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Gait Analysis in Adolescents with Idiopathic Scoliosis: A Systematic Review

Diploma Thesis

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Declaration

This master's thesis is my original work and wherever other sources of information are used, every effort has been made to ensure that due credit has been given to the author(s) of the information through in-text citation and in the bibliography.

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Mandeep Kaur Bains, Prague, 2015

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Abstract

Title Gait Analysis in Adolescents with Idiopathic Scoliosis: A Systematic Review.

Aim The role of spine is vital as a gait stabilizer. Gait analysis may provide a more holistic view of how the body behaves to idiopathic scoliosis among adolescents. The aim of this thesis is to review the effectiveness and validity of gait analysis in examining AIS, and secondly to assess how the gait of AIS patients differ from adolescents without scoliosis.

Method A systematic review of the topic was conducted. Information was gathered from six e-databases, and seventeen articles were selected, of which seven focusing solely on AIS subjects (i.e. non-comparative) and ten were focusing on AIS in relation to control subjects (i.e. comparative).

Results Spatio-temporal (STP), kinematic, kinetic and EMG parameters show significant changes in AIS subjects during walking. But variations between results, lack of data for certain parameters and no significant relationship between gait parameters and scoliosis was also seen. Furthermore, AIS subjects differ in performance compared to non-scoliosis adolescents in at least one gait parameter across all studies. This includes abnormalities in muscle activity, less economical use of the body, poorer performance in kinematic parameters and differences in STP such as step length and step initiation.

Conclusion It is clear that gait analysis is a valid method for exploring the consequences of AIS during walking. The evidence base is nonetheless diverse, inconclusive and limited. Also, although AIS individuals show a different gait pattern than non-AIS individuals, the ability to generalize these findings is low. Future research should try more replications of the same methodologies applied in the literature on gait and AIS, but in new settings.

Keywords adolescent idiopathic scoliosis, AIS, gait, gait analysis, walking, locomotion, spatio-temporal, kinematic, kinetic, asymmetry and posture

Souhrn

Název Analýza způsobu chůze u dospívajících pacientů s idiopatickou skoliózou. Systematický přehled.

Cíl Úloha páteře je životně důležitá jako stabilizátor chůze. Analýza chůze může poskytnout více holistický pohled na to, jak se tělo chová při idiopatické skolióze u dospívajících jedinců. Cílem této práce bylo vyhodnotit účinnost a validitu analýzy chůze při vyšetření AIS a dále jak se liší způsob chůze u pacientů s AIS od chůze u dospívajících jedinců bez skoliózy.

Metoda Bylo provedeno systematické vyhodnocení problému. Informace byly získány ze šesti elektronických databází a vybráno bylo 17 článků, z nichž 7 se soustředilo výhradně na subjekty s AIS (tj. nejednalo se o komparativní sledování) a 10 článků se soustředilo na AIS ve vztahu ke kontrolním subjektům (tj. komparativní sledování).

Výsledky Spaciotemporální (STP), kinematické, kinetické a elektromyografické (EMG) parametry prokazují významné změny při chůzi u subjektů. Byly ale rovněž pozorovány odchylky mezi výsledky, nedostatek údajů u určitých parametrů a nebyl pozorován významný vztah mezi parametry způsobu chůze a skoliózou. Ve všech studiích se subjekty s AIS dále liší ve výkonnosti alespoň v jednom parametru způsobu chůze v porovnání adolescenty bez skoliózy. To se týká abnormalit ve svalové aktivitě, méně ekonomického využití těla, horší výkonnosti u kinematických parametrů a rozdílu v STP, jako je délka kroku a zahájení kroku.

Závěr Je evidentní, že analýza způsobu chůze je validní metoda pro zkoumání důsledků AIS během chůze. Východiska důkazů jsou nicméně nejednoznačné, nepřesvědčivé a omezené. I když jedinci s AIS mají rozdílné vlastnosti chůze než jedinci bez skoliózy, schopnost generalizace těchto nálezů je nízká. Výzkum v budoucnu by se měl pokusit o více replikací stejných metodologií použitých v literatuře o způsobu chůze a AIS, ale v novém prostředí.

Klíčová slova idiopatická skolióza u adolescentů, AIS, způsob chůze, analýza chůze, chůze, lokomoce, spaciotemporální, kinematický, kinetický, asymetrie, držení těla

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List of abbreviations

AIS	adolescent idiopathic scoliosis
COP	centre of pressure
CS	control subjects
EMG	electromyography
f.	females
GGI	Gillette Gait Index
GRF	ground reaction force
L	lumbar
m.	males
n	number of articles
OGA	observational gait assessment
ROM	range of motion
SI	symmetry index
STP	spatio-temporal parameters
T	thoracic
TL	thoracolumbar
y.	years

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1. Introduction

Walking is a common daily activity for the body, and its efficiency rely on the mobility of the joints, muscle activity, coordination of the body and ability to move the centre of gravity. The role of the spine is vital in this process as a gait stabilizer. Thus, the presence of a spinal deformity will impact the efficiency of locomotion. Adolescent idiopathic scoliosis, a lateral deviation of the normal vertical line of the spine, is not only a spinal deformity, but also results in the development of a pathological gait pattern (Herring, 2013; Stepien, 2012; Syczewska, Graff, Kalinowska, Szczerbik,& Domaniecki, 2012).Gait analysis can provide a betterunderstanding of how the body behaves to idiopathic scoliosis among adolescents.

Studies examining gait in adolescents with idiopathic scoliosis have shown somewhat contradictory results (Syczewska et al., 2012). A systematic review of the topic will provide a better overview of the landscape. Stepien (2012) have addressed the issue of the impact of AIS on gait, but have focused on recent advances in scoliosis rather than undertaking a systematic and comprehensiveexamination. A study by Simon, Ilharreborde, Souche and Kaufman (2015) is the only systematic review to date, whichexplores the consequences of spinal deformities on gait in a broad fashion. The studyincludes scoliosis,low back pain, ankylosing spondylitis and postoperative flat back syndrome, and reviews studies as far back as 1959. The present study is differentiated in that it undertakes an in-depth focus on gait in AIS only, as well addressing how gait of AIS subjects differ from non-AIS individuals. In addition, it aligns this with a wider discussion on the limitations and practicalities of gait analysis.

