ACTA UNIVERSITATIS CAROLINAE,
KINANTHROPOLOGICA Vol. 48, 2 – 2012 Pag. 189–200

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DEGENERATIVE CHANGES IN THE CERVICAL SPINE WITH A FOCUS ON THE INTERVERTEBRAL DISC PROLAPSE AND ITS VERIFICATION USING IMAGING AND 3D MODEL

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SUMMARY

Degenerative changes in the cervical spine naturally come from the aging of the organism, but a number of modifiable factors accelerate the onset. Among such factors include especially hypokinesia and unilateral overloading of cervical spine. Modern imaging techniques can in detail detect these pathological processes, but are limited by the patient's position during the investigation. The resulting series of images are used as the basis for further processing and creation of 3D model, which displays tissue specific for patients and generally can be used for other solutions space and stress calculation procedures in mathematical modeling of biomechanical solutions to the problem in the cervical segment of the axial system of man.

Keywords: degenerative changes, the cervical spine, imaging methods, 3D model

INTRODUCTION

The spine is one of the structural parts of the axial system. Axial system is a subsystem of the postural system which has a function to provide an upright posture of man. The basic functional unit of the spine is a motion segment with the supporting, hydrodynamic and kinetic function. Among the carrier and passive fixation components of the segment belong vertebrae and intervertebral ligaments. The hydrodynamic component are the intervertebral discs and spinal vascular system. Kinetic and active fixation component are spinal joints and muscles (Véle, 2006). Interplay of these components creates posture of body and spine – statics. Under physiological circumstances the statics is trying to keep the center of gravity of the body in the sagittal plane (cervical and lumbar lordosis and thoracic kyphosis) and right-left plane (scoliosis) (Mlčoch, 2008). Static disorder affects the entire body components, ie passive and active, and changes the setting of ideal contact surfaces in other joints, causing a dynamics disorder as well. There is evidence that to increased wear of the structure and damage to musculoskeletal system leads not only musculoskeletal strain, but also the lack of movement (hypokinesis) (Dragojevic and Zivkovic, 2003; Véle, 2006; Novotny et al., 2009; Janda 2001, etc.).

Degenerative changes of the cervical spine

Degenerative spine processes come with advancing age, and studies show that there can already be pathological changes identified at the children's spine (Urban, 2003). According to Chrobok (2006), Bednařík and Kadaňka (2000) the development of the pathogenetic chain begins with degeneration of intervertebral disc. According to Lewit (2003), the place of beginning of degenerative changes of the cervical spine is the processus uncinatus. Degenerative disc changes lead to a reduction of the intervertebral space and thus to an increased mobility of adjacent vertebrae and instability throughout the spinal motion segment. Annulus fibrosus becomes stiffer and weaker through loss of proteoglycans and water (Adams and Roughley, 2006). The boundary between the annular circles and the core are blurring and annular ring becomes thinner and disorganized. It can lead to cracks and fissures. The final stage has a structure which is composed of granular or scar tissue. However, it is difficult to distinguish the boundaries of the natural aging from pathological changes, because there are no precise characteristics, morphological or biochemical, that would distinguish these two processes (Urban, 2000).

Degenerative changes in the spine may or may not cause subjective symptoms, as shown by many domestic and foreign studies (Cabadaj, 2007; Friedenberg et al., 1960, Matsumoto et al., 1998). From a clinical point of view, we may encounter in practice limited mobility of the cervical spine because of pain, muscle spasms of neck muscles (or even scapulohumeral muscle) with migraine or tension type headaches, cervical cranialgia, dizziness, symptoms of vestibular and cochlear impairment, with dysphagia and other functional disabilities, to radiculopathy and myelopathy (Trnavský and Kolařík, 1997). On the emergence of degenerative changes participate both unmodifiable factors: genetic (Battie et al., 2008), the natural aging of the body, injury, excessive overloading of the musculoskeletal system including the vibration exposure, environmental factors (especially physical and biochemical) and modifiable factors, which mainly relate to our lifestyle – physical behavior, nutrition, smoking (Shankar et al., 2009). The task of a physiotherapist, who mastered the diagnosis of musculoskeletal disorders, is to reveal the causes of these disorders and the subsequent solution using available means, including physical therapy.

Reparation possibilities of structural deffects of cervical spine

Although the herniation of intervertebral disc is a structural change, which is still today considered by many authors as an irreversible change (Zdražilová, 2006; Kaštánková, 2011, etc.), it is possible in some cases in a particular time to record visible changes in the affected tissue and healing of structural defects in the cervical spine. Images (Figure 1, Figure 2) show two such cases.

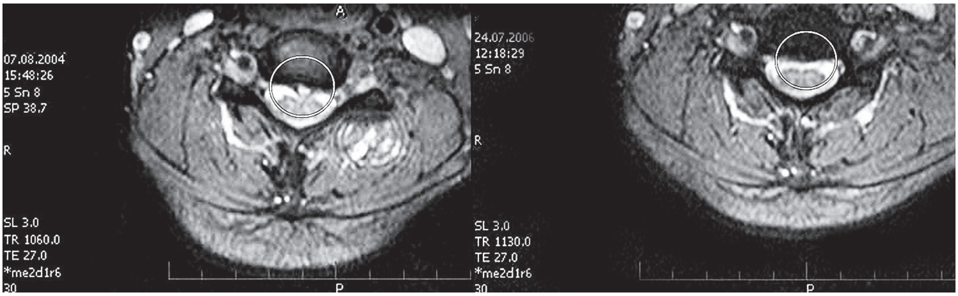


Figure1. Examination of the cervical spine using MRI, axial slices. On the left in examination from 7 August 2004 a dorsomedial disc herniation is evident in segment C5/C6. In the picture on the right is the examination from 24 July 2006 of the same segment, where we can see a regression of sequestrated tissue.

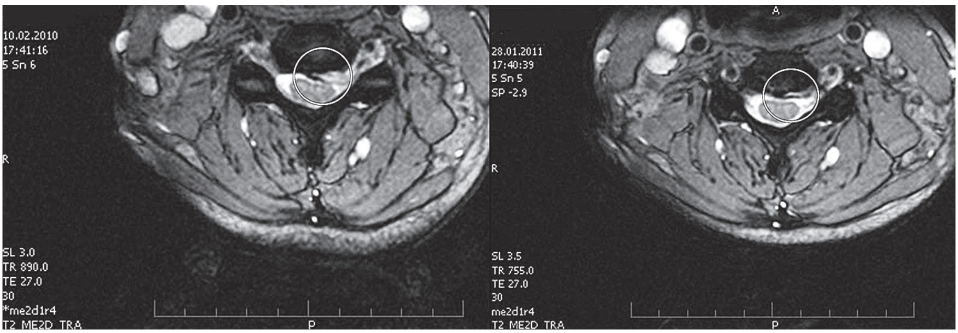


Figure 2. Examination of the cervical spine using MRI, axial slices. On the left in examination from 10 February 2010 a broad medial lateral or intraforaminal left hand prolapse of disc C4/C5 is evident. In the picture on the right is the examination from 28 January 2011, where we see the regression of root oppression, residual protrusion of C4/C5 is evident.

PURPOSE

The purpose of this work is to describe and compare the graphic software that provides an ability to detect pathological processes in a cervical spine. This software will help us create a 3D model of the patient's cervical spine.

METHODS

Well chosen imaging methods of examination can clarify the diagnosis and make treatment more effective. Degenerative changes of the spine are detected mainly using native radiography (X-ray), computer tomography (CT) and magnetic resonance (MR). Using X-ray and CT examinations are assessed primarily the bone changes. X-ray examination of the spine from a functional point of view provides information about the full segments of the spine, their position and the mutual relations (Rychlíková, 2012). CT is commonly used for clinical validation radicular syndrome and finding a prolapsed disc after injuries and other illnesses. From a functional point of view it is limited to one or more motion segments, therefore we have no opportunity to assess the overall spine posture and its response to various morphological changes. Unlike conventional X-ray view the CT has greater sensitivity and dynamic range thanks to the electronic image scanning, filtration and image modulation adjustability (brightness, contrast). MR examination in addition to the osseous structures shows all soft tissues and their pathological changes with consequences which they cause. The patient does not get burdened with radiation exposure. As a result, the selection of the method depends on the tissue we want to evaluate.

Magnetic resonance imaging

Magnetic resonance is due to its characteristics often used to show degenerative changes in the spine (Firooznia, Rafii and Golimbu, 1997). Standard MR examination is performed while lying, in supine or prone position. Typically, these devices operate with the force of the magnetic field from 1.0 to 3.0 T, which determines the final quality of the image (Medical Policy, 2010). The higher the magnetic field strength, the better the spatial resolution (Small, 2011). The need to display spinal structures in other positions of the patient (in the axial load, in position provoking pathology, etc.) gave rise to the so-called "Position MRI", which however works with the strength of the magnetic field only 0.6 T, which affects the final quality of images (Health Technology Assessment, 2007).

3D scan

The term "3D" is now commonly used to describe the world, represented by three dimensions that depict the Cartesian coordinate system (X, Y, and Z). By displaying the human tissues in 3D we are adding the third dimension to flat 2D objects – depth and thus moving closer to reality (Menclík, 2012). Modern devices allow us to make whole series of spatially (3D) connecting planar images (Kršek and Krupa, 2005). These can then be processed in the special graphic programs and use various functions for further editing.

Entry image data quality

Based on literature review and practical familiarization with the available graphics programs we state that the segmentation of individual tissues can be performed manually, automatically, or automatically with the following manual correction. The validity of the resulting 3D image depends on the quality of image data (Potočnik, 2004; Well et al., 1996). To determine the dependence of the resulting quality of the 3D model on the quality of the input data, we made two series of MR examinations of a single patient. Both series differ primarily in the number and thickness of slices. In the first series of slices the parameters were set to a higher quality, the second series presents the standard quality of the cervical spine MR examination. To create 3D models of the spinal canal, we used the method of automatic segmentation (Figure 3, Figure 4). The result shows that the parameters of the standard MR examination are not sufficient for processing and creation of 3D model and the low quality of examination makes further processing virtually impossible (Fig. 4).

