, as girls spend more time in language, literacy, art, and fine motor activities and boys in a number of different ball games and gross motor activities [40]. However, Thomas and French [15] had difficulty confirming this hypothesis after observing that boys were better at throwing in children as young as 3 years old, before environmental and socio-cultural factors could play a large role. Later, Nelson et al. [42] found sex differences in qualitative aspects in throwing skills of 5- to 9-year old children, and attributed the lower mastery of girls in that skill to a lack of practice and encouragement for girls in object control skills. As the present study utilized a cross-sectional design, meaning that age groups could not be compared to each other and patterns of FMS development could not be determined from the data, a longitudinal follow-up of children may allow for more accurate explanation as to why boys begin to outperform girls at object control skills as they get older. Lastly, the data presented should not be viewed as novel normative values, but instead indicate that preschool children of all ages and both sexes should not be compared to one another in the Czech Republic. Future researchers should determine if the same holds true in larger sample sizes across multiple countries.

Although MABC-2 norms exist, they are age-group specific and do not allow for the comparison of FMS between age groups. The data from this study provide evidence that FMS proficiency differs between sexes in preschool children, but that these differences are not uniform through a whole age categories when analyzing by year of age. Therefore, in order to successfully identify children whom lack FMS proficiency, sex- and age-specific normative values for each FMS test should be created to allow for more appropriate, multifaceted, and individualized motor intervention programs for developing FMS proficiency in preschoolers.

Supporting information

S1 Dataset.
(XLSX)

Acknowledgments

The study was supported by the Czech Science Foundation project No. 14-29358P and program Progress Q19 Social-Sciences Aspects Of Human Movement Studies II.

Author Contributions

Conceptualization: JK MM JJT.

Data curation: JK.

Formal analysis: JK MM JJT.

Funding acquisition: JK MM JJT.

Investigation: JK.

Methodology: JK MM.

Project administration: JK MM.

Resources: JK.

Software: JK.

Supervision: JK MM JJT.

Validation: JK MM JJT.

Visualization: JK MM JJT.

Writing – original draft: JK MM JJT.

Writing – review & editing: JK MM JJT.

References

1. Stodden D, Goodway J, Langendorfer S, Roberton M, Rudisill M, Garcia C et al. A developmental perspective on the role of motor skill competence in physical activity: an emergent relationship. Quest. 2008; 60(2):290–306.
2. Gallahue DL, Ozmun JC. Goodway JD. Understanding motor development: Infants, children, adolescents, adults. 7th ed. New York: McGraw-Hil; 2011.
3. Clark JE., Metcalfe JS. The mountain of motor development: A metaphor. In: Clark JE, Humphrey JH, editors. Motor development: Research and reviews. Reston: NASPE. p. 163–190.
4. Lubans D, Morgan P, Cliff D, Barnett L, Okely A. Fundamental movement skills in children and adolescents. Sports Med. 2010; 40(12):1019–1035. https://doi.org/10.2165/11536850-000000000-00000 PMID: 21058749
5. Okely A, Booth M, Patterson J. Relationship of physical activity to fundamental movement skills among adolescents. Med Sci Sports Exerc. 2001; 33(11):1899–1904. PMID: 11689741
6. Barnett L, Morgan P, van Beurden E, Beard J. Perceived sports competence mediates the relationship between childhood motor skill proficiency and adolescent physical activity and fitness: a longitudinal assessment. Int J Behav Nutr Phys Act. 2008; 5(1):40.
7. Barnett L, van Beurden E, Morgan P, Brooks L, Beard J. Childhood Motor Skill Proficiency as a Predictor of Adolescent Physical Activity. J Adolesc Health. 2009; 44(3):252–259. https://doi.org/10.1016/j.jadohealth.2008.07.004 PMID: 19237111
8. Okely A, Booth M, Chey T. Relationships between Body Composition and Fundamental Movement Skills among Children and Adolescents. Res Q Exerc Sport. 2004; 75(3):238–247. https://doi.org/10.1080/02701367.2004.10609157 PMID: 15487288
9. Reeves L. Relationship of fitness and gross motor skills for five- to six-yr.-old children. Percept Mot Skills. 1999; 89(7):739.
10. Haga M. Physical fitness in children with high motor competence is different from that in children with low motor competence. Phys Ther. 2009; 89(10):1089–1097. https://doi.org/10.2522/ptj.20090052 PMID: 19679648
11. Allender S, Cowburn G, Foster C. Understanding participation in sport and physical activity among children and adults: a review of qualitative studies. Health Educ Res. 2006; 21(6):826–835. https://doi.org/10.1093/her/cyl063 PMID: 16857780
12. Henderson SE, Sugden DA, Barnett AL. Movement Assessment Battery for Children-2 (MABC-2): Examiner's manual. London: Pearson Assessment; 2007.
13. Psotta R. MABC-2: Test motoriky pro děti (1. české vydání) [The Movement Assessment Battery for Children-2 test (1st Czech edition)]. Praha, Czech Republic: Hogrefe-Testcentrum; 2014.
14. Malina R. Motor development during infancy and early childhood: overview and suggested directions for research. Int J Sport and Health Sci. 2004; 2:50–66.
15. Thomas J, French K. Gender differences across age in motor performance: a meta-analysis. Psychol Bull. 1985; 98(2):260–282. PMID: 3901062
16. Foulkes J, Knowles Z, Fairclough S, Stratton G, O'dwyer M, Ridgers N, et al. Fundamental movement skills of preschool children in northwest england. Percept Mot Skills. 2015; 121(1):260–283. https://doi.org/10.2466/10.25.PMS.121c14x0 PMID: 26270852
17. Flatters I, Hill L, Williams J, Barber S, Mon-Williams M. Manual control age and sex differences in 4 to 11 year old children. Plos One. 2014; 9(2):e88692. https://doi.org/10.1371/journal.pone.0088692 PMID: 24523931
18. Hardy L, King L, Farrell L, Macniven R, Howlett S. Fundamental movement skills among Australian preschool children. J Sci Med Sport. 2010; 13(5):503–508. https://doi.org/10.1016/j.jsams.2009.05.010 PMID: 19850520

19. LeGear M, Greyling L, Sloan E, Bell R, Williams B, Naylor P, et al. A window of opportunity? Motor skills and perceptions of competence of children in Kindergarten. Int J Behav Nutr Phys Act. 2012; 9(1):29.
20. Van Waelvelde H, Peersman W, Lenoir M, Smits Engelsman B, Henderson S. The Movement Assessment Battery for Children: similarities and differences between 4- and 5-year-old children from Flanders and the United States. Pediatr Phys Ther. 2008; 20(1):30–38. https://doi.org/10.1097/PEP.0b013e31815ee2b2 PMID: 18300931
21. Pope M, Liu T, Getchell N. Object-control skills in Hispanic preschool children enrolled in head start. Percept Mot Skills. 2011; 112(1):193–200. https://doi.org/10.2466/10.11.17.24.PMS.112.1.193-200 PMID: 21466092
22. Spessato B, Gabbard C, Valentini N, Rudisill M. Gender differences in Brazilian children's fundamental movement skill performance. Early Child Dev Care. 2013; 183(7):916–923.
23. Robinson L. The relationship between perceived physical competence and fundamental motor skills in preschool children. Child Care Health Dev. 2010; 37(4):589–596. https://doi.org/10.1111/j.1365-2214.2010.01187.x PMID: 21143273
24. Goodway J. Gender differences in fundamental motor skill development in disadvantaged preschoolers from two geographical regions. Res Q Exerc Sport. 2010; 81(1).
25. Livesey D, Coleman R, Piek J. Performance on the Movement Assessment Battery for Children by Australian 3-to 5-year-old children. Child Care Health Dev. 2007; 33(6):713–719. https://doi.org/10.1111/j.1365-2214.2007.00733.x PMID: 17944780
26. van Beurden E, Zask A, Barnett L, Dietrich U. Fundamental movement skills—How do primary school children perform? The 'Move it Groove it' program in rural Australia. J Sci Med Sport. 2002; 5(3):244–252. PMID: 12413042
27. Singh DKA., Rahman NNAA, Rajikan R, Zainudin A, Nordin NAM, Karim ZA, Yee YH. Balance and motor skills among preschool children aged 3 to 4 years old. Malaysian Journal of Medicine and Health Sciences. 2015; 11(1):63–68.
28. Shala M. Assessing gross motor skills of Kosovar preschool children. Early Child Dev Care. 2009; 179 (7):969–976.
29. Sigmundsson H, Rostoft M. Motor development: exploring the motor competence of 4-year-old Norwegian children. Scand J Educ Res. 2003; 47(4):451–459.
30. Venetsanou F, Kambas A. The effects of age and gender on balance skills in preschool children. Physical Education and Sport. 2011; 9:81–90.
31. Vlachos F, Papadimitriou A, Bonoti F. An investigation of age and gender differences in preschool children's specific motor skills. European Psychomotricity Journal. 2014; 6(1):16–18.
32. Morris A, Williams J, Atwater A, Wilmore J. Age and sex differences in motor performance of 3 through 6 year old children. Res Q Exerc Sport. 1982; 53(3):214–221.
33. Field A. Discovering statistics using ibm spss statistics +spss version 22.0. 1st ed. London: Sage Publications; 2014.
34. Kourtessis T, Tsougou E, Maheridou M, Tsigilis N, Psalti M, Kioumourtzoglou E. Developmental coordination disorder in early childhood: a preliminary epidemiological study in Greek schools. The International Journal of Medicine. 2008; 2(1):95–99
35. Vandaele B, Cools W, de Decker S, de Martelaer K. Mastery of fundamental movement skills among 6-year-old Flemish pre-school children. Eur Phy Educ Rev. 2011; 17(1):3–17.
36. Cools W, De Martelaer K, Samaey C, Andries C. Movement skill assessment of typically developing preschool children: a review of seven movement skill assessment tools. J Sports Sci Med. 2009; 8 (2):154–168. PMID: 24149522
37. Alexander G, Wilcox T. Sex Differences in Early Infancy. Child Dev Perspect. 2012;(64):400–406.
38. Piek J, Gasson N, Barrett N, Case I. Limb and gender differences in the development of coordination in early infancy. Hum Mov Sci. 2002; 21(5–6):621–639. PMID: 12620715
39. Hanlon H, Thatcher R, Cline M. Gender differences in the development of EEG coherence in normal children. Dev Neuropsychol. 1999; 16(3):479–506.
40. Pate R. Physical activity among children attending preschools. Pediatrics. 2004; 114(5):1258–1263. https://doi.org/10.1542/peds.2003-1088-L PMID: 15520105
41. Barnett L, van Beurden E, Morgan P, Brooks L, Beard J. Gender differences in motor skill proficiency from childhood to adolescence: a longitudinal study. Res Q Exerc Sport. 2010; 81(2):162–170. https://doi.org/10.1080/02701367.2010.10599663 PMID: 20527301
42. Nelson K, Thomas J, Nelson J. Longitudinal change in throwing performance: gender differences. Res Q Exerc Sport. 1991; 62(1):105–108. https://doi.org/10.1080/02701367.1991.10607526 PMID: 2028085

7. RELATION BETWEEN AMOUNT OF BODY FAT AND FUNDAMENTAL MOTOR SKILLS IN PRESCHOOLERS

Since for several decades now societies around the world have been facing the problem called obesity, with different intensity in each country, it was just a matter of time when research studies would start to focus on the relation between FMS and obesity. In locomotion it was revealed that obese children displayed lower cadence along with longer cycle duration and lower relative velocity compared to normal-weight subjects (Hills & Parker, 1992). Till the beginning of the 21st century there was a certain inconsistency in results related to the association between body status, body composition or adipose profile and the degree of FMS. Ellery (1991) or Raudsepp and Jürimäe (1996) found only a weak relationship in preschool children and pre-pubertal boys between skinfold thickness and performance in FMS. Further, Graf et al. (2004)[1] or Williams et al. (2008) or Yang Lin and Tsai (2015) did not reveal any meaningful significant relations between BMI and the degree of FMS. Whereas, Malina et al. (1995); Burton and Miller (1998); McKenzie et al. (2002); Lopes Stodden and Rodrigues (2014) and others found a significant negative correlation between the degree of FMS and body status (BMI). When we look in more detail at research which revealed inverse relations between the degree of FMS and overweight and obesity, we will find that body weight or body status (defined for instance by BMI) does not affect the results of all sub-concepts (locomotion, object control, balance) of FMS. The majority of studies conducted on preschoolers and pre-pubescent children agree that locomotor and balance skills are significantly poorer in overweight and obese children compared to their non-obese peers (e.g., Okely, Booth & Chey, 2004; Southall, Okely & Steele, 2004; D'Hondt, Deforche, De Bourdeaudhuij & Lenoir, 2009; Cliff, Okely, Morgan, Jones, Steele & Baur, 2012; Roberts, Veneri, Decker & Gannotti, 2012). In addition, only some studies revealed that overweight and obese children also performed significantly worse in object control activities (e.g., Okely et al., 2004; D'Hondt et al., 2009; Vameghi, Shams & Dehkordi, 2013). The aforementioned studies that revealed

[1] Graf et al. (2004) stated that BMI and FMS are significantly negatively related based on correlation coefficient $r=-0.164$ ($p<0.01$). This study was conducted on a sample of $n=668$ participants. Even though this correlation is statistically significant from the effect size point, we believe it has no practical effect.

negative associations between body status and the degree of FMS worked with a sufficiently large research samples and FMS were assessed by widely used valid and reliable instruments (e.g., BOTMP; CHAMPS; MABC-2; OSU-SIGMA scale; TGMD-2). In addition to the conclusions about the existence of differences in the degree of FMS regarding body status with a negative effect for overweight and obese individuals, we see as very important the findings of D'Hondt et al. (2013). These authors longitudinally observed (in two years cycle) changes in gross motor skills in the population of overweight, obese and non-obese pre-pubescent (age 6-10 years) children. The results of this research proved that: 1) in the first measurement overweight and obese children had a lower degree of gross motor skills compared to non-obese peers; 2) the gap in gross motor skills between overweight, obese children and non-obese controls widened significantly after two years. These results suggest that gross motor skills as part of the FMS concept are not only generally delayed in overweight and obese children but that the development of gross motor skills seems to be decelerating in these children during the pre-pubescent age period.

To sum up, we have quite solid support for the negative implication of body weight or body status for certain aspects of FMS. However, almost all studies were focused on comparisons of non-obese and overweight and obese children. Even though previous research has verified that for motor performance it is also necessary to have a sufficiently developed lean mass component (Morris, Naughton, Gibbs, Carlson & Wark, 1997; Ortega, Ruiz, Castillo & Sjöström, 2008), much less attention has been paid to the question whether the status of underweight children could be also negatively related to performance in FMS. We found only one study Roberts et al. (2012), which included also underweight children. However, it was more focused on the implication of excessive weight on FMS. In this study, only 150 out of about 4,600 children were identified as underweight according to BMI cut offs. The results of this study (see Roberts et al., 2012, p. 356) clearly show that underweight children performed similarly to overweight and obese peers, whose performances, particularly in catching skills and balance, were worse compared to healthy weight counterparts. The hypothesis that also very skinny underweight children have lower level of certain motor competences was also supported by research of Khodaverdi, Bahram and Jafarabadi (2012). These authors focused on the relation between body status and the degree of motor ability. Results of their investigation showed that underweight children had significantly lower motor ability than their healthy-weight peers.

Due to the lack of information about whether underweight body status is inversely related to the degree of FMS, we formulated the following research questions:

1) Underweight children defined using BMI and the amount of subcutaneous fat will display a significantly lower degree of FMS compared to their healthy non-obese peers
2) Severe impairment of fundamental motor skills will be significantly more frequently identified in preschoolers aged 3-6 years with the amount of body fat higher than the 85th centile of norms.

Since to date the majority of studies carried out on preschool children have used only BMI as an indicator of overweight and obesity even though research has pointed out its limits (see Okorodudu et al., 2010; Sedlak et al., 2015), we decided to collect selected skinfold parameters for estimation of body fat in our preschool children.

Research sample:

Four randomly selected kindergartens (not private) from two specific districts of Prague, Czech Republic, were involved in the study. These kindergartens did not have any specialization (e.g., sport, language, art). The final research sample consisted of n=492 (females=241, males=251) preschoolers aged 3 to 6.9 years (x=4.75; ±1.21) whose parents signed a voluntary inform consent. The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University,

Procedure:

Anthropometry:

All anthropometric measurements were done according to the reference manual Lohman, Roche and Martorell (1988) using standardized equipment. We measured:

Weight: medical calibrated weight type TPLZ1T46CLNDBI300 was used to assess weight to the nearest 0.1 kg

Height: portable anthropometer P375. Measurements were taken to the nearest 0.1 cm

Skinfolds: triceps and subscapular skinfolds were measured by Harpenden type caliper (skinfolder) with accuracy of 0.2 mm

Percentage of body fat (%BF) was calculated according to equations Slaughter et al. (1988) using the data of skinfold measurements on triceps (SFT) and subscalpular (SFS).

Since we estimated the percentage of body fat in the somatic part, we finally decided to classify children in slightly different way than is usual (i.e., underweight, overweight etc.). We determined three categories with respect to the amount of body fat as follows: 1) underfat, 2) proportionate fat, 3) overfat

The final classification of individuals into categories was done according to norms of Schwandt, Eckerstein and Haas (2012), who used Slaughter equations approach.

1) underfat<15th centile

2) proportionate fat 16th–85th centile

3) overfat>86th centile

Fundamental motor skills:

Same as in the previous study we used the Movement Assessment Test Battery for Children-2 (MABC-2) (Henderson et al., 2007). In particular, we used the age band (AB1) variant intended for children aged 3-6 years. Since the number of children in each kindergarten would overwhelm one trained research team, which collected the data in the previous study, we had to train two additional teams. So, finally we had three independent research teams with 5 trained people within each team for collecting data. From the perspective of inter-rater reliability it was necessary to verify the data collection consistency between teams. Therefore, before own data collection we carried out pre-testing on a sample of 20 preschoolers who were not included in the results of this study. In each team the responsibility of each individual examiner for examining of a definite portion of items was defined. The inter-rater reliability (InRel) between teams and examiners respectively was InRel=0.91.

FMS degree cut offs:

A child whose performance in the MABC-2 was: 1) ≤15th centile was defined as having significant motor difficulties; 2) ≤5th centile was defined as having severe motor difficulties; 3) ≥16th centile was described as not having significant motor difficulties.

For more details concerning the methods, see full text Musálek et al. (2017) at the end of this chapter.

Results:

In order to have a clear idea about the measured sample of preschoolers from somatic perspective, we first compared weight, height and thickness of skinfolds of the participants with the latest national norms (Vignerová et al., 2006). While the values of weight and height were on the 49th and the 52nd centile of the national norms respectively, the thickness of two measured skinfolds (triceps and subscapula) was significantly higher than the average, in particular on the 75th centile of the national norm. However, this finding was not surprising and it corresponds with studies from many countries that reported an increased prevalence of overweight and obesity even in preschoolers in at least the last three decades (e.g., Kalies, Lenz, & Von Kries, 2002; Luo & Hu, 2002; Sedlak, Pařízková, Daniš, Dvořáková & Vignerová, 2015).

In our study, out of the whole sample of 496 children, 12 were identified as underfat, 306 had proportionate adiposity and 178 children were identified as overfat. The number of children in each of the defined categories indicates a highly unbalanced sample. Therefore, the interpretation of the results in the following parts, particularly with respect to underfat children, will be very careful.

Prevalence of risk of motor difficulties[2] and severe motor difficulties:

The first important finding was that overfat as well as underfat children displayed twice as much frequency of significant and severe motor difficulties compared to proportionate fat peers Chi-square=12.71, df=4, Effect size=0.16 (Fig. 15).

[2] Additionally, we decided to identify performance in MABC-2 ≤15th centile as being at risk of motor difficulties instead of being at risk of DCD. This decision was made based on the currently accepted nomenclature in the MABC-2 manual.

Table 2. Incidence of movement difficulties with regard to amount of adipose tissue

Proportion of children with and without motor difficulties	Under fat<15th centile (n=12)	Proportionate fat 15th–85th centile (n=306)	Overfat>86th centile (n=178)
Proportion of participants in each category in %	2.5	61.7	35.8
Proportion of children in risk of DCD MABC-2≤15th centile	3 (25%)**	38 (12.4%)	38 (21.4%)**
Proportion of children with severe motor difficulties MABC-2≤5th centile	2 (16.7%)**	17 (5.55%)	26 (14.6%)**
Proportion of children without motor difficulties MABC-2≥16th centile	9 (75%)	268 (87.6%)	140 (78.6%)

Note: ** significantly higher frequency of severe motor difficulties and risk of DCS $p<0.05$; Effect size >0.14

Figure 15. Incidence of movement difficulties corrected to amount of adipose tissue
Adapted from Musálek, Kokštejn, Papež, Jírovec and Honsová. (2017). Relation Between Percent Body Fat and Fundamental Motor Skills in Preschool Children age 3-6 years. *Sport Mont*, *15*(2), 9-13.

Although we have to interpret this result carefully due to the very unbalanced sample, this finding led to the question whether the frequency of children on the opposite side of the performance spectrum, that is children with above average performance in the MABC-2, will also differ significantly between underfat, proportionate fat and overfat children. Above average performance in the MABC-2 was defined as being ≥90th centile.

Table 3. Difference in Total test score (TTS), total standard score (TSS) and proportion of high above centile score (PCT)≥90th centile

	Under fat<15th centile (n= 12)	Proportionate fat 15th–85th centile (n=306)	Overfat>86th centile (n=178)
Mean (SD) TTS	71.18 (16.7)	77.97 (10.02)	74.9 (12.5)*
Mean (SD) TSS	8.45 (3.2)	10.64 (8.4)	9.1 (3.29)*
PCT (proportion in %)≥90th centile	0 (0%)	32 (10.4%)	15 (8.4%)

Note: * significantly higher score $p<0.05$ however with unsufficient Effect size $r<0.30$

Figure 16. Difference in TTS, TSS and portion of high above centile score (PCT)≥90th from MABC-2
Adapted from Musálek et al. (2017). Relation Between Percent Body Fat and Fundamental Motor Skills in Preschool Children age 3-6 years. *Sport Mont*, *15*(2), 9-13.

Before comparing the frequencies of children with above average values achieved in the MABC-2, we shall give on a brief description of average results. It was revealed that underfat children achieved statistically the worst average results in the MABC-2. However, due to the very unbalanced number of participants in each category, this finding was not supported by Effect size. A further analysis of above average values led to surprising findings. Firstly, no underfat children achieved value ≥90th centile.

Moreover, frequencies of children with results ≥90th centile did not different between proportionate fat children and overfat children (Fig. 16).

Summary:

This study, oriented on the relation between FMS performance and body composition in preschoolers, revealed two main findings. Firstly, overfat as well as underfat children had a significantly higher prevalence of significant and severe motor difficulties compared to proportionate fat counterparts. If we took into consideration only the results of overfat children, our finding would only support previous conclusions that excessive body or obese status negatively influence performance in FMS (e.g., Okely et al., 2004; Cliff, et al., 2012; Sedlak et al., 2015; Vameghi et al., 2013; Roberts et al., 2012).

However, in addition, we found that the relation between adiposity and prevalence of motor difficulties might be seen from two different perspectives. It means that too much body fat, but also too little body fat, can negatively influence FMS performance. This assumption was further supported by the fact that underfat children also achieved the worst average results in the MABC-2. This finding could be indirectly in conformity with Roberts et al. (2012), where underweight, but not defined as underfat, children, also achieved worse results in FMS compared to normal weight peers. Although we knew about the prevalence of significant or sever motor difficulties as well as about average results of children in each defined category, we did not know yet whether the data distribution, particularly in case of underfat and overfat children, would differ. The assumption of different data distribution between underfat and overfat children was made based on the fact that although underfat children had the same prevalence of motor difficulties compared to overfat children, their average value from the MABC-2 was worse. Finally, we were not interested in the complete data distribution profile but we focused on the results ≥90th centile from the MABC-2, which are considered as above average. Results of frequency analysis showed that no underfat child was above average in the MABC-2. On the other hand, above average results were achieved by 8.4% of overfat and 10.4% of proportionate fat children. The main question remains as to why overfat children were able to achieve above average performance in the MABC-2 while underfat peers were not. Here, however, we once again need to emphasise that due to the very unbalanced sample this conclusion that too little fat could contribute to higher motor difficulties and lower probability to achieve above average performance in the MABC-2 still leaves many questions unanswered.

One possible suggestion to explain the differences in data distribution between overfat and underfat preschoolers could be that these two categories of children differ in their biological maturation. In preschool age, a well-known phenomenon called adiposity rebound appears, which refers to a moment when until then declining BMI starts to increase. Although it has not been confirmed that earlier adiposity rebound would be connected to advanced biology maturation in preschool age rather than in pre-pubescence and pubescent age (Rolland-Cachera et al., 1984; Williams & Dickson, 2002; Cameron, Pettifor, De Wet & Norris, 2003; Malina, 2014), some studies (e.g., Frisancho & Flegel, 1982) found that advanced biological maturation from early childhood could be linked to the amount of both centripetal adipose tissue and internal adipose tissue. Therefore, in future research it would be very interesting to verify whether the amount of centripetal adipose tissue is linked to biological maturation of even preschool age children which might bias the results of FMS batteries, which are scored according to chronological but not biological age.

We would also add some closing remarks regarding studies whose aim is to investigate the influence of body status on definite motor performance. We assume that the interpretation of body status (overweight and particularly obesity) just by BMI without any additional information about the adiposity profile can contribute to the inconsistency in results between studies mainly caused by low sensitivity of BMI – a fact that has been often criticised (e.g., Pařízková, 1977, 2008; Scheffler et al., 2007; Okorodudu et al., 2010; Morano, Colella & Caroli, 2011; Bogin & Varela-Silva, 2012). Further, we would also not recommend using only raw values of measured skinfolds for correlation or regression analysis like it was done in study Ellery (1991), in which the whole sample without any categorization was analysed. When we additionally correlated the total test score (TTS) MABC-2 with the sum of two measured skinfolds considering age and sex (unpublished additional results for this thesis), we received very low non-significant relation r=-0.12. Therefore, we would first suggest categorizing participants according to standard reference cut offs (e.g., underweight or underfat, normal weight or proportionate fat, overweight, obese or overfat) based on body composition approaches (skinfolds, pletysmographmy, DXA, etc.) where lean and fat mass can be distinguished. Then researchers can use the whole sample or divide the sample to definite categories for a concrete analysis, mainly depending on the defined research problem and aims. However, the portion of participants in each category should always be known because similarity or diversity of participants and their distribution in the selected sample directly affects data variance, which plays a key role in the calculated relations and causes.

References:

Bogin, B., & Varela Silva, M. I. (2012). The Body Mass Index: The Good, the Bad, and the Horrid. Online on https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/14017 (Accessed on 3rd of February 2019).

Burton, A. W., & Miller, D. E. (1998). *Movement skill assessment*. Human Kinetics.

Cameron, N., Pettifor, J., De Wet, T., & Norris, S. (2003). The relationship of rapid weight gain in infancy to obesity and skeletal maturity in childhood. *Obesity research*, *11*(3), 457-460.

Cliff, D. P., Okely, A. D., Morgan, P. J., Jones, R. A., Steele, J. R., & Baur, L. A. (2012). Proficiency deficiency: mastery of fundamental movement skills and skill components in overweight and obese children. *Obesity*, *20*(5), 1024-1033.

D'Hondt, E., Deforche, B., De Bourdeaudhuij, I., & Lenoir, M. (2009). Relationship between motor skill and body mass index in 5-to 10-year-old children. *Adapted Physical Activity Quarterly*, *26*(1), 21-37.

D'Hondt, E., Deforche, B., Gentier, I., De Bourdeaudhuij, I., Vaeyens, R., Philippaerts, R., & Lenoir, M. (2013). A longitudinal analysis of gross motor coordination in overweight and obese children versus normal-weight peers. *International journal of obesity*, *37*(1), 61-67.

Ellery, P. J. (1991). *The relationship between gross motor skill performance and skinfold thickness, physical activity instruction, age, gender, and parental income in preschool age children* (Doctoral dissertation, The Ohio State University).

Frisancho, A. R., & Flegel, P. N. (1982). Advanced maturation associated with centripetal fat pattern. *Human Biology*, 717-727.

Graf, C., Koch, B., Kretschmann-Kandel, E., Falkowski, G., Christ, H., Coburger, S., ... & Predel, H. G. (2004). Correlation between BMI, leisure habits and motor abilities in childhood (CHILT-project). *International journal of obesity*, *28*(1), 22.

Hills, Andrew P., and A. W. Parker. (1992). Locomotor characteristics of obese children. *Child: care, health and development, 18*(1), 29-34.

Kalies, H., Lenz, J., & Von Kries, R. (2002). Prevalence of overweight and obesity and trends in body mass index in German pre-school children, 1982–1997. *International Journal of obesity*, *26*(9), 1211-1217.

Khodaverdi, F., Bahram, A., & Jafarabadi, M. A. (2012). Quality of life, motor ability, and weight status among school-aged children of Tehran. *Iranian journal of public health*, *41*(6), 97-102.

Lohman, T. G., Roche, A. F., & Martorell, R. (1988). *Anthropometric standardization reference manual*. Human kinetics books.

Lopes, V. P., Stodden, D. F., & Rodrigues, L. P. (2014). Weight status is associated with cross-sectional trajectories of motor co-ordination across childhood. *Child: care, health and development*, *40*(6), 891-899.

Luo, J., & Hu, F. B. (2002). Time trends of obesity in pre-school children in China from 1989 to 1997. *International journal of obesity*, *26*(4), 553-558.

Malina, R. M. (2014). Top 10 research questions related to growth and maturation of relevance to physical activity, performance, and fitness. *Research Quarterly for Exercise and Sport*, *85*(2), 157-173.

Malina, R. M., Beunen, G. P., Claessens, A. L., Lefevre, J., Eynde, B. V., Renson, R., ... & Simons, J. (1995). Fatness and physical fitness of girls 7 to 17 years. *Obesity Research*, *3*(3), 221-231.

McKenzie, T. L., Sallis, J. F., Broyles, S. L., Zive, M. M., Nader, P. R., Berry, C. C., & Brennan, J. J. (2002). Childhood movement skills: Predictors of physical activity in Anglo American and Mexican American adolescents?. *Research quarterly for exercise and sport*, *73*(3), 238-244.

Morano, M., Colella, D., & Caroli, M. (2011). Gross Motor Skill Performance in a Sample of Overweight and Non-Overweight Preschool Children. *Pediatric Obesity*, *6*(S2), 42-46.

Morris, F. L., Naughton, G. A., Gibbs, J. L., Carlson, J. S., & Wark, J. D. (1997). Prospective ten-month exercise intervention in premenarcheal girls: positive effects on bone and lean mass. *Journal of bone and mineral research*, *12*(9), 1453-1462.

Musalek, M., Kokstejn, J., Papez, P., Jírovec, J., & Honsová, S. (2017). Relation Between Percent Body Fat and Fundamental Motor Skills in Pre-School Children age 3-6 years. *Sport Mont, 15*(2), 9-13.

Okely, A. D., Booth, M. L., & Chey, T. (2004). Relationships between body composition and fundamental movement skills among children and adolescents. *Research quarterly for exercise and sport*, *75*(3), 238-247.

Okorodudu, D. O., Jumean, M. F., Montori, V. M., Romero-Corral, A., Somers, V. K., Erwin, P. J., & Lopez-Jimenez, F. (2010). Diagnostic Performance of Body Mass Index to Identify Obesity as Defined by Body Adiposity: A Systematic Review and Meta-Analysis. *International Journal of Obesity*, *34*(5), 791-799.

Ortega, F. B., Ruiz, J. R., Castillo, M. J., & Sjöström, M. (2008). Physical fitness in childhood and adolescence: a powerful marker of health. *International journal of obesity*, *32*(1), 1-11.

Pařízková J. (1977). *Body Fat and Physical Fitness: Body Composition and Lipid Metabolism in Different Regimes of Physical Activity*. The Hague, Martinus Nijhoff B.V./Medical Division.

Pařízková, J. (2008). Impact of Education on Food Behaviour, Body Composition and Physical Fitness in Children. *British Journal of Nutrition*, *99* (S1), S26-S32.

Raudsepp, L., & Jürimäe, T. (1996). Relationships between somatic variables, physical activity, fitness and fundamental motor skills in prepubertal boys. *Biology of sport*, *13*, 279-290.

Roberts, D., Veneri, D., Decker, R., & Gannotti, M. (2012). Weight status and gross motor skill in kindergarten children. *Pediatric Physical Therapy*, *24*(4), 353-360.

Rolland-Cachera, M. F., Deheeger, M., Bellisle, F., Sempe, M., Guilloud-Bataille, M., & Patois, E. (1984). Adiposity rebound in children: a simple indicator for predicting obesity. *The American journal of clinical nutrition*, *39*(1), 129-135.

Sedlak, P., Pařízková, J., Daniš, R., Dvořáková, H., & Vignerová, J. (2015). Secular Changes of Adiposity and Motor Development in Czech Preschool Children: Lifestyle Changes in Fifty-Five Year Retrospective Study. *Biomed Research International*, *2015*

Sedlak, P., Pařízková, J., Daniš, R., Dvořáková, H., & Vignerová, J. (2015). Secular changes of adiposity and motor development in Czech preschool children: Lifestyle changes in fifty-five year retrospective study. *BioMed research international*, *2015*.

Scheffler, C., Ketelhut, K., & Mohasseb, I. (2007). Does Physical Education Modify the Body Composition?—Results af a Longitudinal Study of Pre-School Children. *Anthropologischer Anzeiger*, 193-201.

Schwandt, P., von Eckardstein, A., & Haas, G. M. (2012). Percentiles of percentage body fat in German children and adolescents: an international comparison. *International journal of preventive medicine*, *3*(12), 846-852.

Slaughter, M. H., Lohman, T. G., Boileau, R., Horswill, C. A., Stillman, R. J., Van Loan, M. D., & Bemben, D. A. (1988). Skinfold equations for estimation of body fatness in children and youth. *Human biology*, 709-723.

Southall, J. E., Okely, A. D., & Steele, J. R. (2004). Actual and perceived physical competence in overweight and nonoverweight children. *Pediatric Exercise Science*, *16*(1), 15-24.

Vameghi, R., Shams, A., & Dehkordi, P. S. (2013). The effect of age, sex and obesity on fundamental motor skills among 4 to 6 years-old children. *Pakistan journal of medical sciences*, *29*(2), 586-589.

Vignerová, J., Bláha, P., Riedlová, J., Kobzová, J., Krejčovský, L., & Brabec, M. (2006). *6. Celostátní antropologický výzkum dětí a mládeže 2001 Česká republika*. 6th National, Anthropological research of children and youth 2001, Czech republic, Prague: SHI

Williams, H. G., Pfeiffer, K. A., O'neill, J. R., Dowda, M., McIver, K. L., Brown, W. H., & Pate, R. R. (2008). Motor skill performance and physical activity in preschool children. *Obesity*, *16*(6), 1421-1426.

Williams, S., & Dickson, N. (2002). Early growth, menarche, and adiposity rebound. *The Lancet*, *359*(9306), 580-581.

Yang, S. C., Lin, S. J., & Tsai, C. Y. (2015). Effect of sex, age, and BMI on the development of locomotor skills and object control skills among preschool children. *Perceptual and motor skills*, *121*(3), 873-888.