1.1 Aim and overview

Specifically, this endeavour seeks to identify, evaluate, select and report on quality research (Hemingway, 2009)on the use of gait analysis in examining adolescents with idiopathic scoliosis in order to assessitseffectiveness and validity and, secondly, review how the gait of adolescents with idiopathic scoliosis differ from adolescents without scoliosis. The remainder of the thesis is organised as follow. Chapter 2 introduces gait analysis and AIS. Chapter 3 outlines the methodological framework. In Chapter 4, the results from the research are presented, while Chapter 5 summarise and discuss findings, methodological challenges, and practical and clinical use of gait analysis. Chapter 6 concludes.

2. Theoretical Overview

2.1 Gait analysis

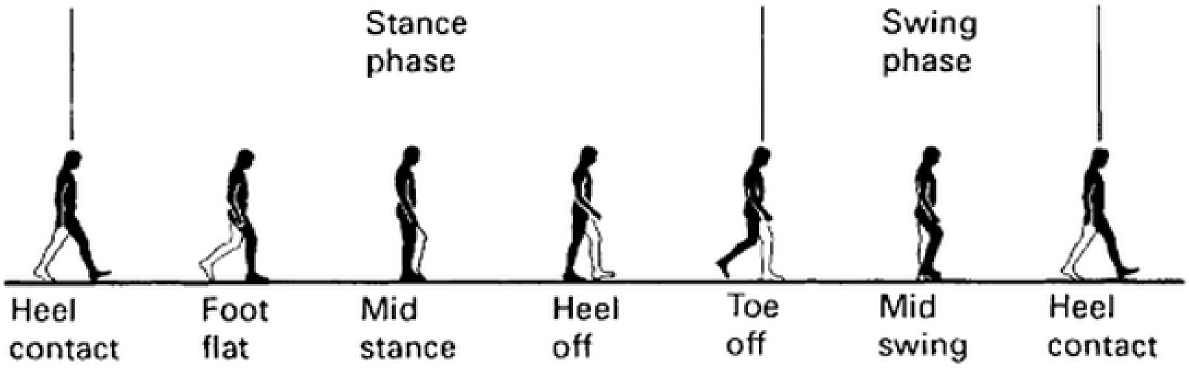
2.1.1 Gait analysis in general

Gait analysis can be defined as a systematic study of human walking. This method is often helpful in the medical management of diseases affecting the locomotors system (Whittle, 2007) and gives the potential to determine those impairments and functional limitations that probably contribute to the walking disability (Kerrigan, 1998). Therefore, gait analysis looks at the entire body as a holistic organism to identify any deviations of normal gait (Lyman, n.d).

The study of gait can be performed as an observational gait analysis or instrumental gait analysis (Malouin, 1995). Observational gait analysis is defined as a visual inspection of walking where any deviations found during gait are identified and graded based on the observer´s experience and individual bias (Sisto, (1998). Instrumental gait analysis, on the other hand, is performed by using equipment that can be as simple as a video recorder or other advanced instruments, such as electromyography electrodes, footswitches, motion markers, force platform and so forthfor an in-depth assessment of movement dysfunction (Bontrager, 1998; Mosley, Romaine,&Samll, 2009). This assessment involves information about temporal and spatial parameters, joint angles, ground reaction, and muscle activity patterns (Soutas-Little, 1998).

In order to understand gait analysis it is important to learn about the normal gait cycle. The gait cycle for a given limb is divided into stance phase, when the foot is in contact with the floor, and the swing phase, when it is not in contact with the ground. The stance phase is also called the “support phase” or “contact phase” and represents 60% of one cycle, while the swing phase makes up 40% of one cycle (Baker, n.d.; Rothstein, Serge, Wolf,& Scalzitti, 2012; Vaughan, Davis,& O´Connor, 1999; Whittle, 2007). Figure 1 illustrates this:

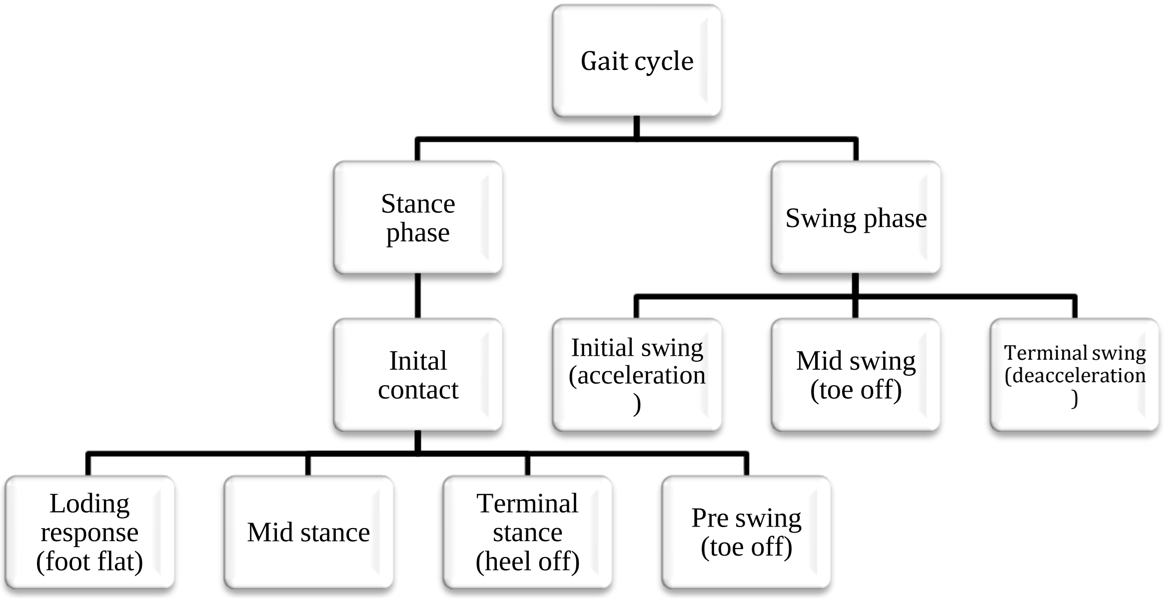
Figure 1: Phases of gait cycle



Source: Whittle, 1991, p.53

These two phases are further subdivided into eight periods according to the position of the feet in the cycle, as shown in Figure 2:

Figure 2: Division of a gait cycle



Source: Levine, Richards & Whittle, 2012, p. 32.

2.1.2 Gait parameters

The actual analysis of gait involves the measurement and interpretation of certain parameters with the purpose of drawing conclusions about subjects (Tasch et al., 2008). The analysis is the measurement of spatio-temporal parameters (STP), kinematic parameters, kinetic parameters and dynamic electromyography (EMG).