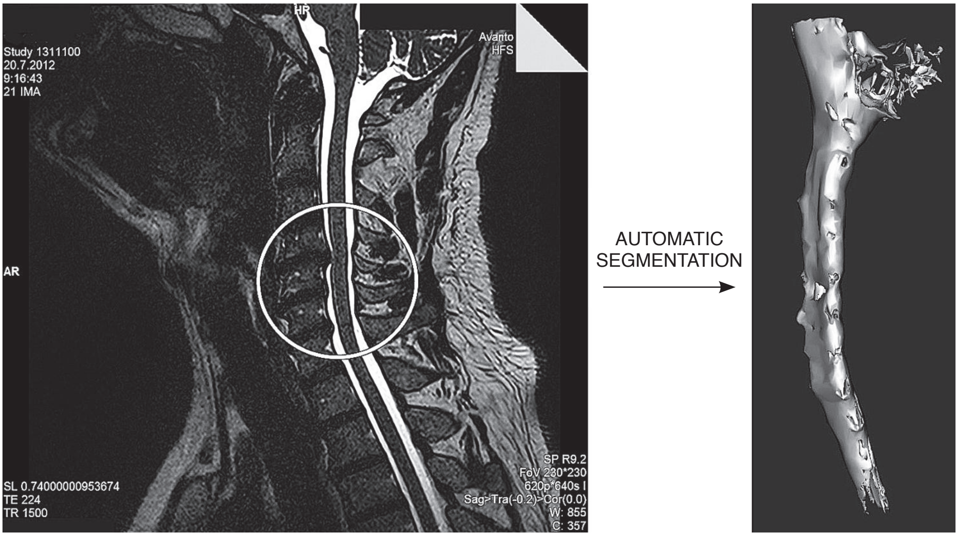


Figure 3. On the left is a sagittal section from the MR examination, highlighted area of C4/C5 disc herniation. Technical parameters: SL (slice width) about 0.74 mm, the total number of slices 52. On the right is 3D model of the spinal canal made with the automatic segmentation program 3DimViewer, highlighted area of disc herniation forming a hole through the spinal canal

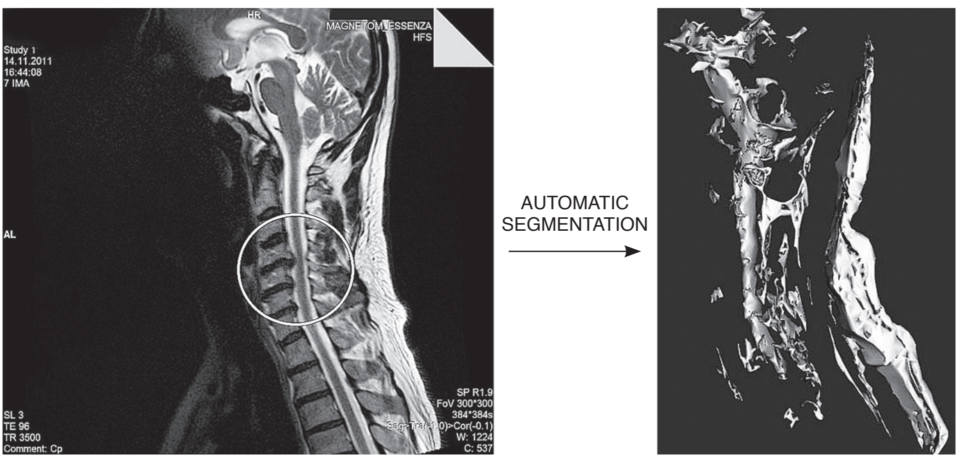


Figure 4. On the left is a sagittal section from the MR examination, highlighted area of C4/C5 disc herniation. Technical parameter: SL (slice width) approximately 3 mm, the total number of slices 15. On the right is 3D model of the spinal canal made with the automatic segmentation program 3DimViewer, to the left is a highlighted area of disc herniation forming the hole

To create a 3D model of the intervertebral discs of the first series, we used manual segmentation (Fig. 5). 3D model is created by tracing the structures of the intervertebral discs in the individual sections and the subsequent generation using special programming functions. The quality and validity of the resulting 3D model depends on the quality of the input data, on the experiences and abilities of a worker who has to correctly distinguish between individual tissues.

Among the most common parameters that affect the quality of the input MR (CT) data belong *volume data resolution* (frame size, number and thickness of slices) and the presence of *artifacts*. Thinner slices have better spatial resolution and better show small structures (Atlas, 2009). On the other hand, with a higher number of cuts a time consumption of examination grows thereby increasing the contribution of noise in the resulting images (slices). Applying the method of *data interpolation* we can get more slices and the reconstructed shape of the object can achieve greater accuracy (Mikulka, 2010).

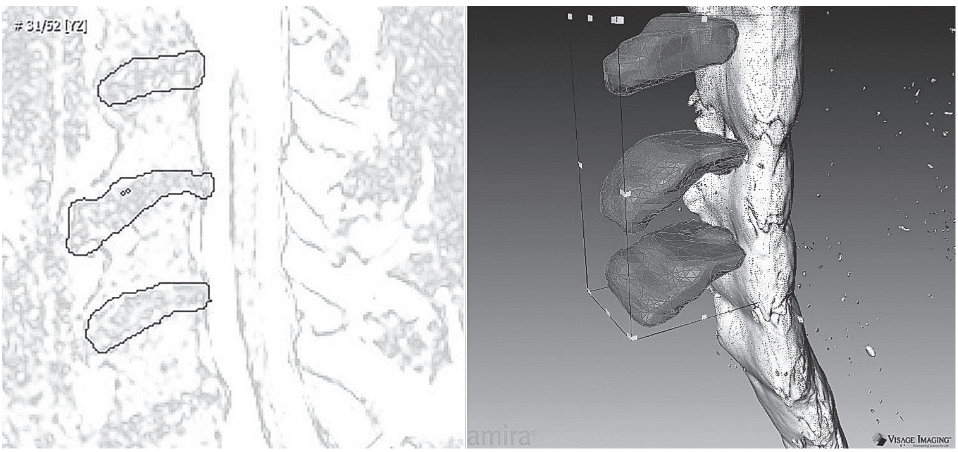
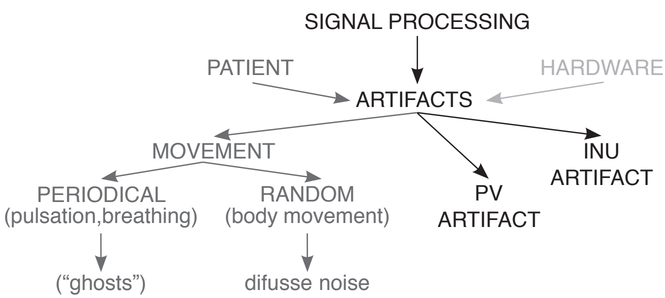


Figure 5. Example of manual segmentation of intervertebral discs from the cervical spine MR examination, sagittal section, the Amira program. Manual segmentation is unclear in this case and further processing of the 3D model lacks validity.



Figue 6. Origin of artifacts produced in the resulting MR image.

Periodic motion causes artifacts in the final image in the form of "ghosts", the patient motion then causes a diffuse noise. Two main artifacts appear during signal processing:

- *PV artifact* – means that voxels (3D image units) consist of more than one type of tissue;
- *INU artifact* – rises from a fast-changing gradient fields of coils and manifests itself as a non-linearity in the image function transmission

The diagram in Figure 6 shows that the artifacts in the final image originate from the patient, occur in signal processing and are determined by the quality of the device. Among the artifacts affecting the quality of further processing are therefore noise, as well as non-linearity in the image function transmission (INU) and voxels consisting of more than one type of tissue (PV). Image noise is caused by electromagnetic noise in the human body, emerging from motion of charged particles and minor anomalies of the measuring electronics. Signal-to-Noise Ratio (S/N) is one of the main factors determining the quality of images, which increases with higher S/N. Increase in this value is achieved by the use of filters (Malá, 2011). INU artifact is a continuous change in MR signal intensities over the entire image and is attributed to eddy currents that arise due to fast switching of gradient fields and the anatomy of the human body, both inside and outside the scanned area. PV artifact is caused by the final spatial resolution of digital MR images (Janoušová, 2008). The resulting image is then burdened with many interferences that affect the quality of the subsequently created 3D model. Thanks to this the automatic segmentation of tissues alone is usually insufficient and needs manual adjustments. This is a time consuming task for large number of slices (Kršek and Krupa, 2005). Therefore, this work should belong to professionals who have the necessary equipment and facilities. Diagram of such a work place was created from the work of doctors in Brno (Kršek et al., 2007).

RESULTS

Data processing – graphic programs

A part of our research was to find and compare special graphic programs that allow us to create as well as graphically edit the 3D models of tissues. The series of images from the MR examination therefore served as a basis for processing in these programs, some of which are freely available on the Internet (eg 3D Slicer, 3DimViewer, …) and some are paid (Amira, Simpleware, …).

3DimViewer program is a viewer of medical images in DICOM format. It is a simple tool for creating 3D models using automatic segmentation, as well as viewing and manipulation. It is well understandable, available free of charge and is the only tested one using Czech. Its disadvantage is the lack of graphics functions and therefore an additional, more interesting work with the model.

Graphical program 3D Slicer is, unlike the previous, full of various tools for graphic editing and creating 3D models. It's also available for free and to use it you need to be familiar with the attached manual. Big disadvantage is the starting and running of the program itself. It often suddenly turns off or “freezes”.

Simpleware and Amira programs are quality tools for creating and editing 3D graphical models of human tissues. They are both paid and offer free trials. While Amira is using the software license keys to unlock the program, for obtaining Simpleware program you have to fill in an online form containing your personal data and requiring the purpose for which you want to try the program. Even after completing all the required information you would receive an email with a request for more detailed description of your interest in the use of Simpleware software. Due to the fact that both programs already require closer cooperation with the manual, they are quite difficult for the inexperienced user and the limited accessibility of the trial version is insufficient for more detailed analysis.

In our case, we had an unlimited access to the Amira program at the FTVS UK and it became the main tool for a better understanding the possibilities of MR data processing into 3D models and their graphical manipulation.

Results of our work are shown in the following figures (Fig. 7, Fig 8, Fig. 9). In practical terms, it is only an outline of what you can create in such a program. For a better acquaintance with all the possibilities of modeling of human tissues further work is needed dealing with this issue.