Sport Mont 15 (2017) 2: 9–13
Original scientific paper
UDC 572.512:796.012-053.2

Relation Between Percent Body Fat and Fundamental Motor Skills in Pre-School Children age 3-6 years

Martin Musalek, Jakub Kokstejn, Pavel Papez, Jan Jírovec and Sárka Honsová
Charles University, Faculty of Physical Education and Sport, Prague, Czech Republic

ABSTRACT

It is quite well known that excessive body fat in children is interpreted as a marker of inhibited physical activity and motor performance. This study aimed to establish whether severe impairment of fundamental motor skills (defined as performance under 5th centile of norms) will be significantly more frequently identified in pre-schoolers age 3-6 years with amount of body fat higher than 85th centile of norms. Research sample consisted of 496 (females=241, males=255) pre-schoolers selected from specific district of Prague, Czech Republic. The MABC-2 was used for the assesment fundamental motor skills. Equations for body fat estimation in children identified 35.8% children with body fat>85th centile of norms, 61.7% within 15th–85th centile, and 2.5% of children<15th centile of norms. Results revealed that children whose body fat was higher than 85th centile of norms or lower than 15th centile had double the frequency of severe motor problems. Interestingely on the other hand we found no signficant differences in the frequency of high above average performances>90th centile in MABC-2 between fat 8.4% and non fat children 10.7%. We suggest that amount of body fat is not a clear predictor for the degree of fundamental motor skills.

Key words: *fundamental motor skills, MABC-2,motor performance, pre-school chidren, adipose tissue, fat*

Introduction

Previous research proved that the decreased amount of physical activity (PA) is a cause of poor performance in motor abilities in childhood (Deforche et al., 2003; Wedderkopp, Froberg, Hansen & Andersen, 2004; Pařízková, Sedlak, Dvořáková, Lisá & Bláha, 2012). A significant negative correlation between obesity and less daily moderate physical activity and daily vigorous physical activity in pre-school and middle school child populations is also a well-known fact (Trost, Kerr, Ward & Pate, 2001; Davies, Gregory & White 1995; Salbe et al., 2002; Graf et al., 2004). On the other hand, much less attention has been paid–and especially in pre-school children–to examining whether over-weight and obese individuals have higher prevalence for severe motor difficulties in fundamental motor skills (FMS). FMS is described by fine and gross motor skills, coordination and balance manifestations. The degree of FMS has a direct impact on motor development of an individual and plays a crucial role in early child´s physical, cognitive and social development (Gallahue, Ozmun & Goodway, 2011; Cools, Martelaer, Samaey & Andries, 2009). Currently, a few studies suggested a potential relationship between preschoolers' level of FMS and the amount of PA (Butcher & Eaton, 1989; Saakslahti et al., 1999; Fisher et al., 2005). However, the revealed results have not provided a clear enough support to establish a clear link. In particular performance in FMS correlates low with the amount of PA. Moreover, results of study Cliff, Okely, Smith and McKeen (2009) showed that the relationship between FMS and PA may be conditioned in pre-shoolers by different variables including: gender, movement skill sub-domain or intensity of physical activity. Studies of the relation between body size measured by BMI and FMS performance show similar inconsistent results. Williams et al. (2008) revealed low non-significant correlations (from 0.03 to 0.13) in pre-schoolers between z-BMI and FMS measured by Motor Skill Protocol performance. Siahkouhian, Mahmoodi and Salehi (2011), examined the relation between BMI and the degree in FMS measured by Motor Skill Protocol at 7 to 8 year old children also concluded that „hypothesis of a perceptual-motor deficit in obese children is rather speculative and must therefore be addressed further". On the other hand, Okely, Booth and Chey (2004) found that results of six FMS (run, vertical jump, catch, overhand throw, forehand strike, and kick) are significantly related to BMI and waist circumference. In this research, normal weight middle age school children were two to four times more likely to be more advanced in FMS than overweight and obese children of both sexes. Differences in FMS performance with the emphasis on the performance in each FMS sub-domains were provided by Morano, Colella and Caroli (2011). They revealed that overweight and obese children showed the poorest performance in locomotor and object-control tasks. D'Hondt, Deforche, De and Lenoir (2009), who examined relationship between FMS assessed by Movement assessment battery for children (MABC-2) and BMI in 5 to 10 year olds, also discovered significant relation between FMS and body size. However, in their study only obese children scored significantly worse in FMS in comparison to their normal-weight and overweight peers. Logan, Scrabis-Fletcher, Modlesky and Getchell (2011) did not reveal any significant relation between BMI and MABC-2 r=-0.237 in pre-school children. However, these authors pointed that pre-school children classified as over-weight and obese might have lower FMS than their normal weight and underweight counterparts.

It is evident from aforementioned studies that previous research has been mainly focused solely on the absolute difference in FMS performances between normal-weight, overweight and obese children. Therefore, there is a lack of information whether children with high adipose tissue generally expressed

Received for publication May 20, 2017

more severe motor difficulties in FMS. Moreover, to date the majority of studies have used only one indicator for assessing of morphological composition of the BMI which has its definite limitations. Our hypothesis is that severe impairment of fundamental motor skills will be significantly more frequently identified in pre-schoolers aged 3-6 years with the amount of body fat higher than the 85th centile of norms.

Methods

Research sample

The research sample consisted of 496 (females=241, males=255) pre-schoolers aged 3 to 6.9 years ($\bar{x}$=4.75; ±1.21) selected from a specific district of Prague, the Czech Republic. Four kindergartens were selected randomly from a reference list of all general kindergartens (not private kindergartens) on the territory of Prague which do not have any specialization (e.g., sport, language). The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed voluntary an informed consent. The data were anonymized.

Data collection

Anthropometry - all anthropometry markers were measured in the same time of the day from 2 pm to 4 pm by three trained research persons. All anthropometric measurements were done according to the reference manual Lohman, Roche and Martorell (1988) using standardized equipment. We measured:

Weight: medical calibrated weight type TPLZ1T46CLND-BI300 was used to assess weight to nearest 0.1 kg

Height: portable anthropometer P375. Measurements were taken to nearest 0.1 cm

Skinfolds: triceps and subscapular skinfolds were measured by Harpenden type caliper (skinfolder) with accuracy of 0.2 mm

Percentage of body fat (%BF): the amount of body fat was calculated according of equations Slaughter et al., (1988) using the data of skinfold measuremnst on triceps (SFT) and subscalpular (SFS)

For male with the sum of skinfolds less than 35 mm the following equation was used: %BF=1.21(SFT + SFSRr) − 0.008*(SFT + SFS)^2 − 1.7

For female with the sum of skinfolds less than 35 mm the following equation was used: %BF=1.33*(SFT + SFS) − 0.013*(SFT + SFS)^2 − 2.5

For male with the sum of skinfolds higher than 35 mm the following equation was used: %BF=0.783*(SFT + SFSr) + 1.6

For female with the sum of skinfolds higher than 35 mm the following equation was used: %BF=0.546*(SFT + SFS) + 9.7

(Slaughter et al., 1988)

Inter-rater reliability of measurement - Since skinfolds were measured by three examiners, firstly a pilot testing of measurement consistency on n=20 pre-schoolers from selected kindergartens was conducted.

Inter-rater reliabilities as intra-class correlation coefficients (ICC) of three examiners in skinfolds measurement were: ICC triceps=0.91; ICC subscapula=0.95; ICC suprailiaca=0.90; ICC calf=0.94.

The final classification of individuals into categories was done according norms (Schwandt, Eckerstein & Haas, 2012):

1) underfat<15th centile
2) proportionate fat 16th–85th centile
3) overfat>86th centile

Fundamental Motor Skills - The test of the Movement Assessment Test Battery for Children-2 (MABC-2) (Henderson, Sugden & Barnett, 2007) was used for assessing of the degree of FMS. In particular the age band (AB1) variant intended for children aged 3-6 years was used. Data collection from MABC-2 was carried out by three research trained teams. Each team contained five trained persons who measured FMS by MABC-2 in selected kindergartens in the same time of the day from 9 am to 11 am. Children were assessed individually.

According to Henderson et al. (2007), MABC-2 is a comprehensive diagnostic tool for evaluation of motor development and revealing of motor difficulties with different severity. MABC-2 AB1 included eight indicators divided into three domains.

1) dexterity – a) Post coins; b) Threading beads, c) Drawing trail
2) Aiming and Catching – a) Catching bean bag; b) Throwing bean bag onto mat
3) Balance – a) One-leg balance; b) Walking heels raised; c) Jumping on mats

According to the Examiner's manual (Henderson et al., 2007), all raw scores were converted to standard age-normed scores and further to a total test score (TTS PCT) In literature there are many solutions how to assess the degree of motor difficulties. In this study we adopted the recommendations of the following authors: Henderson et al. (2007); Schott, Alof, Hultsch and Meermann (2007). According to these recommendations, TTS PCT≤5th centile showed severe motor difficulties with high probability of developmental coordination disorder (DCD). TTS PCT≤15th of centile is considered as an indicator of risk of DCD.

Data analysis

Frequencies of MABC-2 TTS PCT (i)≤5th centile, (ii)≤15th centile and (iii)≥16th centile and their differences between 1) underfat children; 2) proportionate fat children and 3) overfat children were analysed by chi-square statistic: contingency tables and Fischer's exact test $p<0.05$ and effect size ES>0.14. The differences in total and standard scores from MABC-2 between proportionate fat children and overfat children were analysed by non-parametric Mann Whitney U test $p<0.05$ ES r>0.30 (Cohen, 1988). All statistical procedures were carried out in the NCSS2007 program (Version 2007; NCSS, Kaysville, UT, USA).

Results

Table 1 shows basic descriptive information about mean values of the selected research sample. Mean values of weight

Table 1. Personal height, weight and amount of body fat in pre-school children

Variables	3 years (n=118)	4 years (n=139)	5 years (n=121)	6 years (n=118)
Age M(SD)	3.5 (0.27)	4.41 (0.29)	5.41 (0.29)	6.5 (0.30)
Height in cm M(SD)	100.44 (4.89)	107.26 (5.25)	113.7 (4.92)	119.72 (6.01)
Weight in kg M(SD)	15.80 (2.19)	17.58 (2.26)	19.66 (2.86)	22.59 (3.15)
Subcutaneous fat in % M(SD)	15.39 (2.41)	15(2.49)	15.27(3.37)	15.46 (3.7)

Note: M – mean, SD – standard deviation

and height in each age category of measured pre-school children reflected the 49th up to 52th centile of Czech norms (Vignerová et al., 2006). However, average values of subcutaneous fat were in all age categories on the 75th centile of norms (Schwandt et al., 2012). This result confirmed a previously observed long term trend in increasing of adipose tissue even in pre-school children.

From the entire sample, 178 children (35.8%, 112 boys and 66 girls) were identified as having higher percentage of body fat than the 85th centile; 306 children (61.7%, 140 boys and 166 girls) had proportionate body fat and 12 children (2.5%, 6 boys and 6 girls) were identified as underfat with the percentage of body fat<15th of centile. Further it was revealed that overfat and underfat children have double the frequency of severe motor difficulties and risk of DCD in comparison to proportionate fat counterparts Chi-square=12.71, df=4, Effect size=0.16 (Table 2).

Table 2. Incidence of movement difficulties with regard to amount of adipose tissue

Proportion of children with and without motor difficulties	Under fat<15th centile (n=12)	Proportionate fat 15th–85th centile (n=306)	Overfat>86th centile (n=178)
Proportion of participants in each category in %	2.5	61.7	35.8
Proportion of children in risk of DCD MABC-2≤15th centile	3 (25%)**	38 (12.4%)	38 (21.4%)**
Proportion of children with severe motor difficulties MABC-2≤5th centile	2 (16.7%)**	17 (5.55%)	26 (14.6%)**
Proportion of children without motor difficulties MABC-2≥16th centile	9 (75%)	268 (87.6%)	140 (78.6%)

Note: ** significantly higher frequency of severe motor difficulties and risk of DCS $p<0.05$; Effect size >0.14

From this perspective it seems that the amount of adipose tissue plays a crucial role in FMS performance. Neverthless, we were interested to know whether the category of overfat children will have the average score in MABC-2 significantly worse in comparison to their peers. The analysis of differences in MABC-2 total score (TTS), standard scores (TSS), and highly above TTS PCT≥90th centile are provided solely for overfat children and their proportionate counterparts as the sample size of underfat children (n=12) does not have adequate power.

Table 3. Difference in Total test score (TTS), total standard score (TSS) and proportion of high above centile score (PCT)≥90th centile

	Under fat<15th centile (n= 12)	Proportionate fat 15th–85th centile (n=306)	Overfat>86th centile (n=178)
Mean (SD) TTS	71.18 (16.7)	77.97 (10.02)	74.9 (12.5)*
Mean (SD) TSS	8.45 (3.2)	10.64 (8.4)	9.1 (3.29)*
PCT (proportion in %)≥90th centile	0 (0%)	32 (10.4%)	15 (8.4%)

Note: * significantly higher score $p<0.05$ however with unsufficient Effect size $r<0.30$

Overall differences in the average TTS and TSS presented in tab 3 showed that overfat children scored significantly worse in MABC-2. However, these differences were identified as significant only in terms of statistical significance z-2.37 and z-2.58; $p<0.05$. The effect sizes of TTS and TSS respectively between overfat and proportionate fat children were low $r=0.11$. Moreover, the results surprisingly revealed that in children with significantly high above average score TTS PCT≥90th centile is not significantly less overfat in comparison to their counterparts (Table 3).

Discussion

Our hypothesis is that severe impairment of fundamental motor skills will be significantly more frequently identified in pre-schoolers aged 3-6 years with the amount of body fat higher than the 85th centile of norms. Results from MABC-2 revealed that children whose body fat was>85th centile of norms or<15th centile had double the frequency of severe motor difficulties TTS PCT≤5th centile in comparison to peers with body fat in the range between 15th–85th centile. The finding of a higher frequency of motor difficulties in overfat pre-school children is in agreement with finding of Okely et al. (2004). In their research over-weight and obese pre-school children aged four and six years had double the frequency of the lowest mark on artificially established 5 point FMS scale in comparison to their non-overweight peers. However, beside that our results interestingly showed that not only a high amount of adipose tissue but also a very low amount of tissue may represent a predisposition for poor FMS performance. Further, in conformity with previous studies (D'Hondt et al., 2009; Morano et al., 2011) we found that overfat pre-schoolers generally scored significantly worse in FMS performance in comparison to proportionate fat peers. However, in this research differences in the total score and standard score between proportionate fat children and overfat children significantly differ only statistically $p<0.05$. When the effect size (practical significance) was checked, no significant differences were revealed $r=0.11$ between the two groups. This finding is in contrast with the results from previous researches because the degree of difference in FMS performance between sub-samples classified according to the centile rank of BMI was much larger. For instance, the results in Logan et al. (2011) showed that children with BMI>85th centile had MABC-2 average centile score TTS PCT=38.7 and children with BMI in the range between 25th–85th centile TTS PCT=60.7. It means the difference was 22 centile points.

However, in our study the average centile difference of 5.7 centile points on the scale between overfat TTS PCT=42.28 and proportionate fat TTS PCT=47.98 was found. According to many authors (Scheffler, Ketelhut, & Mohasseb, 2007; Rietsch, Eccard, & Scheffler, 2013) value of BMI is constituted by others body compartments in comparison to itself estimated amount of subcutaneous body fat. Therefore one of possible cause of this inconsistency in results could be obviously due to different information which provides BMI in comparison to estimated amount of subcutaneous body fat. Although it seemed that overfat pre-school children generally have a lower level of FMS in comparison to their proportionate fat peers, one finding from this study goes contrary to it. Surprisingly, overfat and proportion fat children had proportionally almost the same distribution of scores in FMS>90th centile of MABC scale. Therefore, it seems that the high amount of subcutaneous fat may not have such an evident decreasing effect for FMS performance. However, it must be mentioned that even in early childhood there is evidence that overfat children have faster tempo of biology maturation (Pařízková, 2010). Therefore without information about biology age of children we can't confirm if similarity in frequency of above average performance between proportionate and fat children is not caused mainly due to their biological maturation diversity. However, these results suggest that detailed investigations of FMS performance levels with equally distributed sample sizes of underfat, overfat or overweight and obese children is necessary to understand the importance of the amount of adipose tissue in the domain of FMS. We do realize the highly unequal representation of individuals in each sub-sample to be a definite source of limitations.

Children whose body fat was>85th centile of norms or<15th centile had double the frequency of severe motor difficulties TTS PCT≤5th centile in comparison to peers with body fat in the range between 16th–84th centile. Interestingly, these results showed that not only a high amount of adipose tissue but also a very low amount of fat tissue may represent a predisposition for poor FMS performance. On the other hand, overfat and proportion fat children had proportionally almost the same distribution of high above average scores in FMS>90th centile of MABC scale. Therefore, it seems that amount of body fat in pre-school children doesn't represent sufficient predictors of the level of fundamental motor skills. We suggest that greater emphasize should be put on research where connection between FMS, body composition, cognitive abilities and motor experiences in pre-schoolers would be assessed.

Acknowledgment:

This study was supported by a Czech Science Foundation project No. 14-29358P and progres Q19 Social-Sciences Aspects of Human Movement Studies II.

REFERENCES

Butcher, J., & Eaton, O. (1989). Gross and fine motor proficiency in preschoolers: Relationships with free play behavior and activity level. *Journal of Human Movement Studies, 16*, 27–36.

Cliff, D.P., Okely, A.D., Smith, L.M., & McKeen, K. (2009). Relationships between fundamental movement skills and objectively measured physical activity in preschool children. *Pediatric Exercise Science, 21*(4), 436-449.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Earlbaum Associates.

Cools, W., Martelaer, K., Samaey, C., & Andries, C. (2009). Movement skill assessment of typically developing preschool children: A review of seven movement skill assessment tools. *Journal of Sports Science and Medicine, 8*(2), 154-168.

D'Hondt, E., Deforche, B., De, B.I., & Lenoir, M. (2009). Relationship between Motor Skill and Body Mass Index in 5- to 10-Year-Old Children. *Adapted Physical Activity Quarterly, 26*(1), 21-37.

Davies, P.S., Gregory, J., & White, A. (1995). Physical activity and body fatness in pre-school children. *International Journal of Obesity and Related Metabolic Disorders: Journal of the International Association for the Study of Obesity, 19*(1), 6-10.

Deforche, B., Lefevre, J., Bourdeaudhuij, I., Hills, A.P., Duquet, W., & Bouckaert, J. (2003). Physical Fitness and Physical Activity in Obese and Nonobese Flemish Youth. *Obesity Research, 11*(3), 434-441.

Fisher, A., Reilly, J.J., Kelly, L.A., Montgomery, C., Williamson, A., Paton, J.Y., & Grant, S. (2005). Fundamental movement skills and habitual physical activity in young children. *Medicine and Science in Sports and Exercise, 37*(4), 684-688.

Gallahue, D.L., Ozmun, J.C., & Goodway, J. (2011). *Understanding motor development: infants, children, adolescents, adults*. New York: McGraw-Hill Higher Education, London : McGraw-Hill.

Graf, C., Koch, B., Kretschmann-Kandel, E., Falkowski, G., Christ, H., Coburger, S., Lehmacher, W., & Predel, H.G. (2004). Correlation between BMI, leisure habits and motor abilities in childhood (CHILT-project). *International journal of obesity, 28*(1), 22-26.

Henderson, S.E., Sugden, D.A., & Barnett, A.L. (2004). *Movement Assessment Battery for Children-2*. London: Harcourt Assessment.

Logan, S.W., Scrabis-Fletcher, K., Modlesky, C., & Getchell, N. (2011). The Relationship between Motor Skill Proficiency and Body Mass Index in Preschool Children. *Research Quarterly for Exercise and Sport, 82*(3), 442-448.

Lohman, T.G., Roche, A.F., & Martorell, R. (1988). *Anthropometric standardization reference manual*. Human kinetics books.

Morano, M., Colella, D., & Caroli, M. (2011). Gross motor skill performance in a sample of overweight and non-overweight preschool children. *International Journal of Pediatric Obesity, 6*, 42-46.

Okely, A.D., Booth, M.L., & Chey, T. (2004). Relationships between Body Composition and Fundamental Movement Skills among Children and Adolescents. *Research Quarterly for Exercise and Sport, 75*(3), 238-247.

Pařízková, J. (2010). *Nutrition, physical activity, and health in early life*. Bocan Raton, Fla: CRC Press.

Pařízková, J., Sedlak, P., Dvořáková, H., Lisá, L & Bláha, P. (2012). Secular Trends of Adiposity and Motor Abilities in Preschool Children. *Journal of Obesity & Weight Loss Therapy, 2*(9).

Rietsch, K., Eccard, J.A., & Scheffler, C. (2013). Decreased external skeletal robustness due to reduced physical activity?. *American Journal of Human Biology, 25*(3), 404-410.

Saakslahti, A., Numminen, P., Niinikoski, H., Rask-Nissilä, L., Viikari, J., Tuominen, J., & Välimäki I. (1999). Is physical activity related to body size, fundamental motor skills, and CHD risk factors in early childhood? *Pediatric Exercise Science, 11*, 327–340.

Salbe, A.D., Weyer, C., Harper, I., Lindsay, R.S., Ravussin, E., & Tataranni, P.A. (2002). Assessing Risk Factors for Obesity Between Childhood and Adolescence: II. Energy Metabolism and Physical Activity. *Pediatrics, 110*(2), 307-314.

Scheffler, C., Ketelhut, K., & Mohasseb, I. (2007). Does physical education modify the body composition?: Results of a longitudinal study of pre-school children. *Anthropologischer Anzeiger, 65*(2), 193-201.

Schott, N., Alof, V., Hultsch, D., & Meermann, D. (2007). Physical fitness in children with developmental coordination disorder. *Research quarterly for exercise and sport, 78*(5), 438-450.

Schwandt, P., Eckerstein Von, A., & Haas, G.M. (2012). Percentiles of percentage body fat in german children and adolescents: an international comparison. *International Journal of Preventive Medicine, 3*(12), 846-52

Siahkouhian, M., Mahmoodi, H., & Salehi, M. (2011). Relationship between fundamental movement skills and body mass index in 7-to-8 year-old children. *World Applied Sciences Journal, 15*(9), 1354-1360.

Slaughter, M.H., Lohman, T.G., Boileau, R., Horswill, C.A., Stillman, R.J., Van Loan, M.D., & Bemben, D.A. (1988). Skinfold equations for estimation of body fatness in children and youth. *Human biology*, 709-723.

Trost, S.G., Kerr, L.M., Ward, D.S., & Pate, R.R. (2001). Physical activity and determinants of physical activity in obese and non-obese children. *International Journal of Obesity, 25*(6), 822-829.

Vignerová, J., Bláha, P., Riedlová, J., Kobzová, J., Krejčovský, L., & Brabec, M. (2006). *6. Celostátní antropologický výzkum dětí a mládeže 2001 Česká republika.* 6th National Anthropological research of children and youth 2001, Czech republic, Prague: SHI.

Wedderkopp, N., Froberg, K., Hansen, H.S., & Andersen, L.B. (2004). Secular trends in physical fitness and obesity in Danish 9-year-old girls and boys: Odense School Child Study and Danish substudy of the European Youth Heart Study. *Scandinavian Journal of Medicine & Science in Sports, 14*(3), 150-155.

Williams, H.G., Pfeiffer, K.A., O'Neill, J.R., Dowda, M., McIver, K.L., Brown, W.H., & Pate, R.R. (2008). Motor skill performance and physical activity in preschool children. *Obesity (silver Spring, Md.), 16*(6), 1421-1426.

M. Musalek
Charles University, Faculty of Physical Education and Sport, Jose Martiho31. Praha 6 Veleslavin, 162 52, Prague, Czech Republic
e-mail: musalek.martin@seznam.cz

8. CONSTRUCT VALIDITY OF MOVEMENT ASSESSMENT BATTERY FOR CHILDREN – 2nd edition (AB1) IN CZECH ENVIRONMENT

From previous chapters it is evident that we used the MABC-2 for assessing of FMS in preschool age children. The MABC-2 is widely respected and it has been used since the validation of the second edition in 2007 done by Henderson et al. (2007). The MABC-2 is composed from three constructs (factors): 1) manual dexterity (MD); 2) aiming and catching (AC); 3) balance (BAL). According to Henderson et al. (2007), these factors are not significantly related to each other and they do not form a hierarchical structure (one construct is superior to another construct).

When we conducted the analyses in our previously presented studies, in addition to our main research aims we were also interested to reveal which sub-test seemed to cause the biggest difficulties to participants or which items in each sub-test seemed to have the biggest effect on the final sub-test standard score. To obtain such information we had to check the raw date repeatedly (e.g., raw scores in each sub-test or even in each item). This detailed investigation showed that some of the items seemed to be too easy for our participants or had low discrimination power due to very similar results with only little variance. Particularly in sub-test BAL we revealed using the data from studies Kokštejn et al. (2017) and Musalek et al. (2017) that more than 50% of children reached the ceiling effect in items 1) walking heels raised and 2) jumping on mats. Although we do realize that the main aim of the MABC-2 is to identify children with significant motor impairment that should seek treatment, there are studies which recommend using the MABC or the MABC-2 also for cross sectional and comparison studies for assessing FMS in neurotypically developing (ND) children (Burton, & Miller, 1998; Henderson et al., 2007; Cools, De Martelaer, Samaey & Andries, 2009). Therefore, the question remains as to whether the defined scales of items and sub-tests in the MABC-2 are appropriately built in case we seek to receive a sufficiently detailed picture about FMS of ND children.

When we looked for feedback on the MABC-2 from the academic sphere, we found that two years after the MABC-2 was made available to researchers, Brown and Lalor (2009) did the first critical review. These authors mentioned that, for instance, the

MABC-2 manual provides only limited information about its reliability. Reliability of MABC-2 AB1 items for preschoolers was carried by test-retest method on a small n=20 research sample. Time stability of results from each sub-test was MD=0.77; AC=0.84; BAL=0.77 and TTS=0.80 (Hendersen et al., 2007). Nevertheless, the same authors pointed out that reliability for younger children from AB1 3 and 4 years was much lower in the range 0.48 – 0.68. In conclusion, in their ciritical review Brown and Lalor stated that the MABC-2 might be a useful clinical tool; however, the final interpretation of its outcomes should be done with care. It has been 10 years since Brown and Lalor published their study in 2009 and many other studies have tried to verify especially the validity of the originally suggested three-factor structure of the MABC-2.

From the point of view of so-called non-criterial validity (e.g., face validity or content validity) it was shown that the semantic content of the MABC-2 items sufficiently corresponds with information that these items should provide in each sub-test (manual dexterity, aiming and catching, balance) (Wagner, Kastner, Petermann & Bös, 2011).

However, further studies which verified the construct validity of items and fitness of the original three-factor model of the MABC-2 using CFA approach (Schulz, Henderson, Sugden & Barnett, 2011; Hua, Gu, Meng & Wu, 2013; Psotta & Brom, 2016) mostly did not find mathematically supporting results for the acceptance of the originally suggested three-factor model. Rather, Schulz et al. (2011) and Psotta and Brom (2016) suggested that some of the items are related to more than one subtest. When Schultz et al. (2011) rejected the original three-factor model in AB1, they tried to find another, more appropriate model. Finally, a bi-factor structure with one general factor (*g* motor skill factor) for all variables in the MABC-2 and three separate constructs (manual dexterity, aiming and catching, and balance) produced the best fits. However, in this type of model quite a strong assumption must be made that correlations between each sub-tests should be fixed to zero. First, in this study correlations between factors were not fixed to zero and secondly, it must be stated that the suggestion that manual dexterity, aiming and catching, and balance measure totally different movement properties (it is common sense that manual dexterity – aiming and catching must share at least a certain portion of hand-eye coordination) does not have a strong behavioural background. Further, a bi-factor structure often gives nice fits; nevertheless, according to Brown, these adjustments primarily made to receive the best fit for our data, can be a double-edged sword. On one side, we get "easily" acceptable values of fit indices for our model and we can interpret loadings between the *g* factor and each item. On the other side, factor loadings between items and sub-tests (e.g., MD, AC and BAL) can mean anything and it is usually hard to provide arguments about the cause or explanation of these loadings. Even though the suggested bi-factor structure with *g* motor skill factor can be problematic for interpretation, we found that the possible existence of *g* motor skills factor was apparently supported by Smits-Engelsman, Niemeijer and van Waelvelde (2011). These authors revealed that the items in AB1 have strong internal consistency Cronbach 0.81 to 0.87. It means that each defined sub-test (MD, AC, BAL) could underlie motor performance in all tests items. Another approach to how to deal with a non-acceptable model fit of the original three-factor model was introduced in Psotta and Brom (2016), who also tried to find a more suitable model by additional analysis. Since these authors stated that the *g* factor structure could not be accepted due to non significant loadings, they used the original three-factor model with modification indices. Modification indices are mathematical operations that are used to find solutions (mathematically, not behaviourally or empirically) how to achieve the best model for the collected empirical data. Nevertheless, the use of information provided by modification indices is conditioned on strong behavioural support for these mathematical suggestions (e.g., free correlation of errors between items, multi factor relations of some items, etc.). Using modification indices, Psotta and Brom (2016) finally suggested that the item *threading beads* has multifactor membership and should be related to two sub-tests MD and BAL. Moreover, to get an acceptable fit of the three-factor model it was recommended to add correlations of errors between items *posting coins* and *drawing trail* and between *drawing trail* and *catching beanbag*. The question is what these errors between items really mean; otherwise we have an acceptable fit of the model without any clear explanation why it is acceptable from the behavioural perspective. Hua et al. (2013), who investigated the model fit in MABC-2 on Chinese population, revealed an unacceptable fit of the original model and low factor validity of certain items (drawing trail, walking heels raised). Interestingly, these authors only removed the problematic items with the poorest factor validity and then stated that the MABC-2 with six instead of eight items could be used.

The only one study which supported the original three-factor model was Ellinoudis, Evaggelinou, Kourtessis, Konstantinidou, Venetsanou and Kambas (2011).

However, in this study a relatively small sample of n=183, 3- to 5-year-old preschoolers was used.

Surprisingly, none of the studies aimed to verify the originally suggested structure considered the possible influence of age and gender throughout the entire preschool period, which has recently been shown to affect the MABC-2 test scores (Kokštejn et al., 2017). Based on suggestion of Schultz et al. (2011) that future research should examine the structure of factors in the MABC-2 test at different ages, we assume that the rather ambiguous results of the aforementioned studies indicate that throughout the preschool period (3-6 years), a wide range of individual differences in motor-skill development is likely present between different ages and genders (Gidley Larson, et al., 2007; Van Waelvelde, Peersman, Lenoir, Engelsman & Henderson, 2008; Kambas et al., 2012). Specifically, our previous research Kokštejn et al. (2017) provided evidence that FMS proficiency assessed by the MABC-2 differs between preschool boys and girls and that this FMS proficiency is not uniform regarding sex during whole preschool period. Therefore, we recommended that sex- and age-specific norms should be created for the MABC-2 test. However, as our previous study only assessed the differences between genders and ages, it would be logical that the discriminatory abilities of each test item should also be assessed before new sex- and age-specific norms are developed. By assessing the construct validity of the individual subtests within the MABC-2, it may be possible to make recommendations regarding which test items should remain and which should be adjusted. Therefore, the aim of this study was to use CFA to verify the construct validity of the MABC-2 test in the Czech population of preschool children with respect to gender and age. We hypothesized that variability in the children's test performance with respect to age or gender may be the cause of the inconsistent construct validity in the MABC-2 test.

Research sample:

Since our sample had to be sex and age balanced, we decided to use a stratified sampling method. In the first step, we determined the accessible area of public (not private) kindergartens without any special programmes (sport, language, art) in the capital city of Prague and in adjacent parts in the radius of 20 km from the limits of Prague. In cooperation with the management, we distributed a presentation for parents of the children in each kindergarten. Finally, we made a selection of study participants from 10 randomly selected kindergartens which matched the aforementioned criteria. Those parents who were interested provided a written informed consent for their child's participation in the study, in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Faculty of Physical Education and Sport at Charles University, Prague. Children who had been previously diagnosed with mental or other serious clinical impairments (n = 6) were excluded from the study. Final research sample consisted of a total of 510 preschool children (4.9 ± 1.1 years; 247 girls and 263 boys). After data analyses were done, parents of all involved children received a FMS profile of their child with suggestions especially for those children whose test scores were below the 15th percentile.

Procedure:

The MABC-2 test for age band 1 (3-6 years old) was used. According to the MABC-2 manual the raw score achieved in each test item is to be converted into the age-normed standard score available for Czech population. Further, standard scores of three MD tests, two AC tests and three BAL tests are converted to final total test score (TTS). In the current study the main aim was to verify the structural hypothesis about the existence and suitability of the three-factor structure suggested by Henderson et al. (2007) with respect to sex and age. Therefore, we will work with standard scores from each item rather than with final TTS which is used for the determination of whether a child has significant motor difficulties.

Unlike in the previous study, children were tested by one trained research team. Examiners from the research team performed the same tests for all children, meaning that there were no inter-rater testing procedures.

Statistical analysis:

CFA was used to verify the structural hypothesis about the three-factor model suitability and factorial validity of the MABC-2 items. There are several options how to estimate of parameters, which are mainly dependent on data distribution. Since the Mardia test, the Henze–Zirkler's test and the Royston's test rejected multivariate normal distribution, the robust maximum likelihood estimate parameter was used (Ferron &

Hess, 2007; Muthén & Muthén, 2010). The following fit indices with certain cut offs as guidelines for model suitability were used (1) model discrepancy: Chi-square (S-B$\chi 2$), model significance $p > 0.05$; (2) approximating error: root mean square error of approximation (RMSEA) < 0.06, standardized root mean square residual (SRMR) ≤ 0.08; and (3) incremental fit indices: comparative fit index (CFI) > 0.95, Tucker–Lewis Index (TLI) > 0.95 (McDonald, 1999). Further, differences between observed and model predicted correlation of two variables were investigated through normalized residual matrices. Values in normalized residual matrices higher than 1.96 were considered to share significant unexplained part of correlation. Additionally, the frequencies of a child achieving the maximum score in each test (i.e., ceiling effects) were also evaluated.

Due to the sufficient sample size in each age category we firstly applied separate CFA on three year3-year-old, 4-year-old, 5-year-old and 6-year-old children. Secondly, we did a separate CFA for boys and girls. Comparisons of model fits between each age category and between boys and girls were done using the Bayesian information criteria (BIC) coefficient. Differences between two BIC coefficients were evaluated using the approach of Raftery (Raftery, 1995), which respects the inner algorithm of the M-plus software, version 6 (Muthén & Muthén, 2010), which was used for data analysis.

Results:

In the first step, we used CFA for all n=510 children regardless of age and sex. From fit indices values, see first raw in (Fig. 17), it is quite clear that the original three-factor model did not sufficiently explain the empirical data in Czech children aged 3-6 (CFI and TLI <0.95).

TABLE 2 | Fit indices of the original three-factor model of movement assessment battery for children-second edition for all children; girls of all ages and boys of all ages; and boys and girls combined for separate age categories.