STP include time-distance variables such as stride time (duration of one gait cycle), step time (the time from initial contact of one foot to the initial contact of the opposite foot), step width (measure of the medio-lateral separation of the feet), stride length (the distance between initial contact of the foot and initial contact of the same foot with the ground in two consecutive gait cycles), and step length (the distance between the initial contact of the foot with the ground and initial contact of the opposite foot with the ground). Cadence and velocity are additional parameters, with the former referring to the stride frequency or number of steps per minute, while the latter is understood as the product of cadence and stride length (Baker, n.d.; Switaj, Hoke &O'Connor, 2012; Whittle, 2007).

STP can effectively be measured during gait analysis with cellular pressure mats, sensing foot pressure, force platform, which are dynamometers measuring GRF in time, and motion analysis, a system of stereo photogrammetric cameras for reconstructing body motion, including foot contact timing in three-dimensional space. Temporal but not spatial parameters can be measured with foot switches (on/off devices detecting contact timing of the foot) or instrumented walkways that are covered with electrically conductive substances (Switaj et al., 2012; Whittle, 2007). Spatio-temporal parameters could also be measured using only a stopwatch, making the process more practical in clinical use (Saud, Wall, Al-Yaqoub,& Al-Ghanim, 2003).

Kinematic parameters characterize motion without references to the forces involved. Kinematics is therefore the measurement of movement and is used in gait analysis to record the position and orientation of the body segments, the angle of the joint and the corresponding linear and angular velocities and accelerations (Switaj et al., 2012; Whittle, 2007). Instruments used when measuring kinematic parameters are camera, electrogoniometers, potentiometer devices, flexible strain gauges, active and passive marker systems, and goniometers (Aiswariyadevi& Rajaganapathy, 2014; Whittle, 2007).

Kinetic parameters include forces, moments, masses, and acceleration measured though gait analysis in both passive and active structures in the body, without references to position or orientation of the objects involved. GRF are captured by subjects walking on one or more force platforms placed in the walkway (Whittle, 2007). Center of pressure (COP) is also determined from measuring GRF, and this refers to the center of the distribution of GRF. From knowing segment kinematics and GRF, joint kinetics can also be measured (Switaj et al., 2012). Information about center of mass, mechanical energy, work (Winter, Eng,& Ishac, 1995) is also retrieved from measuring kinetic parameters.

Through EMG it is possible to measure the electrical activity of a contracting muscle during walking. Muscle activity during walking in association with the joint moment patterns can provide an effective description of overall gait function. Joint moments give information about the effect of muscle action, but it is the knowledge of the activation pattern that allows one to distinguish in time which muscles are responsible for the observed joint moment.The most common method to detect muscle activity during gait is with surface electrodes, while fine wire and needle electrodes are less used to record EMG. However, since the activity measured is electrical and not mechanical, EMG cannot be used to distinguish between concentric, isometric and eccentric contraction (Hillstrom & Triolo, 1995; Knutson & Soderberg, 1995; Whittle, 2007).

2.2 Adolescent idiopathic scoliosis (AIS)

2.2.1 AIS in general

Scoliosis is described as a lateral deviation of the normal vertical line of the spine, which is greater than ten degrees when measured through radiography (Herring, 2013). The lateral curvature of the spine makes the deformity three-dimensional since it is most often accompanied by rotation of the vertebrae within the curve (Lehnert-Schroth, 2000). The actual cause of the pathogenesis has not been established, hence the name idiopathic (Hawes & O'Brien, 2006). Idiopathic scoliosis affects nearly 80% of patients with structural scoliosis, which makes it the most common type of scoliosis. A patient is diagnosed with idiopathic scoliosis when all other alternatives are ruled out, such as neurological causes, syndromes and congenital anomalies, through a comprehensive physical and radiographic examination (Fernandes & Bell, 2003).

Idiopathic scoliosis present in patients between 10 and 18 years of age is termed adolescent idiopathic scoliosis (AIS) (Scoliosis Research Society, 2015). The overall prevalence of adolescent idiopathic scoliosis ranges from 0.47% to 5.2% (Konieczny, Senyurt,& Krauspe, 2013).AIS may affect both genders, but is found more commonly in females than in males (ratio of 11:1), and the scoliotic curve in adolescent females tends to progress more often than in males (McIntosh & Weiss, 2012). Among adolescents with idiopathic scoliosis, 2% has a curve higher than 10 degrees, but only 5% of these have a progression of the curve higher than 30 degrees (Van Goethem& Van Campenhout, 2007).

The lateral curve(s) of AIS could occur at all spine levels, but the most usual curve is a right thoracic curve. The thoracic right side curve can either occur as a single curve, forming a “C”-shape, or with another curve to become a “double curve”, bending the opposite way forming a “S”-shaped left lumbar curve (Netter & Parker, 2013; Ullrich, 2004).The most progressive curve is the right thoracic curve, but initial minor curves progresses faster than major left thoracic and lumbar scoliosis (Van Goethem & Van Campenhout, 2007).

2.2.2 Signs

The signs and characteristics of scoliosis are more visible the more severe the scoliotic curve (WebMD, 2014). Scoliosis characteristics can be detected by a postural examination, where the patient is visually examined from anterior, posterior and lateral view (Palmer&Epler, 1998). Some common features of AIS are shoulder asymmetry, unequal scapular prominence, signs of an elevated or prominent hip, increased space between the arm and body in one side (with the arms hanging loosely at the side) and head not being in centered position over the pelvis. Vertebral rotation, which usually is present in structural scoliosis, causes one side of the trunk to appear higher than the other side. This is visible as rib prominence in upper trunk (lumbar region) or as paraspinal fullness in lower trunk (lumbar region). In most cases , anterior view inspection shows asymmetry of the chest or ribcage (Herring, 2013).

2.2.3 Examination/ assessment

Examination and assessment of an AIS patient is conducted by reviewing family history and personal clinical history along with medical and neurological examination. Since the lateral curve of the spine is diagnosed as idiopathic scoliosis only by eliminating all other possible causes, the above mentioned evaluation methods are highly important (Kotwicki et al., 2009).The most used and important non-invasive clinical method for assessing scoliosis is Adam´s forward-bending test. A positive test identifies the rotation of the chest wall that occurs in scoliotic patients (Janicki & Alman, 2007). The test can be combined with the use of a scoliometer, which is a device proven to be highly valuable and is used to assess trunk rotation. The scoliometer is placed at different spinous processes and an angle less than seven degrees is considered within the normal limits (Crawford, Oestreich, D´Andrea, Heller,& Cachill, 2010).