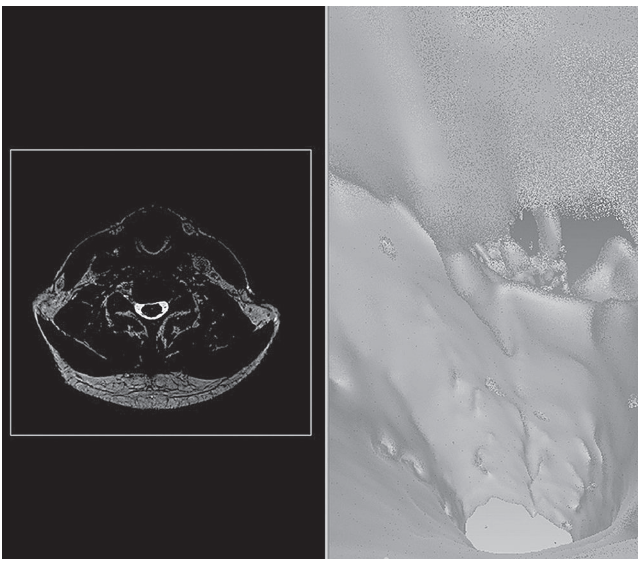


Figure7. On the left is an axial slice acquired by MR examination, the area of disc herniation in C4/C5 segment. On the right is a view inside the 3D model of the spinal canal from the top, area of prolapse creates an opening, the Amira program

Figure 8. 3D model of the spinal canal, the hole in the middle created by the disc herniation into the spinal canal, the Amira program

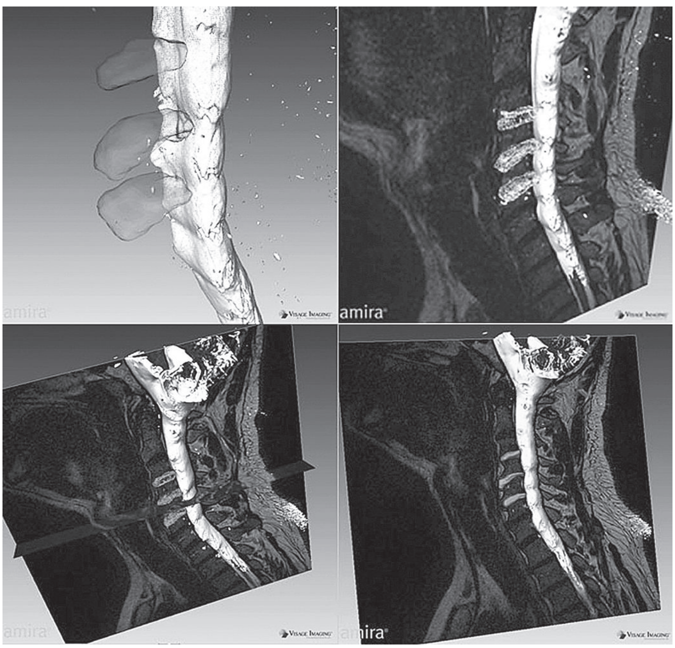


Figure 9. 3D models of the cervical spine, a sample graphic modifications in the Amira program

DISCUSSION

To create quality 3D models it is necessary to clearly define the required scanning parameters of the MR examination. Modeling itself should be in the hands of an experienced worker who would be familiar with the anatomy of the human body and also with the control of the graphic software for creating 3D models. The most appropriate and accurate function to differentiate tissues seem to be the automatic segmentation followed by manual correction. From our perspective, for the creation and subsequent graphic editing of 3D models, the best from the above mentioned programs is Amira.

CONCLUSION

The need for a detailed view of human tissues gave rise to many high-quality examination methods. They have become the basis for a new, modern look into the inner world of the body through three dimensions. The 3D models could be part of the digitized medical image records of the patient. Their big advantage is the absence of additional costs needed to create them. Using 3D visualization we get better orientation in relation to other tissues, which can improve the diagnosis and subsequently the treatment. In addition, the 3D models can be used for educational purposes, and not only for professionals but also for patients themselves. Last but not least, they are only an intermediary step to further processing of spatial and stress calculation procedures in mathematical modeling of biomechanical solutions of the given topic using the finite element method (FEM), which allows, for example, to calculate the pressure load in different parts of the tissue (Fig. 10).

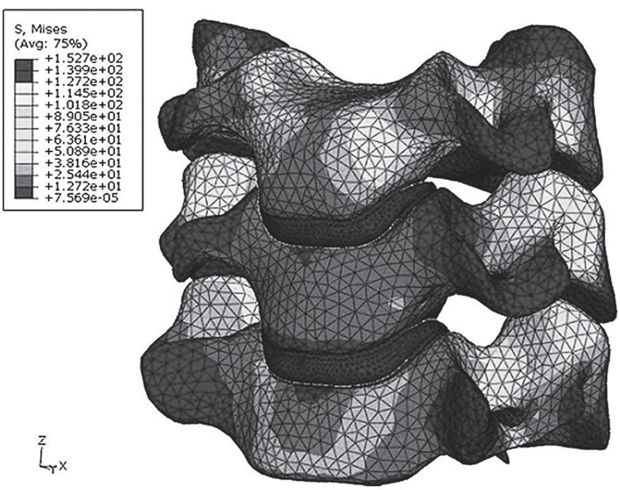


Figure 10. Segmentation of the 3D model into a finite number of elements allows to calculate the stress-strain characteristics in each element (biomechanics.cz, 2012)

ACKNOWLEDGEMENTS

This project is supported by grants GACR 407/10/1624, GAUK 545312, SVV 2012-265603 and project PRVOUK 38.

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DEGENERATIVNÍ ZMĚNY KRČNÍ PÁTEŘE SE ZAMĚŘENÍM NA VÝHŘEZ MEZIOBRATLOVÉ PLOTÉNKY A JEJÍ VERIFIKACE POMOCÍ ZOBRAZOVACÍCH METOD A 3D MODELU

TEREZA PÍGLOVÁ, EVA TLAPÁKOVÁ, KAREL JELEN, PAVEL ŠTURSA

SOUHRN

Degenerativní změny krční páteře přicházejí z části přirozeně se stárnutím organismu, avšak řadou ovlivnitelných faktorů dochází k akceleraci jejich nástupu. Mezi takovéto urychlující faktory patří především hypokineza a jednostranné přetěžování krční páteře. Moderní zobrazovací techniky dokáží detailně tyto patologické procesy detekovat, ale jsou omezeny užitou zobrazovací metodou a polohou pacienta při vyšetřování. Vybrané série snímků jsme použili jako podklad pro další zpracování a tvorbu 3D modelu, který zobrazí tkáně konkrétních pacientů a obecně může sloužit pro další řešení prostorových a napěťově výpočtových postupů při matematickém modelování biomechanických řešení dané problematiky v cervikálním segmentu axiálního systému člověka.

Klíčová slova: degenerativní změny, krční páteř, zobrazovací metody, 3D model

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Neuroendocrinology Letters Volume 38 No. 5 2017
ISSN: 0172-780X; ISSN-L: 0172-780X; Electronic/Online ISSN: 2354-4716
Web of Knowledge / Web of Science: Neuroendocrinol Lett
Pub Med / Medline: Neuro Endocrinol Lett

Possibilities of objective identification of meniscoids in joint blocks of the axial system, by MRI and Transfer Vibration through the Spine

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Submitted: 2017-07-04 *Accepted: 2017-08-10* *Published online: 2017-00-00*

Key words: **functional joint blocks; meniscoids; axial system; MRI; Transfer Vibration through the Spine**

Neuroendocrinol Lett 2017; **38**(5):101–107 **PMID:** ----- NEL380517AXX

Abstract

OBJECTIVE: The aim of the study was to identify the meniscoids of the cervical spine using in-vivo MRI imaging and to determine their potential role in the development of functional joint blocks of the axial system (AS). Another objective was to find out how the articular blocks affect the rheological properties of the spine by the Transfer Vibration through the Spine (TVS) method.
METHOD: In this study were used methods TVS and MRI. The study was conducted on a research file of 12 subjects and was conceived as a pilot one.
RESULTS: It has been shown that the MRI method, in appropriate circumstances, enables the detection of changes in the size and shape of meniscoids in-vivo. On the basis of the investigations carried out, it can be assumed that several mechanisms are involved in the formation of functional joint blocks, and are not primarily caused by the incarceration of meniscoidal tissue. Using the TVS method, it has also been found that a functional articular blockade affects the rheological properties of the axial system, specifically reducing the damping capabilities of the particular spine segment.
CONCLUSION: In the follow-up studies, it will be necessary to verify the theoretical interpretations on a larger statistical set.

INTRODUCTION

The functional joint block is a common clinical term that denotes joint dysfunction, which need not be accompanied by a structural disturbance. In the second half of the 20th century, the foundations for its comprehension were laid down by the description of joint meniscoids (Tondury 1948; Emminger 1967; Kos & Wolf 1972) and barriers (Kimberly 1980). From a phenomenological point of view, a functional joint block is defined as a "joint play" limitation. Thus, it can be looked at as a limitation of passive movement in the joint (in the sense of the shifting, rotation or distraction of the joint surfaces) upon reaching the physiological barrier of the respective articulation.

From the pathophysiological point of view, the functional joint block is a reversible state. It is manifested by muscular hypertonia, the trigger points in its surroundings, furthermore by pain and the reflex chaining of disorders affecting the surrounding soft tissues and internal organs (Lewit 1968). If the blockade occurs on the spine, it will cause hypomobility in the segment. However, because of the compensatory hypermobility of the axial system segments above and below the blockade, the overall motion of the spine need not be limited. In a chronic blockade, we can also observe the structural changes of the spine as a reaction to long-lasting changes in the muscle tension and surrounding tissues (Kříž & Majerová 2009). Malátová and others carried out a study with the help of an instrument called a muscle dynamometer, which enables detailed information about muscle activity in the deep stabilisation spinal system. (Malátová *et al.* 2007; Malátová *et al.* 2008) The joint blocks can be successfully treated with so-called manual therapy using mobilization and manipulation techniques.

The pathogenesis of the formation of functional articular blocks of the axial system has not yet been satisfactorily explained. Lewit (2003) demonstrated through an experiment, conducted in patients with narcosis, that its entity is of a mechanical nature. One of the possible causes of a blockade may be so-called meniscoids. Their existence is demonstrated by anatomical studies of the intervertebral joints of the spine (Kos & Wolf 1972; Kos *et al.* 2002; Engel & Bogduk 1982; Webb *et al.* 2011a; Webb *et al.* 2011b; Yu *et al.* 1987). According to the meniscoid entrapment theory (Digiovanna 2005), the apex of these fibrous folds can get wedged between articular surfaces and stuck there (Kos *et al.* 2002).

From the available studies, the meniscoids are known to be articular capsule and synovial membranes protrusions. The meniscoids are established early in the fetal period and are found in all the intervertebral joints of the spine (Schmincke & Santo 1932; Kos & Wolf 1975). They help with the joint stability and the decomposition of pressures acting in the joint by balancing the incongruence of the joint surfaces. They lubricate the articular cartilage by the secretion and reabsorption of the synovial fluid. The shape, size, and location of the meniscoids are considerably individual. Engel and Bogduk (1982) categorized them histologically into three types: fat pads, fibro-adipose meniscoids and capsular rims.