Group	N	S-Bχ²	P	DF	BIC	RMSEA	RMSEA 90% CI	SRMR	CFI	TLI
All children	510	41.44	0.008	17	19,275.71	0.053	0.033–0.074	0.040	0.92	0.87
Girls: all ages	246	48.01	<0.000	17	9,968.60	0.086	0.058–0.115	0.069	0.79	0.66
Boys: all ages	263	20.61	0.240	17	9,276.97	0.028	0.000–0.066	0.038	0.98	0.96
3-year olds	121	17.82	0.400	17	4,932.55	0.020	0.000–0.086	0.050	0.99	0.98
4-year olds	143	19.14	0.320	17	5,149.36	0.030	0.000–0.084	0.039	0.98	0.97
5-year olds	125	27.85	0.050	17	5,578.96	0.070	0.009–0.118	0.074	0.85	0.75
6-year olds	121	20.75	0.240	17	5,477.35	0.043	0.001–0.096	0.058	0.86	0.76
3- to 4-year-old boys	142	24.50	0.106	17	5,692.82	0.056	0.000–0.101	0.045	0.94	0.89
3- to 4- year-old girls	122	31.37	0.018	17	5,826.58	0.083	0.034–0.128	0.059	0.88	0.80
5- to 6-year-old boys	121	18.36	0.364	17	4,231.36	0.026	0.000–0.088	0.053	0.98	0.97
5- to 6-year-old girls	125	Heywood case correlation between BAL1 and factor balance greater than 1								

S-Bχ², chi-squared; DF, degrees of freedom; BIC, Bayesian information criteria; RMSEA, root mean square error of approximation; CI, confidence interval; SRMR, standardized root mean square residual; CFI, comparative fit index; and TLI, Tucker–Lewis index.
Greater CFI, TLI, and p-values are desirable, indicating a "better" model fit; whereas lower BIC, RMSEA, and SRMR are desirable, indicating a "better" model fit.

Figure 17. Fit of the original three-factor model of MABC-2 for all children, girls of all ages and boys of all ages, each age category separately and combined categories boys and girls
Adapted from Kokstejn, Musalek and Tufano (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

When we looked at the relations within the structure of this model (Fig. 18), we revealed that item BAL3 Jumping on Mats has very low factor loading λ=0.19. Further, CFA in all children showed very strong correlation between sub-test MD (manual dexterity) and BAL (balance) r=0.89 suggesting that there is poor discrimination between these two behaviourally different constructs.

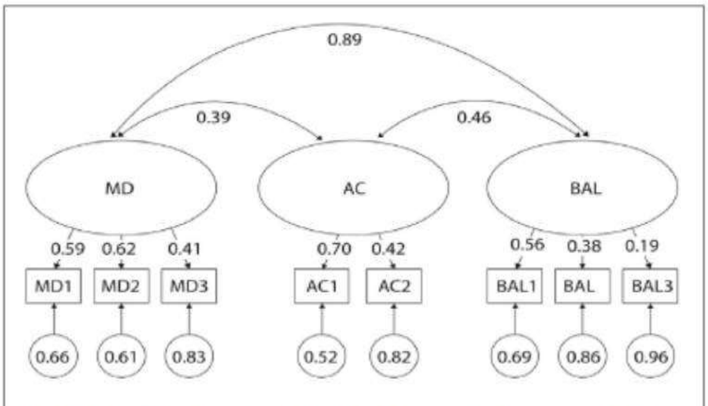


FIGURE 1 | Original three-factor model of the movement assessment battery for children-second edition-2 test for 3- to 6-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

Figure 18. Original three-factor model for all children with factor loadings
Adapted from Kokstejn et al. (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

Since we wanted to know whether the poor fit of the model was sex related, we carried out CFA for boys and girls independently. Results from the MABC-2 indicated that the original three-factor model of FMS seems to be suitable to be applied for boys (p=0.24) but not for girls (p<0.05), whose fit was the worst from all analysis that were carried out, see Fig XX. A detailed analysis of factor loadings and correlations between sub-tests of MABC-2 in both boys and girls models found several significant lacks. For girls poor factor loadings were found in MD3 – Drawing Trail λ=0.31 for, BAL2 – Walking Heels Raised λ=0.19, BAL3 – Jumping on Mats λ=0.23. In boys "only" one really poor factor loading was revealed in BAL3 – Jumping on Mats λ=0.16. Additionally, the correlation was too high in girls as well as boys between factors MD and BAL (*r* = 0.97 and *r* = 0.83) (Fig. 19 (Figures 2 and 3)). When we looked into normalized residual matrices on a portion of unexplained correlation, we found significantly higher values, not satisfactory (>1.96) in girls between MD3 – Drawing Trail and BAL1 – One-Leg BAL = 2.373; AC2 – Throwing a Beanbag onto a Mat and BAL2 – Walking Heels Raised = 2.172; and AC2 – Throwing a Beanbag onto a Mat and BAL3 – Jumping on Mats = 1.973.

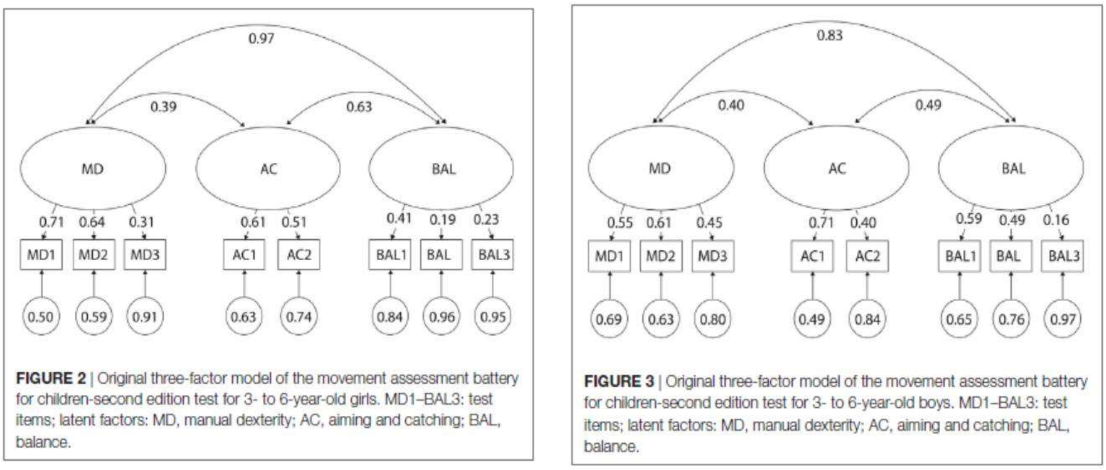


Figure 19. FIGURE 2 Original three factor model with factor loadings for all girls; FIGURE 3 Original three factor model with factor loadings for all boys
Adapted from Kokstejn et al. (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

Further, based on the finding of Henderson that reliability of an item is, mainly in younger pre-school age children, questionable, we were interested whether the original three-factor model would fit equally across all ages. Although the RMSEA, SRMR, and *p*-values generally suggested that empirical covariances of MABC-2 items agreed with the predicted model covariances in all age categories (Fig. 17), different BIC index values and poor CFI and TLI scores revealed significant variability in model fits between age categories and models for five and six years old children had to be rejected. We can say that the possible troublemakers in the models seems to be mainly items related to the BAL sub-test (age of 4 – BAL3; age of 5 – BAL3; age of 6 – BAL2 and BAL3) and then also item AC1 in 6-year-old children (Fig. 20 and Fig. 21).

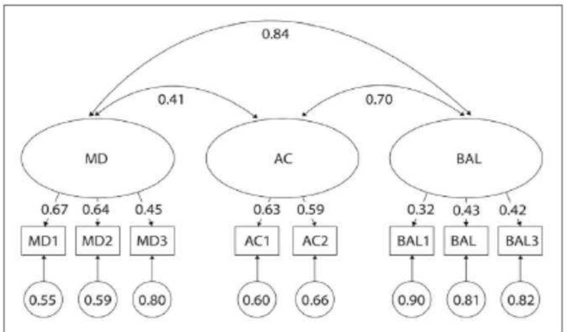


FIGURE 4 | Original three-factor model of the movement assessment battery for children-second edition test for 3-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

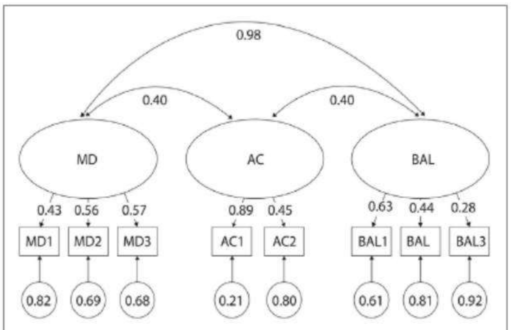


FIGURE 5 | Original three-factor model of the movement assessment battery for children-second edition test for 4-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, –aiming and catching; BAL, balance.

Figure 20. FIGURE 4 Original three factor model with factor loadings for 3-years old children; FIGURE 5 Original three factor model with factor loadings for 4-years old children
Adapted from Kokstejn, Musalek, and Tufano (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

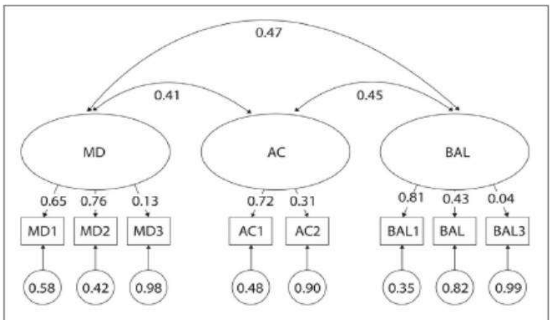


FIGURE 6 | Original three-factor model of the movement assessment battery for children-second edition test for 5-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

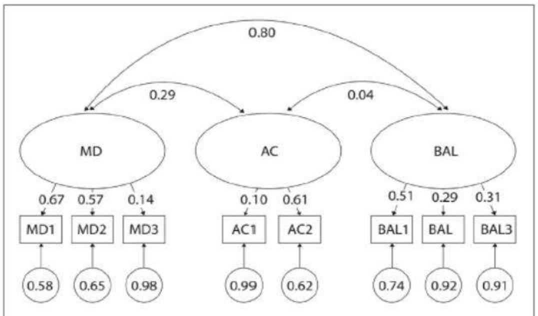


FIGURE 7 | Original three-factor model of the movement assessment battery for children-second edition test for 6-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

Figure 21. FIGURE 6 Original three factor model with factor loadings for 5-years old children; FIGURE 7 Original three factor model with factor loadings for 6-years old children
Adapted from Kokstejn, Musalek, and Tufano (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

The last question which still remained unanswered in this study was to verify a possible interaction between age and sex. Therefore, we divided the children to four groups (3- to 4-year-old boys, 3- to 4-year-old girls, 5- to 6-year-old boys, and 5- to 6-year-old girls). Subsequent CFAs revealed that for both age groups of boys, the original three-factor model fits well. In contrast, the fit was not so good in girls of all age groups, especially in 5- to 6-year-old girls, where a Heywood case was detected (Fig. 17). We talk about a Heywood case when negative variance is present in an analysis. It may have different causes (from sample size problems to collinearity between items). In other words, the results in 5- to 6-year-old girls showed too little variance to be explained in the construct, thus forcing structural error variance to be negative. Nevertheless, a Heywood case means serious problems in a model, which cannot be accepted.

Summary:

In conformity with the majority of previous studies (Schultz et al., 2011; Hua et al., 2013; Psotta and Brom, 2016), we did not find sufficient support to accept the original three-factor model of MBAC-2 AB1 when CFA was used for children in the range 3-6 years. Henderson et al. (2007) wrote in the MABC-2 Manual that the correlation between scores obtained from MD and BAL is 0.26. Nevertheless, this correlation does not represent a between-factor (construct) correlation received from CFA which showed how much the constructs behaviourally overlap and whether they share too much common variance. In contrast, the results of our study showed that the correlation between factors (constructs) MD and BAL =0.89 which means that these constructs measure a very similar domain. As a rule of thumb, according to some methodologists, the cut off that allows us to accept that two constructs measure a similar domain is put at around construct correlation =0.80 (Kline, 2011). When we compared our results with previous CFAs carried out on the MABC-2, we revealed that the between-factor correlation of MD and BAL was in Hua et al. (2013) r=0.63 and in Psotta and Brom (2014) r=0.75. However, in the Psotta and Brom (2016) study this between-factor correlation was obtained after adding an error correlation parameter between the MD1 and MD2 items. The between-factor correlation of MD and BAL is not mentioned in the original model. Nevertheless, Psotta and Brom are the closest to our study by research design because they conducted their research also on Czech children. Further, Schultz et al. (2011) did not provide the original between-factor correlation and just stated that the three-factor model with intercorrelated factors of MD, AC and BAL had to be rejected because of poor fit indices. Nevertheless, the study Schultz et al. (2011) gave us a certain idea why the aforementioned factors correlate more than it would be assumed. These authors used information from Rarick, Dobbins and Broadhead (1976), who allegedly revealed three factors 1) Fine Visual Motor Coordination equal to MD; 2) Gross Limb-Eye Coordination equal to AC; 3) Balance on sample of 145 typically developing children. However, this study investigated the structure of the motor domain and its correlations in educationally handicapped children citation "*describes an investigation primarily concerned with the identification of the basic components of the motor behavior of educable mentally retarded children through the use of factor analysis technique"* (Rarick et al., 1976). So the question is whether a structure of the defined factors: 1) Fine Visual Motor Coordination equal to MD; 2) Gross Limb-Eye Coordination equal to AC; 3) Balance determined in an exploratory not confirmatory way can be equally replicated on neurotypical developed children. Even though Schultz et al. (2011) supported this reasonably devised platform with the results of later studies Bruininks and Bruininks, (2005) (BOTMP) and Sun, Zhu, Shih, Lin and Wu, (2010) (Preschooler Gross Motor Quality Scale - PGMQ), we should be very careful to generally confirm the existence of three factors that do not measure a similar domain in pre-school age children. Firstly, the item banks of BOTMP and PGMQ are different from those in MABC-2; secondly, both abovementioned batteries contained a much greater number of items scored in each sub-test (greater diversity); thirdly, the study Sun et al. (2010) used only one fit index RMSEA based on which the authors accepted the whole model. Further, when we looked at the relations between the items and the sub-tests, we revealed, similarly to Hua et al., (2013) and Psotta and Brom (2016), problems in the BAL sub-test, more specifically the poor factor validity of BAL2 λ=0.19. We can conclude, based on the information provided in this paragraph, that it would be rather problematic to consider the defined factors (constructs) MD, AC and BAL as clearly separable areas in motor development and FMS in preschoolers at least in a situation when researchers do not know how the structure would changed when considering basic covariates like age and sex.

Unlike previous studies, which used CFA and tried to find the best model for the data from the MABC-2, we were interested whether the variables of age and sex would give us a better insight into the structure of FMS. Separate CFAs applied on girls (3-6) and boys (3-6) rejected the three-factor model in girls ($p<0.05$), where all fit indices where even poorer than in a CFA carried out on all 510 children. In addition to an almost direct relationship between the MD and BAL factors (constructs) $r=0.97$, poor factor validity was found in BAL1=0.41(one-leg balance), BAL2 = 0.23, (walking heels raised) BAL3; BAL3 = 0.19 (jumping on mats), which suggests that these items did not estimate and discriminate well between certain degrees of Balance in girls. In contrast, empirical data in boys were explained from 24% by the three-factor model and therefore seemed to be acceptable. However, item BAL3 jumping on mats showed poor factor validity also in boys. The results of CFAs considering sex independently provided support for the conclusion from our previous study Kokštejn et al. (2017) that boys and girls do not acquire motor skills in parallel. This unequal development has many causes, which we explained in the previous two chapters. It is mainly the combination of biological and environmental factors (for more information see chapter 5.1). Further, it is interesting to note that four separate CFAs of four age groups (three, four, five, six) revealed difference model fits. While three-factor models of the MABC-2 for 3- and 4-year old children could be accepted, the same three-factor models for older, 5- and 6-year olds expressed poor fit CFI<0.95 and TLI<0.95 and had to be rejected. It is also noteworthy that in girls the consistency of rejecting the three-factor model was confirmed also when splitting the girls into age categories of 3-4 years and 5-6 years. On the other hand, in boys it seems to depend more on the developmental process because the model for 3- to 4year-old boys could not be accepted, while the model for 5- to 6-year-old boys showed acceptable values of all fit indices.

From the perspective of suitability of the three-factor model we can conclude that the three-factor structure of the MABC-2 seemed to be reasonable for boys and for children of both sexes up to the age of four. During CFAs we detected so-called troublemaker items with poor factor validity. Those were mostly items for assessing of Balance and also one item from Manual dexterity MD3 – drawing trail. There is more than one reason why a certain item does not fit to the given structure. Usually problems arise from the semantic content of an item, its intelligibility to the examinee or its difficulty. Since we only used the empirical quantitative scores, we focused our attention on the difficulty of the problematic items. In our study, a large percentage of children achieved the highest possible score in BAL2 (78% and 85% in 5- and 6-year olds, respectively), BAL3 (94% and 96% in 5- and 6-year olds, respectively) and MD3 (70% in 6-year olds). These results also match the finding of Psotta and Brom (2016). In addition, an agreement between poor performance (≤16th percentile) in MD3, BAL2 and BAL3 and poor TTS (≤16th percentile) was 65% in 3-year olds, 60% in 4-year olds, 44% in 5-year olds, and 47% in 6-year olds. Thus, a strong ceiling effect and weak ability of discrimination for MD3 BAL2, and BAL3 appear as possible causes of the low discriminatory ability in dynamic BAL and MD in 5- and 6-year-old preschoolers. The data from the present study confirm the suggestions set forth by Kokštejn et al. (2017) and Livesey et al. (2007) that gender-specific normative values should be determined so that the MABC-2 can effectively identify children with motor difficulties, ultimately resulting in more appropriate motor intervention programmes for preschool children.

References:

Brown, T., & Lalor, A. (2009). The movement assessment battery for children—second edition (MABC-2): a review and critique. *Physical & occupational therapy in pediatrics*, *29*(1), 86-103.

Burton, A. W., & Miller, D. E. (1998). *Movement skill assessment*. Human Kinetics.

Cools, W., De Martelaer, K., Samaey, C., & Andries, C. (2009). Movement skill assessment of typically developing preschool children: A review of seven movement skill assessment tools. *Journal of sports science & medicine*, *8*(2), 154-168.

Ellinoudis, T., Evaggelinou, C., Kourtessis, T., Konstantinidou, Z., Venetsanou, F., & Kambas, A. (2011). Reliability and validity of age band 1 of the Movement Assessment Battery for Children–Second Edition. *Research in Developmental Disabilities*, *32*(3), 1046-1051.

Gidley Larson, J. C., Mostofsky, S. H., Goldberg, M. C., Cutting, L. E., Denckla, M. B., & Mahone, E. M. (2007). Effects of gender and age on motor exam in typically developing children. *Developmental neuropsychology*, *32*(1), 543-562.

Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *Movement assessment battery for children – 2 examiner's manual*. London: Harcourt Assessment.

Hua, J., Gu, G., Meng, W., & Wu, Z. (2013). Age band 1 of the Movement Assessment Battery for Children-: Exploring its usefulness in mainland China. *Research in Developmental Disabilities*, *34*(2), 801-808.

Kambas, A., Venetsanou, F., Giannakidou, D., Fatouros, I. G., Avloniti, A., Chatzinikolaou, A., ... & Zimmer, R. (2012). The Motor-Proficiency-Test for children between 4 and 6 years of age (MOT 4–6): An investigation of its suitability in Greece. *Research in Developmental Disabilities*, *33*(5), 1626-1632.

Kline, R. B. (2011). *Principles and practice of structural equation (3rd ed.)*. New York: Guildford Press.

Kokstejn, J., Musalek, M**.,** & Tufano, J. J. (2018). Construct Validity of the MABC-2 Test in Preschool Children with Respect to Age and Gender. *Frontiers in Pediatrics*, *6*, 12.

Kokštejn, J., Musálek, M., & Tufano, J. J. (2017). Are sex differences in fundamental motor skills uniform throughout the entire preschool period?. *PLoS one*, *12*(4), e0176556.

Livesey, D., Coleman, R., & Piek, J. (2007). Performance on the Movement Assessment Battery for Children by Australian 3-to 5-year-old children. *Child: care, health and development*, *33*(6), 713-719.

McDonald, R. P. (1999). *Test theory: A unified treatment*. Mahwah, N.J: L. Erlbaum

Musalek, M., Kokstejn*,* J., Papez*,* P., Jírovec, J., *&* Honsová, S. (2017). Relation Between Percent Body Fat and Fundamental Motor Skills in Pre-School Children age 3-6 years. *Sport Mont, 15*(2), 9-13.

Muthén, L. K., & Muthén, B. O. (2010). *Mplus user's guide: Statistical analysis with latent variables: User'ss guide*. Muthén & Muthén.

Psotta, R., & Brom, O. (2016). Factorial structure of the movement assessment battery for children test-second edition in preschool children. *Perceptual and motor skills*, *123*(3), 702-716.

Raftery, A. E. (1995). Bayesian model selection in social research. *Sociological methodology*, 111-163.

Rarick, G. L. Dobbins, D. A., & Broadhead, G. D. (1976). *The Motor Domain and its Correlates in Educationally Handicapped Children.* Washington, DC.; Joseph P. Kennedy, Jr. Foundation, Washington, DC.

Schulz, J., Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2011). Structural validity of the Movement ABC-2 test: Factor structure comparisons across three age groups. *Research in Developmental Disabilities*, *32*(4), 1361-1369.

Smits-Engelsman, B. C., Niemeijer, A. S., & van Waelvelde, H. (2011). Is the Movement Assessment Battery for Children-a reliable instrument to measure motor performance in 3 year old children?. *Research in developmental disabilities*, *32*(4), 1370-1377.

Sun, S. H., Zhu, Y. C., Shih, C. L., Lin, C. H., & Wu, S. K. (2010). Development and initial validation of the preschooler gross motor quality scale. *Research in Developmental Disabilities*, *31*(6), 1187-1196.

Van Waelvelde, H., Peersman, W., Lenoir, M., Engelsman, B. C. S., & Henderson, S. E. (2008). The movement assessment battery for children: similarities and differences between 4-and 5-year-old children from Flanders and the United States. *Pediatric Physical Therapy*, *20*(1), 30-38.

Wagner MO, Kastner J, Petermann F, Bös K. (2011). Factorial validity of the movement assessment battery for children-2 (age band 2). *Res Dev Disabil,* 32(2):674–80. doi:10.1016/j.ridd.2010.11.016 17.

frontiers in Pediatrics

ORIGINAL RESEARCH
published: 30 January 2018
doi: 10.3389/fped.2018.00012

Construct Validity of the Movement Assessment Battery for Children-Second Edition Test in Preschool Children with Respect to Age and Gender

*Jakub Kokštejn, Martin Musálek and James J. Tufano**

Faculty of Physical Education and Sport, Charles University, Prague, Czechia

Background: The Movement Assessment Battery for Children-second edition (MABC-2) Age Band 1 is widely used to identify preschoolers with motor difficulties. Despite unsatisfactory construct validity of the original three-factor model, MABC-2 (manual dexterity, aiming and catching, and balance), previous research has not considered possible age and gender differences throughout the entire preschool period.

Aim: The aim of this study was to verify the construct validity of the MABC-2 Age Band 1 in a population of Czech preschoolers with respect to age and gender.

Methods: Using data from 510 Czech preschoolers (3–6 years; 4.9 ± 1.1 years), confirmatory factor analyses (CFA) were used for each age category and gender.

Results: The goodness-of-fit indices of CFA supported the original three-factor model of the MABC-2 only in 3- and 4-year-old children, and in boys (3–6 years). Low factor loadings and ceiling effects of several test items (Drawing Trail, Walking Heels Raised, and Jumping on Mats) seem to be a probable cause of weak fit indices in 5- and 6-year-old children and in girls (3–6 years).

Conclusion: These results suggest that the MABC-2 can be a valid tool for assessing motor development and identifying motor difficulties among 3- to 4-year olds, and generally fits better for preschool boys in the Czech Republic. However, in 5- to 6-year olds, ceiling effects and a low power of discrimination was found for the Drawing Trail, Walking Heels Raised, and Jumping on Mats tests. Therefore, the three-factor model is not appropriate for all preschoolers, and separate norms should be established for each age and gender.

Keywords: motor assessments, movement difficulties, confirmatory factor analysis, motor skills, motor development

Edited by:
Frederick Robert Carrick, Bedfordshire Centre for Mental Health Research, University of Cambridge, United Kingdom

Reviewed by:
John Stins, VU University Amsterdam, Netherlands
Jody L. Jensen, University of Texas at Austin, United States

Correspondence:
James J. Tufano
james.j.tufano@gmail.com

Specialty section:
This article was submitted to Child Health and Human Development, a section of the journal Frontiers in Pediatrics

Received: *07 November 2017*
Accepted: *12 January 2018*
Published: *30 January 2018*

Citation:
Kokštejn J, Musálek M and Tufano JJ (2018) Construct Validity of the Movement Assessment Battery for Children-Second Edition Test in Preschool Children with Respect to Age and Gender. Front. Pediatr. 6:12. doi: 10.3389/fped.2018.00012

INTRODUCTION

During childhood, motor development plays a crucial role in the physical, cognitive, and social development of preschool- and school-aged children (1–3). Particularly, the adequate acquisition of fundamental motor skills (FMS) during early childhood has been considered as a crucial step in developing specialized and more complex motor skills later in life (2, 4, 5). Moreover, Rose et al. (6) have argued that a lack of FMS competency may result in frustration and difficulty in learning more specialized skills, thereby reducing the enjoyment of physical activity as well as the likelihood of developing a physically active lifestyle. Therefore, to design effective motor programs or to support the involvement of a child with special needs, it is important to assimilate valid information about the FMS levels of children (7).

To assess motor proficiency and identify impairments in motor coordination in children, standardized motor performance tests are commonly used (3, 8). Of these tests, the second version of the Movement Assessment Battery for Children-second edition (MABC-2) (9) is one of the most commonly used and includes three age bands: age 3–6 (AB1), 7–10 (AB2), and 11–16 (AB3) (3). The MABC-2 test consists of a three-factor model that assesses motor proficiency in three different motor domains: manual dexterity (MD), aiming and catching (AC), and balance (BAL). Based on the total MABC-2 test score, the "traffic light system" identifies a child's motor competency as fitting into one of three categories: (1) without motor difficulties, (2) at risk of motor difficulties, and (3) severe motor difficulties. Moreover, the final range, with severe motor difficulties, is often associated with the confirmation of a developmental coordination disorder (10).

According to the MABC-2 test manual, the main purposes of the test is to identify motor development problems, evaluate the effectiveness of motor-skill intervention programs, and clinically investigate the motor skills of children (9). Additionally, other child motor development specialists have suggested that the test is suitable for assessing the developmental status of FMS, realizing the achievement of early motor-related milestones, and evaluating specialized movement skills (3, 11). As such, several studies used the MABC-2 to assess and document the levels of FMS competence among normally developing preschool children (12–15). With the MABC-2 being so popular, it is necessary to determine whether the MABC-2 effectively measures separate motor skills in separate domains. If there is a strong relationship between subtest scores, it may be that the separate tests could be measuring similar constructs and essentially counting the score of a shared construct more than once in the total test score (TTS).

Some studies have shown that the MABC-2 test has sufficient content (e.g., MABC-2 tests include different areas of motor skills) and criteria validity (e.g., MABC-2 test scores correlate with motor skills) (16, 17). However, these studies did not enable direct quantitative relationships to be determined between indirectly observed constructs and empirical indicators such as "manual dexterity" and "posting coins," respectively (16). For assessing the relationship between constructs, or between a construct and a directly measured variable in a definite structure, confirmatory factor analysis (CFA) should be used (17).

In a study conducted by Schulz et al. (18), CFA clearly rejected the MABC-2's original three-factor model, and the most appropriate model showed a bi-factor structure with one general (motor skill) factor for all variables in the MABC-2 and three separate constructs (MD, AC, and BAL) where correlations between each construct had to be fixed to a value of 0, indicating that they measured different movement properties and were not correlated to each other. These authors, however, did not look at the possible influence of age and gender throughout the entire preschool period, which has recently been shown to affect MABC-2 test scores (13). Similarly, the three-factor model was also rejected by Hua et al. (19) and Psotta and Brom (8) in samples of 1,823 Chinese and 399 Czech preschoolers, respectively. Although Ellinoudis et al. (20) verified the structure of the three-factor model on a sample of Greek preschoolers, they used a relatively small sample size ($n = 183$) that consisted only of 3- to 5-year-old children, excluding 6-year olds, who likely require different testing procedures, scoring procedures, or both (13).

The rather ambiguous results of the aforementioned studies indicate that throughout the preschool period (3–6 years), a wide range of individual differences in motor-skill development is likely present between different ages and genders (13, 21–24). This consideration was supported by Schulz et al. (18), who suggested that future research should examine the structure of factors in the MABC-2 test at different ages. Additionally, the effect of gender could also affect the validity of MABC-2, as research has shown that motor competencies can differ between boys and girls of the same age (13, 14, 25, 26). Specifically, our research group provided evidence that FMS proficiency assessed by the MABC-2 differs between preschool boys and girls. Further, it was found that these differences are not uniform throughout the entire preschool period (3–6 years old) (13). Therefore, we recommended that sex- and age-specific norms should be created for the MABC-2 test. However, as our previous study only assessed the differences between genders and ages, it would be logical that the discriminatory abilities of each test item should also be assessed before new sex- and age-specific norms are developed. By assessing the construct validity of the individual subtests within the MABC-2, it may be possible to make recommendations regarding which test items should remain and which should be adjusted.

Therefore, the aim of this study was to use CFA to verify the construct validity of the MABC-2 test in a Czech population of preschool children with respect to gender and age. We hypothesized that variability in the children's test performance with respect to age or gender may be the cause of the inconsistent construct validity in the MABC-2 test.

MATERIALS AND METHODS

Participants

A portion of these data (325 children) were previously used to assess whether gender-specific differences in FMS were uniform throughout the entire preschool period (13). As the aims of the present study were starkly different to those of the previous study (13), we also extended our research sample by 185 preschool children to better assess the construct validity of the MABC-2. Therefore, a total of 510 preschool children (4.9 ± 1.1 years; 247 girls and 263 boys) participated in this study. Using gender and age as stratification variables, a stratified sampling method was used to select study participants from 10 randomly selected kindergartens throughout Prague and its surrounding areas. Children who had been previously diagnosed with mental or other serious clinical impairments ($n = 6$) were excluded from the study. In cooperation with the kindergarten's management, parents were informed on the purpose, benefits, and risks of the study. Those who were interested provided written informed consent for their child's participation in the study, in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of the Faculty of Physical Education and Sport at Charles University, Prague. After data collection and analyses, parents received a report with their child's motor performance results, which also contained information about helpful public service programs for children whose test scores were below the 15th percentile.

Instrument

The MABC-2 test for age band 1 (3–6 years old) includes eight test items that represent the three motor domains: MD, AC, and BAL (**Table 1**).

According to the MABC-2 manual with norms for Czech preschoolers [Czech version (27)], the raw score achieved in each test item is to be converted into the age-normed standard score. The better a child performs, the higher the standard score is. In the MABC-2 test, the overall level of motor-skill competency is represented by the TTS, which is then calculated as a sum of the standard scores of all eight test items and converted to a standard score equivalent and percentile equivalent. A TTS lesser than or equal to the fifth percentile indicates significant motor difficulties; a TTS between the sixth and 15th percentile indicates a risk of motor difficulties; and a TTS greater than the 15th percentile indicates typical motor coordination development (9).

Procedure

Children were tested by a team of trained examiners (Master's degrees in Adapted Physical Education, Special Pedagogy, Physiotherapy, etc.), who underwent the user's training program that focused on understanding the theoretical issues and practical skills needed for administering and scoring the test. These research assistants performed the same tests for all children, meaning that there were no inter-rater testing procedures. Children were individually tested in their regular educational setting during morning classes, taking about 20–30 min to complete for each child.

TABLE 1 | Movement assessment battery for children-second edition (MABC-2) test for preschool children (age Band 1).

MABC-2 test motor domain	Task
Manual dexterity (fine motor skills)	MD1 posting coins MD2 threading beads MD3 drawing trail
Aiming and catching (gross motor skills)	AC1 catching beanbag AC2 throwing a beanbag onto a mat
Balance	BAL1 one-leg balance BAL2 walking heels raised BAL3 jumping on mats

Statistical Analysis

For the purpose of data analysis, we used the standard scores of the MABC-2 test items. To verify the factorial validity of the MABC-2, CFA was used. The Mardia test, Henze–Zirkler's test, and Royston's test rejected multivariate normal distribution; therefore, the robust maximum likelihood estimate parameter was used (28, 29). According to the recommendations of McDonald (30) and Maydeu-Olivares and McArdle (31), the following fits were used: (1) model discrepancy: Chi-square (S-Bχ^2), model significance $p > 0.05$; (2) approximating error: root mean square error of approximation (RMSEA), standardized root mean square residual (SRMR); and (3) incremental fit indices: comparative fit index (CFI), Tucker–Lewis Index (TLI). To determine the quality of a model, we respected the recommendations of McDonald and Marsh (32), Hu and Bentler (33), and Kline (34): RMSEA < 0.06; CFI > 0.95; TLI > 0.95; and SRMR ≤ 0.08.

First, separate CFAs were applied to each age category and then to each gender. Comparisons between model fit between each age category and between genders was done using the Bayesian information criteria (BIC) coefficient: a smaller BIC means a better model fit (29, 35). Differences between two BIC coefficients were evaluated using the approach of Raftery (36) which respects the inner algorithm of the M-plus software, version 6 (29), which was used for data analysis. For revealing possible causes of low fit indices of the model, we checked differences in factor loadings of test items and correlations between factors among each age categories.

Except for the fit indices, the differences between the observed and predicted covariances in residual matrices were investigated. Since the multivariate normality of items was rejected, we analyzed values from the normalized residual matrix (37, 38), as they represent the normalized difference between observed and model predicted model correlation of two variables. This difference is then transformed on scale where values higher than 1.96 are considered to be significant (39, 40). In other words, normalized residuals higher than 1.96 indicate that there is a large unexplained portion of a relationship between the empirical and predicted correlation of two variables. Additionally, the frequencies of a child achieving the maximum score in each test (i.e., ceiling effects) were also evaluated.

RESULTS

For the sake of simplicity, only data that do not support the three-factor model are presented in the text and it can be assumed that data that is not reported in the text support the three-factor model. When assessing children of both genders and all ages together, the original three-factor was rejected according to the significant chi-square value ($p < 0.01$) and the poor fit indices (CFI < 0.95, TLI < 0.95) (**Table 2**). Subsequent analysis of factor loading differences revealed poor discriminatory properties (**Figure 1**). For example, although high factor loading values (λ) are desired, they were as low as 0.19 for BAL3 Jumping on Mats. Moreover, a very high correlation was found between MD and BAL ($r = 0.89$), suggesting that there is poor discrimination between these two behaviorally different constructs.

TABLE 2 | Fit indices of the original three-factor model of movement assessment battery for children-second edition for all children; girls of all ages and boys of all ages; and boys and girls combined for separate age categories.

Group	N	S-Bχ^2	P	DF	BIC	RMSEA	RMSEA 90% CI	SRMR	CFI	TLI
All children	510	41.44	0.008	17	19,275.71	0.053	0.033–0.074	0.040	0.92	0.87
Girls: all ages	246	48.01	<0.000	17	9,968.60	0.086	0.058–0.115	0.069	0.79	0.66
Boys: all ages	263	20.61	0.240	17	9,276.97	0.028	0.000–0.066	0.038	0.98	0.96
3-year olds	121	17.82	0.400	17	4,932.55	0.020	0.000–0.086	0.050	0.99	0.98
4-year olds	143	19.14	0.320	17	5,149.36	0.030	0.000–0.084	0.039	0.98	0.97
5-year olds	125	27.85	0.050	17	5,578.96	0.070	0.009–0.118	0.074	0.85	0.75
6-year olds	121	20.75	0.240	17	5,477.35	0.043	0.001–0.096	0.058	0.86	0.76
3- to 4-year-old boys	142	24.50	0.106	17	5,692.82	0.056	0.000–0.101	0.045	0.94	0.89
3- to 4- year-old girls	122	31.37	0.018	17	5,826.58	0.083	0.034–0.128	0.059	0.88	0.80
5- to 6-year-old boys	121	18.36	0.364	17	4,231.36	0.026	0.000–0.088	0.053	0.98	0.97
5- to 6-year-old girls	125	Heywood case correlation between BAL1 and factor balance greater than 1								

S-Bχ^2, chi-squared; DF, degrees of freedom; BIC, Bayesian information criteria; RMSEA, root mean square error of approximation; CI, confidence interval; SRMR, standardized root mean square residual; CFI, comparative fit index; and TLI, Tucker–Lewis index.
Greater CFI, TLI, and p-values are desirable, indicating a "better" model fit; whereas lower BIC, RMSEA, and SRMR are desirable, indicating a "better" model fit.