A newly proposed and valid method for screening trunk asymmetry is the TRACE scale, which is a 12-point scale based on a visual evaluation of the shoulders, scapulae, waist and hemithorax asymmetries. Some other preferable evaluation tools that are easy and practical to use in clinical contexts include plumbline, the inclimed and the arcometer. These are devices that measure the sagittal profile, which is usually altered in scoliotic patients (Negrini et al., 2012).

Internal assessment of the trunk is done through radiographic imaging. The magnitude of the curve(s) is measured through Cobb´s angle and the rotation of the spine is measured using Nash-Moe method or Perdriolle's torsiometer. Although radiographic examination gives detailed information about scoliosis, it is important supplement radiography more frequently with other follow-up methods due to the negative effects of radiation (Crawford et al., 2010; Knott et al., 2014).

Internal examination can also be done through magnetic resonance imaging (MRI) and Computed tomography (CT) scan. MRI is a detailed neurophysiological examination used to demonstrate intra-spinal anatomy, but some experts argue that the use of MRI is not so much needed for a neurologically intact patient with AIS as for those with severe degree of scoliosis who might be more in risk of neurological complications (Crawford et al., 2010). Spinal MRI has also been shown to be effective for evaluating surrounding soft-tissue structure in patents with scoliosis (Elsebaie, 2010).

Meanwhile, CT examination is used for three-dimensional reconstructions of segmentation abnormalities and soft –tissue structure. CT-scanning is not a routine method for examination of AIS patients, but it is a useful one for assessing rotation and segmentation abnormalities, and is normally used in patients with severe scoliosis (Rajiah, 2013). However, a major disadvantage of CT-scanning compared to MRI is the presence of ionizing radiation affecting the patient´s tissue (Crawford et al., 2010).

Surface topography is another method that has been widely used, but mainly for research purposes. It has only in recent time entered the clinical setting. This method identifies the presence of scoliosis and level and side of the scoliosis curvature in individuals with standard rotation, but it is not possible to determine the magnitude of the scoliosis in a precise manner for this method to be clinically effective (Herring, 2013).

2.3 Gait analysis and AIS

AIS can affect spinal anatomy, spine mobility, trunk balance and gait mechanisms (Karimi, Kavyani,& Etemadifar, 2014; Syczewska, Graff, Kalinowska, Szczerbik,& Domaniecki, 2010). It is known that AIS generates postural alterations (Haumont, Gauchard, Lascombes,& Perrin, 2011), sensory perturbations (Bruyneel et al., 2009; Simoneau, Mercier, Blouin, Allard,&Teasdale, 2006) and standing instability (Dalleau, Allard, Beaulieu, Rivard,& Allard, 2007) and can affect quality of movements, walking and quality of life in general (Bruyneel et al., 2009; Negrini et al., 2015; Stępień, 2012).

However, there are only a few studies focusing on the effect of spine deformity on gait in AIS (Stępień, 2012). It is conceivable that gait analysis can widen our understanding of AIS. The use of gait analysis falls into three categories, viz. diagnosis, monitoring and research (Kirtley, 2006), and is conducted on patients with a disability (or injury) as well as nondisabled (non-injured) control subjects for comparison to categorize the severity of disability, evaluate the efficiency of intervention, improve performance and to identify the mechanisms causing the gait dysfunction (Oatis, 1995). Several diseases such as, inter alia, cerebral palsy, Parkinsonism, lower limb amputation, stroke, spinal cord injury and multiple sclerosis can influence the neuromuscular and musculoskeletal systems and may therefore result in disorders of gait (Levine et al., 2012). This also includes AIS, which due to its impact on spinal anatomy, mobility, and trunk symmetry, can modify human movement (Mahaudens, Detrembleur, Mousny, & Banse, 2009).

Normally, in gait, the lower limbs perform the dynamic movement, while the trunk helps in the maintenance of balance and connect with the limb movements to manage efficient locomotion. Furthermore, the shoulder and pelvis girdles rotate to opposite side so that the position of the head is controlled when progressing forward, and this opposing rotation is facilitated by spine segmental movement In normal gait, the activation pattern of muscles of spine and lower extremity also maintain segmental mobility and trunk equilibrium (Elftman, 1951; Mahaudens et al., 2009).

The presence of AIS, however, affects the efficiency of locomotion. The mechanisms behind the relationship between AIS, spine mobility and gait is well-explained by Polyzos (2012). According to the author, the existence of any deviation upon the body structures or tissues through scoliosis will lead to a misbalance and an impact on the normal distribution of forces on and around a joint, ligament, bone or muscle. As a consequence of this misbalance, a change of all physical quantities exerted from various parts of the body in the upper and lower trunk and upper and lower extremities and their relative joints will take place. The joints of the lower extremities are involved in the gait cycle, and the influence from scoliosis changes their function during the gait cycle and one can expect loss of or restricted movement. In addition, gait is a challenging balance task and AIS also affect trunk balance. Trunk is an active assistant of controlling whole body mechanics to achieve the objective of effective locomotion, but a spinal deformity modify the natural balance of walking (Rusovs, Pavare, Ananjeca, & Vetra, 2010; Simon et al., 2015).

In sum, the spine therefore plays a key role as stabilizing factor for human gait, and gait analysis can provide complementary information that can give a more complete picture and enhanced management of AIS. This thesis aims to review whether gait analysis can be an effective and valid method in examining AIS and to explore the impact of AIS during gait compared to the norm.

3. Methodology

The methodological approach in this study is described as a systematic review of relevant literature. This chapter therefore contains a description of selection criteria for relevant literature and data collection according to the research questions raised:

1. Can gait analysis be used as a valid and effectivein identifying and examining adolescents with idiopathic scoliosis?
2. How does the gait of adolescents with idiopathic scoliosis differ from adolescents without scoliosis?

A key aim of a systematic review is to minimize bias in terms selecting studies and the rigorousness of this process is what constitutes the systematization (Schlosser, 2007). The following sections describe the process used in this study.

3.1 Population

In the articles reviewed, the population was determined according to the following factors

- Gender ratio between subjects.
- Age narrowed to adolescents aged 11-18.
- Subjects without any kind of surgery for AIS.
- Healthy control subjects with no serious diseases or injuries.