Fat pads are typical for atlanto-occipital joints, their wide bases are attached to the joint capsule and the free rounded edges projecting towards the centre of the joint. They consist primarily of adipose tissue, loose connective tissue and blood vessels. Fibro-adipose meniscoids occur most frequently throughout the cervical spine. The wider base passes into a thin free apex which extends between the articular facets and is freely mobile over the articular cartilages. The core of the base consists predominantly of adipose tissue infiltrated with the collagen fibers from the joint capsule. Sometimes, adipose tissue can be lacking and the base is formed by collagen fibres and blood vessels. The apical region and free border of the meniscoids are made up of collagen. Capsular rims are wedge-shaped structures around the marginal parts of the joint (Mercer & Bogduk 1993).

Meniscoids are innervated by small diameter nerves immunoreactive for neuropeptides which are involved in the transmission of pain. The apical part is collagenous and is not innervated (Inami *et al.* 2001). The presence of meniscoids is not sex-dependent and decreases with increasing age (Fletcher *et al.* 1990). With an incipient ankylosis, the meniscoids disintegrate and disappear (Kos *et al.* 2002).

An important fact for the *in vivo*-study is that meniscoids can be shown by the MRI method (Friedrich *et al.* 2007 and 2008). However, due to their size, these formations are at the very distinctive limit of the method. The mechanical properties of the axial system as a whole can be objectively assessed by the method of Transfer Vibration through the Spine (Panská *et al.* 2016).

Based on the meniscoid entrapment theory that has been conceived from the above findings, the following questions arise:

- Is it possible to detect the changes in the size and shape of meniscoids *in vivo* by using the MRI method, before and after the treatment of the functional joint block of the axial system using manual therapy.
- Does the manual therapy of the functional joint block of axial system have effects on its mechanical properties?

In connection with the research questions, the following main objective of the work was set: To find the possibilities of the objective identification of the cervical spine meniscoids and to determine their role in the pathogenesis of AS joint blocks. Furthermore, to find out how the joint block affects the AS rheological properties.

METHODS

The study is conceived as a pilot one. In view of the identified research questions, its design was divided into two separate parts. At first, attention was paid to the morphological nature of the problem (MRI method), then to the mechanical properties of the axial system (TVS method).

MRI method

Meniscoids and their shape changes were first investigated on anatomical preparations and their presence, size, shape and location in the intervertebral joints of the cervical spine were verified. The meniscoids found were evaluated in two ways. First, by the orthographic view of the upper and lower facet, and also, in the sagittal section through the intervertebral joints of the cervical spine (Figure 1).

The follow-up MRI imaging of joints was performed at the Na Homolce radiodiagnostic department using

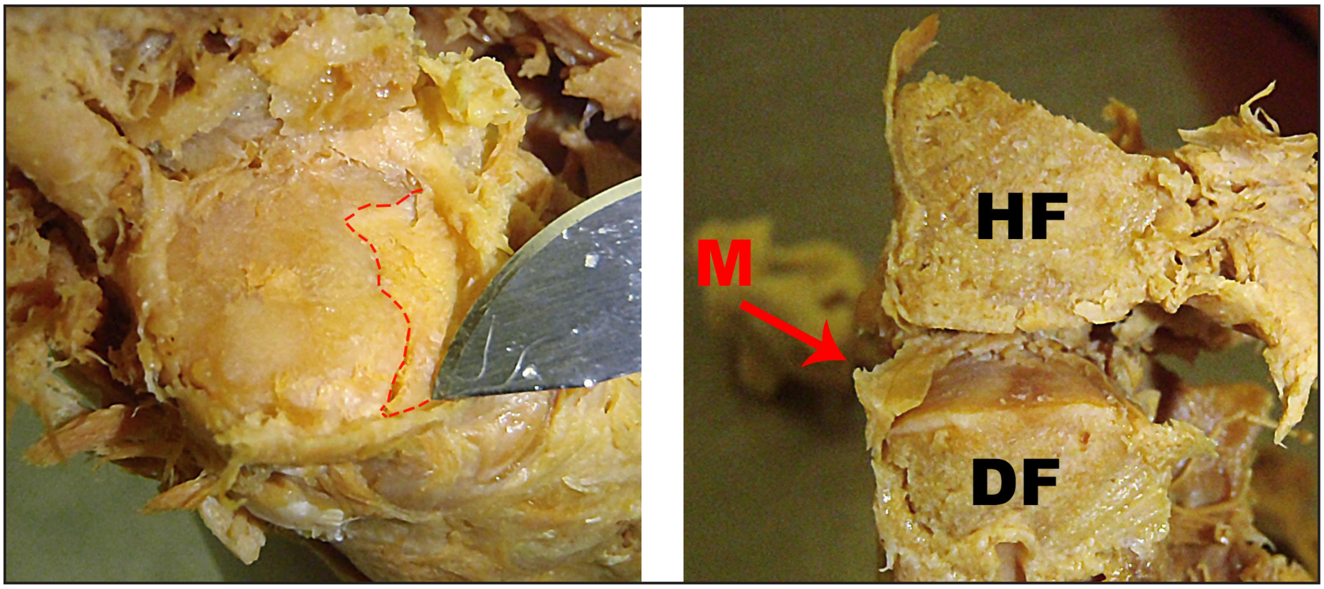

Fig. 1. a) Orthogonal view of the articular face of segment C3/4; **b)** In a sagittal section, meniscoids marked in red.

the Siemens Skyra (3T) apparatus. The examination of the meniscoids was focused on a cervical spine section. A high-density segment (32 channel) head coil was used, which also covered the atlanto-occipital junction. The initial investigations were conducted on anatomical preparations of two heads with the cervical spine. The in-vivo examination of the cervical spine was performed on ten subjects. The first three subjects were examined to determine the appropriate MRI setting and the in-vivo identification of meniscoids.

For the seven additional subjects, positively evaluated for the presence of functional joint blocks, the manipulation of cervical spine (from the head joints to the C/Th junction) was applied after the initial MRI examination. This was followed by the checking examinations. Using the sagittal sections, we evaluated the changes in the positions and shapes of the meniscoidal tissue.

At this point, it is worth mentioning that the visibility of the meniscoids depends heavily on the technical parameters of the device (the magnetic field strength, the pulse sequence selected, etc.), the properties of the segment under consideration (size, location, height, etc.) and last but not least on the motion of the person under investigation and other artifacts (breathing, pulsation) arising during the examination. The display of anatomical preparations was not limited by examination time and the artifacts associated with physiological movement. In this way, it was possible to test different MRI sequences (proton density, T1 and T2 weighted). For the linked up methodological (Nm=3) and comparative (Nc=7) investigations, the sequence *de3d* was selected. The sequence was set up with isotropic resolution, which enables reconstruction in any plane. Moreover, this sequence provided best contrast for imaging the meniscoids. The detection of MRI images on a given device with the mentioned sequence takes 6:53 minutes. This allows a full view of meniscoids, when using the localizer sequences, under 9 minutes. The time is extended by automatic auxiliary measurements of the inhomogeneity of the magnetic field with the instrument. The resolution of the sequence is $0.7 \times 0.7 \times 0.7$ mm. The acquisition is done in two parallel volumes (slabs), which are in distance of 20% of these volumes. In the direction of phase coding, the 100% oversampling is proven. In the Z-axis (i.e., cranio-caudial), the oversampling of 25% will do. There, 48 layers with a thickness of 0.67 mm, a repetition time of 15.58 ms, an echo time of 5.06 ms and a flip angle of 20 degrees are scanned.

In the strong 3T field, especially in devices with a wider 70 cm gantry, significant geometrical distortions may be present. Therefore we elected to apply K-space based correction (Siemens function) to improve the preciseness of evaluation of small meniscoids.

TVS method

The Transfer Vibration through the Spine (TVS) method is based on the ability of substances (tissues) to transfer their external force through their structure. If the exciting force is the pulse character, the pressure waves propagate through the affected tissue. They generate corresponding changes in the density of mechanical energy (Maršík & Dvořák 1998). This mechanical energy is, due to the viscoelastic properties of the tissue, partially absorbed in the form of elastic deformation and partially damped down (dissipated) by their viscosity. In addition, the velocity of the pulse wave transfer and its amplitude decrease are related to the parameters of the tissue, through which the wave passes (Kloučková *et al.* 2011).

As shown in Panská *et al.* (2016), it is possible, by the excitation of vibrations on the selected vertebra of the spinal system and by detecting their attenuation on other spinal segments, to assign objective mechanical parameters to the parts of the axial system under investigation (the modulus of elasticity and the dynamic viscosity). Specifically, for the viscosity m [Pa.s] of the examined tissue, the relationship applies:

$$\mu = b \cdot f(\rho, \omega_r, \lambda)\,.$$

Thus, the viscosity of the respective segment of the axial system can be determined from the product of the value of the attenuation coefficient b [] and the function f that is partly dependent on the density r [kg.m^{-3}] of the tissue explored and partly on the resonance frequency w_r [s^{-1}] of the standing wave of the wavelength l [m]. The natural attenuation coefficient can be estimated from the approximation of the acceleration of the individual oscillating vertebrae (y-axis) at their distance (position) from the excitation source (x-axis) by the function:

$$y = Ae^{-bx}\,.$$

It follows from the above that, when the resonance frequency w_r or the attenuation coefficient of the axial system segment monitored are changed, its viscosity changes as well (see Panská *et al.* 2016). These two selected descriptors of mechanical properties of tissues will be given attention to in the results section of the text.

In the experiment, two persons (N_{TVS}=2) with functional joint blocks diagnosed in the cervical spine (subject No.1 in the region C_{3-5}, subject No.2 in the region C_{2-4}) were examined. The vibration by excitation took place on the processus spinosus vertebra C_7. The transmission trough the axial system was scanned with the accelerometers located on the processus spinosus of the vertebrae C_6, C_5, C_4, C_3, C_2 and the occiput (Figure 2).

In order to avoid adaptive changes due to the neuromotoric reactions of the body to the mechanical load of the spine (van Dieen *et al.* 2003), periodic rising and falling frequencies from 5 to 180 Hz were applied and vice versa. The entire recording cycle lasted 3 × 3 minutes, i.e., there were 3 pairs of rising and decreasing sequences of excitation frequencies recorded.

As in the first case, the treatments of the cervical spine (from the head joints to the C/Th junction) were applied after the initial examination. A follow-up examination and evaluation of changes in the damping properties of AS was followed.

All the results of AS responses to mechanical excitation were processed, evaluated and graphically interpreted using an especially developed software.

RESULTS

MRI method

For all the persons under investigation (N_m=3, N_c=7), the presence of large wedge-shaped meniscoids was detected in the segment C1/C2, both from the dorsal and ventral joint parts. They equalize the convexly shaped articulation facies between the atlas and axis. For this segment, there is also a typical thicker layer of cartilage covering the articular joint facies and the hyperintense signal likely indicating the presence of a greater amount of synovial fluid in the joint cavity. In the other segments, smaller meniscoids were found, irregularly extending only from the dorsal or ventral side, or bilaterally. The decreasing signal intensity in the caudal direction and the movement artifacts of the investigated persons are the reason for reduced sharpness in the image in the lower parts of the cervical spine. No other patterns in the location and shape of the meniscoids in the lower segments were found.