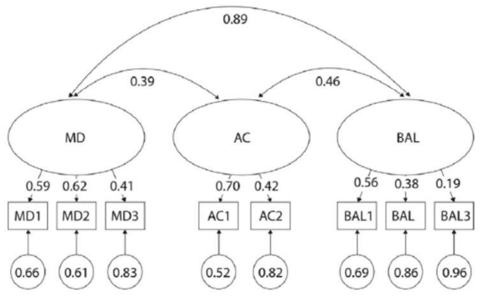


FIGURE 1 | Original three-factor model of the movement assessment battery for children-second edition-2 test for 3- to 6-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

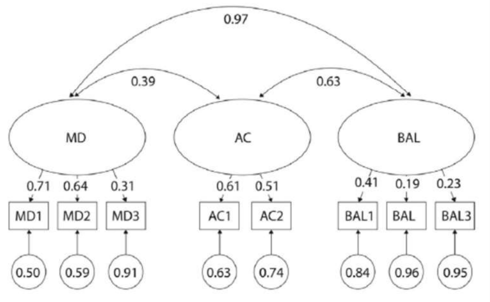


FIGURE 2 | Original three-factor model of the movement assessment battery for children-second edition test for 3- to 6-year-old girls. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

When combining children of all ages together but assessing each gender independently, the three-factor model of the MABC-2 test did not fit in girls (S-Bχ^2 = 48.01. $p < 0.01$) with the lowest fit indices of all analyses within this study (TLI = 0.66, CFI = 0.79) (**Table 2**). Subsequent analysis of factor loading differences revealed the lowest discriminatory properties with λ values as low as 0.31 in girls for MD3—Drawing Trail, 0.19 in girls for BAL2—Walking Heels Raised, and 0.23 and 0.16 in both girls and boys, respectively, for BAL3—Jumping on Mats. Additionally, the correlation was too high in girls between factors MD and BAL ($r = 0.97$ and $r = 0.83$) (**Figures 2 and 3**). Normalized residual matrices were not satisfactory (>1.96) in girls between MD3—Drawing Trail and BAL1—One-Leg BAL = 2.373; AC2—Throwing a Beanbag onto a Mat and BAL2—Walking Heels Raised = 2.172; and AC2—Throwing a Beanbag onto a Mat and BAL3—Jumping on Mats = 1.973.

When combining both genders together but assessing each age category independently, CFA showed that the original three-factor model of MABC-2 did not fit equally across all ages

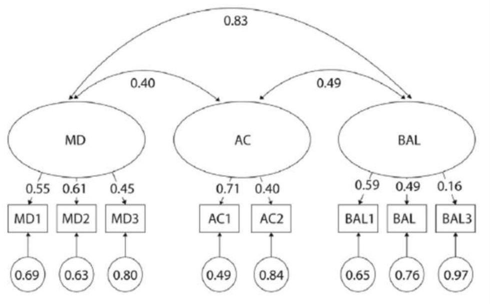


FIGURE 3 | Original three-factor model of the movement assessment battery for children-second edition test for 3- to 6-year-old boys. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

(**Table 2**). Although the RMSEA, SRMR, and *p*-values generally suggested that empirical covariances of MABC-2 items agreed with the predicted model covariances in all age categories, different BIC index values and poor CFI and TLI scores revealed significant variability in model fits between age categories.

In the next step of our analysis, we divided children according to age and gender, focusing on age and gender interactions. Subsequently, four CFAs (3- to 4-year-old boys, 3- to 4-year-old girls, 5- to 6-year-old boys, and 5- to 6-year-old girls) revealed that for both age groups of boys, the original three-factor model fits well. On the other hand, the fit was not as good in girls of all age groups, especially in 5- to 6-year-old girls where a Heywood case was detected. A Heywood case represents negative variance which indicates that there can be any combination of problems within the model such as too little variance of a directly measured item explained in construct, an item discrimination that is either too high or too low, a singularity in the matrix, an unusual random sample, or other causes. In our study, BAL1 showed the greatest variance compared to BAL2 and BAL3. It seemed that in the model, the majority of variance of construct was, therefore, explained by BAL1 and other items did not contribute significantly. As a result of the analysis for 5- to 6-year-old girls, it is not possible to compose a construct by one significant item. In other words, the results in 5- to 6-year-old girls showed too little variance to be explained in the construct, thus forcing structural error variance to be negative.

Several test items from the MABC-2 had poor discriminatory properties across age categories (**Figures 4–7**). For example, λ values were as low as $\lambda = 0.13$ and 0.14 in 5- and 6-year olds, respectively for MD3—Drawing; $\lambda = 0.10$ in 6-year olds for AC1—Catching Beanbag; $\lambda = 0.31$ in 5-year olds for AC2—Throwing a Beanbag onto a Mat; $\lambda = 0.32$ in 3-year olds for BAL1—One-Leg BAL; and $\lambda = 0.04$, 0.28, and 0.31 in 5-, 4-, and 6-year olds, respectively for BAL3—Jumping on Mats. Additionally, correlations were too high between certain factors across age categories (**Figures 4–7**). For example, *r* values were as high as 0.80, 0.84, and 0.98 for MD and BAL in 6-, 3-, and

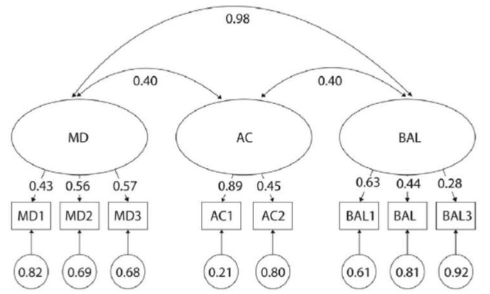


FIGURE 5 | Original three-factor model of the movement assessment battery for children-second edition test for 4-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, –aiming and catching; BAL, balance.

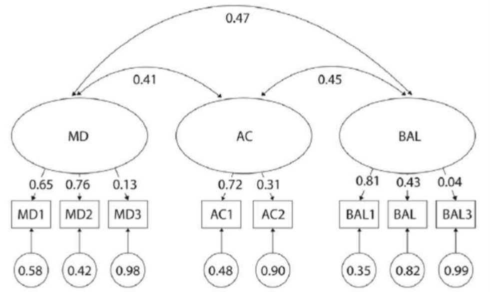


FIGURE 6 | Original three-factor model of the movement assessment battery for children-second edition test for 5-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

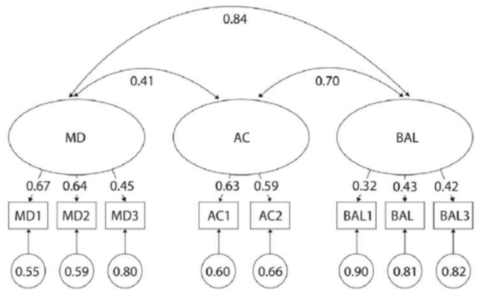


FIGURE 4 | Original three-factor model of the movement assessment battery for children-second edition test for 3-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

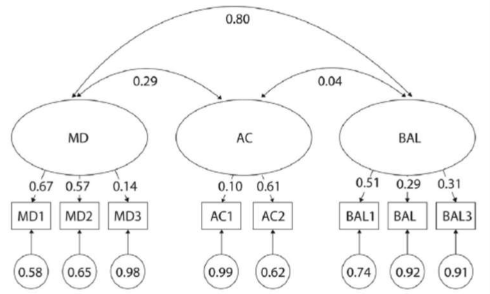


FIGURE 7 | Original three-factor model of the movement assessment battery for children-second edition test for 6-year-old children. MD1–BAL3: test items; latent factors: MD, manual dexterity; AC, aiming and catching; BAL, balance.

4-year olds, respectively. Normalized residual matrices were satisfactory (<1.96) for 3- and 4-year olds, but not 5- and 6-year olds (>1.96). In 5-year olds, the normalized residual was 3.166 for MD3—Drawing Trail and AC2—Throwing a Beanbag onto a Mat; and 2.690 for MD3—Drawing Trail and BAL2—Walking Heels Raised. In 6-year olds, the normalized residual was 2.134 for AC2—Throwing a Beanbag onto a Mat and BAL2—Walking Heels Raised. Moreover, a very strong ceiling effect (high percentage of children who reached the maximal score) was found in BAL2—Walking Heels Raised (78 and 85% in 5- and 6-year olds, respectively), BAL3—Jumping on Mats (94 and 95% in 5- and 6-year olds, respectively), and MD3—Drawing Trail (70% in 6-year olds).

DISCUSSION

Based on the results of previous studies (8, 18, 19), we hypothesized that variability in children's motor performance in relation to age or gender may be the underlying origin of inconsistent psychometric properties in the MABC-2 test. To our knowledge, this is the first study to verify the, apparent lack of, factorial validity of the original three-factor model of the MABC-2 motor test for each age category separately during the entire preschool period while also accounting for gender. As hypothesized, the three-factor model's goodness-of-fit indices were not satisfactory when grouping all (n = 510) preschool children together (RMSEA = 0.053; SRMR = 0.040; CFI = 0.92; TLI = 0.987). Specifically, the model did not fit when girls of all ages were grouped together, nor did it fit for 5-year olds or 6-year olds when boys and girls of the same age were grouped together. Moreover, the most serious problems were found in 5- to 6-year-old girls where the model showed a Heywood case, identifying problems specifically in the BAL construct. However, the present model did fit for 3-year olds of both genders, 4-year olds of both genders, and boys of all ages. All things considered, the findings of the present study suggest that the current three-factor model should not be applied to preschoolers of all ages and both genders, and that age- and gender-specific testing and scoring procedures should be developed.

Other researchers have also noted that the three-factor model may not accurately explain the empirical data that the MABC-2 purports to unveil (8, 18, 19). Particularly low factor loadings and a large number of standardized residuals were the main causes of the unsatisfactory fit of the original model of the MABC-2 in these studies. To obtain a satisfactory fit, the authors subsequently made additional statistical adjustments (excluding the weak test items, adding the correlated measurement errors, double factor loading of some test items, or creating general motor factor). Although the authors tried to defend their modification of the original model of MABC-2 test, such adjustments often decrease the theoretical nature of the model's constructs. Despite modifying these variables to achieve good fit indices of the model, these authors did not consider the possible effect of age and gender in the entire population of preschool children. Only Psotta and Brom (8) divided the sample into younger (3–4 years old) and older (5–6 years old) preschoolers while attempting to verify the construct validity of the MABC-2, but the authors did not report a satisfactory fit of the original three-factor model for either of the two age groups.

With respect to age, the results of CFA in the present study revealed substantial variability between different age categories. The findings clearly suggest that the three-factor model appears to sufficiently fit for 3- and 4-year-old Czech children independently, but not for 5- and 6-year olds. In contrast to a general motor factor as a possible indicator of children's overall motor competence (18), our results support the validity of the original three-factor model MABC-2 which is able to distinguish motor performance in different motor domains (fine motor skills, gross motor skills, and BAL) only in 3- and 4-year-old children.

We found substantial variability of factor loadings in MD3 (0.13–0.57), AC1 (0.10–0.89), BAL1 (0.32–0.81), BAL3 (0.04–0.42) between age categories. These findings showed that the aforementioned test items discriminate the level of three motor domains in significantly different ways across the entire preschool period. Moreover, we also revealed very low factor loadings of MD3, BAL2, and BAL3. These findings support the results of previous research where MD3 and BAL2 (19), MD3 and BAL3 (18), and BAL2 and BAL3 (8) were also identified as problematic due to their poor factor validity. Thus, the results suggest that these test items probably do not sufficiently represent their corresponding motor domains.

Although determining the construct validity was the primary aim of this study, our results identified a somewhat problematic phenomenon: many children achieved the highest possible score in some tests, indicating that a ceiling effect was present. The purpose of the MABC-2 test is to identify children who may be at risk of developing motor difficulties. However, if scoring procedures are too lenient or the test is too easy, the scores may artificially inflate a child's overall FMS performance, masking a possible motor impairment. In our study, a large percentage of children achieved the highest possible score in BAL2 (78 and 85% in 5- and 6-year olds, respectively), BAL3 (94 and 96% in 5- and 6-year olds, respectively) and MD3 (70% in 6-year olds), similar to Psotta and Brom (8). Thus, the tests are either likely too easy for 5- and 6-year olds, or the scoring criteria are too lenient, both indicating that the tests may not be able to discriminate between children who lack motor deficiencies, those at risk of deficiency, or those who have sever motor impairments. To further investigate the possible problematic nature of the testing and scoring procedures for these tests, we determined the discrimination function of MD3, BAL2, and BAL3 in relation to a TTS. An agreement between poor performance (≤16th percentile) in MD3, BAL2, and BAL3 and poor TTS (≤16th percentile) was 65% in 3-year olds, 60% in 4-year olds, 44% in 5-year olds, and 47% in 6-year olds. Thus, a strong ceiling effect and weak ability of discrimination for MD3, BAL2, and BAL3 appear as possible causes of the low discriminatory ability in dynamic BAL and MD in 5- and 6-year-old preschool children.

The original three-factor model showed good fit indices in boys (3–6 years), but the goodness-of-fit indices for girls were not satisfactory. Poor factor loadings of MD3 and BAL2 in girls and BAL3 in both genders suggests that these manifest variables likely measure different latent variables. This suggestion is supported by a very high correlation between the MD and BAL MABC-2 subtests ($r = 0.97$ in girls and $r = 0.83$ in boys). However, this assumption is hypothetical and cannot be determined using the data at hand. On the contrary, low factor loadings (poor discrimination property) of MD3 and BAL3 could be due to the presence of ceiling effects, indicating that the test requirements are too easy, or the scoring criteria are too lenient. Double factor loading, when manifest variables are significantly related to two latent factors, were also found in studies of Schulz et al. (18) and Psotta and Brom (8). Another possible explanation for the differences in the model fit indices for both genders in our study could be different rates in motor development between boys and girls. Recently, studies have shown that preschoolers develop FMS at different rates (13, 25, 26) and that these differences are not uniform through throughout the entire preschool period (13). As a result, consideration for separated norms for boys and girls had already been suggested (13, 14), and are again affirmed here.

Ambiguous results about the quality of the original three-factor model of MABC-2 were found in our study with respect to age and gender during entire preschool period. Particularly, low factor loadings and ceiling effects of several test items seem to be possible problems of the unsatisfactory construct validity of MABC-2 in 5- and 6-year-old children, and especially in girls 3–6 years old. The data from the present study confirm the suggestions set forth by Kokštejn et al. (13) and Livesey et al. (14) that gender-specific normative values should be determined so that the MABC-2 can effectively identify children with motor difficulties, ultimately resulting in more appropriate motor intervention programs for preschool children.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this article.

FUNDING

The study was supported by the Czech Science Foundation project No. 14-29358P and program Progress Q19 Social-Sciences Aspects of Human Movement Studies II.

REFERENCES

1. Gabbard CP. *Lifelong Motor Development: Pearson New International Edition*. 6th ed. Philadelphia: Pearson Higher Education (2013).
2. Gallahue DL, Ozmun JC, Goodway JD. *Understanding Motor Development: Infants, Children, Adolescents, Adults*. 7th ed. New York: McGraw-Hill (2011).
3. Cools W, De Martelaer K, Samaey C, Andries C. Movement skill assessment of typically developing preschool children: a review of seven movement skill assessment tools. *J Sports Sci Med* (2009) 8(2):154–68.
4. Stodden D, Goodway J, Langendorfer S, Roberton M, Rudisill M, Garcia C, et al. A developmental perspective on the role of motor skill competence in physical activity: an emergent relationship. *Quest* (2008) 60(2):290–306. doi:10.1080/00336297.2008.10483582
5. Clark JE, Metcalfe JS. The mountain of motor development: a metaphor. *Motor Dev Res Rev*. Reston, VA: NASPE (2002) 2:163–90.
6. Rose B, Larkin D, Berger BG. The importance of motor coordination for children's motivational orientations in sport 1. *Adapt Phys Activ Q* (1998) 15(4):316–27. doi:10.1123/apaq.15.4.316
7. Hands BP. How can we best measure fundamental movement skills? *Health Sciences Conference Papers*. Launceston Tas (2002). 5 p.
8. Psotta R, Brom O. Factorial structure of the movement assessment battery for children test-second edition in preschool children. *Percept Mot Skills* (2016) 123(3):702–16. doi:10.1177/0031512516666072
9. Henderson SE, Sugden DA, Barnett AL. *Movement Assessment Battery for Children-2 (MABC-2): Examiner's Manual*. London: Pearson Assessment (2007).
10. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders*. 5th ed. Arlington: American Psychiatric Publishing (2013).
11. Burton AW, Miller DE. *Movement Skill Assessment*. Champaign: Human Kinetics (1998).
12. Fisher A, Reilly JJ, Kelly LA, Montgomery C, Williamson A, Paton JY, et al. Fundamental movement skills and habitual physical activity in young children. *Med Sci Sports Exerc* (2005) 37(4):684–8. doi:10.1249/01.MSS.0000159138.48107.7D
13. Kokštejn J, Musálek M, Tufano JJ. Are sex differences in fundamental motor skills uniform throughout the entire preschool period? *PLoS One* (2017) 12(4):e0176556. doi:10.1371/journal.pone.0176556
14. Livesey D, Coleman R, Piek J. Performance on the movement assessment battery for children by Australian 3- to 5-year-old children. *Child Care Health Dev* (2007) 33(6):713–9. doi:10.1111/j.1365-2214.2007.00733.x
15. Ziviani J, Poulsen A, Hansen C. Movement skills proficiency and physical activity: a case for engaging and coaching for health (EACH)–child. *Aus Occup Ther J* (2009) 56(4):259–65. doi:10.1111/j.1440-1630.2008.00758.x
16. Wagner MO, Kastner J, Petermann F, Bös K. Factorial validity of the movement assessment battery for children-2 (age band 2). *Res Dev Disabil* (2011) 32(2):674–80. doi:10.1016/j.ridd.2010.11.016
17. Brown T, Lalor A. The movement assessment battery for children—second edition (MABC-2): a review and critique. *Phys Occup Ther Ped* (2009) 29(1):86–103. doi:10.1080/01942630802574908
18. Schulz J, Henderson SE, Sugden DA, Barnett AL. Structural validity of the movement ABC-2 test: factor structure comparisons across three age groups. *Res Dev Disabil* (2011) 32(4):1361–9. doi:10.1016/j.ridd.2011.01.032
19. Hua J, Gu G, Meng W, Wu Z. Age band 1 of the movement assessment battery for children-second edition: exploring its usefulness in mainland China. *Res Dev Disabil* (2013) 34(2):801–8. doi:10.1016/j.ridd.2012.10.012
20. Ellinoudis T, Evaggelinou C, Kourtessis T, Konstantinidou Z, Venetsanou F, Kambas A. Reliability and validity of age band 1 of the movement assessment battery for children-second edition. *Res Dev Disabil* (2011) 32(3):1046–51. doi:10.1016/j.ridd.2011.01.035
21. Gabbard CP. *Lifelong Motor Development*. 7th ed. Philadelphia: Pearson Higher Education (2011).
22. Kambas A, Venetsanou F, Giannakidou D, Fatouros IG, Avloniti A, Chatzinikolaou A, et al. The motor-proficiency-test for children between 4 and 6 years of age (MOT 4–6): an investigation of its suitability in Greece. *Res Dev Disabil* (2012) 33(5):1626–32. doi:10.1016/j.ridd.2012.04.002
23. Van Waelvelde H, Peersman W, Lenoir M, Smits Engelsman B, Henderson S. The movement assessment battery for children: similarities and differences between 4- and 5-year-old children from Flanders and the United States. *Pediatr Phys Ther* (2008) 20(1):30–8. doi:10.1097/PEP.0b013e31815ee2b2
24. Gidley Larson JC, Mostofsky SH, Goldberg MC, Cutting LE, Denckla MB, Mahone EM. Effects of gender and age on motor exam in typically developing children. *Dev Neurol* (2007) 32(1):543–62. doi:10.1080/87565640701361013
25. Hardy L, King L, Farrell L, Macniven R, Howlett S. Fundamental movement skills among Australian preschool children. *J Sci Med Sport* (2009) 13(5):503–8. doi:10.1016/j.jsams.2009.05.010
26. Foulkes J, Knowles Z, Fairclough S, Stratton G, O'dwyer M, Ridgers N, et al. Fundamental movement skills of preschool children in northwest England. *Percept Mot Skills* (2015) 121:260–83. doi:10.2466/10.25.PMS.121c14x0
27. Psotta R. *MABC-2: Test motoriky pro děti (1. českévydání) [The Movement Assessment Battery for Children-2 Test (1st Czech edition)]*. Praha, Czech Republic: Hogrefe-Testcentrum (2014).

28. Ferron JM, Hess MR. Estimation in SEM: a concrete example. *J Behav Exp x* (2007) 32(1):110–20. doi:10.3102/1076998606298025
29. Muthén LK, Muthén BO. *Mplus: Statistical Analysis with Latent Variables: User's Guide*. Los Angeles: Muthén&Muthén (2010).
30. McDonald RP. *Test Theory: A Unified Treatment*. Mahwah, NJ: L. Erlbaum Associates (1999).
31. Maydeu-Olivares A, McArdle JJ. *Contemporary Psychometrics*. Mahwah NJ: Lawrence Erlbaum (2005).
32. McDonald RP, Marsh HW. Choosing a multivarite model: noncentrality and goodness of fit. *Psychol Bull* (1990) 107(2):247–55. doi:10.1037/0033-2909.107.2.247
33. Hu L, Bentler PM. Fit indices in covariance structure modeling: sensitivity to underparametrized model misspecification. *Psychol Methods* (1998) 3(4):424–53. doi:10.1037//1082-989X.3.4.424
34. Kline RB. *Principles and Practice of Structural Equation*. 3rd ed. New York: Guildford Press (2011).
35. Findley DF. Counter examples to parsimony and BIC. *Ann Inst StatMath* (1991) 43:505–14. doi:10.1007/BF00053369
36. Raftery AE. Bayesian model selection in social research. *Sociol Methodol* (1995) 25:111–63. doi:10.2307/271063
37. Bollen KA. *Structural Equations with Latent Variables*. New York: Wiley Interscience (1989).
38. Hausman JA. Specification tests in econometrics. *Econometrica* (1978) 46(6):1251–71. doi:10.2307/1913827
39. Jöreskog KG, Sörbom D. *LISREL 8 User's Reference Guide*. Chicago, IL: Scientific Software International (1993).
40. Brown TA. *Confirmatory Factor Analysis for Applied Research*. New York: Guilford Press (2006).

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

9. NORMAL WEIGHT OBESITY: WHAT IS HIDDEN FOR BMI

Before we start the next and last chapter of this thesis, we feel we should point out, especially to young researchers, that in our opinion to succeed in a research field, you should be guided by common sense and thirst for knowledge.

In previous studies we usually defined a research problem based on a detail literature search (e.g., the chapter about handedness and its structures) or evident and comprehensible clinical experience (e.g., FMS and body status), which we "just" verified by "objective" methods. However, in study Musalek et al. (2017), where the main aim was to verify whether excessive body fat is negatively related to the degree of FMS in preschoolers, we firstly encountered a situation to which we had not immediate answer. We recognised a certain portion of children who looked, when dressed, average but who had a surprisingly high amount of body fat. Since our raw data sheet contained, in addition to skinfold parameters, also the height and weight of the measured children, we decided, after publishing study Musalek et al. (2017), to re-evaluate this data and divide the children using a combination of skinfolds value and BMI into 3 categories: 1) underfat – low BMI; 2) proportional fat – normal BMI and 3) overfat – high BMI. In adding children into the first and second category there were minimal discrepancies when using cut off of skinfolds and cut off of BMI from Czech reference. Sensitivity of skinfolds and BMI parameters for the categorization of 1) underfat – low BMI; 2) proportinal fat – normal BMI, was higher than 95%. Nevertheless, within the sample of n=178 children originally determined as overfat >86th centile in sum of skinfolds, we revealed n=47 of them, whose BMI was in the range of 25 – 80th centile; however, their fatness was >86th centile. In other words, those children looked as normal weight but had an excessive amount of body fat. When we analysed their performance from the MABC-2, we found that their results were in average as bad as of the clearly (manifestly) overfat, (overweight and obese) peers. This important finding led us to a series of questions. Who are these children? How can we define them? Has this category of people or even children been already discovered? Was the presence of this sub-sample just incidental and caused by the sampling or is it a common diagnosis, and what is its frequency? And finally….What about their motor skills?

At the start of our investigation into how to define people with a "normal" weight but with a high amount of body fat, we had to find the answer to the question about which searching formula would provide relevant results. The combination of the words latent, hidden, obesity, normal weight showed that no unified term used to describe this "diagnosis" existed in global research. Samples of individuals with a normal weight and a high amount of body fat were called in different time periods latently obese, metabolically obese-normal weight, normal weight obese.

Peer-reviewed studies carried out on humans revealed based on using all aforementioned terms were published between 1964 and 2017.

The first studies that we investigated included studies published in Czechoslovakia (Rath & Petrásek, 1964; Petrásek, Rath & Mašek, 1965), which focused on women population. Both studies found women with abnormally high body fat among Czech women with "normal" body status assessed by Broca's index. The authors called this status in Czechoslovak environment as "latent obesity". A follow-up research conducted by Rath, Petrásek and Mašek, (1967) on a sample of women in the age range 15-50 revealed that latently obese women had significantly higher cholesterolaemia and lipaemia in comparison to normal non-obese counterparts. Further, results of this study also showed that frequency of latently obese women is apparently positively age related. It means that the frequency of latently obese women increased along with age. In the following decade from 1970 to 1979, we found just two comments where latent obesity was mentioned and in both cases we believe these comments were used as a reminder that this type of obesity existed. In the monograph Ošancová and Hejda, (1975) it is mentioned on page 58 that assessing of body fat is an essential method for identification of obesity, including latent obesity. From a sociological and historical perspective of obesity, Simeons (1971, p. 1799) states: *"Wherever abnormal fat was regarded as an asset, sexual selection tended to propagate the trait. It is only in very recent times that manifest obesity has lost some of its allure, though the cult of the outsize bust always a sign of* ***latent obesity*** *shows that the trend still lingers on"*.

Among subsequent research we consider as very important the study of Ruderman, Schneider and Berchtold (1981), who did a review of metabolic abnormalities in the population called: "metabolically-obese," normal-weight. Metabolically-obese, normal-weight individuals are characterized by an increased probability of hyperinsulinism and endogenous hypertriglyceridemia, along with the presence of physically larger individual fat cells. In addition, Ruderman et al. (1981)

stated that those individuals are in fact obese according to their metabolic response on nutrition but their obesity cannot be identified by usually applied methods and measured parameters like weight and height or even by measurements of skinfobd thickness or adipose mass. So, our interpretation of this description is that there exists a population with a higher probability of serious metabolic problems, whose weight is normal and even that these people need not to be but can have a high amount of fat essentially due to larger fat cells. About 17 years later Ruderman and collegues (see Ruderman Chisholm, Pi-Sunyer & Schneider, 1998) revised the research findings concerning metabolically-obese, normal-weight individuals and provided extended conclusions compared to previous study Ruderman et al. (1981). According to Ruderman et al. (1998), metabolically-obese, normal-weight people tended to have a higher amount of central fat distribution with average or slightly higher BMI and that their aerobic capacity assessed by Vo2max was significantly lower compared to their normal weight metabolically non-obese peers. Primarily the question of fat distribution and the ratio of fat and lean mass seemed to be essential for the determination of the currently most commonly used nomenclature. Researchers (e.g., De Lorenzo, Martinoli, Vaia, & Di Renzo, 2006; Oliveros, Somers, Sochor, Goel, & Lopez-Jimenez, 2014) pointed out that most studies have been oriented on so-called "manifest obesity" defined as having a high level of body fat along with a high body mass index (BMI) although there is evidence for people who have "normal weight" or normal BMI along with excessive amount of body fat. The combination of "normal" weight along with excessive amount of fat led to the introduction of the term normal weight obesity. Normal weight obesity was quantitatively defined as having BMI in range 18 – 24,9 along with body fat >30% for males and >33% for females. However, we want to accentuate no methodologically accepted method for the identification of normal weight obese individuals had existed yet (Oliveros et al., 2014).

Research investigating the relation between normal weight obese status and health indicators has shown that normal weight obese (NWO) adults have a higher risk of functional, metabolic and cardiovascular health problems (De Lorenzo et al., 2006; Marques-Vidal et al., 2008; Romero Corral et al., 2009; Oliveros et al., 2014; Franco, Silveira, Lima, Horst & Cominetti, 2017). Furthermore, it was revealed that NWO people are, apart from early inflammatory status, probably contextually exposed to oxidative stress related to metabolic abnormalities accompanying obesity. Renzo et al. (2010) showed that NWO subjects had a significantly lower level of antioxidant nonproteic, and a significantly higher presence of lipid hydroperoxide capacity compared to their normosthenic peers. In the area of self-esteem, Di Renzo et al. (2016) also found that NWO women have a significantly higher drive for thinness, and a higher level of body dissatisfaction compared to their normal weight non-obese peers.

The majority of aforementioned research devoted to normal weight obesity was conducted on adult female populations and its conclusions supported the findings of Rath et al. (1967), who used the term latent obesity instead of normal weight obesity. Surprisingly, when we focused our attention on studies interested in normal weight obesity in children, we found only very limited body of research.

In their longitudinally study, Wiklund et al. (2017) showed that NWO girls 11 to 18 years old were virtually indistinguishable from their normal weight and normal BMI peers in terms of personal weight and BMI values, even though the NWO girls had a significantly greater amount of body fat according to dual-energy x-ray absorptiometry (DXA). Furthermore, in the same study, the NWO girls displayed cardiometabolic risk in childhood (measured by a metabolic score which includes diastolic blood pressure, systolic blood pres-sure, abdominal fat mass, fasting plasma glucose; serum HDL cholesterol), with this difference persisting into early adulthood. Olafsdottir, Torfadottir and Arngrimsson (2016) revealed that NWO adolescents within a selected group of Icelandic students had about six kilograms more fat and slightly lower mineral bone density assessed by DXA than their counterparts with normal weight and normal BMI values. In addition, NWO participants achieved significantly worse results in Vo2max test, which also corresponded with the previous suggestion of Ruderman et al. (1998).

Although we found that the population of preschool children revealed after the re-evaluation of raw data in our sample from study Musálek et al. (2017) could be called normal weight obese and that normal weight obesity is a serious term with serious negative health impacts, which was verified especially in middle age females, we asked further why there was only little evidence for normal weight obesity in children populations.

One of the reasons for this might be that thus far only those parameters that could be analyzed under the guidelines of, for example, Cole et al. (2007) – such as total body weight, height and BMI – have been widely used for children. However, in research as it was discussed in chapter 7 of this thesis, there has been strong evidence that body weight and BMI are not sensitive enough for adiposity identification (Okorodudu et al., 2010). This is mainly related to a limited ability to distinguish between fat and lean body mass using BMI (Bogin and Varela-Silva 2012), which could result in a failure to detect NWO children. The low sensitivity of BMI implies that individuals – especially during growth periods – with different degrees of adiposity can have the same BMI values, and vice versa. Therefore, more exact measurements of body composition and other parameters, including adiposity, have been recommended (Jean, et al., 2014; Pařízková, 2015).

We also realized that using BMI especially in research aimed at the relation between BMI and the degree of FMS brought rather ambiguous results, as explained in chapter 7. With respect to the relation between body composition and the degree FMS some studies claimed that there exists a negative relationship between BMI, while others (e.g., Graf, et al., 2004; Williams et al., 2008; Yang et al., 2015) did not find any significant association between BMI and the degree of FMS. Would it be possible that in these studies a certain portion of children with "normal" BMI were in fact normal weight obese? Would it be possible that these children were clumsier in FMS compared to their normal weight non-obese peers? Previous findings suggested that NWO individuals have poor aerobic capacity and are probably less physically active (Ruderman et al., 1998; Olafsdottir et al., 2016). It is logical that if someone has "normal BMI" along with a high amount of body fat then this person must have lower lean mass development. There is a large body of studies that have verified the importance of lean mass during childhood adult age and in elderly people. The level of general physical activity, exercise and sport participation – and their sufficiency (character, intensity and volume – are the main factors of lean mass and bone development. In addition, this physical loading should start early in childhood (Pařízková, 1985, 2010) or at least before the pubescent growth spurt (Vicente-Rodriguez, Ara, Perez-Gomez, Dorado & Calbet, 2005). On the other hand, a low level of lean mass and a low level of muscular strength and endurance are strongly associated with cardiovascular diseases also in the population of children (Magnussen, Schmidt, Dwyer & Venn, 2012). The quantity of lean body mass is considered to be a significant indicator of muscular competence, physical fitness, bone health and self-esteem in children and adolescents (Pařízková, 1977; Pařízková & Hills, 2010; Smith et al., 2014). Specifically, the increase in lean body mass is significantly related to bone mineralization and the growth of bone mass during the prepubescent period (e.g., Frost, 2000; Rauch, Bailey, Baxter-Jones, Mirwald & Faulkner, 2004; Vicente-Rodriguez, et al., 2005).

So we can conclude that NWO children are at least very good candidates for achieving weaker results in motor tests (physical fitness or FMS).

In the introduction of this chapter we provided evidence that normal weight obesity has been considered a relatively new syndrome in the society and that there is only minimum information about basic health parameters from the anthropometric perspective (bone development or FM/LM on limbs) and also about the motor profile of normal weight obese children (e.g., the degree of FMS in NWO children). Therefore, we conducted two following studies focused on:

1) The relationship between normal weight obesity and the degree of fundamental motor skills in pre-school children (differences in FMS between normal weight obese, normal weight non-obese, overweight and obese pre-school age children),

2) Lean mass development and skeletal robustness of normal weight children in middle school age in comparison to their normal weight non-obese counterparts.

9.1 Fundamental Motor Skills in Normal Weight Obese Preschoolers

Research sample:

For the purpose of the first study we received agreement with research from four randomly selected kindergartens. These kindergartens had status were public kindergartens and were situated in a specific district of Prague, Czech Republic. None of the kindergartens had a special movement programme or any other specialization (e.g., extended language or sport activities). The data were collected from n = 492 preschoolers: (boys = 251, girls = 241).

The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed an informed consent.

The data were anonymized.