3.2Data Collection

The search for studies in a systematic review should be extensive, and the selection criteria for articles and studies should flow directly from the research questions (Khan, Kunz, Kleijnen & Antes, 2003). To identify and collect all relevant data on gait analysis in adolescents with idiopathic scoliosis, the following conditions were applied:

- Search for studies published from the year 1995 to 2015. 1995 was selected as a reasonable cut-off date to ensure a comprehensive search as well to include mainly up-to-date treatment approaches and philosophy in terms of gait analysis of AIS subjects.
- Search for studies (articles, book chapters, dissertations and reports) in the following databases: EMBASE, EBSCO, Spine Journal, Ovid, ProQuest and Science Direct. Multiple databases have been used to reduce the risk of database bias.
- Search for material (articles, books, unpublished dissertations, conference reports and other “grey literature”) in search engines like Google was also conducted to reduce

source selection bias.

- Search conducted with a combination of the following terms: adolescent idiopathic scoliosis, AIS, gait, gait analysis, walking, locomotion, kinematic, kinetic, symmetry, and posture.
- Secondary references that includes any of the abovementioned terms in the title was also culled for.

Studies were excluded based on screening the abstracts and/or the following criteria for elimination:

- Written in language other than English, Norwegian, Swedish and Danish. Although linguistic constraints necessarily introduces a language bias, the inclusion of some non-English languages contributes somewhat in alleviating a bias in favor of solely English (Schlosser, 2007)
- Population with other primary injuries or diseases, which makes AIS a secondary condition, such as Scheuermann's disease, vertebral spondylosis, cerebral palsy, spina bifida, polio, genetic disorders, rheumatoid arthritis, fractures, developmental diseases (osteogenesis imperfekta, brittle bone disease, Duchenne and Beckers genetic disease) etc.
- Research under ethically questionable conditions.
- Analysis performed on any other activity than straight-ahead walking on plain surface and/or treadmill. The rationale for this is to ensure that appropriate comparisons between studies and research results can be made.
- Type of quality of evidence included other than filtered information, such as: systemic reviews, meta-analyses, critically appraised topics and also critically appraised individual articles.

A log of rejected studies and reasons for rejection has been maintained, and can be provided upon request.

4. Results

This chapter summarizes the literature review by describing study range and characteristics and synthesizing the data in tabulation form. The data found in the selected studies is subdivided into themes, equipment and parameters,anda summary of results is provided in light of the research questions.

4.1 Search yield

A total of 2301 titles were found during electronic searches in the various databases and search engines. Out of these, 2264 articles were eliminated after screening of titles and abstracts. The number of articles were then narrowed down following the inclusion and exclusion criteria described in section 3.2, resulting in a selection of 15 articles for review. Further two articles were obtained based on the reference lists in the primary articles, giving a final result of 17 articles presented in Tables 1 and 2[1].

4.2. Study characteristics

The research designin the population of articlescan becategorized as overt observational research where the researchers co-operate openly with the subjects and the purpose of the study is explained to the research participants. Out of the totalof 17 selected articles, seven articles were non-comparative studies (1; 2; 3; 4; 5; 6; 7), meaning they did not include a control groupand ten studies were comparative (8; 9; 10; 11; 12; 13; 14; 15; 16; 17), meaning they included control subjects.

One article (5) included in the non-comparative group of studies is self-proclaimed as a comparative study, but without a control group during the actual research process. Rather, the approach by the authors in this study was to compare results with those found in similarly performed studies on control subjects. However, in this thesis only the results of AIS subjectsin this particular study are included, andunder the label of non-comparative study and not comparative study.

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[1] Referencing of selected articles in chapter four (Results) are linked to Table 1 and Table 2 (i.e. that the reference are the two tables and not the bibliography) for the sake of practicality.

16 out of 17 studies were carried out with AIS walking on ground while one (14) was conductedwith AIS subjectswalkingon a treadmill. In 12 out of 17 studies, subjectswalked in normal comfortable walkingspeed, while in two studies (3; 14) they walked at different speeds, and in three articles the speed of walking was not reported. One study (3) tested the subjects on two occasions and compared the data found from the first and second testing day. This was the only study specifically assessing repeatability and reliability of gait parameters (spatio-temporal, kinematic and kinetic) in AIS subjects through an inter-trial and test-retest design, rather than studying the direct relationship between gait parameters and scoliosis in adolescent subjects.

4.3 Subjects

In the non-comparative studies, the total number of subjects varied from study to study. Most of the articles (1; 2; 3; 4; 5; 6) had less than 26 participants, but one study (7) had 63 participants. In the comparative studies, the numberand composition of participants, i.e. AIS subjects and non-AIS subjects, also varied between studies.Three studies (9; 10; 14) had more AIS participants compared to control subjects, while seven studies (8; 11; 12; 13; 15; 16; 17) had around the same number ofparticipants in the AIS group and control group.

Subject characteristics, including age (mean age 11-17), physical features (mean Cobb´s angle 19°-68°, single curve to the left or single curve to the right, single and/or double curve, and rotation), and intervention type (pre-AIS surgery and post- or pre- brace-/conservative therapy) also varied among the articles under review. In addition, the ratio between female and male was uneven in both comparative studies and non-comparative studies. In the studies that include both genders, the number of male participants was always less than the number of female participants. Seven studies included both genders, while six studies included only female participants and four studies did not mention the gender of the subjects.

Table 1: Overview of the studies investigating gait analysis in AIS subjects.

Author(s), Year	**Intervention(s)**	**Subjects (gender, mean age)**	**Cobb´s angle, curves**	**Equipment (type)**	**Parameters**	**Gait conditions**
Chockalingam et al., (2004) (1)	N/A	16 AIS 12f., 4m. 11y.	Mean 68.37°	1 Force platform (AMTI)	Kinetic	Normal speed 3 trials
Chockalingam et al., (2008) (2)	9 scheduled surgery	9 AIS 8f., 1 m. 15.33y.	Mean 61°	Video analysis (Motion analysis) 1 Force platform (AMTI)	Kinetic	Normal speed 3 trials
Fortin et al., (2007) (3)	N/A	20 AIS f. 12-17y.	Range 17°-50°	Video analysis (Optotrak system) 3 Force platforms (AMTI) 3 Foot switches on each foot	Kinematic Kinetic STP	Self-selected normal and fast speed 5 trials 10m walkway Self-owned running shoes

Kramers de Quervain et al., (2004) (4)	3 brace treatments 3 without treatment during gait study 4 scheduled surgery	10 AIS f. 14.4y.	Right T curve Range 0-73° Left L Range 9-47°	Video analysis (Vicon system) 2 Force platforms (Kistler)	Kinematic Kinetic STP	Self-selected comfortable speed 10 trials 25m walkway Barefoot
Schiaz et al., (1998) (5)	5 previously treated 7 conservatively treated 8 awaiting surgery	21 AIS 20f., 1 m. 16.1y.	Mean TL curve 34° Mean L curve 35°	2 Force platforms (Kistler)	Kinetic	Self-selected speed 5 trials 8m walkway Barefoot
Syczewska et al., (2006) (6)	25 conservatively treated	24 AIS f. 12-16y.	Range 20°-35°	Video analysis (Vicon system) 2 Force platforms (Kistler)	Kinematics Muscle activity	6 trials

				EMG		
Syczewska et al., (2012) (7)	No previous treatment or surgery 63 starting on conservative treatment	63 AIS f. 12-17y.	Range 20°-61° Mean 36°	Video analysis (Vicon system)	Kinematics STP	Self-selected speed 6 trials 6m walkway

Table 2: Overview of the studies investigating gait analysis in AIS subjects and controls.