In the scope of methodical examinations (N_m=3), a long thin tongue-like meniscoid was found in the C0/C1 segment, with its base on the dorsal side of the joint, which extended deep into the articular cavity (Figure 3). A similar finding was published in Friedrich (2008) and marked the state as an entrapment

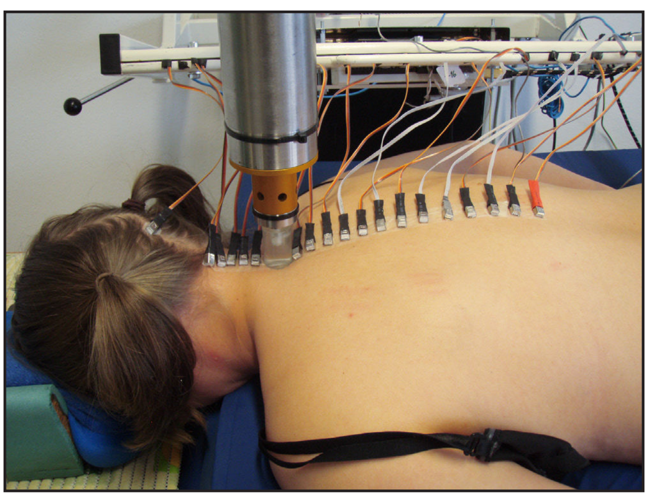

Fig. 2. Examination of the rheological properties of the cervical spine using the TVS apparatus.

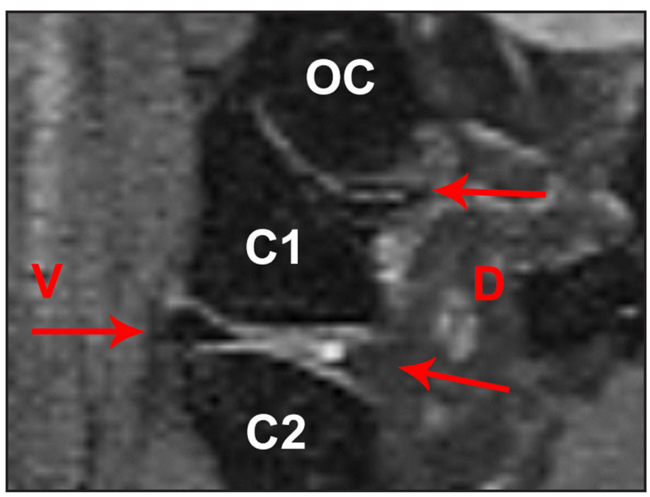

Fig. 3. Sagittal MRI section of the C0/C1 a C1/C2 segments. Meniscoids are shown with red arrows from the ventral (V) and dorsal (D) sides.

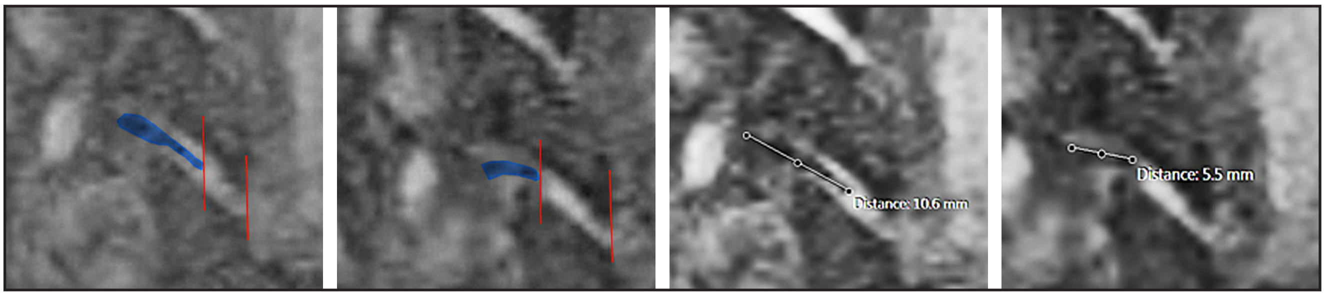

Fig. 4. The resulting shift of the meniscoid ventrally placed in the C6 /7 segment. Left before and right after the handling treatment application. The meniscoidal tissue is stained with blue color. In the space between the red lines, the residual volume (or its projection, respectively) of the joint cavity, caused by the slip of the meniscoid, is indicated. The scale is shown in the next figures.

(see above). In this case, we did not apply manipulation treatment and check-ups, and therefore we cannot objectively claim it to be a trapped meniscoid. The MRI method was used inter alia by Masopust *et al.* To investigate the influence of perioperative Epidural Steroid application on the development of Epidural fibrosis (Haeckel & Masopust 2009).

In the case of comparative examinations (Nc=7) before and after manipulatory treatment, any differences in the storage, change in shape or size of meniscoids tissue were sought. As mentioned above, all seven persons were positively evaluated for the presence of blockades in the cervical spine. Manipulation was objectively accompanied by the acoustic phenomenon of joint cracking with a subsequent release of tone in the soft tissues and by increasing the range of movement in the cervical spine. The patients sensed a subjective relief, a decreased muscle tension, and an increased range of motion in the cervical spine.

In one patient, the MRI scanning was able to detect a shift of the meniscoid in the left intervertebral joint segment C6/7 from the ventral side. This corresponds to the meniscoid entrapment theory (Figure 4). Using manual segmentation of a meniscoid on a computer screen, it is possible to compare its size and location in the joint cavity before and after the manipulation treatment. It is evident that, in the case of pre-therapy, the meniscoid is bulky and extends deep into the articular cavity. The part of the joint cavity without the meniscoid is bounded with the red lines. During the manipulation, the articular casing is tightened and the meniscoid slides out of the articular cavity and thus looks to be relatively shorter. The volume of the joint cavity, without the meniscoid tissue, increases significantly after the manipulation. The Figure 4 shows that the displayed length of the meniscoid after manipulation was reduced to approximately 60% of its original length before handling.

TVS method

The summary results from the experimental survey (N_{TVS}=2) by the TVS method are shown in the graphs in Figure 5. The following findings arise from them. Before the manipulation treatments (graphs A and C), the strongest response of the vertebrae to the vibrational load in a defined range of excitation frequencies *f* is evident in both the investigations (cf. Table 1). Specifically, for the subject No. 1, this is the band of 110-150 Hz, for subject No. 2, this is at the intervals of 60-90 and 130–170 Hz. They also contain all the resonance frequencies w_r^i of the system under study. Their values are identical to the corresponding excitation frequencies f^i and correspond, positionally, to the local extremes of individual curves. Thanks to 3D graphics, it is well-perceptible that these local extremes form one or two continuous ridges in the cases prior to manipulation treatment (A, C).

Tab. 1. Changes in monitored rheological parameters before and after manipulation treatment.

Subject	Before		After	
	band ω_r^i (Hz)	*b* ()	band ω_r^i (Hz)	*b* ()
no. 1	110–150	0.28	40–160	0.39
no. 2	60–90, 130–170	0.20	50–175	0.47

Legend: Band $\boldsymbol{\omega_r^i}$ – the frequency band range, where the resonance frequency ω_r^i occurs, **b** – the attenuation coefficient.

Conversely, in the cases after the manipulation treatment (graphs B, D), there is a strong dispersion of these local extremes or resonance frequencies, respectively. Depending on the individual vertebrae, they include 3/4 of the frequency band used (cf. Table 1).

From the observed dependencies (Figure 5), it is possible to determine the attenuation coefficient ***b*** of the entire cervical segment of the spine. The results are shown in Table 1. It is evident that in both the subjects, after the application of manipulation treatment, this parameter was increased. This result indicates an increase in the damping ability of the axial system due to manipulation treatment.

In principle, it is also possible, from the obtained data, to estimate the viscosity ***m*** or its change. Here, however, it should be noted that this parameter is, inter alia, dependent on the resonant frequency of the entire segment. With regard to the heterogenity of the axial system as a whole, such a frequency of resonance