Procedure:

In all children four skinfolds were measured: triceps, subscapula, suprailiaca, calf. All anthropometry markers were measured at the same time of the day from 2 pm to 4 pm by three trained research professionals. All anthropometric measurements were done according to the reference manual Lohman et al., (1988), using standardized equipment. Weight: medical calibrated weight type TPLZ1T 46CLNDBI300 was used to assess weight to the nearest 0.1 kg

• Height: portable anthropometer P375. Measurements were taken to the nearest 0.1 cm

• Skinfolds: triceps, subscapula, suprailiaca and calf skinfolds

Since there is more than one type of skinfolder/calliper, we must mention that for the purpose of this study and also with regard to the available Czech skinfold norms for pre-school children (Blaha, 1990), we measured all skinfolds by a modified Best type caliper (skinfolder) with constant pressure 28 g/mm2 (Pařízková-Čapková, 1957) with accuracy of 0.5 mm. To ensure accuracy and meet physical and concentration demands of skinfold measurement, we established a skinfold team composed from three trained examiners, each of them responsible for measuring of specific skinfold/s. To carry out ensure an acceptable systematic error of skinfold measurement we first verified inter-rater reliability of examiners in pre-measuring on n=30 children who were not included in the following research study. Inter-rater reliability analysed as intraclass correlation (ICC) was: ICC triceps = 0.93; ICC subscapula = 0.96; ICC suprailiaca = 0.90; ICC calf = 0.92.

Further, the MABC-2 AB1 was used for assessing the level of FMS (for detailed description of MABC-2 see chapter XX). Data collection from MABC-2 AB1 was carried out by three research trained teams at the same time of the day from 9 am to 11 am. Children were assessed individually.

In the introduction to this chapter we claimed that there was no standard validation method for the identification of NWO children. Therefore, we had to select an adequate procedure with a strong background that would support the finding that children that we consider as NWO really correspond, by their body composition profile, to NWO individuals. As skinfold norms for Czech children are available only for Best caliper and also due to certain criticism aimed at using body fat equations for so young children (for instance by Slaughter et al., 1988, equations which are recommended for middle age school children), we decided to determine NWO children based on values received from skinfold measurement along with available norms from Blaha (1990).

To be able to compare the results from the MABC-2 between normal weight obese, normal weight non-obese, overweight and obese pre-school age children, we defined three categories of children:

1) Overweight and obese (OWOB) – individuals with high BMI and high amount of body fat: a) overweight BMI > 85th centile along with values of each skinfold > 85th centile of national norm, b) obese BMI > 95th centile of the national norm according to Cole et al. (2007), along with values of each skinfold > 95th centile

of the national norm according to Bláha (1990)

2) Normal weight obese (NWO) – individuals with normal BMI but excess body fat. Although this looks relatively easy, we realized that if we used the same range of BMI for NWO and normal weight non-obese peers (25th – 84th centile), we could get into possible trouble as there exists a potential danger that some children with BMI around 84th along with average sum of skinfolds around 86th centile would be defined as NOW, but in fact these children would be in fact borderline overweight. For this reason we narrowed the range of BMI for NWO children to 25th–60th centile along with average values of each skinfold >85th of the national norm
3) Normal weight non-obese individuals with BMI in the range of 25th–84th centile along with values of each skinfold 25th–84th of the national norm

Four pre-school children with unusual combination of BMI and skinfolds were excluded from the sample of overweight and obese individuals. These pre-schoolers had BMI in the range of 85th–88th centiles; however, their values of skinfolds were in the range of 54th–62th centiles of the national norm. The sample of normal weight non-obese pre-schoolers originally contained n = 392 children. From these n = 392 we randomly selected the final proportional research sample of n = 52 normal weight non-obese pre-school children using the Randomizer software. These children did not show any significant differences in anthropometry and FMS performance from the original sample of normal weight non-obese sample of n = 392.

The final research sample consisted of n = 152 preschoolers aged 3–6.9 years (x = 4.78; ±1.10):
A) n = 49 Overweight and obese children - OWOB (females = 25, males = 24)
B) n = 51 Normal weight obese children - NWO (females = 27, males = 24)
C) n = 52 Normal weight non-obese children - NWNO (females = 26, males = 26)

Results:

When we compared basic anthropometric parameters such as personal height and personal weight, we recognised that NWO girls are taller and heavier compared to their NWNO counterparts. On the other hand, NWO boys were shorter and also lighter in comparison to NWNO peers. Nevertheless, the main outcome from Fig. 22 is that BMI of NWO children and NWNO children did not significantly differ in BMI, which was one of our main requirements for further analyses.

Table 2. Description of weight, height and body size status.

Group	n	Age	Height cm	Weight kg	BMI
NWO female	25	4.86	110 ±8.22	18.3 ± 2.78	15.05 ± 0.73
NWO male	26	4.7	109.6 ±9.38	18.3 ± 2.88	15.13 ± 0.60
Normal weight non-obese female	26	4.8	107.2 ±6.43	17.5 ± 2.5	15.14 ± 0.74
Normal weight non-obese male	26	5.07	111.2 ±9.81	19.1 ± 3.5	15.3 ± 0.75
OWOB female	25	5.15	111.8 ±8.62	22.9 ± 4.49	18.15 ± 1.42
OWOB male	24	5.03	113.7 ±9.3	23.03 ± 3.70	17.7 ± 0.83

Figure 22. Basic anthropometry characteristic of NWO, NWNO and OWOB children with regard to sex
Adapted from Musalek et al. (2017). Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years. *Anthropologischer Anzeiger; Bericht uber die biologisch-anthropologische Literatur*. 203-212

Since NWO individuals are described as those indistinguishable by BMI from NWNO peers but with excessive amount of body fat, Fig. 23 provides a clear support of this assumption. NWO children had around 30% higher value of the sum of skinfolds and these children were also closer in values from the sum of skinfolds to OWOB counterparts. When we looked at the sum of skinfolds is relation to sex, post hoc analyses revealed that boys had a significantly greater amount of adipose tissue compared to normal weight non-obese peers ((F 2, 73) = 28.17 $p < 0.001$). In addition, NWO boys did not have a significantly higher of the sum of skinfolds than OWOB boys. Also NWO girls had a significantly higher value of the sum of skinfolds compared to NWNO peers. On the other hand, NWO girls had a significantly lower value of the sum of skinfolds than OWOB girls ((F 2, 74) = 24.83 $p < 0.001$).

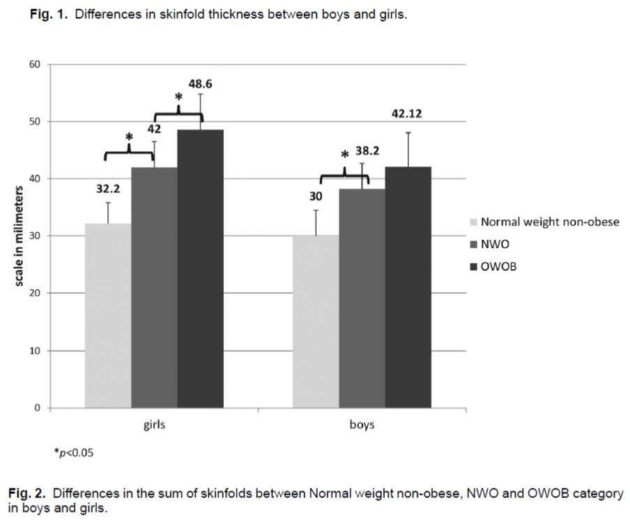


Figure 23. Differences in skinfold thickness between NWO NWNO and OWOB with regard to sex
Adapted from Musalek et al. (2017). Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years. *Anthropologischer Anzeiger; Bericht uber die biologisch-anthropologische Literatur, 74*(5), 203-212.

Therefore, from anthropomeric perspective, our criteria and methodology used for dividing children into three categories, worked well to distinguish with sufficient sensitivity the category of children, which can be labelled as NWO. These children were indistinguishable by their BMI from NWNO counterparts, but in addition these children had a significantly higher amount of body fat.

In the next step we investigated the differences in the degree of FMS between categories of: NWO, NWNO and OWOB children. In Fig. 24 (Table3) it is evident that NWO children scored constantly more poorly in the majority of MABC-2 tests. Although NWO children generally did worse in the majority of MABC-2 tests, a significantly worse performance was found only in AC1 – catching a bean bag, where NWO boys scored significantly worse compared to NWNO boys (F 126 3) = 3.34 $p <$ 0.05. However, the constant poor performance of NWO children in each MABC-2 caused that NWO children achieved a significantly poorer final total test score TTS (Fig. 24, Table 4). Since the MABC-2 contains two cut offs for emerging of present severe motor difficulties we were interested to learn whether the prevalence for motor difficulties will be also higher in the NWO group of children.

Table 3. Performance of NWO, Normal weight non-obese and OWOB pre-school children in MABC-2.

	MD1	MD2	MD3	AC1	AC2	BAL1	BAL2	BAL3
NWO female	**9.36** ± 2.85	**9.68** ± 2.88	9.36 ± 2.64	9.72 ± 3.3	**8.44** ± 3.52	9.2 ± 2.98	**8.72** ± 2.30	**10.24** ± 1.12
NWO male	**8.80** ± 2.67	**9.61** ± 4.12	**8.5** ± 3.24	**8.34*** ± 3.54	**8.53** ± 2.37	**8.57** ± 3.07	**9.15** ± 3.21	**9.65** ± 2.42
normal weight non-obese female	10 ± 2.17	11.5 ± 2.17	9.34 ± 2.92	9.77 ± 2.60	9.5 ± 3.17	9.2 ± 3.42	10.23 ± 2.47	10.65 ± 1.61
normal weight non-obese male	9.57 ± 3.74	10.23 ± 3.10	9.27 ± 3.17	10.27* ± 2.44	9.08 ± 2.64	10.19 ± 3.17	9.80 ± 2.66	10.30 ± 1.56
OWOB female	9.5 ± 2.71	10.03 ± 2.78	**8.15** ± 3.07	**8.61** ± 4.00	8.23 ± 3.91	**8.11** ± 3.13	9.61 ± 2.46	10.30 ± 1.8
OWOB male	9.08 ± 2.26	9.67 ± 2.85	9.29 ± 2.16	9.79 ± 3.15	9 ± 3.74	9.88 ± 2.23	10.13 ± 1.70	10.41 ± 1.18

*$p < 0.05$
MD1 Post coins; MD2 Threading beads; MD3 Drawing trail; AC1 Catching bean bag; AC2 Throwing bean bag onto mat; BAL1 One-leg balance; BAL2 Walking heels raised; BAL3 Jumping on mats.
Boldface – the worst result between groups regarding to sex.

Table 4. Differences in total and in centile scores between NWO, normal weight non-obese and OWOB children.

Group	Total test score, TTS	M PCT, centile
NWO	8.64 ± 3.25*	38.82 ± 29.92*
Normal weight non-obese	10.27 ± 3.35*	52.27 ± 31*
OWOB	9.29 ± 3.35	42.55 ± 30.84

*$p < 0.05$

Table 5. Frequency of severe motor deficits ≤ 5th centile MABC-2 in NWO, Normal weight non-obese and OWOB pre-school children.

Group	Frequency ≤ 5th centile MABC-2
NWO n = 51	23% (3 girls / 11 boys) *
Normal weight non-obese n = 52	8.2% (2 girls / 4 boys)
OWOB n = 51	7.1% (4 girls / 0 boys)

*$p < 0.05$

Figure 24 TABLE 3 Standard scores in each test from MABC-2 achived by NWO, NWNO and OWOB with regard to sex; TABLE 4 Difference TTS and PCT scores between NWO, NWNo and OWOB children; TABLE 5 Frequency of severe motor deficits ≤5th centile in NWO, NWNO and OWOB children
Adapted from Musalek et al. (2017). Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years. *Anthropologischer Anzeiger; Bericht uber die biologisch-anthropologische Literatur*. 203-212

From Fig. 24 (Table 5) we can see that the the highest frequency of individuals with severe motor problems ≤ 5th centile were found in the category of NWO, Chi-square df 3 $X^2 = 8.85$ $p < 0.05$. NWO children had a more than 3.5 times higher chance of severe motor deficit incidence than normal weight non-obese counterparts ODDS ratio (OR) = 3.69 ($p = 0.03$) CI95% (1.10; 12.35). There were no significant differences in the prevalence of severe motor deficits between normal weight non-obese and OWOB children.

Summary:

As we informed in the introduction part to this chapter, the valid, globally used method for the identification of NWO individuals has not existed yet (Oliveros et al., 2014). Therefore, the first question in this study was whether the methodology we used sufficiently differentiated NWO children from their NWNO peers and whether the category of NWO children matched the general definition of NWO individuals. In conformity with Wiklund et al. (2017), our NWO children were visually and by BMI indistinguishable from NWNO peers, even though NWO had significantly higher values of the sum of skinfolds. In our research more than 10% (10.5%) of pre-schoolers from the total number of pre-schoolers were identified as normal weight obese (NWO). The ratio of normal weight obese children among boys and girls was slightly higher in girls population: NWO girls 11.16% (n = 27 from n = 241); NWO boys 9.45% (n = 24 from n = 251).

Although the main aim of this study was to investigate the differences in the degree of FMS of NWO compared to another group of children (NWNO and OWOB), we believe it is important to emphasise that the low sensitivity of BMI in the identification of NWO individuals might have serious implications for the research field. Since the BMI parameter is usually used for body status estimation in children studies, we suggest that the missing information concerning the body fat mass could be one of the reasons why previous studies (e.g., Castelli & Valley 2007; Erwin et al. 2008; Hume et al. 2008) failed to detect any evidence for an association between body size status (fatness) and FMS in pre-school children, school children and adolescents. In addition, we consider it essential to define NWO individuals as those with non-significantly different BMI but an excessive amount of body fat compared to their NWNO counterparts. When we look at previous research, we can find studies (e.g., Di Renzo et al., 2013; Olafsdottir et al., 2016), where NWO individuals had significantly higher BMI compared to NWNO peers. Therefore, it is unclear whether the authors of these studies really worked with the population of NWOs or whether they rather worked with a population which is close in their anthropometric profile to the overweight population.

In MABC-2, NWO children had a significantly poorer performance. NWO children had more than three times higher frequency OR= 3.69 CI95% (1.10; 12.35) of severe motor deficit performance ≤5th centile of the MABC-2 norm. These results support the conclusion that severe motor deficits are linked to high percentage of body fat (e.g., Chirico et al., 2011; Silman, Cairney, Hay, Klentrou, & Faught, 2011; Cairney, Kwan, Hay, & Faught, 2012). However, on the other hand, our results are not in agreement with the conclusion of the systematic review Hendrix, Prins, and Dekkers (2014), which suggested that the prevalence of severe motor deficits diagnosed as developmental coordination disorder is associated with increasing BMI in child population.

Interestingly, OWOB children had better results compared to NWO but worse than normal weight non-obese children. Previous studies showed that OWOB individuals have, at least during childhood and adolescence, more lean mass than NWNO peers (e.g., Ellis, Shypailo, Wong, & Abrams, 2003; Ogden & Flegal, 2010). Further, we also have information that skeletal muscle cells of obese children have a maximal oxidative capacity similar to that of non-obese children, independent of their adiposity. In other words, overweight and obese children probably can use their lean mass if stimulated (Reid, 2008). In addition, a couple of decades ago it was also suggested that there were two types of obesity in childhood. "The first is characterized by increased LBM in addition to fat, by a tendency to tallness and advanced bone age, and to have been overweight since infancy" (Forbes, 1964). Nevertheless, we have to add here that it has not been confirmed that earlier adiposity or rapid weight gaining is connected to advanced biology maturation in pre-school age (e.g., Cameron, et al., 2003; Malina, 2014; Rolland-Cachera, et al., 1984). However, if we take into account all aforementioned findings about overweight and obese children, we can conclude that their higher portion of lean mass and maybe in specific cases also advanced maturation can give them an advantage in motor performance over their NWO counterparts. This suggestion matches the findings which did not support the conclusion of Ellery (1991), where no significant relation between the sum of two skinfolds (triceps, subscapula) and qualitative assessing of FMS by the test of gross motor development in pre-schoolers was found. However, it is important to note that in this study no categorization of children was carried out. The authors of this study used regression analysis applied on all children. It is a question whether the regression analysis fulfilled all requirements, particularly when the data distribution was not normal like in case of skinfolds, the distribution of which is significantly skewed to the right. Our results are in conformity with Logan et al. (2011) or Okely, Booth & Chey (2004), who revealed that high BMI or category of OWOB children performed significantly poorer in FMS tests. Further, in preschoolers, Scheffler et al. (2007) provided evidence that the changes in the ratio between lean mass and body fat influenced by controlled regular long-term physical activity caused improved motor skills and cardiovascular parameters. The reason why OWOB children had non-significantly poorer performance in FMS than normal weight non-obese counterparts may be the fact that we put together overweight and obese individuals. D'Hondt et al. (2009) established a separate category for obese and a separate category for overweight children and found that the performance in FMS was better in normal weight and overweight children than in obese children.

NWO children had more than three times higher frequency OR= 3.69 CI95% (1.10; 12.35) of severe motor deficit performance ≤5th centile of the MABC-2 norm. These results support the conclusion that severe motor deficits are linked to high percentage of body fat (e.g., Chirico et al., 2011; Silman et al., 2011; Cairney et al., 2012). However, on the other hand, our results are not in agreement with the conclusion of the systematic review Hendrix et al. (2014), which suggested that the prevalence of severe motor deficits diagnosed as developmental coordination disorder is associated with increasing BMI in child population.

Based on the aforementioned findings we suggest that the performance in FMS is significantly influenced by the body composition status already in pre-school age. Therefore, our results on preschoolers contribute to previous research which showed that the increasing amount of adipose tissue in middle age school children and adolescents is related to decreasing performance in balance, object control and manual dexterity (Malina, 1995; McKenzie et al., 2002; Okely et al., 2004; Logan et al., 2011). Moreover, we assume that not only fatness but also the ratio between the amount of body fat and the amount of lean mass may play a crucial role in the degree of FMS in early childhood. So, the currently investigated secular trends in decreasing of physical fitness and FMS in children could be related to the increasing amount of NWO children who have been hidden due to poor sensitivity of BMI in the category of normal weight non-obese children. Our findings also correspond with recent studies that concluded that the increasing in adiposity, primarily on the trunk, acting as a marker of metabolic syndrome present at an early age (Pařízková, Sedlak, Dvořáková, Lisá & Bláha, 2012;

Sedlak et al., 2015), has been apparent, mostly, without significant changes in BMI values (Sedlak et al., 2017).

Limitations of study:

Firstly, no international standards are available for determination of normal weight obese children. Therefore, in this study we defined criteria of normal weight obese children only based on synthesis and recommendations from previous research that was done on adults. Secondly, since this research has a cross-sectional design, no causality can be established if normal weight obese children have poor motor performance or if their poor motor performance caused their normal weight obese status.

Anthropol. Anz. 74/3 (2017), 203–212
J. Biol. Clin. Anthropol.
Published online 1 August 2017, published in print September 2017

Article

Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years

Martin Musalek[1,*], Jakub Kokstejn[1], Pavel Papez[1], Christiane Scheffler[2], Rebekka Mumm[3,4], Anna-Franziska Czernitzki[2] and Slawomir Koziel[5]

[1] Faculty of Physical Education and Sport, Charles University, Prague, Jose Martiho 31. Praha 6 Veleslavin, 162 52, Czech Republic
[2] Institute of Biochemistry and Biology, University of Potsdam, Potsdam, Germany
[3] Department of Biological Anthropology, University of Freiburg, Germany
[4] Evolutionary Biology and Animal Ecology, Insitute of Biology, Faculty of Biology, University of Freiburg, Freiburg, Germany
[5] Hirszfeld Institute of Immunology and Experimental Therapy Polish Academy of Sciences, Department of Anthropology, Poland
[*] Corresponding author: musalek.martin@seznam.cz

With 3 figures and 5 tables

Abstract: Normal weight obesity is defined as having excessive body fat, but normal BMI. Even though previous research revealed that excessive body fat in children inhibited their physical activity and decreased motor performance, there has been only little evidence about motor performance of normal weight obese children. This study aims to establish whether normal weight obese pre-school children aged 3–6 years will have a significantly worse level of fundamental motor skills compared to normal weight non-obese counterparts. The research sample consisted of 152 pre-schoolers selected from a specific district of Prague, the Czech Republic. According to values from four skinfolds: triceps, subscapula, suprailiaca, calf, and BMI three categories of children aged 3–6 years were determined: A) normal weight obese n = 51; B) normal weight non-obese n = 52; C) overweight and obese n = 49. The Movement Assessment Battery for Children (MABC-2) was used for the assessment of fundamental motor skills. Normal weight obese children had significantly higher amount of adipose tissue $p < 0.001$ than normal weight non-obese children but the same average BMI. Moreover, normal weight obese children did not have significantly less amount of subcutaneous fat on triceps and calf compared to their overweight and obese peers. In majority of MABC-2 tests, normal weight obese pre-schoolers showed the poorest performance. Moreover, normal weight obese children had significantly worse total standard score = 38.82 compared to normal weight non-obese peers = 52.27; $p < 0.05$. In addition, normal weight obese children had a more than three times higher frequency OR = 3.69 CI95% (1.10; 12.35) of severe motor deficit performance ≤ 5[th] centile of the MABC-2 norm. These findings are strongly alarming since indices like BMI are not able to identify normal weight obese individual. We recommend verifying real portion of normal weight obese children as they are probably in higher risk of health and motor problems than overweight and obese population due to their low lean mass.

Keywords: normal weight obesity; fundamental motor skills; MABC-2; performance; pre-school children; skinfolds; adipose tissue; lean mass

Introduction

Fundamental motor skills (FMS) play a crucial role in early child's physical, cognitive and social development (e.g., Diamond 2000; Clark & Metcalfe 2002; Cools et al. 2009). A lot of previous research focused on children and adolescents proved that overweight and obesity negatively affect the level of fundamental motor skills (FMS) and motor performance (Deforche et al. 2003; Goulding et al. 2003; D'Hondt et al. 2008; Deforche et al. 2009; Gentier et al. 2013; Sedlak et al. 2015). Specifically severe deficits in FMS diagnosed as developmental coordination disorder (DCD) were significantly linked to high percentage of body fat (Faught et al. 2005; Cairney et al. 2011; Chirico et al. 2011; Silman et al. 2011; Cairney et al. 2012). Nevertheless, studies focused on relations between body composition or body size status and FMS performance in pre-schoolers brought rather ambiguous results. Differences in FMS performance with the emphasis on the performance in each FMS sub-domain were provided by Morano et al. (2011). They revealed that over-

DOI: 10.1127/anthranz/2017/0752
www.schweizerbart.de
0003-5548/2017/0752 $ 2.50

weight and obese children showed the poorest performance in locomotor and object-control tasks. On the other hand, Williams et al. (2008) revealed low non-significant correlations (from 0.03 to 0.13) in pre-schoolers between z-BMI and FMS measured by Motor Skill Protocol performance. In addition, Ellery (1991) did not find any significant relation between thickness of skinfolds and gross motor performance in 220 pre-schoolers. Further, Logan et al. (2011) did not reveal any significant relation between BMI and results from Movement Assessment Battery for children where manual dexterity, object control and balance was assessed (r = – 0.237) in pre-school children. However, these authors pointed out that pre-school children classified as over-weight and obese might have lower FMS than their normal weight and underweight counterparts. In addition, McKenzie et al. (2002) found inverse association between adiposity and FMS in pre-school children, though only in boys.

Most of the studies in pre-school children determined obesity or average body size status by internationally accepted cut-off for BMI as suggested by Cole et al. (2007). However, according to many authors BMI should be used only as really crude estimation of fatness or body composition (e.g. Scheffler et al. 2007; Williams et al. 2008; D'Hondt et al. 2009; Logan et al. 2011; Morano et al. 2011). The limitation of using BMI, specifically in individuals with BMI above the 97th centile lies in its failure to differentiate between an elevated amount of body fat and increased lean mass (Franzosi 2006; Poirier 2007; Wildman et al. 2008; Lopez-Jimenez 2009). In addition, Okorodudu et al. (2010) showed that BMI had high specificity (97%) but poor sensitivity (42%) to detect obesity. Therefore, individuals with excessive body fat and low lean mass can still fall in the category of average or normal BMI (Ruderman et al. 1981; Romero-Corral et al. 2010).

This status, i.e. excessive body fat and low lean mass, is described as normal weight obesity (NWO) (Mokhtar et al. 2001; De et al. 2006; Marques-Vidal et al. 2010). Although NWO has been defined, so far there has not been any norm available for determining normal weight obese individuals. The main reason is probably the fact that there is no clear consensus on how to define obesity based on the percentage of body fat (Oliveros et al. 2014). Romero-Corral et al. (2010) defined NWO criteria for adults as BMI 18.5–24.9 kg/m^2 and body fat > 23.1% in males, > 33.3% in females, respectively. On the other hand, Marques-Vidal et al. (2010) determined NWO for adults in the age range 35–75 as individuals with BMI < 25 kg/m^2 and body fat > 66th centile of specific sex norm. In general, normal weight obese people are defined as those with BMI < 25 kg/m^2 whose body fat, however, is > 30% (Oliveros et al. 2014).

Previous research in adults and elder women showed that NWO is associated with high prevalence of metabolic abnormalities (Ruderman et al. 1981; Ruderman et al. 1998; De et al. 2006; Romero-Corral et al. 2010; Marques-Vidal et al. 2010). However, much less attention has been paid on investigating relations between normal weight obesity and physical fitness or motor development status (e.g. Olafsdottir et al. 2016). Moreover, there is no information available as to whether normal weight obesity has significant impact on FMS performance in child population. Therefore, the aim of this study is to investigate if normal weight obese pre-school children have poorer FMS performance compared to normal weight non-obese children due to excessive adipose tissue and if they differ from their clearly obese counterparts. We assume that NWO obese children will have due to decreased amount of lean mass significantly deteriorated degree of FMS compared to normal weight non-obese peers.

Methods

Research sample

Four kindergartens were randomly selected from a reference list of all public kindergartens from a specific district of Prague, Czech Republic which do not have any specialization (e.g., sport, language). Data were collected from n = 496 pre-schoolers: boys = 254, girls = 242). Subsequently, values of four measured skinfolds – triceps, subscapula, suprailiaca, calf were compared with last available anthropometry standards for Czech pre-schoolers according to Bláha (1990). Based on the results, three categories of children were defined:

1 Overweight and obese (OWOB) – individuals with high BMI and high amount of body fat : a) overweight BMI > 85th centile along with values of each skinfold > 85th centile of national norm, b) obese BMI > 95th centile of the national norm according to Cole et al. (2007), along with values of each skinfold > 95th centile of the national norm according to Bláha (1990)
2 Normal weight obese (NWO) – individuals with normal BMI but excess body fat: BMI 25th–60th centile along with values of each skinfold > 85th of the national norm
3 Normal weight non-obese individuals with BMI in range 25th–84th centile along with values of each skinfold 25th–84th of the national norm

From the sample of overweight and obese individuals four pre-school children with unusual combination of BMI and skinfolds were excluded. These pre-schoolers had BMI in range 85th–88th centiles; however, their values of skinfolds were in range of 54th–62th centiles of national norm.

The sample of Normal weight non-obese pre-schoolers originally contained n = 396 children. From these n = 396 we randomly selected the final proportional research sample of n = 52 Normal weight non-obese pre-school children using the Randomizer software. These children did not show any significant differences in anthropometry and FMS performance from the original sample of Normal weight non-obese sample of n = 396.

The research sample finally consisted of n = 152 pre-schoolers aged 3–6.9 years ($\bar{x} = 4.78; \pm 1.10$):

A) n = 49 Overweight and obese children (females = 25, males = 24)
B) n = 51 Normal weight obese children (females = 27, males = 24)
C) n = 52 Normal weight non-obese children (females = 26, males = 26)

The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed an informed consent. The data were anonymized.

Data collection

Anthropometry

In anthropometry personal weight and height was measured in all children by one researcher. Due to restricted time, condition skinfolds were measured by the team of three examiners (see more details in section 'Skinfolds').

All anthropometry markers were measured in the same time of the day from 2 pm to 4 pm by three trained research professionals. All anthropometric measurements were done according to the reference manual Lohman (1988), using standardized equipment. We measured:

- Weight: medical calibrated weight type TPLZ1T 46CLNDBI300 was used to assess weight to the nearest 0.1 kg
- Height: portable anthropometer P375. Measurements were taken to the nearest 0.1 cm
- Skinfolds: triceps, subscapula, suprailiaca and calf skinfolds were measured by modified Best type caliper (skinfolder) with constant pressure 28 g/mm^2 (Pařízková-Čapková 1957) with accuracy of 0.5 mm (Bláha 1986). The values of skinfolds were compared with the latest norms for Czech pre-schoolers (Bláha 1990)

Each examinee for skinfolds measurement was responsible for specific skinfold variable(s):
Examinee No. 1: triceps plus calf skinfolds
Examinee No. 2: subscapula skinfold
Examinee No. 3: suprailiaca skinfold
Trained examinators measured skinfolds in all 496 children.

Inter-rater reliability of measurement

Since skinfolds were measured by three examiners, firstly a pilot testing of measurement consistency on n = 30 pre-schoolers from selected kindergartens was conducted.

Inter-rater reliabilities as intra-class correlation coefficients (ICC) of three examiners in skinfolds measurement were: ICC triceps = 0.93; ICC subscapula = 0.96; ICC suprailiaca = 0.90; ICC calf = 0.92.

Fundamental motor skills

The test of the Movement Assessment Test Battery for Children-2 (MABC-2) age band 1 (AB1) (Henderson et al. 2007) was used for assessing the level of FMS – manual dexterity; aiming and catching; balance. MABC-2 is a clinically used diagnostic tool divided to three age band versions (from pre-school age till adolescence) for evaluation of motor development and revealing of motor difficulties with different severity (Henderson et al. 2007; Brown & Lalor 2009; Ellinoudis et al. 2011).

In particular, the age band (AB1) variant intended for children aged 3–6 years was used. Data collection from MABC-2 was carried out by three research trained teams in the same time of the day from 9 am to 11 am. Children were assessed individually.

MABC-2 AB1 included eight indicators divided into three domains.

1 Manual dexterity – a) Post coins (MD1); b) Threading beads (MD2), c) Drawing trail (MD3)
2 Aiming and Catching – a) Catching bean bag AC1; b) Throwing bean bag onto mat (AC2)
3 Balance – a) One-leg balance (BAL1); b) Walking heels raised (BAL2); c) Jumping on mats (BAL3)

According to the Examiner's manual (Henderson et al. 2007), all raw scores were converted to standard scores conditioned on age (SS) and further to a total test standard score (TTSS). In the first step we compared average TTSS in three determined groups a) overweight and obese, b) normal weight obese, c) normal weight with proportional BMI and skinfold values. In the second step we focused on occurrence of pre-schoolers with severe motor difficulties presented in each defined group. In the literature there are many solutions how to assess the degree of motor difficulties. In this study we adopted the recommendations of the following authors: Henderson et al. (2007); Johnson & Wade (2009); Schott et al. (2007). According to recommendations, total test score on centile scale (TTS PCT) ≤ 5th centile showed severe motor difficulties with high probability of developmental coordination disorder (DCD).

Data analysis

Analysis of variance ANOVA with factors groups (OWOB; NWO and Normal weight non-obese) and sex (boys; girls) was used to analyze anthropometry differences and differences in MABC-2 standard scores as well as MABC-2 total test score. Differences in chance of frequency of severe motor problems between defined groups: 1) OWOB; 2) NWO; 3) Normal weight non-obese were analysed by ODDS ratio $p < 0.05$. All statistical procedures were carried out in the NCSS 2007 program (Version 2007; Hintze 2007, NCSS, Kaysville, UT, USA).

Results

According to Chi-square test there were no significant differences in number of participants between each defined category ($p > 0.05$ degree of freedom (df) (2) (range: $p = 0.12–0.90$)) as well as within each category regarding to sex ($p > 0.05$ df(1) (range: $p = 0.22–1.00$) (Table 1)).

No significant differences were also found in average age between males and females ((F 1, 151) = 0.36; $p = 0.55$) either in average age between each category – a) NWO, b) Normal weight non-obese c) obese ((F 2, 150) = 1.42; $p = 0.24$).

OWOB pre-schoolers were significantly taller than Normal weight non-obese children. Specifically Normal weight non-obese girls were significantly shorter compared to OWOB girls (F 2, 74) = 4.37 $p < 0.05$. No significant difference in height status was revealed between NWO and Normal weight non-obese. In body weight status OWOB boys and girls were significantly heavier, boys: (F 2, 73) = 13.66 $p < 0.001$; and girls: (F 2, 74) = 19.39 $p < 0.001$ compared to Normal weight non-obese and NWO children. The same finding was revealed in BMI, boys: (F 2, 73) = 96.69 $p < 0.001$; girls: (F 2, 74) = 62.51 $p < 0.001$. No significant differences were revealed in weight status and in BMI between Normal weight non-obese and NWO children of both sexes (Table 2).

Girls had significantly greater values in all measured skinfolds. The greatest sex differences were revealed in triceps and suprailiaca skinfolds: triceps: (F 1, 151) = 6.38 $p < 0.05$; subscapula: (F 1, 151) = 4.89 $p < 0.05$; suprailiaca: (F 1, 151) = 5.33 $p < 0.05$; calf: (F 1, 151) = 3.95 $p < 0.05$). In addition, girls also had a significantly higher amount of adipose tissue expressed by the sum of four measured skinfolds $p < 0.001$ (Fig. 1 and Fig. 2).

In the sum of skinfolds NWO boys ((F 2, 73) = 28.17 $p < 0.001$) had a significantly greater amount of adipose tissue compared to Normal weight non-obese peers. In addition, NWO boys did not significantly differ in the sum of skinfolds compared to OWOB boys. In girls category there were also revealed significant differences in the sum of skinfolds ((F 2, 74) = 24.83 $p < 0.001$). Post hoc tests showed that NWO girls had significantly greater adipose tissue compared to Normal weight non-obese but also had significantly less adipose tissue than OWOB girls (Fig. 2).

Sum of skinfolds in each group (OWOB, NWO, Normal weight non-obese) compared with Czech norms for pre-schoolers:

1 OWOB = 98th centile, both sexes
2 NWO = 90th centile, both sexes
3 Normal weight non-obese: boys = 49.5th centile, girls = 53th centile

Normal weight non-obese children of both sexes showed the lowest values of all measured skinfolds: triceps skinfold ((F 2, 150) = 24.37 $p < 0.001$); calf skinfold ((F 2, 150) = 16.43 $p < 0.001$); subscapula (F 2, 150) = 27.10 $p < 0.001$ and suprailiaca (F2, 150) = 34.66 $p < 0.001$) compared to NWO and OWOB children. Post hoc tests also revealed that on suprailiaca and subscapula skinfold NWO pre-schoolers had significantly less amount of subcutaneous fat in comparison to OWOB counterparts. However, no significant differences were found in the amount of subcutaneous fat of triceps and calf skinfolds, between OWOB and NWO children (Fig. 3).

FMS performances differed between the groups. NWO children performed worst in the majority of the MABC-2 tests. Moreover, NWO boys did significantly worse in sub-

Table 1. Frequencies of participants in each defined group.

Group	Female age 3	Male age 3	Female age 4	Male age 4	Female age 5	Male age 5	Female age 6	Male age 6
NWO	N = 6	N = 9	N = 5	N = 8	N = 11	N = 6	N = 4	N = 3
Normal weight non-obese	N = 9	N = 7	N = 8	N = 5	N = 7	N = 7	N = 4	N = 5
OWOB	N = 5	N = 5	N = 7	N = 8	N = 5	N = 4	N = 9	N = 7

Table 2. Description of weight, height and body size status.