Author(s), Year	**Intervention(s)**	**Subjects (gender, mean age)**	**Cobb´s angle and curves**	**Equipment (type)**	**Parameters**	**Gait conditions**
Bruyneel et al., (2010) (8)	10 8±3 months of brace treatment No surgery	10 AIS f. 13.8±2.15y. 15 CS f. 12.57±1.34y.	Mean right T single curve 33.4°± 18.74°	2 Force platforms (AMTI)	Kinetic STP	10 trials
Chan et al., (2006) (9)	N/A	19 AIS 17f., 2 m. 13.8y. 9 CS 7f., 2m. 11.6y.	Mean 43.5°	Video analysis (Vicon system)	Kinematic STP	Self-selected speed 3 trials Barefoot
Chen et al., (1998) (10)	N/A	30 AIS 28f., 2m. 16.6±3.8y. 15 CS	T, TL and L curve range 22°-67°	Video analysis (Elite system) 2 Force platforms (Kistler)	Kinematic STP	Natural comfortable speed 6 trials

		13f., 2m. 16.6±3.8y.				10 m walkway Barefoot
Dangerfield et al., (1995) (11)	N/A	28 AIS age, gender N/A 26 CS age, gender N/A	N/A	1 Force platform (AMTI)	Kinematic Kinetic	Normal speed 10 trials 10 gait sequences 10 m walkway
Giakas et al., (1996) (12)	No conservative treatment 20 surgery required	20AIS f. 13y. 20CS f. 13y.	Range 25°-62° Mean 42°	1 Force platform (AMTI)	Kinetic STP	Normal speed 10 trials 15 m walkway
Mahaudens et al., (2005) (13)	No conservative or surgical treatment	12 AIS gender N/A 13.2±0.8y. 12 CS gender N/A	TL or L curve Range/mean N/A	Video analysis (Elite system) 1 Force platform (Pharos)	Kinematic Kinetic Muscle activity	Comfortable speed 10 m walkway

		12.9±9y.		EMG (Telemg, BTS) Foot switch soles	STP	
Mahaudens and Mousny (2010) (14)	No conservative or surgical treatment	41 AIS gender N/A 12-17y. 13 CS age, gender N/A	TL and L curve range 20°-40°	4 Force transductors EMG	Kinematic Kinetic Muscle activity	Treadmill walk 4km/h (comfortable speed) Barefoot
Mallau et al., (2007) (15)	None under active treatment No surgical treatment	17 AIS 9 f., 8 m. 14.3y. 16 CS 9f., 7m. 14.1y.	Range 11°-13° Mean 19.5°±5.2°	Video analysis (Elite system)	Kinematic STP	Normal speed 5 trials 3m walkway
Park et al., (2012) (16)	8 previously treated conservatively	6 AIS gender N/A 17 ±1.1y.	Range 20° or less	Videoanalysis (Motion master)	Kinematic Muscle	7 trials

	8 awaiting surgery	5 CS gender N/A 14.4±0.5y.		EMG	activity	
Yang et al., (2013) (17)	No conservative or surgical treatment	20 AIS 18 f., 2 m. 14.9 ± 1.0y. 20 CS 15 f., 5 m. 14.4 ± 1.0y.	TL and T curve range 9°-34°	Video analysis (Motion analysis) 2 Force platforms (Bertec)	Kinematic Kinetic STP	Comfortable speed 5 trials 10 m walkway

4.4 Equipment

4.4.1 Camera and marker system

A total of ten studies used 3D camera systems such as Vicon (n=4), Elite (n=3) Motion analysis (n=2) and Motion master (n=1), with either four, five or six cameras. For motion measurement, researchers applied passive external markers on subjects´ bodies. The only marker placement protocol type mentioned was the Helen Hays marker-set, used in three studies (6; 7; 17), while seven out of nine studies (3; 4; 9; 10; 13; 14; 15) mentioned that they used retroreflective markers.

Markers were placed on the surface of the skin, bilaterally on anatomical landmarks, including: head (on the jaw joint, median suture, sagittal suture and/or mastoid), upper extremity (sternal notch, sternoclavicular joint, clavicle, acromion process, glenohumeral joint, radial epicondyle and/or dorsum of the wrist), trunk (spinous process of C7, T1, T4, T6, T8, T9, T12, L2, L3, L4, S1 and/or S2), pelvis (anterior superior iliac spines, posterior superior iliac spines and/or iliac crest), thighs (greater trochanter, midline of thighs and/or lateral/medial femoral condyle), legs (head of fibula, lateral tibial plateau and/or midline of legs), and feet (bilateral lateral/medial malleolus, bilateral posterior aspect of calcaneus, dorsum of foot, bony prominence of heel, lateral heel, second metatarsal head, between the second and third metatarsal head and/or lateral fifth metatarsal head).

4.4.2 Force platforms

The force transducer type used in the studies were either piezoelectric (4; 5; 6; 10) or strain gauge (1; 2; 3; 8; 11; 12; 13; 17). Two Kistler-type piezoelectric force platforms (n=4) and one, two or three AMTI (n=6), Bertec (n=1) or Pharos (n=1) strain gauge platforms were used in the walkways. One study (14) performed gait analysis on a treadmill using four force transducers located corners of the treadmill. Four studies (7; 9; 15; 16) did not use any force platforms. Five articles (1; 5; 8; 11; 12) used force platforms as a measure of ground reaction force (GRF), but in other studies the information from the force platforms was used in combination with other equipment for data collection to analyse different gait parameters, rather than GRF only.