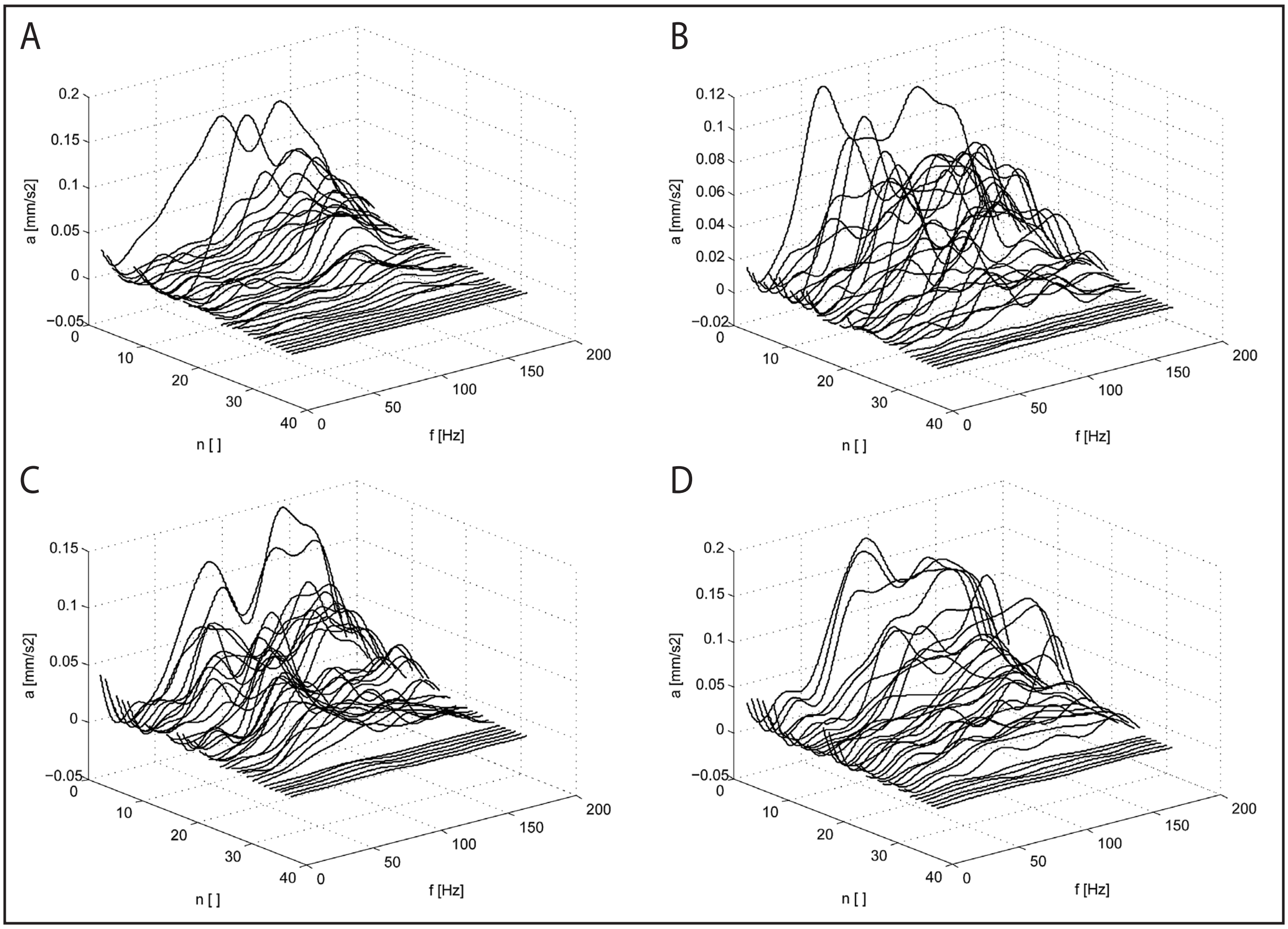

Fig. 5. Comparison of the results by the TVS method in the cervical spine. The 3D graphs show the responses (acceleration a) of each vertebra, depending on the excitation frequency f. To the left before handling, right after handling, the subject 1 at the top, the subject 2 on the bottom. The graph shows the results from the sensors on C6-C0 and always after 6 reps. The variable n has the following meanings: 1 to 6 measurements on C6, 7 to 12 measurements on C5, 13 to 18 measurements on C4, 19 to 24 measurements on C3, 25 to 30 measurements on C2, 30 to 36 measurements on C0. The resonance frequencies w_r^i are displayed as the local extremes of the respective curve for each vertebra.

that suitably characterizes the whole system cannot be uniquely chosen. This is particularly noticeable in cases after the manipulation treatment (graphs B, D). These graphs show a distinctly higher number of own resonant frequencies of the monitored section than before manipulation. The increase in the number of individual resonant frequencies of individual vertebrae can be explained by releasing the appropriate joint block by the manipulation therapy applied. Therefore, this calculation of unambiguous viscosity determination in this section could not be made.

DISCUSSION

The aim of the research study was to objectify the role of meniscoids in the functional joint blocks of the axial system. From the initial experiments on MRI, the appropriate sequences were obtained to evaluate meniscoids of the cervical spine *in vivo*. Using the head coil at the apparatus with a magnetic field force of 3T, a cube volume resolution level of 0.7 mm was reached. The cranial sections of cervical spine were evaluated best, where the bulky meniscoids in the C1/2 segment were identified from both the dorsal and ventral sides of the spine.

In other segments of individual persons, the meniscoids were found irregularly in the left and right intervertebral joints of the cervical spine. They varied in sizes and locations – ventral, dorsal or bilateral. Due to the small sizes of meniscoids and the low image sharpness, caused by the movement artifacts of the investigated persons, it was not possible to identify meniscoids in some segments. It can be stated that the MRI method allows, under appropriate circumstances, to detect changes in the shape and location of meniscoids *in vivo*.

In one subject, a trapped meniscoid was found between the articular surfaces of vertebra C6/7. By applying the manipulation techniques, we managed to release it, as described by the meniscoid entrapment theory.

Using the TVS method, it has been found that the manual therapy of functional joint blocks affects the change in the AS mechanical properties, in particular the attenuation coefficients, which reached 39% in the case of the 1st subject, after manipulation therapy, and even 135% in the case of the 2nd subject, compared to the baseline. The viscosity, as an additional rheological parameter of AS, was not possible to determine unambiguously. It will be necessary to look further at the methodology of calculating the viscosity from the values detected of the AS response to mechanical excitation.

CONCLUSION

The result of the study is the visual documentation of the release of the trapped meniscoid *in vivo*. This is probably the primary objective documentation of this focus.

Due to the fact that more than one blockade was diagnosed in the investigated subjects without a corresponding shifting of the meniscoids to the MR, we assume that more mechanisms are involved in the development of the joint block than just the incarceration of the meniscoidal tissue.

On the basis of the investigations carried out, it can be assumed that the blockades also have a negative effect on the mechanical properties of the axial system, especially on the damping ability of the spine. However, in the follow-up studies, it will be necessary to verify the theoretical interpretations indicated on a larger statistical set.

ACKNOWLEDGEMENT

This project was supported by grants PROGRES Q41, GAUK 962314 and SVV 260466 for the year 2017.

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Neuroendocrinology Letters Volume 37 No. 4 2016
ISSN: 0172-780X; ISSN-L: 0172-780X; Electronic/Online ISSN: 2354-4716
Web of Knowledge / Web of Science: Neuroendocrinol Lett
Pub Med / Medline: Neuro Endocrinol Lett

Evaluation of rheological parameters of the axial system using the Transfer Vibration through Spine (TVS) method

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Submitted: 2016-07-01 *Accepted: 2016-08-28* *Published online: 2016-00-00*

Key words: **TVS method; axial system; mechanical loading; rhythmic gymnastics**

Neuroendocrinol Lett 2016; **37**(4):101–107 **PMID:** ----- NEL370416AXX © 2016 Neuroendocrinology Letters • **www.nel.edu**

Abstract

OBJECTIVE: The human motion system reacts to both hypo and hyperactivity loads by changes to the rheological properties of tissues. This study deals with changes to the axial system (AS) compartment. Using the appropriate methodologies and mathematical-physical methods, these changes can be identified and quantified.

METHODS: This study describes the noninvasive TVS (Transfer Vibration through Spine) method, which was applied to assess the AS selected mechanical properties in various modes. A pilot study was conducted on a top-level twelve-year-old girl-gymnast. The data detection was carried out in three cycles, before and after a peak 3.5 hour training session and the next day, after resting, just before the next training.

RESULTS: Specifically, the values of selected rheological parameters, the AS damping coefficient b and viscosity μ, were obtained. The dynamics of their changes, in the stated load cycles, has also been shown. The damping coefficient b fell from the value of 0.626 to 0.324 before training and increased to 0.394 after resting. The viscosity coefficient μ showed a similar trend, namely falling from the value of 9.85 [Pa.s] to 2.15 [Pa.s] and then increasing to 3.8 [Pa.s] .

CONCLUSIONS: With its computational solution, the TVS method,is a diagnostic apparatus making it possible to classify AS properties, both quantitatively and qualitatively, or its chosen segments and their changes, respectively. It can be used in classifying, preventing and treating the consequences of extreme motion and relaxing modes. The TVS application also makes it possible to control AS states over therapeutic, recovery, ergonomic and other loading modes of the human locomotion system.

ORIGINAL ARTICLE

INTRODUCTION

Vertebrogenic disorders are a common health problem, whichcan be seen in populations spanning all age groups. These problems can be caused by many factors. They may be problems caused due to the lack of physical activity – hypokinesia, or vice versa due to overloading – hyperkinesia (Jelen *et al.* 2013) connected e.g. with unhealthy lifestyles, obesity, improper nutritional regimes, and other factors, including genetic ones (Panská *et al.* 2013) negatively acting on all the organ systems including the axial system (AS).

A number of changes in the rheological properties of biological components of AS occur in the course of a lifetime due to ageing and load bearing. An example of this is degeneration of intervertebral discs (IVD), which has a significantly higher prevalence of degeneration in comparison with the musculoskeletal tissue.

Such issues manifest themselves by reducing the nucleus pulposus gelled form, changes to the disc morphology and frequent irregularities of the annuli fibrosi lamellae and disorganization of the collagen and elastin networks, an ingrowth of blood vessels and nerves to fissures or the incidence of necrotic (50% in adults) or apoptotic cells, biochemical changes, etc. (Urban & Roberts 2003).

The loss of proteoglycan in the degenerated intervertebral plate (Lyons *et al.* 1981) has a great influence on its behavior under load. With the loss of proteoglycan, reducing the osmotic pressure in IVD (Urban & McMullin 1988) it is less capable of maintaining hydration in the load. Less water is contained in degenerate IVD than a healthy plate (Lyons *et al.* 1981) and thus the loadlosesitsheight, respectively. volume (Frobin *et al.* 2001) and the fluid quickly. The discs subsequently have a tendency to prolapse.

Proteoglycan loss and degradation of the matrix also have other important effects on the mechanical properties, because, due the subsequent loss of hydration, the degenerated IVD no longer behaves as a highly viscous, almost incompressible tissue when loaded (Adams, McNally & Dolan 1996). The loading could then lead to inappropriate stress accumulation along the pressure plates – the end plates, or in the fibrous ring. The load concentration, observed in the degenerated IVD, has also been associated with pain resulting from IVD changes (McNally *et al.* 1996).

Changes to the IVD behavior have a strong influence on other spinal structures and can influence their function and susceptibility to damage. For example, due to altitude rapid loss of the IVD degenerated at loading, the apophyseal joints, adjacent to these discs, may suffer from abnormal loads (Adams *et al.* 1990), and finally osteoarthritis changes may develop at these sites. IVD height loss can affect other structures. For example, these changes reduce ligamentum flavum voltage power, and hence they may cause a change in structure and consequent thinning. With subsequent loss of elasticity (Postacchini *et al.* 1994), the ligament will tend to bulge into the spinal canal, resulting in spinal stenosis – a problem which increasingly appears not only in the ageing population.

A domain, in which we can certainly meet hyperkinetic loading, is the field of sports training. Top level sporting performance is often reached through specific monotonous or one-sided loading, affecting human organism more commonly from early childhood, and furthermore, often with an insufficiently designed compensational and regenerative regime. Acute macrotraumas, overuse, injuries linked to repetitive microtraumas aren´t sporadic events, quite to the contrary(Kerssemakers et. al., 2009).

We consequently can encounter premature detritions and degeneration (wear and tear) of tissues and structures of spine, for example: the degeneration, herniation and height reduction of intervertebral discs, the deterioration of vertebral apophyses, spondylolysis, spondylolhistesis etc. As a result of on-going degenerative changes and hypo-/hyper- kinetic loads, the organism continuously reacts, for example by neuromotor responses, which may lead up to e.g. muscle contractures and facet joint blocks (spinal motion segments). Evenvertebrae position misalignments may arise which are also affected by trunk muscles recruitment patterns and a prestress in the passive structures (ligaments, facet joints and other structures including intervertebral discs). Furthermore, the position of the vertebrae is affected by the spine profile, body weight and its distribution, ageing and the extent of degeneration (Zander *et al.* 2016).