Group	n	Age	Height cm	Weight kg	BMI
NWO female	25	4.86	110 ±8.22	18.3 ± 2.78	15.05 ± 0.73
NWO male	26	4.7	109.6 ±9.38	18.3 ± 2.88	15.13 ± 0.60
Normal weight non-obese female	26	4.8	107.2 ±6.43	17.5 ± 2.5	15.14 ± 0.74
Normal weight non-obese male	26	5.07	111.2 ±9.81	19.1 ± 3.5	15.3 ± 0.75
OWOB female	25	5.15	111.8 ±8.62	22.9 ± 4.49	18.15 ± 1.42
OWOB male	24	5.03	113.7 ±9.3	23.03 ± 3.70	17.7 ± 0.83

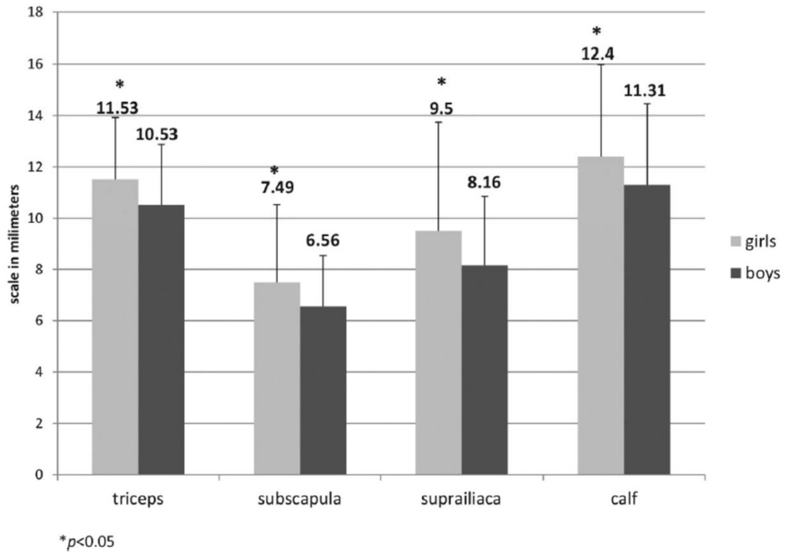


Fig. 1. Differences in skinfold thickness between boys and girls.

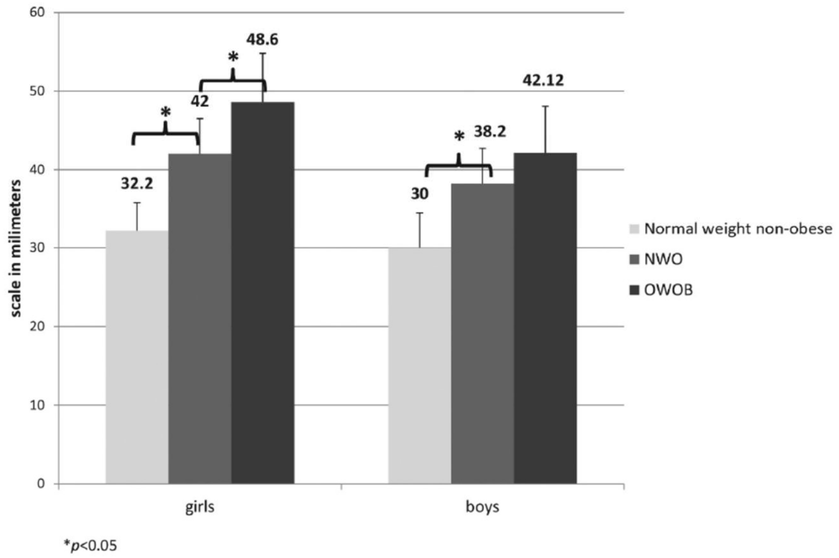


Fig. 2. Differences in the sum of skinfolds between Normal weight non-obese, NWO and OWOB category in boys and girls.

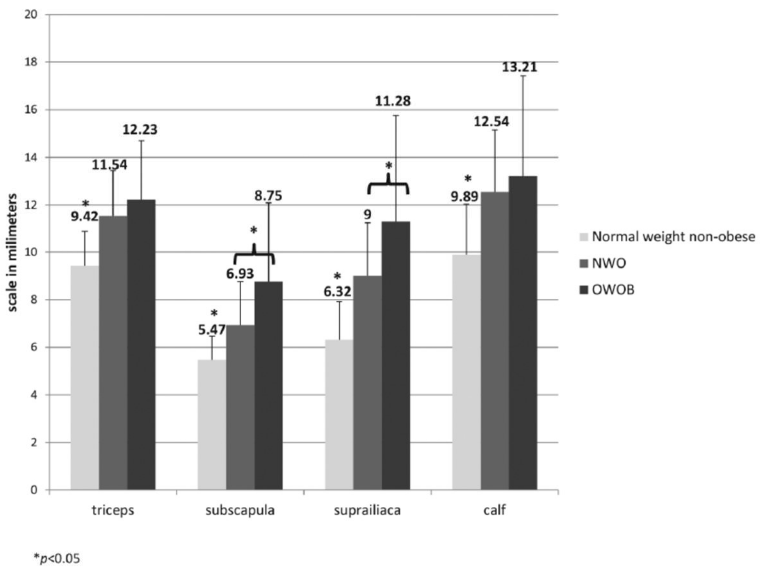


Fig. 3. Differences in skinfold thickness between Normal weight non-obese, NWO and OWOB children.

test Catching bean bag (AC1) (F 126 3) = 3.34 $p < 0.05$ than their Normal weight non-obese counterparts (Table 3).

NWO pre-schoolers generally performed even worse in FMS than OWOB peers. In TTS and PCT scores of MABC-2, NWO children were significantly worse than Normal weight non-obese (Table 4).

The highest frequency of individuals with severe motor problems ≤ 5th centile were found in category of NWO, Chi-square df 3 $X^2 = 8.85$ $p < 0.05$. NWO children had a more than 3.5 times higher chance of severe motor deficit incidence than Normal weight non-obese counterparts ODDS ratio (OR) = 3.69 ($p = 0.03$) CI95% (1.10; 12.35). There were no significant differences in the prevalence of severe motor deficits between Normal weight non-obese and OWOB children (Table 5).

Discussion

Normal weight obese pre-school children had a significantly poorer degree of FMS and a significantly higher chance of severe motor difficulties than Normal weight non-obese.

More than 10% (10.5%) of pre-schoolers from the total sample of n = 496 children were identified as Normal weight obese (NWO). The ratio of normal weight obese children among boys and girls was slightly higher for girl population: NWO girls 11.16% (n = 27 from n = 242); NWO boys 9.45% (n = 24 from n = 254).

The prevalence of NWO is similar to data collected in a 7- to 15-year old child population of the Czech Republic, where 8.3% of children were identified as NWO. In contrast to our findings, Kopecký et al. (2011) observed a strong sex bias in the prevalence of NWO (boys = 3.5%; girls = 13.1%). The difference in prevalence was particularly apparent in children aged 11 and older.

In the present study, NWO children had significantly greater values of all measured skinfolds than their normal weight counterparts (Normal weight non-obese) although they did not significantly differ in BMI. The greatest differences between NWO and Normal weight non-obese were observed in suprailiaca and calf skinfolds. The increased amount of adiposity on trunk (suprailiaca) is especially alarming as it is strongly associated with the later occurrence of the metabolic syndrome (Graversen et al. 2014). Moreover, NWO children had a similar amount of subcutaneous fat on triceps and calf skinfold than their overweight and obese counterparts (OWOB). This finding supports the conclusions of previous studies that BMI cannot identify NWO individuals (Kennedy et al. 2009; Romero-Corral et al. 2008; Okorodudu et al. 2010). We assume that the low sensitivity of BMI could be one of the reasons why previous studies (e.g., Erwin et al. 2008; McKenzie et al. 2002; Okely et al. 2004; Castelli & Valley 2007; Hume et al. 2008) failed to detect evidence for an association between body size status (fatness) and FMS in pre-school children, school children and adolescents.

Table 3. Performance of NWO, Normal weight non-obese and OWOB pre-school children in MABC-2.

	MD1	MD2	MD3	AC1	AC2	BAL1	BAL2	BAL3
NWO female	**9.36** ± 2.85	**9.68** ± 2.88	9.36 ± 2.64	9.72 ± 3.3	**8.44** ± 3.52	9.2 ± 2.98	**8.72** ± 2.30	**10.24** ± 1.12
NWO male	**8.80** ± 2.67	**9.61** ± 4.12	**8.5** ± 3.24	**8.34*** ± 3.54	**8.53** ± 2.37	**8.57** ± 3.07	**9.15** ± 3.21	**9.65** ± 2.42
normal weight non-obese female	10 ± 2.17	11.5 ± 2.17	9.34 ± 2.92	9.77 ± 2.60	9.5 ± 3.17	9.2 ± 3.42	10.23 ± 2.47	10.65 ± 1.61
normal weight non-obese male	9.57 ± 3.74	10.23 ± 3.10	9.27 ± 3.17	10.27* ± 2.44	9.08 ± 2.64	10.19 ± 3.17	9.80 ± 2.66	10.30 ± 1.56
OWOB female	9.5 ± 2.71	10.03 ± 2.78	**8.15** ± 3.07	**8.61** ± 4.00	8.23 ± 3.91	**8.11** ± 3.13	9.61 ± 2.46	10.30 ± 1.8
OWOB male	9.08 ± 2.26	9.67 ± 2.85	9.29 ± 2.16	9.79 ± 3.15	9 ± 3.74	9.88 ± 2.23	10.13 ± 1.70	10.41 ± 1.18

*$p < 0.05$

MD1 Post coins; MD2 Threading beads; MD3 Drawing trail; AC1 Catching bean bag; AC2 Throwing bean bag onto mat; BAL1 One-leg balance; BAL2 Walking heels raised; BAL3 Jumping on mats.

Boldface – the worst result between groups regarding to sex.

Table 4. Differences in total and in centile scores between NWO, normal weight non-obese and OWOB children.

Group	Total test score, TTS	M PCT, centile
NWO	8.64 ± 3.25*	38.82 ± 29.92*
Normal weight non-obese	10.27 ± 3.35*	52.27 ± 31*
OWOB	9.29 ± 3.35	42.55 ± 30.84

*$p < 0.05$

Table 5. Frequency of severe motor deficits ≤ 5th centile MABC-2 in NWO, Normal weight non-obese and OWOB pre-school children.

Group	Frequency ≤ 5th centile MABC-2
NWO n = 51	23% (3 girls / 11 boys) *
Normal weight non-obese n = 52	8.2% (2 girls / 4 boys)
OWOB n = 51	7.1% (4 girls / 0 boys)

*$p < 0.05$

Previous studies focused on NWO adults. E.g. Ruderman et al. (1981), Dvorak et al. (1999), and Kosmala et al. (2012) found that NWO individuals are in high risk of metabolic disorders. Therefore, it would be suitable to establish unique methodic (measurement) material for assessing normal weight obesity in pre-school and school children.

In MABC-2 NWO children had a significantly poorer performance $\bar{x} = 38.82$ than Normal weight non-obese peers $\bar{x} = 52.27$. OWOB children performed better in FMS $\bar{x} = 42.55$ than NWO but worse than Normal weight non-obese. However, this difference was not significant. Nevertheless, it is evident that OWOB pre-schoolers performed more similarly in MABC-2 to NWO compared to Normal weight non-obese peers. A deeper analysis showed that NWO pre-schoolers had the poorest performance in MABC-2 in all 8 sub-tests. NWO had the greatest motor difficulties when compared to normal weight non-obese in Threading beads (MD2), Catching beanbag (AC1) and One-leg balance (BAL1). NWO boys had a significantly poorer performance in Catching beanbag (AC1) compared to Normal weight non-obese counterparts. Our findings do not support the conclusion of Ellery (1991), where no significant relation between the sum of two skinfolds (triceps, subscapula) and qualitative assessing of FMS by Test of gross motor development in pre-schoolers was found. Yet, Ellery (1991) only studied the association using regressions. Moreover, in this study pre-schoolers were not categorized as normal weight, overweight or obese individuals. Our results are in conformity with Logan et al. (2011) who showed that pre-schoolers with high BMI were associated with poor performance in MABC-2. Our results also support findings of Okely et al. (2004) who showed that OWOB children in the age range 9–16 had poorer performance in FMS than Normal weight non-obese. However, in this research only the importance of association between weight status and locomotor skills was discussed. Scheffler et al. (2007) provided evidence, that changes in ratio between lean mass and body fat influenced by controlled regular long term physical activity caused improved motor skills and cardiovascular parameters in pre-schoolers. D'Hondt et al. (2009) established separate categories for obese and for overweight children and found that normal weight and overweight children performed better in FMS than obese children.

The prevalence of severe motor deficit performance ≤ 5th centile of the MABC-2 norm in NWO children was more than three times higher (OR = 3.69 CI95% (1.10; 12.35)) in comparison to Normal weight non-obese children. These results suggest that severe motor deficits are linked to high percentage of body fat (e.g. Cairney et al. 2012; Chirico et al. 2011; Silman et al. 2011). On the other hand our results are not in agreement with the conclusion of the systematic review Hendrix et al. (2014) who suggested that the prevalence of severe motor deficits diagnosed as developmental coordination disorder is associated with increasing BMI in a child population.

Based on the aforementioned findings we suggest that the performance in FMS is significantly influenced by the body composition status already at pre-school age. Our results in pre-schoolers contribute to previous studies which showed that the increasing amount of adipose tissue in school children and adolescents in the age range 7–16 is related to decreasing performance in balance, object control, and manual dexterity (Malina 1995; Okely et al. 2004; McKenzie et al. 2002; Logan et al. 2011). Moreover, we assume that not only fatness but also the ratio between the amount of body fat and the amount of lean mass may play a crucial role in the degree of FMS in early childhood.

Previous studies suggested a link between the volume of physical activity and skeletal robustness (Rietsch et al. 2013; Scheffler et al. 2014). Therefore, we recommend obtaining detailed information about skeletal parameters in NWO pre-school children. Based on findings of Mumm et al. (2016) the question remains if NWO children represent a separate category which starts to be formed in early childhood by environmental factors.

Limitations of the study

No international standards are available for determining normal weight obese children. Therefore, we had to define criteria for normal weight obese children that were based only on recommendations for adults. Since the design of this study was cross-sectional, no causality can be established if normal weight obese children have poor motor performance or if their poor motor performance is responsible for their normal weight obese status.

Conclusions

Normal weight obese pre-schoolers had a significantly greater amount of subcutaneous fat than their normal weight non-obese counterparts even though they did not differ in BMI. Therefore, BMI cannot identify normal weight obese individuals. The increased amount of adipose tissue on trunk (suprailiaca) is especially alarming as it is associated with the development of the metabolic syndrome. It would be suitable to establish a unique methodic (measurement) material for assessing normal weight obesity in pre-school and school children. Normal weight obese children showed poor performance in fundamental motor skills and showed a three time higher incidence of severe motor deficits compared to their normal weight non-obese peers. We assume that not only fatness but also the ratio between the amount of body fat and the amount of lean mass plays a crucial role in developing FMS in early childhood.

Acknowledgements: This study was supported by a Czech Science Foundation project No. 14–29358P and PROGRES Q19 Social-Sciences Aspects of Human Movement Studies II.

References

Bláha, P. (1986): Anthropometric Studies of the Czechoslovak Population from 6 to 55 years. Volume I., part 1. – ÚNV VS, Praha.

Bláha, P. (1990): Anthropometric Studies of the Czech Pre-school Children from 3 to 7 years. – ÚSM, Praha.

Brown, T. & Lalor, A. (2009): The Movement Assessment Battery for Children-Second Edition (MABC-2): A Review and Critique. – Physical & Occupational Therapy in Pediatrics 29 (1): 86–103.

Cairney, J., Hay, J., Veldhuizen, S. & Faught, B. (2011): Assessment of body composition using whole body air-displacement plethysmography in children with and without developmental coordination disorder. – Research in Developmental Disabilities 32 (2): 830–835.

Cairney, J., Kwan, M.Y.W., Hay, J.A. & Faught, B.E. (2012): Developmental Coordination Disorder, gender, and body weight: Examining the impact of participation in active play. – Research in Developmental Disabilities 33 (5): 1566–1573.

Castelli, D.M. & Valley, J.A. (2007): Chapter 3: The Relationship of Physical Fitness and Motor Competence to Physical Activity. – Journal of Teaching in Physical Education 26 (4): 358–374.

Chirico, D., O'Leary, D., Cairney, J., Klentrou, P., Haluka, K., Hay, J. & Faught, B. (2011): Left ventricular structure and function in children with and without developmental coordination disorder. – Research in Developmental Disabilities 32 (1): 115–123.

Clark, J.E. & Metcalfe, J.S. (2002): The mountain of motor development: A metaphor. – Motor Development: Research and Reviews 2: 163–190.

Cole, T.J., Flegal, K.M., Nicholls, D. & Jackson, A.A. (2007): Body mass index cut offs to define thinness in children and adolescents: international survey. – British Medical Journal 335 (7612): 194.

Cools, W., Martelaer, K., Samaey, C. & Andries, C. (2009): Movement skill assessment of typically developing preschool children: A review of seven movement skill assessment tools. – Journal of Sports Science and Medicine 8 (2): 154–168.

De, L.A., Martinoli, R., Vaia, F. & Di, R.L. (2006): Normal weight obese (NWO) women: An evaluation of a candidate new syndrome. – Nutrition, Metabolism and Cardiovascular Diseases 16 (8): 513–523.

Deforche, B., Lefevre, J., Bourdeaudhuij, I., Hills, A.P., Duquet, W. & Bouckaert, J. (2003): Physical Fitness and Physical Activity in Obese and Nonobese Flemish Youth. – Obesity Research 11 (3): 434–441.

Deforche, B.I., Hills, A.P., Worringham, C.J., Davies, P.S., Murphy, A.J., Bouckaert, J.J. & De Bourdeaudhuij, I.M. (2009): Balance and postural skills in normal-weight and overweight prepubertal boys. – International Journal of Pediatric Obesity 4 (3): 175–182.

D'Hondt, E., Deforche, B., De Bourdeaudhuij, I. & Lenoir, M. (2008): Childhood obesity affects fine motor skill performance under different postural constraints. – Neuroscience Letters 440 (1): 72–75.

D'Hondt, E., Deforche, B., De, B.I. & Lenoir, M. (2009): Relationship between Motor Skill and Body Mass Index in 5- to 10-Year-Old Children. – Adapted Physical Activity Quarterly 26 (1): 21–37.

Diamond, A. (2000): Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. – Child Development 71 (1): 44–56.

Dvorak, R.V., DeNino, W.F., Ades, P.A. & Poehlman, E.T. (1999): Phenotypic characteristics associated with insulin resistance in metabolically obese but normal-weight young women. – Diabetes 48 (11): 2210–2214.

Ellery, P.J. (1991): The relationship between gross motor skill performance and skinfold thickness, physical activity instruction, age, gender, and parental income in pre-school age children (motor development). – Dissertation Abstracts International 52 (09A): 3216

Ellinoudis, T., Evaggelinou, C., Kourtessis, T., Konstantinidou, Z., Venetsanou, F. & Kambas, A. (2011): Reliability and validity of age band 1 of the Movement Assessment Battery for Children – second edition. – Research in Developmental Disabilities 32 (3): 1046–1051.

Erwin, H. E. & Castelli, D. M. (2008): National Physical Education Standards: A Summary of Student Performance and Its Correlates. – Research Quarterly for Exercise and Sport 79 (4): 495–505.

Faught, B.E., Hay, J.A., Cairney, J. & Flouris, A. (2005): Increased risk for coronary vascular disease in children with developmental coordination disorder. – Journal of Adolescent Health 37 (5): 376–380.

Franzosi, M. G. (2006): Should we continue to use BMI as a cardiovascular risk factor? – The Lancet 368 (9536): 624–625.

Gentier, I., D'Hondt, E., Shultz, S., Deforche, B., Augustijn, M., Hoorne, S., Verlaecke, K., De Bourdeaudhuij, I. & Lenoir, M. (2013): Fine and gross motor skills differ between healthy-weight and obese children. – Research in Developmental Disabilities 34 (11): 4043–4051.

Goulding, A., Jones, I.E., Taylor, R.W., Piggot, J.M. & Taylor, D. (2003): Dynamic and static tests of balance and postural sway in boys: Effects of previous wrist bone fractures and high adiposity. – Gait & Posture 17: 136–141.

Graversen, L., Sørensen, T.I., Petersen, L., Sovio, U., Kaakinen, M., Sandbaek, A., Laitinen, J., Taanila, A., Pouta, A., Järvelin, M.R. & Obel, C. (2014): Preschool weight and body mass index in relation to central obesity and metabolic syndrome in adulthood. – Plos One 9 (3): e89986.

Henderson, S.E., Sugden, D.A. & Barnett, A.L. (2007): Movement Assessment Battery for Children-2. – Harcourt Assessment, London.

Hendrix, C.G., Prins, M.R. & Dekkers, H. (2014): Developmental coordination disorder and overweight and obesity in children: a systematic review. – Obesity Reviews 15 (5): 408–423.

Hintze, J. (2007): NCSS 2007. – NCSS, LLC. Kaysville, Utah, USA. www.ncss.com.

Hume, C., Okely, A., Bagley, S., Telford, A., Booth, M., Crawford, D. & Salmon, J. (2008): Does weight status influence associations between children's fundamental movement skills and physical activity? – Research Quarterly for Exercise and Sport 79 (2): 158–165.

Johnson, D.C. & Wade, M.G. (2009): Children at risk for developmental coordination disorder: judgement of changes in action capabilities. – Developmental Medicine & Child Neurology 51 (5): 397–403.

Kennedy, A.P., Shea, J.L. & Sun, G. (2009): Comparison of the Classification of Obesity by BMI vs. Dual-energy X-ray Absorptiometry in the Newfoundland Population. – Obesity 17 (11): 2094–2099.

Kopecký, M. (2011): Somatotype and Motor Performance in 7 to 15 Years Old Boys and Girls. – Palacky University in Olomouc, Olomouc.

Kosmala, W., Jedrzejuk, D., Derzhko, R., Przewlocka-Kosmala, M., Mysiak, A. & Bednarek-Tupikowska, G. (2012): Left ventricular function impairment in patients with normal weight obesity: contribution of abdominal fat deposition, profibrotic state, reduced insulin sensitivity and proinflammatory activation. – Circulation: Cardiovascular Imaging 2012: CIRCIMAGING-111. doi: 10.1161/CIRCIMAGING.111.969956

Logan, S.W., Scrabis-Fletcher, K., Modlesky, C. & Getchell, N. (2011): The Relationship between Motor Skill Proficiency and Body Mass Index in Preschool Children. – Research Quarterly for Exercise and Sport 82 (3): 442–448.

Lohman, T.G. (1988): Anthropometric standardization reference manual. – Human Kinetics Books, Champaign, Ill.

Lopez-Jimenez, F. (2009): Speakable and unspeakable facts about BMI and mortality. – Lancet (London) 373 (9669): 1055–1056.

Malina, R. M. (1995): Physical activity and fitness of children and youth: questions and implications. – Med. Exerc. Nutr. Health 4: 123–135.

Marques-Vidal, P., Pécoud, A., Hayoz, D., Paccaud, F., Mooser, V., Waeber, G. & Vollenweider, P. (2010): Normal weight obesity: Relationship with lipids, glycaemic status, liver enzymes and inflammation. – Nutrition, Metabolism and Cardiovascular Diseases 20 (9): 669–675.

McKenzie, T.L., Sallis, J.F., Broyles, S.L., Zive, M.M., Nader, P.R., Berry, C.C. & Brennan, J.J. (2002): Childhood movement skills: predictors of physical activity in Anglo American and Mexican American adolescents? – Research Quarterly for Exercise and Sport 73 (3): 238–244.

Mokhtar, N., Elati, J., Chabir, R., Bour, A., Elkari, K., Schlossman, N.P., Caballero, B. & Aguenaou, H. (2001): Diet culture and obesity in northern Africa. – The Journal of Nutrition 131 (3): 887S–892S.

Morano, M., Colella, D. & Caroli, M. (2011): Gross motor skill performance in a sample of overweight and non-overweight preschool children. – International Journal of Pediatric Obesity 6: 42–46.

Mumm, R., Ipsen, M.J. & Hermanussen, M. (2016): The association of weight, weight variability and socioeconomic situation among children. – European Journal of Clinical Nutrition 70 (6): 650–652.

Olafsdottir, A.S., Torfadottir, J.E., Arngrimsson, S.A. & Buchowski, M. (2016): Health Behavior and Metabolic Risk Factors Associated with Normal Weight Obesity in Adolescents. – Plos One 11 (8): e0161451.

Oliveros, E., Somers, V.K., Sochor, O., Goel, K. & Lopez-Jimenez, F. (2014): The concept of normal weight obesity. – Progress in Cardiovascular Diseases, 56 (4): 426–433.

Okely, A.D., Booth, M.L. & Chey, T. (2004): Relationships between Body Composition and Fundamental Movement Skills among Children and Adolescents. – Research Quarterly for Exercise and Sport 75 (3): 238–247.

Okorodudu, D.O., Jumean, M.F., Montori, V.M., Romero-Corral, A., Somers, V.K., Erwin, P.J. & Lopez-Jimenez, F. (2010): Diagnostic performance of body mass index to identify obesity as defined by body adiposity: a systematic review and meta-analysis. – International Journal of Obesity 34 (5): 791–799.

Pařízková-Čapková, J. (1957): Mereni podkozniho tuku caliperem. (Measurement of subcutaneous fat by a caliper). – Československá Pediatrie 12: 310–314.

Poirier, P. (2007): Adiposity and cardiovascular disease: are we using the right definition of obesity? – European Heart Journal 28 (17): 2047–2048.

Rietsch, K., Eccard, J.A. & Scheffler, C. (2013): Decreased external skeletal robustness due to reduced physical activity? – American Journal of Human Biology 25 (3): 404–410.

Romero-Corral, A., Somers, V.K., Sierra-Johnson, J., Thomas, R.J., Collazo-Clavell, M.L., Korinek, J., Allison, T.G., Batsis, J.A., Sert-Kuniyoshi, F.H. & Lopez-Jimenez, F. (2008): Accuracy of body mass index in diagnosing obesity in the adult general population. – International Journal of Obesity 32 (6): 959–966.

Romero-Corral, A., Somers, V.K., Sierra-Johnson, J., Korenfeld, Y., Boarin, S., Korinek, J., Jensen, M.D., Parati, G. & Lopez-Jimenez, F. (2010): Normal weight obesity: a risk factor for cardiometabolic dysregulation and cardiovascular mortality. – European Heart Journal 31 (6): 737–46.

Ruderman, N.B., Schneider, S.H. & Berchtold, P. (1981): The "metabolically-obese", normal-weight individual. – The American Journal of Clinical Nutrition 34 (8): 1617–1621.

Ruderman, N., Chisholm, D., Pi-Sunyer, X. & Schneider, S. (1998): The metabolically obese, normal-weight individual revisited. – Diabetes 47 (5): 699–713.

Scheffler, C., Ketelhut, K. & Mohasseb, I. (2007): Does physical education modify the body composition? – Results of a longitudinal study of pre-school children. – Anthropologischer Anzeiger 65 (2): 193–201.

Scheffler, C., Gniosdorz, B., Staub, K. & Rühli, F. (2014): Skeletal robustness and bone strength as measured by anthropometry and ultrasonography as a function of physical activity in young adults. – American Journal Human Biology 26 (2): 215–220.

Schott, N., Alof, V., Hultsch, D. & Meermann, D. (2007): Physical fitness in children with developmental coordination disorder. – Research Quarterly for Exercise and Sport 78 (5): 438–450.

Sedlak, P., Pařízková, J., Daniš, R., Dvořáková, H. & Vignerová, J. (2015): Secular Changes of Adiposity and Motor Development in Czech Preschool Children: Lifestyle Changes in Fifty-Five Year Retrospective Study. – Biomed Research International 2015 (1): 1–9.

Silman, A., Cairney, J., Hay, J., Klentrou, P. & Faught, B.E. (2011): Role of physical activity and perceived adequacy on peak aerobic power in children with developmental coordination disorder. – Human Movement Science 30 (3): 672–681.

Wildman, R.P., Muntner, P., Reynolds, K., McGinn, A.P., Rajpathak, S., Wylie-Rosett, J. & Sowers, M.R. (2008): The obese without cardiometabolic risk factor clustering and the normal weight with cardiometabolic risk factor clustering: prevalence and correlates of 2 phenotypes among the US population (NHANES 1999–2004). – Archives of Internal Medicine 168 (15): 1617–1624.

Williams, H.G., Pfeiffer, K.A., O'Neill, J.R., Dowda, M., McIver, K.L., Brown, W.H. & Pate, R.R. (2008): Motor skill performance and physical activity in preschool children. – Obesity (Silver Spring) 16 (6): 1421–1426.

Manuscript received: 03 March 2017
Revisions required: 27 March 2017
Revised version received: 21 April 2017
Accepted: 02 May 2017

9.2 Skeletal Robustness and Lean Mass Development on Limbs in Normal Weight Obese Middle Age School Children

Results from previous study Musalek et al. (2017) pointed out that NWO children achieved significantly worse performance in FMS. If we take into account the significantly higher values of skinfolds thickness revealed in these children compared to their NWNO peers but with the same BMI, then logically NWO children should have a significantly lower amount of lean mass. As it has been previously stated, a low level of lean mass along with excessive body fat is significantly related to poor skeletal development (low level of bone mineralization as well as small bone area) (Rietsch, Eccard, & Scheffler, 2013). The FM/LM ratio also negatively affects muscular strength and endurance (Ortega, Ruiz, Castillo, & Sjöström, 2008) and indicates a higher prevalence of metabolic risk (Benson, Torode, & Fiatarone Singh, 2006, Steene-Johannessen, Anderssen, Kolle, & Andersen, 2009) and cardiovascular diseases (Freedman, Mei, Srinivasan, Berenson, & Dietz, 2007, Magnussen, Schmidt, Dwyer & Venn, 2012) in the child population. Moreover, we have to realize that aforementioned health risks very often continue into adolescence and adult age (Wiklund et al., 2017) with serious and worsening health consequences (Daniels, 2006).

When we looked for information about the anthropometric profile of NWO children, we mostly found results that provided a basic picture of the overall body profile (e.g. the amount of body fat, the amount of whole body fat free mass (FFM) or whole body lean mass). Olafsdottir et al. (2016) revealed that NWO adolescents within a selected group of Icelandic students had about six kilograms more body fat and a slightly lower mineral bone density assessed by dual-energy x-ray absorptiometry (DXA) than their NWNO counterparts. Similar information was provided by Wiklund et al. (2017), who investigated by DXA differences in body composition between NWO and NWNO Finnish girls. According to their results, NWO Finnish girls had about seven kilograms more body fat and slightly less FFM compared to NWNO peers. Despite the similar conclusions of the two previous studies, it is important to emphasise that in the study Olafsdottir et al. (2016), adolescents determined as NWO had a significantly higher BMI compared to their NWNO peers. So, it is open to discussion whether the sample of NWO participants met all criteria to be identified as NWO.

Further, to our knowledge there has not been any study focused on lean mass development of limbs in NWO children. Although it has been proved, especially in elderly population, that lean mass development usually assessed as appendicular skeletal muscle mass index is highly important for the identification of risk of a sarcopenic (loss of muscle mass and muscular strength) (Coin et al., 2013). In addition, it was found that not only the amount or surface of lean mass but specifically also the ratio of FM/LM on limbs seemed to be an important marker in prevalence of sarcopenia. Increasing value of FM/LM index on limbs was found to be related to a higher prevalence of sarcopenia (Schautz, Later, Heller, Müller & Bosy-Westphal, 2012). However, similar information related to NWO population of children is missing. Since research carried out in child population provides support for significant associations between the amount of FM, LM and bone mass (BM) development (Pietrobelli et al., 2002), we can just speculate that these relations could be also valid for specific regions on human body like limbs. Some evidence about the relation between lean and bone mass on limbs in children is known from studies where LM and BM on limbs in an affected sample (like by spastic hemiplegia) of children was compared with LM and BM on limbs in neurotypical developed children. This research found that the affected limbs have a lower amount of LM as well as a decreased level of bone mineral density (BMD) and bone mineral content (BMC) (Lin & Henderson, 1996). Since MECHANOSTAT hypothesis of Frost (2000) and results of other studies (Vicente-Rodriguez et al., 2005; Rauch et al., 2004) investigating relations between physical activity on bone development commonly suggested a positive impact of the amount of muscle contraction on bone health, especially in prepubertal age, in the second study we aimed to investigate the difference in skeletal robustness and lean-fat ratio on the limb as indicators of health development that are important for: muscular competence, physical fitness and bone health, between NWO aged 9-12, NWNO and OWOB peers.

Research sample:

A sample of middle age school children was obtained from ten non-specialized elementary schools (i.e., without a specific orientation toward technical studies, the arts, languages, or sport) from Prague, the capital city of the Czech Republic. All the selected elementary schools are cooperating with the Faculty of Physical Education and Sport and are providing practical training of BA and MA students for their future profession as coaches and teachers. The final sample consisted of n=794 children aged 9 to 12 years.

In next step we determined three categories of children

1) Overweight and obese (OWOB):
    a. overweight children: BMI > 85th percentile along with average values from three skinfolds > 85th percentile of Czech national reference
    b. obese children: BMI > 95th percentile along with average values from three skinfolds > 95th percentile of Czech national reference
2) Normal weight obese (NWO): BMI 25th-60th percentile, along with average values from three skinfolds > 85th of Czech national reference. The narrower range of BMI compared to NWNO children was used with the aim to avoid a situation when NWO should have a significantly higher BMI compared to BMI children
3) Normal weight non-obese individuals (NWNO): BMI in the range of the 25th–84th percentile, along with average values from three skinfolds within the 25th–84th of Czech national reference (29)

The methodology for adding children into concrete category was adapted from previous study Musálek et al. (2017).

We finally received n=72 OWOB children, n=69 NWO children and n=649 NWNO children.

Since we did not want to work with highly unbalanced samples which could significantly affect the statistical power and Type I error rates, we decided to reduce the original sub-sample of NWNO children by randomization procedure.

The research sample finally consisted of 210 middle-school-aged children, from 9 to 11.9 years old (x = 11.3 ±1.09)

A) n = 72 overweight and obese children - OWOB (boys = 40; girls = 32)
B) n = 69 normal weight obese children - NWO (boys = 26; girls = 43)
C) n = 69 normal weight non-obese - NWNO (boys = 34, girls = 35)

The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed an informed consent. The data were anonymized.

Procedure:

Anthropometry:

All anthropometric measurements were carried out according to Lohman, et al., (1988) manual using standardized equipment.

We measured:

1) *Weight, height*:
2) *Skinfolds:* triceps, subscapular, suprailiac, and calf – (the latest available data on the thickness of triceps, subscapular, suprailiac and calf skinfolds for Czech school children were used as references (Vignerová & Bláha, 2001).
3) *Skeletal breadth measurements*: humeral and femoral epicondyle
4) *Limb circumferences:* circumferences on the upper arm and calf

From measured parameters, the following indicators were calculated:

1) The body mass index was calculated as $BMI = \frac{weight\ in\ kg}{(body\ height\ in\ meters)^2}$
2) Frame indices of skeletal robustness according to Frisancho formula (Frisancho, 1990) from humerus and femur breadth epicondyles were calculated
3) Percentage of body fat (%BF): the amount of body fat was calculated according to equations by Slaughter et al. (1988) considering sex.
4) The muscle area on the upper arm and calf was calculated according to Rolland Cachera equations (Rolland-Cachera et al., 1997)

All anthropometric measurements were taken by one professionally trained researcher from the Faculty of Physical Education and Sport. All raw data were transformed to z-scores. Consequently, all results are presented in z-score normalized values to take account of participants' sex and age.

Results:

The first view into anthropometric profile of NWO was provided by the two most used variables – height and weight. NWO children did not differ in their weight and height from NWNO counterparts; however, they were significantly shorter compared to OWOB peers ($p < 0.01$, Hays ω^2=0.10) and lighter ($p < 0.001$, Hays ω^2=0.70). Due to non-significant differences in height and weight between NWO and NWNO children we could confirm an important pre-condition that NWNO and NWO children will not have different BMI (Fig. 25). The highest BMI was revealed in a sub-sample of OWOB children ($p < 0.001$, Hays ω^2=0.76), whose BMI differed from both NWO and NWNO peers.