4.4.3 Dynamic electromyography (EMG)

EMG was used in one non-comparative study (6) and three comparative studies (13; 14; 16). EMG was combined with the use of video (6; 13; 16) and force plate analysis (6; 13; 14) to measure electrical activity of muscles (6; 13; 14; 16) and to find muscular efficiency through external and internal work (13; 14). These measuring tools also retrieved kinetic and kinematic data. Surface electrodes were placed bilaterally on the trunk and lower extremity to measure the activity of semitendinosus (14), latissimus dorsi, psoas (16), gastrocnemius (6; 16) biceps femoris (6; 13), tibialis anterior, rectus femoris (6; 14) gluteus maximus (6; 13;16), erector spinae (6; 13; 14), glutaeus medius (13; 14; 16) and quadratus lumborum (6; 13; 14; 16).

4.4.4 Other equipment

Footswitches were used to record timing of gait in two articles (3; 13). In the first article (3) the foot switches were placed on each foot at the heel, metatarsal head, and first toe with the subject using their own shoes (3), while in the second article (13) small switches were mounted in an insole. As mentioned in point 4.2, only one study (14) was performed on a motor-driven treadmill (Mercury LTmed). The majority of the studies (n=11) do not mention type of footwear used, but in one study (3) subjects wore self-owned running shoes. Meanwhile, some studies performed gait analysis on AIS subjects walking barefoot (n=5)

4.5 Parameters for non-comparative studies

4.5.1 Spatio-temporal parameters (STP)

Distance and time parameters were measured in three articles (3; 4; 7). Step length (7), stride length (3; 4), cadence (3; 4) and velocity (3; 4; 7) parameters were measured using gait analysis. STP parameters were also included for testing in the study by Fortin, Nadeau and Labelle(3). This was also the only study that measured fast walking speed along with normal self-selected walking speed, as opposed to only normal walking speed. In the study (3), normal self-selected walking speed were measured at 1.29 ± 0.16 m/s and fast walking speed determined at 1.82 ± 0.17 m/s. The results for self-selected walking speed from the first and the second testing day increased by 9.4% (1.41 m/41 m/s versus 1.29 m/s). According to the authors, this increase was due to an increase of 5% in stride length and 4% in the cadence. However, no conclusions were suggested on the implications of the results for STP.

In the study by Syczewska et al.(7), AIS subjects were divided into groups according to Cobb´s angle and rotation severity, with resulting differences in the gait speed across the groups. Inter-group differences were also found in terms of cadence and step length in this study. They therefore concluded that gait parameters are affected by the severity of the spine deformity.

In another article by Kramers de Quervain, Müller, Stacoff, Grob and Stüssi(4), it was found that the whole group walked at a normal velocity, viz. 1.22 ± 0.07 m/s. Moreover, the cadence was measured within normal limits compared to published norms, but stride length, which averaged 1.45 ± 0.08, was slightly reduced in the case of some participants. Asymmetry index for step length and for the duration of the gait phases was measured below two, meaning an asymmetry below 2%. All the different asymmetry values fell in the range between zero and seven, which is within the physiological variation (4). In sum, the time-distance parameters in this study did not demonstrate a significant or clinically relevant asymmetry.

Fortin et al. (3) tested the reliability of STP. The results for inter-trial reliability demonstrated that the dependability coefficients (a ratio for variance as a measure of reliability) ranged higher than 0.75, which can be understood as representing strong reliability. The standard error measurement for self-selected and fast stride (both 0.02 m/s) and velocity (0.03 m/s and 0.04 m/s, respectively) were low. STP results for test-retest reliability showed differences between self-selected speed and fast speed. The dependability coefficients for self-selected speed gave a poor reliability value (highest value of 0.58 for cadence, and lesser for the other STP), but for fast walking speed the reliability increased from a moderate to good level (highest value of 0.92) and the standard error management showed a slight decrease.

4.5.2 Kinematic parameters

Kinematic parameters were measured in four articles (3; 4; 6; 7), focusing on motion and range of motion (ROM) of pelvis and upper and lower extremity (4; 6; 7). Hip, knee and ankle motion had a normal motion pattern in sagittal plane in one research (4). Only minor side-to-side variations were registered, but within normal limits. In the same article, asymmetry of arm swing was seen in most of the subjects. With no systematic pattern, a large ROM of flexion and extension in shoulder and the elbow was measured compared to the opposite limb. Increased motion of the right shoulder was observed in five subject cases, while the other five had increased ROM of the left side. The researchers found no relationship between the upper limb motion and the severity of the scoliotic curve. A mean side difference of 1.2° ± 10.9° for elbow motion and of 9.7° ± 10.3° for shoulder motion was reported for the whole group.

In another article (6), position and range of motion of the joints showed abnormalities. An irregular position of the hip joint was observed in both frontal plane and transversal plane in 12 of 24 AIS subjects. In almost half of the subjects, flexion in the knee joint was in the upper normal limit (4°) at the time of ground contact, while ten subjects had a decreased ROM of the hip joint with, consequentially, an increased internal rotation of pelvis in sagittal plan at the time of contact with the ground. The entire group had internal rotation in transverse plane and dorsal flexion of the feet during the swing phase. Another article (7) presented the parallels between Cobb´s angle and rotation through knee F at initial contact and knee ROM. The results showed that the knee angle at initial flexion and knee ROM were highly dependent on the severity of scoliosis. Other parameters in this article also supported this result. The Gillette Gait Index (GGI), a summary index including important kinematic and temporal variables, was lower for the right leg for those with a left side spinal deformity, and the difference between the left and right leg GGIs was significant. No such difference was seen for those with a right side spinal deformity or equal deformity on both sides.

The research by Syczewska, Lukaszewska, Graff and Górak (6) demonstrated abnormal pelvis position in the majority of AIS subjects' sagittal plane. Only two subjects out of a group of 24 individuals had a normal pelvis position while the rest had reduced ante version, ranging from -2° to 5°. An increased ROM of the pelvis in sagittal plane which exceeded 3° was observed for the whole group. Another article (7) investigated the relationship between the pelvic deformity and gait pathology under the assumption that structural deformity of the spine influences the structure of the pelvis. In addition to gait analysis, subjects underwent clinical examination where type of pelvis deformation was measured based on anthropometric measurements. The authors found both obliquity of pelvis and/or rotation of the iliac bone in AIS subjects. The results showed that this pelvic deformation influenced several gait parameters that were dependent on the severity of scoliosis, including pelvic range of movement in sagittal plane, hip range of movement, knee ROM and GGI.