Changes to the mechanical conditions of the spine manifest different activators and co-contraction patterns of muscle recruitment. E.g., an increased activation of the muscles, also in the resting position of the spine, serves to prevent excessive movements within the motion segment and thus provoke pain. Or, e.g., the substitution of the upper body part support during trunk flexion through active muscle power instead of stretching the elastic forces posterior annulata, ligaments and muscles along the spine (van Dieen *et al.* 2003). The vertebral body height, disc height, processi transversi width and spinal curvature belong to the most important variables affecting the spine muscularskeletal load (Putzer *et al.* 2016).

In our methodological study, we will track the changes in the rheological properties of AS biological components as a result of various stress modes. The area of our study focused on the peak of rhythmic gymnastics (RG), where the emphasis is placed on performance owing to a high degree of flexibility of joints in the lower extremities and the entire AS. The impact load caused by the use of large amounts of hops and big jumps is also high, leading to a positive effect on bone metabolism (Helge & Kanstrup 2002; Tournis *et al.* 2010), however these can also negatively influence (a lot of rebounds and impacts) the AS damping abilities.

Due to an excessive degree of using motion shapes which are joint flexibility-intensive, the AS is the most stressed part of body gymnastics. Although RGranks among sports with a low injury rate (Cupisti *et al.* 2007), its common asymmetric load is very problematic, leading on occasion to muscle imbalances but also to irreversible morphological changes (Hutchinson 1999), as well as causing chronic damage. (Papavasiliou *et al.* 2014; Tanchev *et al.* 2000). For extreme loads combined with biological, biochemical and mechanical factors, along with possible injuries, the acceleration of interior-articularpathologies starts, where the prevalence of osteoarthritis in peripheral joints and spine is significantly higher than in the normal population (Gouttebarge *et al.* 2014).

From the above-mentioned facts we can logically deduce a need to identify changes to the AS mechanical properties. For their qualification and quantification it is necessary to use specific detection and mathematical methods which are capable of identifying the onset of vertebrogenic problems early. With their help we can also optimize preventive, training, compensation and regeneration approaches not only in the RG, but also in other sports or working modes, as well as convalescent modes, e.g. following operations.

We will show that the changes of IVD material properties, or the AS entire complex, respectively, can be indicated with some accuracy by analyzing the transmission of spine mechanical waves using the method of Vibration Transfer through Spine -TVS (Figure 1).

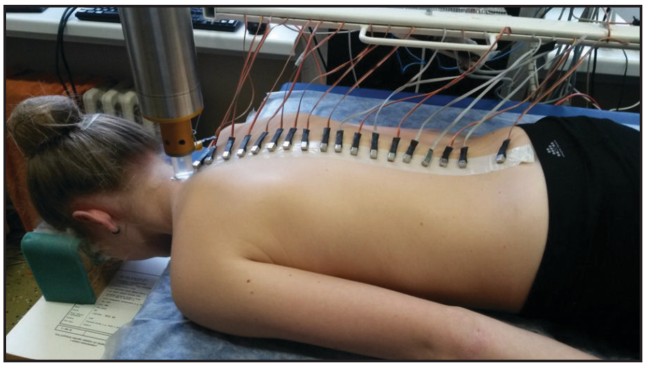

Fig. 1. Oscillation transmission in the axial system (AS) detected using the method of TVS -Transfer Vibration through Spine.

METHODOLOGY

The newly elaborated method of the *Transfer Vibration through Spine* (*TVS)* issues from the publications: (Jelen *et al.* 2010; Machač 2011; Maršík & Dvořák 1998; Maršík *et al.* 2010). It is based on the ability of materials to transmit force pulsations, whichpropagate through tissue pressure pulsations. Pressure pulsations generate in the tissue corresponding density variations of mechanical energy. This mechanical energy is transmitted to tissues, and due to their viscoelastic properties, is partially absorbed (elastic deformation) and partially dampened due to the viscosity. The transmission speed wave (force pulse) and change in amplitude (its drop) is associated with the tissue parameters which are relevant for the transmission of mechanical energy, i.e. elastic modulus, viscosity and plasticity, respectively.

Several studies have been conducted in which the detection of the vibrational excitation transfer to the axis system were made using the TVS method for drivers before and after driving a car. The same measurement of changes in the transmission of AS mechanical waves was also performed with a pregnant female driver at different stages of her pregnancy (Jelen *et al.* 2012).

In our case report, we have presented our TVS method (just in process of completion) when analyzing one top junior girl-gymnast (12 years). Her load mode is a standard training of 18–20 hours per week. To introduce the principle and functionality of the TVS methods, we chose the gymnast 24-hour daily schedule. The data detection took place in three phases. Before training load, immediately after the 3.5-hour training session and the following day before the next training load. When analyzing, the data started from a detecting the AS response to the excitation signal. At the dorsal – ventral side vertebrae (spinal promontories Th_1–Th_4), the one-component acceleration size in response to a driving signal to C_7 (Figure 2) was detected.

From Figure 2 it is clear that AS can be viewed as an assembly of rigid segments representing the vertebral bodies, IVD viscoelastic segments and the muscle ligaments, encircling its own skeletal system. There issues, from this viewpoint, also a design of methods for evaluating the AS response to the selected excitation signal.

The result reveals the amplitude waveforms of the vertebrae monitored at appropriate frequencies. To prevent adaptive changes due toneuromotoricresponses of the organism to the spine mechanical conditions (van Dieen *et al.* 2003), an excitation of the periodically increasing and decreasing frequencies, from 5 to 180 Hz and vice versa, is applied. The entire recording cycle lasts 3 × 3 minutes, i.e., three pairs of increasing and decreasing excitation frequencies are recorded. Schematically, the AS response to the driving signal is shown in Figure 2.

A. The first method provides contracting attenuation values of the excitation signal as

$$y = a\, e^{-bx} \qquad (1)$$

where:
a – amplitude
b – damping coefficient
x – vertebra coordinate

The relationship stated describes the decline pattern expected in the wave amplitude, which spreads in the AS from the site of excitation. To evaluate the response of the AS to the selected excitation signal the variable

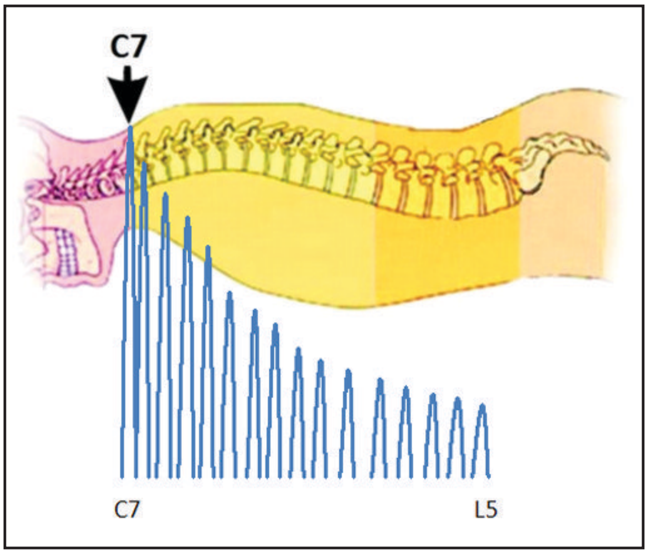

Fig. 2. Schematic representation of the individual vertebrae responses with the AS shock absorbing effect on the excitation signal to C_7.

***b** –damping coefficientis used*. This is marked as a contractual one due to disregarding the real dimensions of the spine measured, when the data of individual vertebrae are in the charts, from which the quantity stated is subtracted, arranged according to their order of 1 (e.g.) to 18 (see Figure 2).

This more heuristic approach shows the AS viscoelastic properties, however the parameters *a,b* have no appropriate interpretation of the material parameters of the examined tissue.

B. The second method is based on an analysis of adjacent vertebrae oscillation, which occurs in the AS resonance to the standing waves. The objective is to determine the viscoelastic properties of an environment for the character oscillation responsible, therefore IVD. This method ensures the evaluation of the AS response to a selected excitation signal the dynamic viscosity, i.e., a variable with a clear physical interpretation. Even in this case it deals with a contract parameter, where, for the simplicity of calculation, we consider the same height of the vertebrae, $l_1 = l_2 = l_3 = l_4$. The stated parameter **μ**, which has physical dimension viscosity [Pa.s] is defined as:

$$\mu_2 = -\frac{2\rho\omega_r\left(l_2+l_3\right)^3}{\left(2\pi\right)^3 l_2}\ln\frac{a_2}{a_1},\quad \mu_3 = -\frac{2\rho\omega_r\left(l_3+l_4\right)^3}{\left(2\pi\right)^3\left(l_2+l_3\right)}\ln\frac{a_3}{a_1} \qquad (2)$$

where:

μ_2 – tissue viscosity between section C_7 and Th_2, it can be assumed that this expresses the IVD viscous properties between vertebrae Th_1, Th_2 [Pa.s]

μ_3 – tissue viscosity between section C_7–Th_3 expresses the IVD viscosity between vertebrae Th1,Th2, Th2 ,Th3 [Pa.s] etc.

π – constant

ρ – density 1000 [$kg.m^{-3}$]

ω_r – resonance frequency [s^{-1}]

a_i– acceleration [$m.s^{-2}$], i=1,2,3,...

$l_{1,2,3}$, – vertebral heights [m]

The idea of the chosen AS model described above is outlined in Figure 3.

EVALUATION OF THE EXPERIMENT

A. Detectionof damping characteristics

Considering the equation (1), we assume that the AS acts as an environment which dampenspassing waves. The decrease in amplitude with increasing distance from the driving point assumes an exponential character. The exponential shape – thus the AS response –

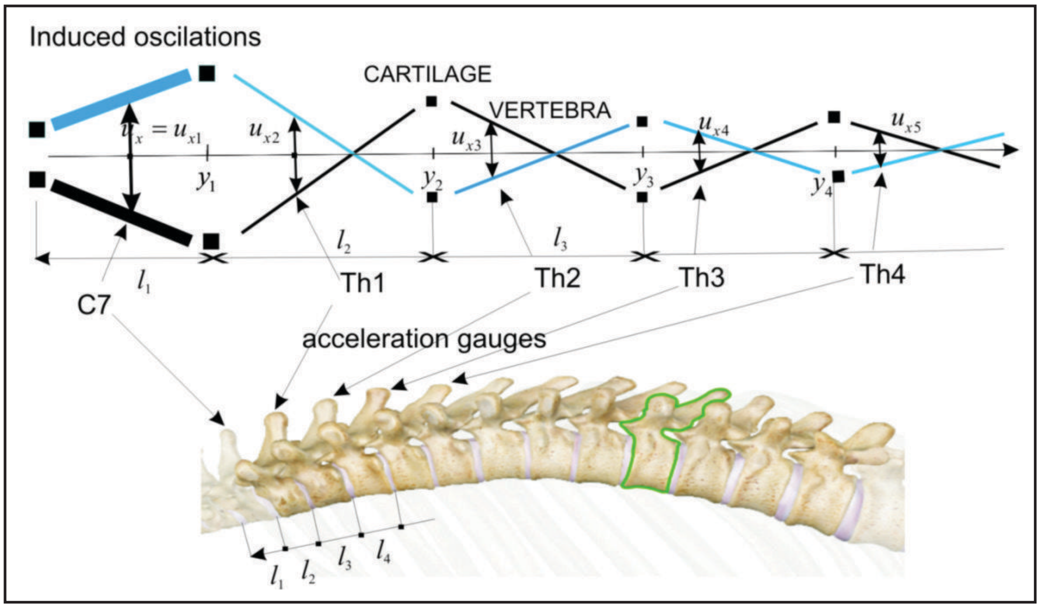

Fig. 3. Geometric scheme of the oscillating AS components and their parameterization. u_x – deflection of the oscillating motion segment [m]; y_i – vertebrae coordinates [m]; $l_{1,2,3}$ – vertebral heights [m]; C_7, Th_1 – vertebra

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depends heavily on the visco-elasticity of the IVD, the surrounding connective and muscle tissues and their ability to dampen these vibrations.