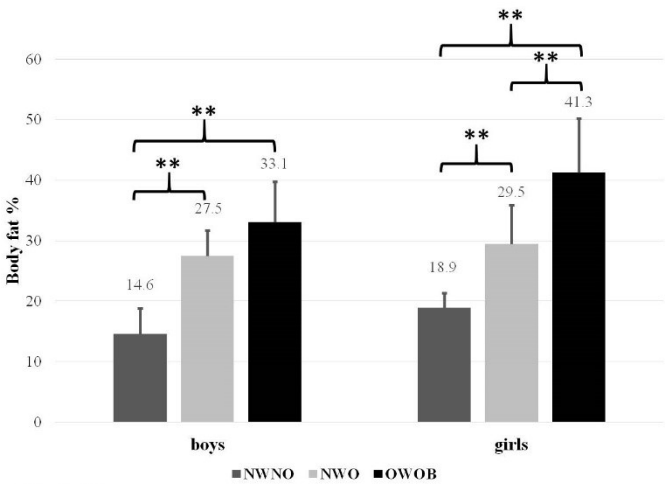
TABLE 2 | Basic anthropometry characteristic across three assessed groups of NWNO, NWO, and OWOB children.

Group	Z-height Mean/*SD*	S.E.	Z-weight Mean/*SD*	S.E.	Z-BMI Median†	S.E.
NWNO	−0.34 ± 1.04	0.12	−0.70 ± 0.47	0.06	−0.69	0.05
NWO	−0.09 ± 0.90	0.11	−0.51 ± 0.45	0.06	−0.58	0.05
OWOB	0.40 ± 0.89**	0.10	1.17 ± 0.67**	0.07	1.24**	0.07

***p < 0.001 unlike the other two groups.*
†Results from non parametric Kruskal Wallis ANOVA.
SD, standard deviation; S.E., standard error; NOW, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

Figure 25. Basic anthropometry characteristic of NWO, NWNO and OWOB middle age school children
Adapted from Musálek et al. (2018). Poor skeletal robustness on lower limbs and weak lean mass development on upper arm and calf: Normal weight obesity in middle-school-aged children (9 to 12). *Frontiers in Pediatrics*, *6*, 371.

Unlike in a previous study conducted on preschool age children Musálek et al. (2017), in this research we estimated the percentage of body fat in all measured children and we found that NWO children displayed a significantly higher amount of body fat compared to NWNO counterparts, even when corrected for sex (girls: $p < 0.001$, Hays ω^2=0.65; boys: $p < 0.001$, Hays ω^2=0.62. Nevertheless, the results of post hoc test also showed that the differences in the amount of body fat were not the same between the defined categories when considering sex. While NWO boys did not significantly differ in the percentage of body fat from their OWOB peers, NWO girls has significantly less percentage of body fat compared to OWOB girls (Fig. 26).



**p<0.001
NWO: nomal weight non-obese; NWO: normal weight obese; OWOB: overweight and obese

Figure 26. Difference in body fat between NWO, NWNO and OWOB
Adpated from Musálek et al. (2018). Poor skeletal robustness on lower limbs and weak lean mass development on upper arm and calf: Normal weight obesity in middle-school-aged children (9 to 12). *Frontiers in Pediatrics*, *6*, 371.

Skeletal robustness, though considered as an important parameter in the process of bone development, is not so often assessed by field anthropometry methods. The use of double x-ray like DXA method is more common, in which the mineral content, bone mass density or bone area are calculated. In this study we used a simple and reliable equation called Frame index developed by Frisancho (Frisancho, 1990) where we needed just personal height and epicondyle breadth of the femur and humerus bones.

NWO children had the lowest z-scores of both Frame indices (on the upper and lower limb) compared to their NWNO peers. Nevertheless, only their Frame index calculated from femur epicondyle ($p < 0.001$, Hays ω^2=0.66) was revealed as significantly lower (compared to NWNO). Significantly highest values of Frame indices calculated from upper and lower limb were found in OWOB children of both sexes. In addition, sex proved to be a major factor affecting robustness of the lower limbs in further analysis ((F 2, 205) = 8.09, $p < 0.001$). The boys had twice poorer robustness of the lower limbs Z-score= -0.85 than NWO girls Z-score = -0.43 as compared to their NWNO and OWOB counterparts ($p < 0.001$; Hays ω^2=0.81) (Fig. 27)

Groups	Frame index upper extremity Z-score		Frame index lower extremity Z-score	
	Mean/*SD*	S.E.	Mean/*SD*	S.E.
BOYS				
NWNO boys	−0.13 ± 0.99	0.16	0.07 ± 1.0	0.17
NWO boys	−0.60 ± 0.89	0.18	−0.85 ± 0.61**	0.13
OWOB boys	0.48 ± 0.87**	0.14	0.47 ± 0.89	0.14
GIRLS				
NWNO girls	−0.29 ± 1.11	0.19	0.08 ± 0.88	0.15
NWO girls	−0.33 ± 0.88	0.14	−0.43 ± 0.98*	0.15
OWOB girls	0.74 ± 0.59**	0.10	0.49 ± 0.94	0.17

$p < 0.01$ unlike the other two groups within each sex category.
***$p < 0.001$ unlike the other two groups within each sex category.*
SD, standard deviation; S.E., standard error; NWO, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

Figure 27. Skeletal robustness in NWO, NWNO and OWOB children with regard to sex
Adapted from Musálek et al. (2018). Poor skeletal robustness on lower limbs and weak lean mass development on upper arm and calf: Normal weight obesity in middle-school-aged children (9 to 12). *Frontiers in Pediatrics*, *6*, 371.

Since in previous analyses conducted in this study it was found that NWO children did not differ in their BMI but had a much more body fat compared to NWNO peers it was logical that we assumed in NWO children a significantly poorer lean mass development (muscle area) on selected regions – upper arm and calf. So, the question was rather by how much smaller the muscle area of NWO children will be compared to NWNO peers. The result was highly alarming because NWO children had about 1.5 Z-score poorer muscle area on the upper arm and 2 Z-scores poorer muscle area on the calf. In addition, when we calculated muscle areas in OWOB children, we found that OWOB children did not have a significantly different size of the muscle area on the upper arm (Hays $\omega^2<0.01$); however, the size of the muscle area on the calf was significantly poorer compared to the results of NWNO peers ($p < 0.001$, (Hays $\omega^2=0.33$) (Fig. 28).

TABLE 4 | Upper arm and calf muscle area across three assessed groups of NWNO, NWO, and OWOB children with respect to sex.

Groups	Rolland Cachera upper arm muscle area Z-score		Rolland Cachera calf muscle area Z-score	
	Mean/*SD*	S.E.	Mean/*SD*	S.E.
BOYS				
NWNO boys	0.47 ± 0.88	0.11	0.89 ± 0.54	0.10
NWO boys	−1.15 ± 0.71**	0.12	−1.34 ± 0.45**	0.10
OWOB boys	0.27 ± 0.70	0.14	0.09 ± 0.61	0.09
GIRLS				
NWNO girls	0.64 ± 0.51	0.12	0.86 ± 0.55	0.11
NWO girls	−0.95 ± 0.64**	0.11	−0.85 ± 0.58**	0.12
OWOB girls	0.54 ± 0.82	0.11	0.20 ± 0.94	0.09

***p < 0.001 unlike the other two groups within each sex category.*
SD, standard deviation; S.E., standard error; NOW, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

Figure 28. Muscle areas on upper limb and calf in NWO, NWNO and OWOB children
Adapted from Musálek et al. (2018). Poor skeletal robustness on lower limbs and weak lean mass development on upper arm and calf: Normal weight obesity in middle-school-aged children (9 to 12). *Frontiers in Pediatrics*, *6*, 371.

Summary:

NWO children of both sexes markedly differ in selected anthropometric indicators, which are closely related to health or health risks parameters. In line with previous studies focused on NWO children or adolescents (Olafsdottir et al., 2016; Wiklund et al., 2017), we found in that NWO children had a significantly higher amount of body fat compared to their NWNO peers. Nevertheless, the questiona still remains as to which methods and criteria should be used for the identification of NWO individuals and whether cut offs might or might not be age and sex independent. Some studies defined NWO people – adults as those, whose BMI is in the range of 18.5–24.5 kg/m^2 and who have body fat ≥30%. However, no unified method has been developed yet. Based on our criteria for the identification of NWO children which we adapted from our previous study Musálek et al. (2017), we obtained again a category of NWO children that did not differ in their BMI from NWNO peers. Further, although we used quite a simple method for body fat estimation where just two skinfolds, height and weight are put into a regression equation, our results were in line with previous studies (e.g., De Lorenzo et al., 2007; Marques-Vidal et al., 2008; Romero-Corral et al., 2009; Di Renzo et al., 2013; Franco et al., 2017), where the amount of body fat of NWO individuals was around 30%.

NWO children of both sexes were significantly more skeletally fragile and had weaker lean mass development on upper and lower limbs compared to their NWNO and OWOB counterparts. The fact that NOW children displayed a significantly poorer physical disposition might indicate that these children probably have an insufficient amount and intensity of physical activity. Although in this study we did not collect data about physical activity of measured children, a number of indices from previous research suggest that poor skeletal robustness and weak lean mass development are consequences of physical inactivity. Moreover, a great deal of previous research has revealed significant relationships between the amount and type of physical activity and bone and lean mass development.

The assumption that physical activity as one of the major drivers of bone area development would support the hypothesis developed by Frost framework called “Mechanostat” (Frost, 1964, 1973, 1987, 1997) have strongly supported the assumption that physical activity is one of the major drivers of bone area development. Further support which directly connects bone and lean mass development came from the Iowa Bone study (Janz et al., 2001; Janz, Rao, Baumann & Schultz, 2003), where it was confirmed that the number of muscle contractions is in close relation to bone mass and bone area development. Since we found the greatest differences in lean mass and skeletal robustness on the lower limb, we asked the question whether lean mass development specifically on calf might be associated with skeletal robustness on the lower limb. Surprisingly, 25 years ago, in 1994, Slemenda et al. (1994) found that the calf muscle area is strongly related to the bone development in the lower limb. So we would interpret this poor skeletal and lean mass development that is markedly evident on the lower limb in NWO children as a result of a possibly very low level of physical activity, particularly in transportation and locomotion (walking, running, jumping).

The issue of lean mass and bone mass development in overweight and obese children has often attracted researchers’ interest. Some studies claimed that overweight and obese children had at least same amount of lean mass and more robust frame compared to NWNO peers (Klein et al., 1998), that adipose tissue stimulates bone development (Clark et al., 2006) or that bone development in overweight children, which seems to be advanced compared to NWNO peers, is rather caused by muscle of these overweight children (Wetzsteon et al., 2008). On the other hand, there is also a large body of studies that came with opposite results to the effect that overweight and obese children had, especially due to the low level of physical activity, a much lower bone density and that those children were more prone to fractures (Zamboni, Soffiati, Giavarina, & Tato, 1988; Mccormick, Ponder, Fawcett & Palmer, 1991; Goulding, Taylor, Jones, McAuley, Manning & Williams, 2000; Rocher et al., 2008). The results from skeletal robustness found in our study rather support the suggestion that OWOB children have a wider bone area compared to NWNO counterparts, which could be caused by body weight. However, a detailed analysis showed that a significantly wider bone area calculated in our study as Frame index was present in OWOB children only on the upper limb. In addition, OWOB children did not differ in Frame index calculated from femur epicondyle compared to NWNO counterparts and moreover OWOB children had a significantly smaller amount of lean mass on the calf. This would also indicate a low volume of transportation activities like walking or running in these children, which has been well documented (Marten & Olds, 2004; Jiménez-Pavón, Kelly & Reilly, 2010).

We have to note that the original Frame index equation developed by Frisanco contained only the humerus epicondyle parameter. However, for the purpose of this study we artificially developed also Frame index for the lower limb (femur epicondyle parameter), which is not part of standard equations for skeletal robustness estimation. Nevertheless, based on our finding, we believe that it would be appropriate to measure under field testing condition also the skeletal robustness from femur epicondyle breadth, which seems to be more sensitive compared to the Frame index calculated from humerus epicondyle breadth. Overall, the main conclusion of this study is that NWOs have a very risky combination of the amount of body fat, lean mass and bone development, which can imply serious problems in the long run. Since simple indices based on personal height and weight cannot identify NWO individuals, we have highlighted the importance of the development of a simple identification of NWO children that could be used by pediatricians.

frontiers in Pediatrics

ORIGINAL RESEARCH
published: 06 December 2018
doi: 10.3389/fped.2018.00371

Poor Skeletal Robustness on Lower Extremities and Weak Lean Mass Development on Upper Arm and Calf: Normal Weight Obesity in Middle-School-Aged Children (9 to 12)

Martin Musálek[1]*, Jana Pařízková[2], Elena Godina[3], Elvira Bondareva[3], Jakub Kokštejn[1], Jan Jírovec[1] and Šárka Vokounová[1]

[1] Faculty of Physical Education and Sport, Charles University, Prague, Czechia, [2] Obesity Management Centre, Institute of Endocrinology, Prague, Czechia, [3] Anuchin Research Institute and Museum of Anthropology, Lomonosov Moscow State University, Moscow, Russia

OPEN ACCESS

Edited by:
Giuliana Valerio,
Università degli Studi di Napoli Parthenope, Italy

Reviewed by:
Luca Scalfi,
Università degli Studi di Napoli Federico II, Italy
Anita Morandi,
Azienda Ospedaliera Universitaria Integrata Verona, Italy

***Correspondence:**
Martin Musálek
musalek@ftvs.cuni.cz

Specialty section:
This article was submitted to Pediatric Endocrinology, a section of the journal Frontiers in Pediatrics

Received: 07 July 2018
Accepted: 12 November 2018
Published: 06 December 2018

Citation:
Musálek M, Pařízková J, Godina E, Bondareva E, Kokštejn J, Jírovec J and Vokounová Š (2018) Poor Skeletal Robustness on Lower Extremities and Weak Lean Mass Development on Upper Arm and Calf: Normal Weight Obesity in Middle-School-Aged Children (9 to 12). Front. Pediatr. 6:371. doi: 10.3389/fped.2018.00371

Background: Normal weight obesity in children has been associated with excessive body fat, lower bone density and decreased total lean mass. However, no studies have been done into whether normal weight obese children differ in skeletal robustness or lean mass development on the extremities from normal weight non-obese, overweight, and obese peers although these are important indicators of healthy development of children.

Methods: Body height, body weight, BMI, four skinfolds, and two limb circumferences were assessed. We calculated total body fat using Slaughter's equations, the Frame index for skeletal robustness and muscle area for the upper arm and calf using Rolland-Cachera equations. Using national references of BMI and measured skinfolds, three subgroups of participants (9–12 years) consisting of 210 middle-school-aged children (M-age = 11.01 ± 1.05)—110 girls and 100 boys—were selected: (A) overweight obese (OWOB) (n = 72); (B) normal weight obese (NWO) (n = 69); and, (C) normal weight non-obese (NWNO) (n = 69). All values, were converted to Z-scores to take account of participant's sex and age.

Results: NWO children had significantly poorer skeletal robustness on lower extremities and poorer muscle area on the upper arm and calf compared to NWNO counterparts with significantly higher evidence in boys–skeletal robustness NWO boys: Z-score= −0.85; NWO girls: Z-score = −0.43; lean mass on the calf: NWO boys Z-score= −1.34; NWO girls: Z-score = −0.85. The highest skeletal robustness—but not muscle area on the calf—was detected in OWOB children.

Conclusions: Further research should focus on whether this poor skeletal and lean mass development: (1) is a consequence of insufficient physical activity regimes; (2) affects physical fitness of NWO children and could contribute to a higher prevalence of health problems in them. We have highlighted the importance of the development of a simple identification of NWO children to be used by pediatricians.

Keywords: normal weight obesity, children, adipose tissue, skeletal robustness, lean mass, body mass index

INTRODUCTION

Normal weight obesity (1–4) is a state in which an excessive amount of total body fat and a decreased lean mass is accompanied by average/normal BMI values.

Previous research has documented that normal weight obese (NWO) adults can have serious functional, metabolic, and cardiovascular problems (3–7). Romero-Corral et al. (8) revealed that the incidence of the metabolic syndrome in NWO subjects was four times higher than in so-called normosthenic population (normal weight, normal BMI, proportional amount of body fat). Some studies also demonstrated that NWO people tend to have a low-grade pro-inflammatory status (2, 8–11) and Di Renzo et al. (4) found that normal weight obesity in adult women population was a significant marker of sarcopenia. Some research has also shown that normal weight obesity is present already during childhood (12–15). Wiklund et al. (14) found in their longitudinal study that NWO girls observed for 7 years (from age 11 to 18) had a greater amount of body fat and a stable lean mass/fat mass ratio (LM/FM) index from childhood to adulthood compared to their normal weight and normal BMI peers. Further, NWO girls displayed cardiometabolic risk in childhood, with the risk persisting into early adulthood. Olafsdottir et al. (12) revealed that NWO adolescents had about six kilograms more fat and slightly lower mineral bone density as assessed by DXA. NWO adolescents were also less physically active (assessed by questionnaire) and performed much worse in VO2max than their counterparts with normal weight and normal BMI values. In the area of motor development, when studying the population of preschoolers Musalek et al. (15) found that NWO preschoolers had a significantly poorer degree of fundamental motor skills (FMS), and a more than three times higher risk of severe motor difficulties compared to their NWNO counterparts.

However, apart from previous evidence showing that NWO children and adolescents have a high amount of body fat along with normal BMI and poorer motor performance, there is no information available concerning their skeletal robustness and lean mass development on the extremities. Yet, these parameters are closely related to health development.

The level of general physical activity, exercise, and sport participation—and their sufficiency (character, intensity, and volume)—are the main factors affecting lean mass and bone development (16–20). On the other hand, a low level of lean mass, excessive body fat and poor skeletal development are associated with a decreased level of physical activity (21), a low level of muscular strength and endurance (22) and a higher prevalence of metabolic risk (23, 24) and cardiovascular diseases in child population (25, 26), which continue to adolescence and adult age (14) with serious and worsening health consequences (27). Therefore, it is very important to determine whether skeletal development—robustness and lean mass development on the limbs of NWO children—is significantly weaker compared to their normal weight non-obese peers. And all the more so as previous research in NWO children only looked at more global measures such as the difference in total lean and fat mass or bone mineralization.

The aim of the present study is to investigate the difference in skeletal robustness and lean-fat ratio on the extremities as indicators of health development that are important for: muscular competence, physical fitness and bone health, between NWO aged 9–12, NWNO, and OWOB peers.

METHODS, SUBJECTS

For the purpose of the present study, data from Ministry Research project No. MSM 0021620864 of the Charles University, Faculty of Physical Education and Sport, were used. The data were collected in 2015 from 10 non-specialized elementary schools (i.e., without a specific orientation toward technical studies, the arts, languages, or sport) from Prague, the capital city of the Czech Republic. The data collection was carried out in all schools at the same times, from 9:00 a.m. to 12:00 p.m., over 10 working days in November 2015.

Altogether, 794 middle school children from 9 to 12 years of age were investigated. It is important to say that until today there has been no standard protocol that would provide a definition of normal weight obese children in terms of percentage of body fat and range of BMI. In our study we used two parameters

1) BMI
   a) We used BMI percentiles from Czech national BMI reference.
   b) We used percentile cut-off points Cole et al. (28) to define normal BMI, overweight and obesity.
2) Skinfolds
   Values of the three skinfolds (over triceps, subscapular, suprailliac) were compared with anthropometric references for Czech children (29).

Using the resulting BMI values and measured skinfolds, three categories of children were defined: NWO; OWOB; NWNO children.

The criteria for each defined group of children were as follows:

1) Overweight and obese (OWOB):
   a. overweight children: BMI >85th percentile along with average values from three skinfolds >85th percentile of Czech national reference
   b. obese children: BMI >95th percentile along with average values from three skinfolds > 95th percentile of Czech national reference
2) Normal weight obese (NWO): BMI 25–60th percentile, along with average values from three skinfolds >85th of Czech national reference; the narrower range of BMI for NWO was selected in order to avoid non-equality of BMI between NWO and NWNO, which is what happened in previous studies. In these studies (4, 12), both NWO and NWNO participants could have BMI in the range of the 25–84th percentile. However, in the end NWO individuals had significantly higher BMI than NWNO peers. Our aim was to select a population of NWO and NWNO that would be indistinguishable based on BMI.

3) Normal weight non-obese individuals (NWNO): BMI in the range of the 25–84th percentile, along with average values from three skinfolds within the 25–84th percentile of Czech national reference (29).

Seven children with abnormal combinations of BMI and skinfold thickness were excluded from the study. These individuals had high BMI (within the range of the 85–90th percentile), along with skinfold values within the range of the 49–58th percentile of the national reference.

A power analysis done in GPower 3.1.3. program showed that when One-way ANOVA (fixed effects, omnibus, one-way); based on Erdfelder, Faul, and Buchner (30), and VanVoorhis and Morgan (31) recommendation with an alpha of 0.05 is used for the three groups (NWO, NWNO, OWOB), a minimum of 159 participants will be required to achieve a size effect of at least (f) 0.25 and power of 80%.

Based on the aforementioned criteria, 72 OWOB children and 69 NWO children were identified from the total studied sample of 787 children. A group of normal weight non-obese children originally included 646 individuals.

In this study our aim was to obtain a research sample which would be as balanced as possible. The main reason was that we wanted to minimize the possible effect of the homogeneity of variance assumption for comparison of defined groups by Analysis of Variance (ANOVA) approach specifically in case of two-way ANOVA. According to (32, 33), both a very unbalanced sample size and heterogeneity variances dramatically affect statistical power and Type I error rates.

To obtain a proportional research sample ($n = 69$) of NWNO children from the total sample of 646 children, a random selection procedure from Randomizer software (www.random.org) was carried out. The research sample finally consisted of 210 middle-school-aged children, from 9 to 11.9 years old ($x = 11.3 \pm 1.09$)

A) $n = 72$ Overweight and obese children (OWOB) (boys = 40; girls = 32)
B) $n = 69$ Normal weight obese children (NWO) (boys = 26; girls = 43)
C) $n = 69$ Normal weight non-obese children (NWNO) (boys = 34, girls = 35)

We realize that the three groups are not fully balanced; however, when using ANOVA, a small violation of balance does not affect the results (31).

Along with the requirement for balanced sample we also analyzed whether the representation of children in each defined category with respect to sex and group did not differ significantly (**Table 1**).

The procedures involved in our study were in accordance with the ethical standards of the responsible Czech national committee on human experimentation and with the Helsinki Declaration of 1975, as revised in 2000. The research was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University, and the parents of all participants signed an informed consent. The data were anonymized.

Measured Variables

Anthropometry

All anthropometric measurements were conducted according to the "Anthropometric Standardization Reference Manual" by Lohman et al. (34) using standardized equipment.

Weight: a medical calibrated scale TPLZ1T46CLNDBI300 was used to assess body weight to the nearest 0.1 kg.

Height: a portable anthropometer P375 (Co. TRYSTOM, spol. s r.o. / 1993-2015 www.trystom.cz) was used. Measurements were taken to the nearest 0.1 cm.

Skinfolds: triceps (tric), subscapular (subsc), suprailiac (suprail), and calf skinfolds were measured with the Harpenden skinfold caliper, with an accuracy of 0.2 mm (35). The latest available data on the thickness of triceps, subscapular, suprailiac, and calf skinfolds for Czech school children were used as references (36).

Skeletal breadth measurements: humeral and femoral epicondyle breadths were measured by the T520 thoracometer (range 0–40 cm) (Co. TRYSTOM, spol. s r.o./1993-2015; http://www.anthropometricinstruments.com/en/modified-thoracometer-t-520/).

Frame indices of skeletal robustness according to Frisancho formula (37) from humerus and femur breadth epicondyles were calculated as follows:

a. Frame index from upper extremity $= [(\frac{\textit{humerus epicondyle breadth in mm}}{\textit{body height in cm}})]*100$
b. Frame index from lower extremity $= [(\frac{\textit{femur epicondyle breadth in mm}}{\textit{body height in cm}})]*100$

The body mass index was calculated as follows:

$$BMI = \frac{weight\ in\ kg}{(body\ height\ in\ meters)^2}$$

Circumferences: circumferences on the upper arm and calf were measured by tape measure to the nearest 0.1 cm

Percentage of body fat (%BF): the amount of body fat was calculated according to equations by Slaughter et al. (38). For males with the sum of skinfolds <35 mm the following equation was used:

$$\%BF = 1.21*(tric + subsc) - 0.008*(tric + subsc)^2 - 1.7$$

For females with the sum of skinfolds <35 mm the following equation was used:

$$\%BF = 1.33*(tric + subsc) - 0.013*(tric + subsc)^2 - 2.5$$

For males with the sum of skinfolds higher than 35 mm the following equation was used:

$$\%BF = 0.783*(tric + subsc) + 1.6$$

For females with the sum of skinfolds higher than 35 mm the following equation was used:

$$\%BF = 0.546*(tric + subsc) + 9.7$$

Slaughter et al. (38)

The muscle area on the upper arm and calf was calculated.
Total upper arm area (TUA)
Upper arm fat area estimate (UFE)
Upper arm muscle area (UMA)
Total calf area (TCA)
Calf fat area estimate (CFE)
Calf muscle area (CMA)

$$TUA = \frac{upper\ arm\ circumference}{(4*\pi)};$$
$$UFE = upper\ arm\ circumeference*\frac{triceps\ skinfold}{2}$$
$$UMA = TUA - UFE$$
$$TCA = \frac{calf\ circumference}{(4*\pi)};$$
$$CFE = calf\ circumference*\frac{calf\ skinfold}{2}$$
$$CMA = TCA - CFE$$

Rolland-Cachera et al. (39)

All anthropometric measurements were taken by one professionally trained researcher from the Faculty of Physical Education and Sport. All raw data were transformed to z-scores. Consequently, all results are presented in z-score normalized values to take account of participants' sex and age.

Data Analysis

Normality tests included the Shapiro-Wilk test and the Kolmogorov-Smirnov test. The main effects of differences between anthropomorphic characteristics in the sub-groups (OWOB, NWO, and NWNO) were evaluated by the one-way analysis of variance (ANOVA) $p < 0.05$ with probabilities adjusted using sequential Bonferroni corrections. In case significant Bonferroni-corrected main effects were revealed, *post-hoc* comparisons were performed using Fisher's Partial Least Significant Difference so that it could be determined which between-group differences were statistically significant. Along with statistical significance, also the effect size Hays ω^2 was calculated with the range $\omega^2 \leq 0.059$ considered as small effect; ω^2 0.059–0.138 as medium effect and $\omega^2 \geq 0.139$ as large effect (40). If effects related to sex were revealed (by two-way ANOVA), then separate ANOVAs were used for boys and girls. When the normality of skinfold values was rejected, the Kruskal Wallis non-parametric ANOVA ($p < 0.05$) was used with *post-hoc* Kruskal-Wallis Multiple-Comparison Z-Value Test (Dunn's Test). Statistical procedures were carried out in the NCSS2007 program (Version 2007; NCSS, Kaysville, UT, USA) (41).

RESULTS

Basic Anthropometry: Height, Weight, and BMI

The analysis revealed significant differences in basic anthropometric variables between the defined categories of NWNO, NWO, and OWOB children. Considering height and weight, NWO children were significantly shorter ($p < 0.01$, Hays $\omega^2 = 0.10$) and lighter ($p < 0.001$, Hays $\omega^2 = 0.70$) compared to OWOB. No significant differences in the weight and height status were found between NWNO and NWO children. This finding implies that NWNO and NWO children did not differ in their BMI, which is an important assumption for normal weight obesity identification. The average BMI of NWO children corresponded to the 49th percentile of Czech norms for 9–12 years-old children (29). In particular, NWO boys had the average BMI values of the 49th percentile and NWO girls of the 49.25th percentile of the corresponding Czech references. Significantly higher BMI values in both sexes were found in OWOB children ($p < 0.001$, Hays $\omega^2 = 0.76$) compared to NWO and NWNO peers (**Table 2**).

Body Fat

In terms of relative body fat (%), significantly greater values were found in NWO children of both sexes (girls: $p < 0.001$, Hays $\omega^2 = 0.65$; boys: $p < 0.001$, Hays $\omega^2 = 0.62$) as compared

TABLE 2 | Basic anthropometry characteristic across three assessed groups of NWNO, NWO, and OWOB children.

Group	Z-height Mean/*SD*	S.E.	Z-weight Mean/*SD*	S.E.	Z-BMI Median†	S.E.
NWNO	−0.34 ± 1.04	0.12	−0.70 ± 0.47	0.06	−0.69	0.05
NWO	−0.09 ± 0.90	0.11	−0.51 ± 0.45	0.06	−0.58	0.05
OWOB	0.40 ± 0.89**	0.10	1.17 ± 0.67**	0.07	1.24**	0.07

***p < 0.001 unlike the other two groups.*
†Results from non parametric Kruskal Wallis ANOVA.
SD, standard deviation; S.E., standard error; NOW, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

TABLE 1 | Number of participants by age and sex in each of the defined groups.

	9 years old		10 years old		11 years old		12 years old	
Group	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
NWNO	N = 6	N = 8	N = 9	N = 8	N = 9	N = 10	N = 10	N = 9
NWO	N = 4	N = 9	N = 5	N = 12	N = 8	N = 11	N = 9	N = 11
OWOB	N = 6	N = 5	N = 12	N = 7	N = 12	N = 10	N = 10	N = 10

The chi-square test in contingency table rejects significant differences in frequencies of children regarding sex and group: chi-square = 8.14; df = 14; ES = 0.17; p = 0.87.
df, degree of freedom; ES, effect size.

to their NWNO peers Further, the *post-hoc* Dunn's test for Kruskall Wallis ANOVA also showed that NWO girls (Dunn's test = 3.45) had significantly less amount of body fat compared to OWOB girls. The *post-hoc* analysis between NWO and OWOB boys revealed no significant differences. The greatest value of body fat was revealed in OWOB children ($p < 0.001$) (**Figure 1**).

Skeletal Robustness

Further significant differences were also found in skeletal robustness parameters. NWO children had the lowest values of the standard Frame index [estimated on the upper limb according to Frisancho (37)], although the difference was not significant compared to their NWNO peers. OWOB children had by far the highest Frame index calculated on the upper limb Hays $\omega^2 = 0.62$. Since skeletal robustness does not have to be always symmetrical on the upper and the lower part of the body, we also calculated the Frame index from the lower extremity parameter (breadth of femur epicondyle). This type of index consequently showed that NWO children had significantly poorer robustness on lower limbs as compared to both NWNO and OWOB children ($p < 0.001$, Hays $\omega^2 = 0.66$). In addition, sex proved to be a major factor affecting robustness of the lower limbs in further analysis [$F_{(2, 205)} = 8.09, p < 0.001$]. Among NWO children, the boys had twice poorer robustness of the lower limbs Z-score= −0.85 than NWO girls Z-score = −0.43 as compared to their NWNO and OWOB counterparts ($p < 0.001$; Hays $\omega^2 = 0.81$) (**Table 3**).

Lean Mass Development on the Extremities—Muscle Area

The results of muscle areas showed that NWO children had significantly weaker muscle area on the upper arm as well as on the calf compared to NWNO and OWOB counterparts ($p < 0.001$, upper arm Hays $\omega^2 = 0.48$; calf Hays $\omega^2 = 0.59$). Further, sex proved to be a major factor. More evidence of the differences in the muscle area on the upper arm and calf was found in boys.

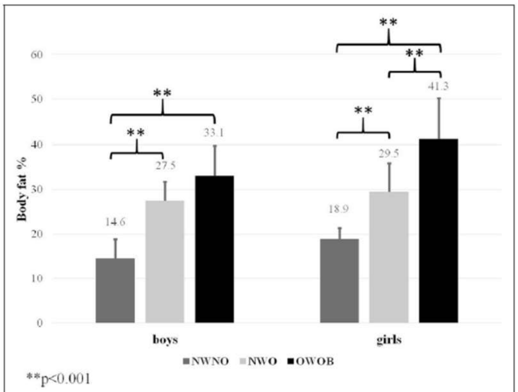


FIGURE 1 | Differences in percentage of body fat estimated by Slaughter equations.

OWOB children did not have a significantly different size of the muscle area on the upper arm (Hays $\omega^2 < 0.01$); however, the size of the muscle area on the calf was significantly poorer compared to the results of NWNO peers ($p < 0.001$, Hays $\omega^2 = 0.33$, **Table 4**).

DISCUSSION

The aim of the present study was to investigate the differences in skeletal robustness and muscle area on the upper arm and calf as an indicator important for: muscular competence, physical fitness, and bone health, which are associated with health development of children, between NWO, NWNO, and OWOB peers aged 9–12 years.

To begin with, we had to find a solution to the problem that was already pointed out by Franco et al. (7), who argued that there was no standard protocol or unified methodology that

TABLE 3 | Skeletal robustness—Frame indices from humerus and femur breadth epicondyles and the differences between NWO, NWNO, and OWOB children with respect to sex.

Groups	Frame index upper extremity Z-score		Frame index lower extremity Z-score	
	Mean/*SD*	S.E.	Mean/*SD*	S.E.
BOYS				
NWNO boys	−0.13 ± 0.99	0.16	0.07 ± 1.0	0.17
NWO boys	−0.60 ± 0.89	0.18	−0.85 ± 0.61**	0.13
OWOB boys	0.48 ± 0.87**	0.14	0.47 ± 0.89	0.14
GIRLS				
NWNO girls	−0.29 ± 1.11	0.19	0.08 ± 0.88	0.15
NWO girls	−0.33 ± 0.88	0.14	−0.43 ± 0.98*	0.15
OWOB girls	0.74 ± 0.59**	0.10	0.49 ± 0.94	0.17

**p* < 0.01 unlike the other two groups within each sex category.
***p* < 0.001 unlike the other two groups within each sex category.
SD, standard deviation; S.E., standard error; NWO, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

TABLE 4 | Upper arm and calf muscle area across three assessed groups of NWNO, NWO, and OWOB children with respect to sex.

Groups	Rolland Cachera upper arm muscle area Z-score		Rolland Cachera calf muscle area Z-score	
	Mean/*SD*	S.E.	Mean/*SD*	S.E.
BOYS				
NWNO boys	0.47 ± 0.88	0.11	0.89 ± 0.54	0.10
NWO boys	−1.15 ± 0.71**	0.12	−1.34 ± 0.45**	0.10
OWOB boys	0.27 ± 0.70	0.14	0.09 ± 0.61	0.09
GIRLS				
NWNO girls	0.64 ± 0.51	0.12	0.86 ± 0.55	0.11
NWO girls	−0.95 ± 0.64**	0.11	−0.85 ± 0.58**	0.12
OWOB girls	0.54 ± 0.82	0.11	0.20 ± 0.94	0.09

***p* < 0.001 unlike the other two groups within each sex category.
SD, standard deviation; S.E., standard error; NOW, normal weight obese; NWNO, normal weight non-obese; OWOB, overweight and obese.

could be used to identify NWO children. Wiklund et al. (14) used retrospective data from growth charts of relative weight to height gain and value of body fat from DXA. In their study, a NWO individual was defined as an individual with a relative weight between −10% and +20% and body fat ≥30%. On the other hand, Olafsdottir et al. (12) defined NWO adolescents as having BMI in the range of 18.5–24.5 kg/m^2 along with body fat ≥17.6% for males and ≥31.6% for females referencing the recommendations of Lohman et al. (42). However, these authors did not establish any criteria for relative body fat standards in the NWO population. In adult population, the guidelines for identifying NWO individuals are clearer. NWO adults are those, whose BMI is in the range of 18.5–24.5 kg/m^2 and who have body fat ≥30%. Some authors (8) even used or recommended gender and age cut-off values (43). Nevertheless, when we looked at previous studies, we found that according to these guidelines NWO participants usually had a significantly higher BMI compared to their normal weight non-obese peers (4, 13). This finding raises the question of whether these people more closely resemble overweight rather than normal weight obese individuals. Therefore, our first major aim in this study was to identify a group of NWO children whose BMI would not differ from BMI of their NWNO counterparts but who will have a significantly greater adipose tissue. Therefore, we defined the range of BMI for NWO as narrower than +- 1SD, specifically from the 25th percentile to the 60th percentile of the national norm. Even though we defined NWNO children as having BMI in the range from the 25th percentile to the 84th percentile of the national norm, in the end the two groups of NWO and NWNO children were indistinguishable from one another by their BMI. In addition, our estimates of body fat that were made using the Slaughter equation were in line with previous studies (2, 4, 6–8, 14), where the amount of body fat of NWO individuals was around 30%.