The frequency response of individual vertebrae monitored on the gymnasts with an extremely heavy-duty top gymnastics training were recorded in the above three phases of the loading regime. On chart no.1, we can see the responses of the individual vertebrae selected in the upper half of the thoracic spine (Th_1–Th_4) excited of C_7.

Monitoring the properties of an AS particular section may be preferable for any of the selected frequencies. In our case, the frequency with the greatest response to a C_7 (about 140 Hz) was selected (Figure 4)

We defined the contractual damping coefficient ***b*** using the size dependence of amplitudes of the individual vertebrae monitored at the resonant frequency of 140 Hz (Figure 5) given by equation (1).

B. Viscosity determination of the vertebrae selected

1. We only evaluated the excited vertebrae, i.e., in our case vertebra C_7 and the four neighboring vertebrae, i.e., Th_1–Th_4.
2. We selected the frequency, which corresponds to the strongest response (resonance) at C_7 at the measuring uplink (up) and downlink (down), e.g., $\Omega = \omega_{r1} = \omega_1 = 140$ Hz for C_7.
3. We deducted the size of the response to C_7, i.e., a_1, that we thought was a reference value and for the surrounding vertebrae Th_1, Th_2, Th_3, Th_4 we found the values a_2, a_3, a_4, a_5. From all the measured values, we calculated their mean values

$$\overline{a}_i = \frac{1}{6}\sum_{j=1}^{6} a_j , \qquad (3)$$

and according to the equation (2) we calculated the corresponding viscosity values.

In Table 1, the responses of respective vertebrae both in the ascending and descending measurement modes are recorded, and according to the methodology above, the viscosity values are determined among the AS individual sections, including the reference section average viscosity of the thoracic spine C_7–Th_4. The viscosity calculation was carried out according to the relation (2) for the tissue density. For the calculation simplicity, in this case of methodological studies we assumed that all the vertebrae are of the same length, i.e., $l_1 = l_2 = l_3 = l_4$, and that the tissue density is equal to the water density. The results of the viscosity specific parameters, or their trend, respectively, will be significantly affected by this simplification.

Assuming the same IVD material properties along AS (assumption of linearity), the attenuation should match the relation (1); the wave dampingin a homogeneous (long enough) "stick" is exponential. The changes tothe viscosity values measured are influenced bythe vertebrae of different lengths and the IVD different characteristics and also the inhomogenity of the ligamentous carapacealong AS.

The detected values at Th_1 should be considered with caution, since thesemay be affected by the excitation proximity to C_7.

In the same manner, the data from the other modes were evaluated, i.e., immediately after the loading and **the next day, after a night's rest**, just before the next training.The dynamics of changes in the searched parameters, the attenuation (damping)coefficient ***b***and viscosity ***μ***in the given modes is shown in the summary Table 2.

RESULTS AND DISCUSSION

From the detected results and the mathematical evaluation of the experiment, it is clear that, due to extreme loading (3.5 hour training RG), changes occur in the selected parameters of the AS mechanical properties (here the damping coefficient and viscosity). The decrease in both the attenuation coefficient and viscosity is achieved by the decrease in the amplitudes of the

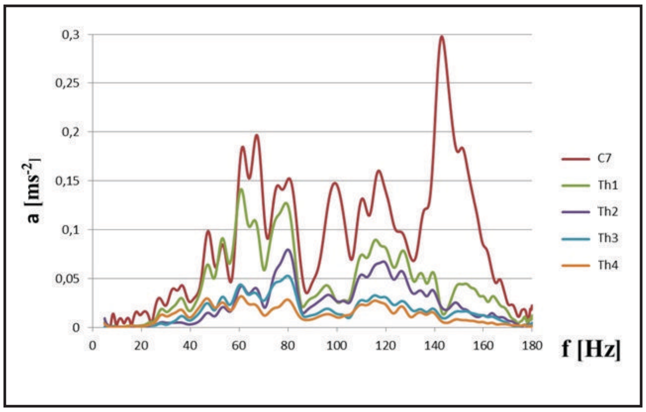

Fig. 4. AS frequency response of the section C_7–Th_4 monitored – before loading

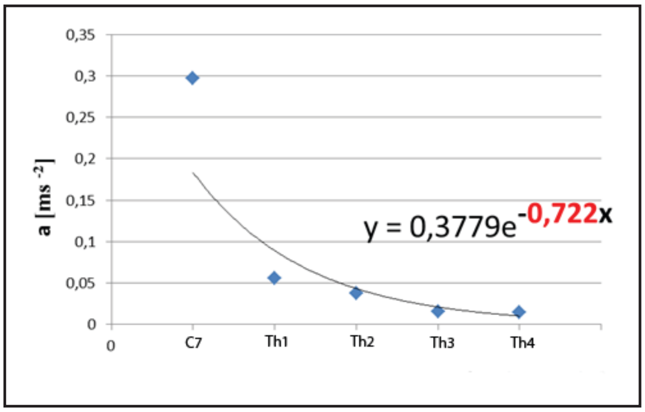

Fig. 5. Dependence of the acceleration size detected at the vertebrae of the spinal segments C_7–Th_4 – before the loading. The coefficient b = 0.772, see the 2nd row in Table 2.

Tab 1. Thoracic spine *ω1* = 140 Hz before the loading.

Vertebr.	No.	Measurement		Responce a_i			$\bar{a}_i$	Length l_i [cm]	ln ($\bar{a}_i$ / $\bar{a}_1$)	μ_i [Pa.s]
C_7	1	a_1	up	0.28	0.30	0.20	0.215	3.5	0	-----
			down	0.17	0.22	0.12				
Th_1	2	a_2	up	0.10	0.06	0.03	0.050	3.5	−1.46	16.2
			down	0.06	0.08	0.06				
Th_2	3	a_3	up	0.05	0.03	0.03	0.045	3.5	−1.6	8.9
			down	0.05	0.07	0.04				
Th_3	4	a_4	up	0.04	0.02	0.02	0.030	3.5	−2.04	**7.5**
			down	0.02	0.03	0.03				
Th_4	5	a_5	up	0.03	0.02	0.01	0.020	3.5	−2.41	6.8
			down	0.02	0.03	0.01				
The viscosity average value of the monitored section C_7–Th_4										9.85

Tab. 2. The dynamics of changes in the damping coefficients **b** and viscosity **μ** of the AS portion selected during the top training of a rhythmic gymnast during 24 hours.

before loading	up	down	$\bar{b}$	$\bar{\mu}$
1.	0.667	0.604		
2.	0.722	0.474		
3.	0.757	0.531		
$\bar{x}$	0.715	0.536	**0.626**	**9.85**
after loading	**up**	**down**	$\bar{b}$	$\bar{\mu}$
1.	0.484	0.309		
2.	0.31	0.213		
3.	0.296	0.33		
$\bar{x}$	0.363	0.284	**0.324**	**2.15**
day after loading	**up**	**down**	$\bar{b}$	$\bar{\mu}$
1.	0.488	0.455		
2.	0.321	0.382		
3.	0.378	0.338		
$\bar{x}$	0.396	0.392	**0.394**	**3.8**

detected mode settings, which means a decrease of the AS damping ability as a whole.

Both the defined values ***b, μ*** assume a similar trend, when the two values score a marked decline after loading and a rise after resting.

A. In the case of ***b*** to 52% and in case of μ to 22% of the starting value, followed by a slight increase after about 18–24 h resting in the case ***b*** to 62% and in case of ***μ*** to 38%of *the starting value.*

B. The increase in value after resting 18–24 h can be also evaluated with respect to *the value after loading*. This comparison revealsthat after resting the coefficient ***b*** increases of 22% and the viscosity ***μ*** of 78% values after loading.

It is apparent from the information stated abovethat the defined parameters show varying degrees of sensitivity to the symptoms investigated and could be advantageously used e.g. to locate a pathology in AS, or a degree of fatigue or resting after i.e. a sport performance, physiotherapy intervention, respectively, etc. The viscoelastic tissues – components forming the AS unit, react to a mechanical load with a decrease in the above parameters and ten after relaxation, limited within the time interval stated above, the values of the parameters gradually return with different dynamics to the original values.

In terms of the length of time required before the original values are reached corresponding to the values before the AS loading and if at all, or how long it reaches the values "acceptable", this is a question for further experimental work. The return towards the original values will be highly individual, and certainly influenced by genetic and other factors, e.g., regeneration process, eating habits, drinking regime, possibly the use of dietary supplements or other medications.

The regenerative process, and thus a return to the baseline of the component rheological properties, is a matter of optimizing the loading mode without negative effects on the human organism, here gymnasts.

An important result of using the methodology presented by Transfer Vibration through Spine will be the ability to use the AS non-invasive diagnostics for evaluating the load, relaxation and regeneration modes, or medical and therapeutic procedures with a high degree of individualization.

CONCLUSION

The methodologyi ntroduced and indicated the ability of AS quality assessment using quantitative analysis. These trends changed in the selected parameters and will continue to be scrutinized to a greater number of homogeneous groups of probands including statistical evaluation.

The objective of the study is to show the possibilities of the TVS method to identify and classify the AS immediate changes manifested after mechanical load. The authors of the studies tend to determine whether the changes in the properties of AS connective tissues are identifiable by TVS and whether their quantification is also possible, regardless of the age and nature of the applied load.

ACKNOWLEDGEMENT

This project was supported by grants PRVOUK 38, SVV 2016 - 260346, GAUK962314

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