NWO children of both sexes that we had defined and selected in the manner explained above had the lowest values of skeletal robustness as well as muscle areas on the upper extremity and calf compared to their NWNO and OWOB counterparts. In other words, these children were skeletally more fragile and suffered from weak lean mass development on the extremities. This finding supported the suggestions (44, 45), which pointed out that a strong correlation existed in children between bone area and body weight, lean mass, and fat mass.

Firstly, we shall compare NWO and NWNO children. NWO children displayed significantly weaker lean mass development on the upper arm but did not have significantly poorer skeletal robustness compared to NWNO peers, calculated from humeral epicondyle breadth by Frisancho equation. This could be explained by the function of the upper arm, which is used mainly for manipulation rather than for transportation as is the case of the lower extremities. Warden et al. (46) found that the bone area in humeral diaphysis increases mainly during throwing activities (throwing ball, throwing stone). In addition, several studies reported that during the last few decades children's throwing skills have significantly deteriorated (47) regardless of body status. Therefore, even though NWNO children have better developed lean mass, they probably have comparable throwing skills to their NWO counterparts. On the other hand, NWO children had significantly weaker skeletal robustness calculated as the Frame index from femur breadth epicondyle compared to their NWNO peers. The difference between NWO and NWNO children in weak lean mass development on the calf was even more pronounced. This might suggest that NWO children have little physical activity, in particular transportation activities like walking or running (48). The assumption that physical activity as one of the major drivers of bone area development would support the "mechanostat" hypothesis developed by Frost (49–52) or the results from the Iowa Bone study (17, 18), who proposed that sufficient physical workload and number of muscle contractions are in close relation to bone mass and bone area development. In addition, Slemenda et al. (53) pointed out that increases in calf muscle area are strongly related to bone development and that physical activity is associated with more rapid bone development in prepubertal children. Our results could also provide support for the finding that skeletal robustness in different children populations has been decreasing (21, 54, 55) and the alarming suggestion that the number of NWO children in the population has been rising in the last 20 years. Moreover, when we consider sex as a factor, the skeletal robustness in the lower extremities as well as lean mass development on the calf in NWO boys has declined by an even more significant degree compared to their NWNO counterparts. It could be explained by the fact that boys displayed a greater level and wider range of physical activity, especially vigorous physical activity and also in sport participation (56), compared to girls (57, 58). In other words, we can expect bigger differences in the amount of produced physical activity in boys than in girls. If we accepted the finding of Slemenda et al. (53) about relation between calf muscle area, physical activity and bone development, and also Olafsdottir et al. (12), who revealed that NWO adolescents were less physically active, we could assume that from a long-term perspective the more pronounced weak skeletal robustness in NWO boys could by caused primarily by low physical activity of NWO children. Secondly we compared the results of skeletal robustness and lean mass development of NWO and OWOB children, a typical pattern emerged. OWOB children had significantly greater skeletal robustness estimated both from humeral and femoral epicondyle breadths. A number of previous studies showed that overweight and obese children have greater values of bone development, which is caused mainly by weight (volume of lean mass), height, and biological age (53, 59, 60). Further, OWOB children had significantly higher amount of lean mass on the upper arm and calf in comparison to NWO peers. However, it is interesting to note that OWOB children had significantly smaller amount of lean mass on the calf and only non-significantly higher Frame index calculated from femur epicondyle compared to NWNO counterparts. This would also indicate a low volume of transportation activities like walking or running in these children, which has been well-documented (53, 61, 62). Based on our finding we believe that it would be appropriate to measure under field testing condition also the skeletal robustness from femur epicondyle breadth, which seems to be more sensitive/discriminative compared to the Frame index calculated from humerus epicondyle breadth.

CONCLUSION

NWO children (boys and girls) had significantly poorer skeletal robustness on the lower extremities and poorer muscle area on the upper arm and calf as compared to NWNO counterparts. Further, a significantly higher prevalence of poor skeletal robustness as well as poor lean mass development on the lower extremities was found in boys. The highest skeletal robustness—but not muscle area on the lower extremities—was detected in OWOB children. Further research should focus on whether this poor skeletal and lean mass development: (1) is a consequence of insufficient physical activity regimes; (2) affects physical fitness of NWO children and could thus contribute to a higher prevalence of health problems in NWO children. We have highlighted the importance of the development of a simple identification of NWO children that could be used by pediatricians.

AUTHOR CONTRIBUTIONS

MM: data collection, introduction, methods, discussion, and conclusion. JP and EG: introdution, methods, and discussion. EB: data analysis and methods. JK: data collection, data analysis, and discussion. JJ: data collection and discussion. ŠV: data analysis and databasing data IT support.

FUNDING

This study was supported by PROGRES Q19, Social-Sciences Aspects of Human Movement Studies II; UNCE; Czech Science Foundation project No. 14–29358P; 17-26-03004-OGN and the title Physical development of modern children, adolescents and young adults in the context of ethnogenetic, socioeconomic and ecological factors and the Russian Foundation for Basic Research (RFFI) No. 16-06-00480.

REFERENCES

1. De LA, Martinoli R, Vaia F, Di RL. Normal Weight Obese (NWO) Women: an evaluation of a candidate new syndrome. *Nutr Metabol Cardiovasc Dis.* (2006) 16:513–23. doi: 10.1016/j.numecd.2005.10.010
2. De Lorenzo A, Del Gobbo V, Premrov MG, Bigioni M, Galvano F, Di Renzo L. Normal-weight obese syndrome: early inflammation? *Am J Clin Nutr.* (2007) 85:40–5. doi: 10.1093/ajcn/85.1.40
3. Oliveros E, Somers VK, Sochor O, Goel K, Lopez-Jimenez F. The concept of normal weight obesity. *Prog Cardiovasc Dis.* (2014) 56:426–33. doi: 10.1016/j.pcad.2013.10.003
4. Di Renzo L, Sarlo F, Petramala L, Iacopino L, Monteleone G, Colica C, et al. Association between– 308 G/A TNF-α polymorphism and appendicular skeletal muscle mass index as a marker of sarcopenia in normal weight obese syndrome. *Dis. Markers* (2013) 35:615–23. doi: 10.1155/2013/983424
5. Ruderman NB, Schneider SH, Berchtold P. The "metabolically-obese," normal-weight individual. *Am J Clin Nutr.* (1981) 348:1617–21. doi: 10.1093/ajcn/34.8.1617
6. Marques-Vidal P, Pécoud A, Hayoz D, Paccaud F, Mooser V, Waeber G, et al. Prevalence of normal weight obesity in switzerland: effect of various definitions. *Eur J Nutr.* (2008) 47:251. doi: 10.1007/s00394-008-0719-6
7. Franco LP, Silveira AGZ, Lima RSDAV, Horst MA, Cominetti C. APOE genotype associates with food consumption and body composition to predict dyslipidaemia in Brazilian adults with normal-weight obesity syndrome. *Clin Nutr.* (2017) 37:1722–27. doi: 10.1016/j.clnu.2017.07.002
8. Romero-Corral A, Somers VK, Sierra-Johnson J, Korenfeld Y, Boarin S, Korinek J, et al. Normal weight obesity: a risk factor for cardiometabolic dysregulation and cardiovascular mortality. *Eur. Heart J.* (2009) 31:737–46. doi: 10.1093/eurheartj/ehp487
9. Madeira FB, Silva AA, Veloso HF, Goldani MZ, Kac G, Cardoso VC, et al. Normal weight obesity is associated with metabolic syndrome and insulin resistance in young adults from a middle-income country. *PLoS ONE* (2013) 8:e60673. doi: 10.1371/journal.pone.0060673
10. Renzo L, Galvano F, Orlandi C, Bianchi A, Giacomo C, Fauci L, et al. Oxidative stress in normal-weight obese syndrome. *Obesity* (2010) 18:2125–30. doi: 10.1038/oby.2010.50
11. Kang S, Kyung C, Park JS, Kim S, Lee SP, Kim MK, et al. Subclinical vascular inflammation in subjects with normal weight obesity and its association with body fat: an 18 F-FDG-PET/CT study. *Cardiovasc Diabetol.* (2014) 13:70. doi: 10.1186/1475-2840-13-70
12. Olafsdottir AS, Torfadottir JE, Arngrimsson SA. Health behavior and metabolic risk factors associated with normal weight obesity in adolescents. *PLoS ONE* (2016) 11:e0161451. doi: 10.1371/journal.pone.0161451
13. Steffl M, Chrudimsky J, Tufano JJ. Using relative handgrip strength to identify children at risk of sarcopenic obesity. *PLoS ONE* (2017) 12:e0177006. doi: 10.1371/journal.pone.0177006
14. Wiklund P, Törmäkangas T, Shi Y, Wu N, Vainionpää A, Alen M, et al. Normal-weight obesity and cardiometabolic risk: a 7-year longitudinal study in girls from prepuberty to early adulthood. *Obesity* (2017) 25:1077–82. doi: 10.1002/oby.21838
15. Musalek M, Kokstejn J, Papez P, Scheffler C, Mumm R, Czernitzki AF, et al. Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years. *Anthropol Anz.* (2017) 74:203–12. doi: 10.1127/anthranz/2017/0752
16. Parízková J. *Body Fat and Physical Fitness: Body Composition and Lipid Metabolism in Different Regimes of Physical Activity.* The Hague: Martinus Nijhoff B.V./Medical Division (1977).
17. Janz KF, Burns TL, Torner JC, Levy SM, Paulos R, Willing MC, et al. physical activity and bone measures in young children: the iowa bone development study. *Pediatrics* (2001) 107:1387–93. doi: 10.1542/peds.107.6.1387
18. Janz KF, Rao S, Baumann HJ, Schultz JL. Measuring children's vertical ground reaction forces with accelerometry during walking, running, and jumping: the iowa bone development study. *Pediatr Exerc Sci.* (2003) 15:34–43. doi: 10.1123/pes.15.1.34
19. Parízková J, Hills A. *Childhood Obesity. Prevention and Treatment.* 2nd ed Boca Raton, FL; London; New York, NY: CRC Press., Taylor and Francis Group (2010).
20. Smith JJ, Eather N, Morgan PJ, Plotnikoff RC, Faigenbaum AD, Lubans DR. The health benefits of muscular fitness for children and adolescents: a systematic review and meta-analysis. *Sports Med.* (2014) 44:1209–23. doi: 10.1007/s40279-014-0196-4
21. Rietsch K, Eccard JA, Scheffler C. Decreased external skeletal robustness due to reduced physical activity? *Am J Hum Biol.* (2013) 25:404–10. doi: 10.1002/ajhb.22389
22. Ortega FB, Ruiz JR, Castillo MJ, Sjöström M. Physical fitness in childhood and adolescence: a powerful marker of health. *Int J Obes.* (2008) 32:1. doi: 10.1038/sj.ijo.0803774
23. Benson AC, Torode ME, Fiatarone Singh MA. Muscular strength and cardiorespiratory fitness is associated with higher insulin sensitivity in children and adolescents. *Int J Pediatr Obes.* (2006) 1:222–31. doi: 10.1080/17477160600962864
24. Steene-Johannessen J, Anderssen SA, Kolle E, Andersen LB. Low muscle fitness is associated with metabolic risk in youth. *Med Sci Sports Exer.* (2009) 41:1361–7. doi: 10.1249/MSS.0b013e31819aaae5
25. Freedman DS, Mei Z, Srinivasan SR, Berenson GS, Dietz WH. Cardiovascular risk factors and excess adiposity among overweight children and adolescents: the Bogalusa Heart Study. *J Pediatr.* (2007) 150:12–7. doi: 10.1016/j.jpeds.2006.08.042

Chapter 9

References:

Benson, A. C., Torode, M. E., & Fiatarone Singh, M. A. (2006). Muscular strength and cardiorespiratory fitness is associated with higher insulin sensitivity in children and adolescents. *International Journal of Pediatric Obesity*, *1*(4), 222-231.

Bláha, P. (1990): *Anthropometric Studies of the Czech Pre-school Children from 3 to 7 years.* – ÚSM, Praha.

Bogin, B., & Varela Silva, M. I. (2012). The Body Mass Index: The Good, the Bad, and the Horrid. Online on https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/14017 (Accessed on 3rd of February 2019).

Cairney, J., Kwan, M. Y., Hay, J. A., & Faught, B. E. (2012). Developmental coordination disorder, gender, and body weight: Examining the impact of participation in active play. *Research in Developmental Disabilities*, *33*(5), 1566-1573.

Castelli, D.M. & Valley, J.A. (2007): Chapter 3: The Relationship of Physical Fitness and Motor Competence to Physical Activity. *Journal of Teaching in Physical Education, 26*(4), 358-374.

Chirico, D., O'Leary, D., Cairney, J., Klentrou, P., Haluka, K., Hay, J., & Faught, B. (2011). Left ventricular structure and function in children with and without developmental coordination disorder. *Research in developmental disabilities*, *32*(1), 115-123.

Clark, E. M., Ness, A. R., Tobias, J. H., & Avon Longitudinal Study of Parents and Children Study Team. (2006). Adipose tissue stimulates bone growth in prepubertal children. *The Journal of Clinical Endocrinology & Metabolism*, *91*(7), 2534-2541.

Coin, A., Sarti, S., Ruggiero, E., Giannini, S., Pedrazzoni, M., Minisola, S., ... & Sergi, G. (2013). Prevalence of sarcopenia based on different diagnostic criteria using DEXA and appendicular skeletal muscle mass reference values in an Italian population aged 20 to 80. *Journal of the American Medical Directors Association*, *14*(7), 507-512.

Cole, T. J., Flegal, K. M., Nicholls, D., & Jackson, A. A. (2007). Body mass index cut offs to define thinness in children and adolescents: international survey. *Bmj*, *335*(7612), 194.

D'Hondt, E., Deforche, B., De Bourdeaudhuij, I., & Lenoir, M. (2008). Childhood obesity affects fine motor skill performance under different postural constraints. *Neuroscience letters*, *440*(1), 72-75.

D'Hondt, E., Deforche, B., De Bourdeaudhuij, I., & Lenoir, M. (2009). Relationship between motor skill and body mass index in 5-to 10-year-old children. *Adapted Physical Activity Quarterly*, *26*(1), 21-37.

Daniels, S. R. (2006). The consequences of childhood overweight and obesity. *The future of children*, *16*(1), 47-67.

De Lorenzo, A., Del Gobbo, V., Premrov, M. G., Bigioni, M., Galvano, F., & Di Renzo, L. (2007). Normal-Weight Obese Syndrome: Early Inflammation? *The American Journal of Clinical Nutrition*, *85*(1), 40-45.

De Lorenzo, A., Martinoli, R., Vaia, F., & Di Renzo, L. (2006). Normal weight obese (NWO) women: an evaluation of a candidate new syndrome. *Nutrition, Metabolism and Cardiovascular Diseases*, *16*(8), 513-523.

Di Renzo, L., Sarlo, F., Petramala, L., Iacopino, L., Monteleone, G., Colica, C., et al. (2013). Association between – 308 G/A TNF-a polymorphism and appendicular skeletal muscle mass index as a marker of sarcopenia in normal weight obese syndrome. *Disease Markers, 35*, 615-623. doi: 10.1155/2013/983424

Di Renzo, L., Tyndall, E., Gualtieri, P., Carboni, C., Valente, R., Ciani, A. S., ... & De Lorenzo, A. (2016). Association of body composition and eating behavior in the normal weight obese syndrome. *Eating and Weight Disorders-Studies on Anorexia, Bulimia and Obesity*, *21*(1), 99-106.

Ellis, K. J., Shypailo, R. J., Wong, W. W., & Abrams, S. A. (2003). Bone mineral mass in overweight and obese children: diminished or enhanced?. *Acta diabetologica*, *40*(1), s274-s277.

Erwin, H. E. & Castelli, D. M. (2008): National Physical Education Standards: A Summary of Student Performance and Its Correlates. *Research Quarterly for Exercise and Sport, 79*(4), 495-505.

Forbes, G. B. (1964). Lean body mass and fat in obese children. *Pediatrics*, *34*(3), 308-314.

Franco, L. P., Silveira, A. G. Z., Lima, R. S. D. A. V., Horst, M. A., & Cominetti, C. (2018). APOE genotype associates with food consumption and body composition to predict dyslipidaemia in Brazilian adults with normal-weight obesity syndrome. *Clinical Nutrition*, *37*(5), 1722-1727.

Freedman, D. S., Mei, Z., Srinivasan, S. R., Berenson, G. S., & Dietz, W. H. (2007). Cardiovascular risk factors and excess adiposity among overweight children and adolescents: the Bogalusa Heart Study. *The Journal of pediatrics*, *150*(1), 12-17.

Frisancho, A. R. (1990). *Anthropometric Standards for the Assessment of Growth and Nutritional Status*. University of Michigan Press

Frost, H. M. (1964). *The Laws of Bone Structure*. Springfield IL. Charles C. Thomas.

Frost, H. M. (1973). *Bone modeling and skeletal modeling errors*. Thomas.

Frost, H. M. (1987). Bone "mass" and the "mechanostat": a proposal. *The anatomical record*, *219*(1), 1-9.

Frost, H. M. (1997). Why do marathon runners have less bone than weight lifters? A vital-biomechanical view and explanation. *Bone*, *20*(3), 183-189.

Frost, H. M. (2000). Muscle, Bone, and the Utah Paradigm: A 1999 Overview. Medicine and *Science in Sports and Exercise, 32*(5), 911-917.

Goulding, A., Taylor, R. W., Jones, I. E., McAuley, K. A., Manning, P. J., & Williams, S. M. (2000). Overweight and obese children have low bone mass and area for their weight. *International journal of obesity*, *24*(5), 627-632.

Graf, C., Koch, B., Kretschmann-Kandel, E., Falkowski, G., Christ, H., Coburger, S., ... & Predel, H. G. (2004). Correlation between BMI, leisure habits and motor abilities in childhood (CHILT-project). *International journal of obesity*, *28*(1), 22-26.

Hendrix, C. G., Prins, M. R., & Dekkers, H. (2014). Developmental coordination disorder and overweight and obesity in children: a systematic review. *Obesity Reviews*, *15*(5), 408-423.

Hume, C., Okely, A., Bagley, S., Telford, A., Booth, M., Crawford, D. & Salmon, J. (2008): Does weight status influence associations between children's fundamental movement skills and physical activity? *Research Quarterly for Exercise and Sport, 79*(2), 158-165.

Janz, K. F., Burns, T. L., Torner, J. C., Levy, S. M., Paulos, R., Willing, M. C., & Warren, J. J. (2001). Physical Activity and Bone Measures in Young Children: The Iowa Bone Development Study. *Pediatrics*, *107*(6), 1387-1393.

Janz, K. F., Rao, S., Baumann, H. J., & Schultz, J. L. (2003). Measuring Children's Vertical Ground Reaction Forces With Accelerometry During Walking, Running, and Jumping: The Iowa Bone Development Study. *Pediatric Exercise Science*, *15*(1), 34-43.

Jean, N., Somers, V. K., Sochor, O., Medina-Inojosa, J., Llano, E. M., & Lopez-Jimenez, F. (2014). Normal-weight obesity: implications for cardiovascular health. *Current atherosclerosis reports*, *16*(12), 464.

Jiménez-Pavón, D., Kelly, J., & Reilly, J. J. (2010). Associations between objectively measured habitual physical activity and adiposity in children and adolescents: Systematic review. *International Journal of Pediatric Obesity*, *5*(1), 3-18.

Klein, K. O., Larmore, K. A., De Lancey, E., Brown, J. M., Considine, R. V., & Hassink, S. G. (1998). Effect of obesity on estradiol level, and its relationship to leptin, bone maturation, and bone mineral density in children. *The journal of clinical endocrinology & metabolism*, *83*(10), 3469-3475.

Lin, P. P., & Henderson, R. C. (1996). Bone mineralization in the affected extremities of children with spastic hemiplegia. *Developmental Medicine & Child Neurology*, *38*(9), 782-786.

Logan, S. W., Scrabis-Fletcher, K., Modlesky, C., & Getchell, N. (2011). The relationship between motor skill proficiency and body mass index in preschool children. *Research quarterly for exercise and sport*, *82*(3), 442-448.

Lohman, T. G., Roche, A. F., & Martorell, R. (1988). *Anthropometric standardization reference manual*. Human kinetics books.

Magnussen, C. G., Schmidt, M. D., Dwyer, T., & Venn, A. (2012). Muscular Fitness and Clustered Cardiovascular Disease Risk in Australian Youth. *European Journal of Applied Physiology, 112*(8), 3167-3171.

Marques-Vidal, P., Pécoud, A., Hayoz, D., Paccaud, F., Mooser, V., Waeber, G., & Vollenweider, P. (2008). Prevalence of normal weight obesity in Switzerland: effect of various definitions. *European journal of nutrition*, *47*(5), 251-257.

Marten, N., & Olds, T. (2004). Physical activity: patterns of active transport in 11–12 year old Australian children. *Australian and New Zealand journal of public health*, *28*(2), 167-172.

Mccormick, D. P., Ponder, S. W., Fawcett, H. D., & Palmer, J. L. (1991). Spinal bone mineral density in 335 normal and obese children and adolescents: evidence for ethnic and sex differences. *Journal of Bone and Mineral Research*, *6*(5), 507-513.

Morano, M., Colella, D., & Caroli, M. (2011). Gross motor skill performance in a sample of overweight and non-overweight preschool children. *Pediatric Obesity*, *6*(S2), 42-46.

Musalek, M., Kokstejn, J., Papez, P., Scheffler, C., Mumm, R., Czernitzki, A. F., & Koziel, S. (2017). Impact of normal weight obesity on fundamental motor skills in pre-school children aged 3 to 6 years. *Anthropologischer Anzeiger; Bericht uber die biologisch-anthropologische Literatur, 74*(3), 203-212.

Musalek, M., Kokstejn, J., Papez, P., Jírovec, J., & Honsová, S. (2017). Relation Between Percent Body Fat and Fundamental Motor Skills in Pre-School Children age 3-6 years. *Sport Mont, 15*(2), 9–13.

Musalek, M., Pařízková, J., Godina, E., Bondareva, E., Kokštejn, J., Jírovec, J., & Vokounová, Š. (2018). Poor skeletal robustness on lower extremities and weak lean mass development on upper arm and calf: Normal weight obesity in middle-school-aged children (9 to 12). *Frontiers in Pediatrics*, *6*, 371.

Ogden, C. L., & Flegal, K. M. (2010). Changes in terminology for childhood overweight and obesity. *Age*, *12*(12).

Okely, A. D., Booth, M. L., & Chey, T. (2004). Relationships between body composition and fundamental movement skills among children and adolescents. *Research quarterly for exercise and sport*, *75*(3), 238-247.

Okorodudu, D. O., Jumean, M. F., Montori, V. M., Romero-Corral, A., Somers, V. K., Erwin, P. J., & Lopez-Jimenez, F. (2010). Diagnostic Performance of Body Mass Index to Identify Obesity as Defined by Body Adiposity: A Systematic Review and Meta-Analysis. *International Journal of Obesity*, *34*(5), 791-799.

Olafsdottir, A. S., Torfadottir, J. E., & Arngrimsson, S. A. (2016). Health Behavior and Metabolic Risk Factors Associated with Normal Weight Obesity in Adolescents. *PloS one*, *11*(8), e0161451.

Oliveros, E., Somers, V. K., Sochor, O., Goel, K., & Lopez-Jimenez, F. (2014). The concept of normal weight obesity. *Progress in cardiovascular diseases*, *56*(4), 426-433.

Ortega, F. B., Ruiz, J. R., Castillo, M. J., & Sjöström, M. (2008). Physical fitness in childhood and adolescence: a powerful marker of health. *International journal of obesity*, *32*(1), 1-11.

Ošancova, K., & Hejda, S. (1975). Epidemiology of obesity. In *Obesity: Its pathogenesis and management* (pp. 57-91). Springer, Dordrecht.

Parízková, J. (1985). Adaptation of functional capacity and exercise. In. K. Blaxter, & J. C. Waterlow: Nutritional adaptation in man. Proceedings of the 6. International

Symposium organized by the Rank Prize Funds, held at Royal Windsor (UK), 1-5 April 1984.

Parizkova, J., Bunc, V., Sprynarova, S., Mackova, E., & Heller, J. (1987). Body composition, aerobic capacity, ventilatory threshold and food intake in different sports. *Annals of sports medicine*, *3*, 171-177.

Parızková, J., Sedlak, P., Dvoráková, H., Lisá, L., & Bláha, P. (2012). Secular trends of adiposity and motor abilities in preschool children. *Journal of Obesity and Weight Loss Therapy*, *2*(9).

Parízková-Capkova, J. (1957). Mereni podkozniho tuku caliperem.(Measurement of subcutaneous fat by a caliper) Cs. *Pediatrie*, *12*, 310-314.

Pařízková, J. (2010). *Nutrition, Physical Activity, and Health in Early Life. 2nd Ed.*, CRC Press, Taylor and Francis Group, Boca Raton - London - New York; 2010.

Pařízková, J. (Ed.). (2015). *Physical Activity, Fitness, Nutrition and Obesity During Growth: Secular Changes of Growth, Body Composition and Functional Capacity in Children and Adolescents in Different Environment*. Bentham science publishers.

Petrásek, K., Rath, R. and Mašek, J. (1965) On the ratio of body fat in relation to different factors. *Review Czechoslovakia Medicine., 11,* 251-258.

Pietrobelli, A., Faith, M. S., Wang, J., Brambilla, P., Chiumello, G., & Heymsfield, S. B. (2002). Association of lean tissue and fat mass with bone mineral content in children and adolescents. *Obesity research*, *10*(1), 56-60.

Rath, R. a Petrásek, R. (1964). K otázce váhové normy. Podíl tuku a jeho vztah k tělesné výšce u žen s normální váhou. *Časopis Lékařů Českých*, *53*, 1182-1185.

Rath, R., Petrásek, R., & Mašek, J. (1967). Ratio of Body Fat, Cholesterolaemia, Esterified Fatty Acids and Blood Pressure of Women with Different Body-Weight. *Annals of Nutrition and Metabolism*, *9*(1), 67-78.

Rauch, F., Bailey, D. A., Baxter-Jones, A., Mirwald, R., & Faulkner, R. (2004). The 'Muscle-Bone Unit' during the Pubertal Growth Spurt. *Bone, 34*(5), 771-775.

Reid, I. R. (2008). Relationships between fat and bone. *Osteoporosis International*, *19*(5), 595-606.

Renzo, L., Galvano, F., Orlandi, C., Bianchi, A., Giacomo, C., Fauci, L., ... & Lorenzo, A. (2010). Oxidative stress in normal-weight obese syndrome. *Obesity*, *18*(11), 2125-2130.

Rietsch, K., Eccard, J. A., & Scheffler, C. (2013). Decreased External Skeletal Robustness Due to Reduced Physical Activity? *American Journal of Human Biology*, *25*(3), 404-410.

Rocher, E., Chappard, C., Jaffre, C., Benhamou, C. L., & Courteix, D. (2008). Bone mineral density in prepubertal obese and control children: relation to body weight, lean mass, and fat mass. *Journal of bone and mineral metabolism*, *26*(1), 73-78.

Rolland-Cachera, M. F., Brambilla, P., Manzoni, P., Akrout, M., Sironi, S., Del Maschio, A., & Chiumello, G. (1997). Body composition assessed on the basis of arm circumference and triceps skinfold thickness: a new index validated in children by magnetic resonance imaging. *The American journal of clinical nutrition*, *65*(6), 1709-1713.

Romero-Corral, A., Somers, V. K., Sierra-Johnson, J., Korenfeld, Y., Boarin, S., Korinek, J., ... & Lopez-Jimenez, F. (2009). Normal weight obesity: a risk factor for cardiometabolic dysregulation and cardiovascular mortality. *European heart journal*, *31*(6), 737-746.

Ruderman, N. B., Schneider, S. H., & Berchtold, P. (1981). The "metabolically-obese," normal-weight individual. *The American Journal of Clinical Nutrition, 34*(8), 1617-1621.

Ruderman, N., Chisholm, D., Pi-Sunyer, X., & Schneider, S. (1998). The metabolically obese, normal-weight individual revisited. *Diabetes*, *47*(5), 699-713.

Sedlak, P., Pařízková, J., Daniš, R., Dvořáková, H., & Vignerová, J. (2015). Secular changes of adiposity and motor development in Czech preschool children: Lifestyle changes in fifty-five year retrospective study. *BioMed research international*, *2015*

Sedlak, P., Pařízková, J., Procházková, L., Cvrčková, L., & Dvořáková, H. (2017). Secular Changes of Adiposity in Czech Children Aged from 3 to 6 Years: Latent Obesity in Preschool Age. *BioMed research international*, *2017*

Schautz, B., Later, W., Heller, M., Müller, M. J., & Bosy-Westphal, A. (2012). Total and regional relationship between lean and fat mass with increasing adiposity—impact for the diagnosis of sarcopenic obesity. *European journal of clinical nutrition*, *66*(12), 1356.

Scheffler, C., Ketelhut, K., & Mohasseb, I. (2007). Does physical education modify the body composition? Results of a longitudinal study of pre-school children. *Anthropologischer Anzeiger*, *65*(2), 193-201.

Silman, A., Cairney, J., Hay, J., Klentrou, P., & Faught, B. E. (2011). Role of physical activity and perceived adequacy on peak aerobic power in children with developmental coordination disorder. *Human Movement Science*, *30*(3), 672-681.

Simeons, A. T. W. (1971). *Pounds and Inches: a new approach to obesity*. Popular Publishing.

Slaughter, M. H., Lohman, T. G., Boileau, R., Horswill, C. A., Stillman, R. J., Van Loan, M. D., & Bemben, D. A. (1988). Skinfold Equations for Estimation of Body Fatness in Children and Youth. *Human Biology*, *60*(5), 709-723.

Slemenda, C. W., Reister, T. K., Hui, S. L., Miller, J. Z., Christian, J. C., & Johnston Jr, C. C. (1994). Influences on skeletal mineralization in children and adolescents: evidence for varying effects of sexual maturation and physical activity. *The Journal of pediatrics*, *125*(2), 201-207.

Smith, J. J., Eather, N., Morgan, P. J., Plotnikoff, R. C., Faigenbaum, A. D., & Lubans, D. R. (2014). The Health Benefits of Muscular Fitness for Children and Adolescents: A Systematic Review and Meta-Analysis. *Sports Medicine, 44*(9), 1209-1223.

Steene-Johannessen, J., Anderssen, S. A., Kolle, E., & Andersen, L. B. (2009). Low muscle fitness is associated with metabolic risk in youth. *Medicine & Science in Sports & Exercise*, *41*(7), 1361-1367.

Vicente-Rodríguez, G., Ara, I., Pérez-Gómez, J., Dorado, C. & Calbet, J. A. (2005). Muscular Development and Physical Activity as Major Determinants of Femoral Bone Mass Acquisition during Growth. *British Journal of Sports Medicine, 39*(9), 611-616.

Vignerová, J., & Bláha, P. (2001). *Sledování růstu českých dětí a dospívajících. Norma, vyhublost, obezita 1. vydání.* Praha, Státní zdravotní ústav, Translation: *Investigation of Growth in Czech Children and Adolescence. Norm, Emaciation, Obesity (1st ed).* Praha, Státní zdravotní ústav, ISBN 80-7071-173-6.

Wetzsteon, R. J., Petit, M. A., Macdonald, H. M., Hughes, J. M., Beck, T. J., & McKay, H. A. (2008). Bone structure and volumetric BMD in overweight children: a longitudinal study. *Journal of Bone and Mineral Research*, *23*(12), 1946-1953.

Wiklund, P., Törmäkangas, T., Shi, Y., Wu, N., Vainionpää, A., Alen, M., & Cheng, S. (2017). Normal-weight obesity and cardiometabolic risk: A 7-year longitudinal study in girls from prepuberty to early adulthood. *Obesity*, *25*(6), 1077-1082.

Williams, H. G., Pfeiffer, K. A., O'neill, J. R., Dowda, M., McIver, K. L., Brown, W. H., & Pate, R. R. (2008). Motor skill performance and physical activity in preschool children. *Obesity*, *16*(6), 1421-1426.

Yang, S. C., Lin, S. J., & Tsai, C. Y. (2015). Effect of sex, age, and BMI on the development of locomotor skills and object control skills among preschool children. *Perceptual and motor skills*, *121*(3), 873-888.

Zamboni, G., Soffiati, M., Giavarina, D., & Tato, L. (1988). Mineral metabolism in obese children. *Acta Pœdiatrica*, *77*(5), 741-746.

APPENDIX

Unpublished data – laterality quotient and mixed laterality in ADHD and non ADHD children (data from study Scharoun et al., 2013)

Boys with ADHD		
LQ Hand	LQ Foot	Frequency of mixed laterality
100	100	1
100	100	1
66,66666667	55,55556	0
100	100	1
100	100	1
100	100	1
100	100	1
66,66666667	55,55556	0
100	100	1
100	100	1
66,66666667	55,55556	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
66,66666667	55,55556	0
100	100	1
33,33333333	11,11111	0
100	100	1
100	100	1
33,33333333	11,11111	0
100	100	1
66,66666667	55,55556	0
100	100	1

Boys without ADHD		
LQ Hand	LQ Foot	Frequency of mixed laterality
100	100	1
100	100	1
66,66667	55,55556	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
66,66667	88,88889	0
100	100	1
33,33333	11,11111	0
100	100	1
100	100	1
33,33333	11,11111	0
100	100	1
66,66667	88,88889	0
100	100	1

100	100	1

100	66,66667	0

girls with ADHD		
LQ Hand	LQ Foot	Frequency of mixed laterality
100	100	1
100	66,66667	0
100	100	1
100	100	1
100	100	1
33,33333333	11,11111	0
100	100	1
33,33333333	11,11111	0
100	100	1
66,66666667	88,88889	0
100	100	1
100	100	1
100	100	1
0	0	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
66,66666667	88,88889	0
66,66666667	22,22222	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
66,66666667	22,22222	0
100	100	1

girls without ADHD		
LQ Hand	LQ Foot	Frequency of mixed laterality
100	100	1
0	0	1
100	100	1
100	100	1
66,66667	88,88889	0
100	100	1
100	100	1
33,33333	77,77778	0
100	100	1
33,33333	77,77778	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
33,33333	77,77778	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1
66,66667	88,88889	0
100	100	1
100	100	1
100	100	1
100	100	1
100	100	1

LQ – laterality quotient

1 – strong lateralization

0 –weak lateralization