In frontal plane during walking, the results from the study by Kramers de-Quervain et al.(4) showed an oblique pelvis position in 16 subjects and rotation of pelvis along the gait direction line was found in 24 subjects in the transverse plane. Significant asymmetry was also found in the transverse plane. Asymmetry of the upper body was understood as increased forward rotation while pelvis and head rotated symmetrically in the study. This position of the trunk created a torsional offset that measured at its minimal (mean 1.0°) at right heel strike and at maximal (11.4°) during left heel strike. The magnitude of the torsional offset during gait correlated with the severity of the thoracic deformity, but no correlation was found in the analysis of the torsional offset in relation to the severity of the lumbar curves.

When assessing the reliability of the kinematic gait parameters (3), positive results were seen at self-selected speed and fast speed between trials. The dependability coefficients ranged from 0.85 to 0.98 for the angular displacements, indicating high reliability. The highest coefficients were observed for the hip, knee and ankle in due order. The test-retest reliability for angular displacement was poor to good at self-selected speed according to the authors, andthe knee showed the highest reliability (dependability coefficient of 0.86) in sagittal plane, followed by the ankle and hip. In the frontal plane, only the maximal hip adduction angle at initial stance showed strong reliability.

4.5.3 Kinetic parameters

A total of five articles (1; 2; 3; 4; 5) measured kinetic data, including centre of pressure (COP) (2), force-time parameters (1; 4; 5), GRF in medial-lateral, anterior-posterior and vertical direction (1; 2; 3; 4) and impulse (1). One article (2) measured COP of the AIS group and found a wide variation of displacement in medial-lateral direction. No displacements of COP were found in anterior-posterior direction. The authors suggest that the cause of the wide displacement variation of COP in medial-lateral direction could be connected to the laterality of both primary and secondary scoliotic curves among subjects. Medial-lateral COP displacement between the left and right side also showed considerable differences due to the scoliosis. The displacement of COP to the right was detected through findings of negative symmetry index values, where the symmetry index for loading and unloading rate differed for each individual subject. The values did not follow any specific pattern, but clearly indicated asymmetry.

In terms of force-time variables, Schiaz, Kramers-de Quervain, Stüssi and Grob (5) found that parameters like the loading and unloading factor were those with the highest asymmetry. A loading rate of 4.42 ± 0.85 kN/s and an unloading rate of 4.43 ± 0.79kN/s was recorded for AIS subjects. Other parameters measured in this research reflected normal values. Asymmetries in magnitude of the two peaks were also observed, but to a lesser extent. Those differences were not related to the side or the magnitude of the spinal deformity. A study by

Chockalingam, Dangerfield, Rahmatalla, Ahmend and Cochrane (1)measured the average force value and average loading rate and found no major differences between the left and right side of the feet. In the same article, the symmetry index for loading and unloading differed from individual to individual, but the findings did not reveal any particular pattern. Subjects with a left curve or a left compensatory curve had higher symmetry index for a left-side impulse, and subjects with minor to no compensatory curve had a greater right-side impulse. According to the authors, these results indicate a possible occurrence of gait compensation where the subjects compensate on the opposite pelvis/lower limb to that of the curve. In addition, no specific relationship between the magnitude of the curve and symmetry index for impulse was found.

Kramers de Quervain et al. (4) found no significant asymmetry for the whole subject group when measuring the vertical, medial-lateral and anterior-posterior forces. The most important asymmetry discovered in this study was in the free rotational moment and the angular momentum. The right side had a significantly lower internal rotation and a significantly higher external rotational moment peak. This finding was related to the result described in the section about kinematic parameters, noting a torsional offset of the upper trunk in relation to the symmetrically rotated pelvis. The asymmetry index of the vertical and anterior–posterior GRF parameters was within normal range. No increased asymmetry was noted in individuals with more severe scoliotic curves. Chockalingam, Bandi, Rahmatalla, Dangerfield and Ahmed (2) measured moment about S2 vertebral prominence and found that subjects with higher left compensatory curve had greater displacement to the left.

The reliability study by Fortin et al. (3) found that the speed was higher for the vertical and anterior-posterior components and somewhat lower for the medial-lateral forces, when testing for inter-trial repeatability of GRF. Standard error measurement ranged from 3 N to 16 N at self-selected speed and from 5 N to 21 N at fast speed. The test-retest reliability was moderate to good at self-selected-speed for the absolute GRF parameters. The dependability coefficients were higher for the vertical component (0.92–0.99) followed by the anterior-posterior component (0.81 and 0.82) and the medial-lateral component (0.72-0.85). The standard error measurements were lower than 29, 13, and 6 N for the vertical, anterior-posterior, and medial-lateral GRFs, respectively.

Inter-trial repeatability for moments and power parameters also had stronger reliability for self–selected speed (dependability coefficients of 0.93– 0.99 and 0.89–0.96, respectively) and standard error measurements were lower than 3.2 Nm (moment) and 8.9 W (power). Ankle moments in dorsiflexion decreased significantly when walking in fast speed (dependability coefficient of 0.60) compared to self-selected walking speed (0.92). The moment and power parameters remained somewhat the same. Self-selected gait speed was described as poor to good for moments of force and power parameters when conducting test-retest reliability. The highest dependability coefficients were observed for the ankle plantar flexion moment in the sagittal plane (0.97) and for the hip power in frontal plane (0.90). The least reliable parameters for self-selected speed were dorsiflexor moment, the first peak of hip extension moment and hip and knee power parameters in sagittal plane. Hip extension moment was affected by fast walking speed (dependability coefficient of 0.55 for self-selected speed versus 0.83 for fast speed) and the reliability level for knee power in sagittal plane changed from poor to good.

4.5.4 Muscle activity

Only the research by Syczewska et al. (6) analyzed muscle activity. In this case, EMG recorded abnormal and asymmetric activity of gluteus maximus muscles and trunk muscles along the vertebral column, at the lumbar and thoracic levels.

4.6 Parameters for comparative studies

4.6.1 Spatio-temporal parameters (STP)

A total of seven studies included (8; 9; 10; 12; 13; 15; 17) measurement of STP, comparing AIS subjects with controls. Step initiation (8), step length (13), stride length (10; 15; 17), stride duration (15), stance phase (10; 13) cadence (9; 10; 13; 17) and velocity (9; 13; 15; 17) parameters were measured during gait analysis. With regard to walking speed, there were no significant differences between the groups in one article (9). All subjects walked at an average speed of 1.19 ± 0.13 m/s and cadence of 112.2 ± 8.6 steps per minute. Meanwhile, another article (10) found that the cadence of AIS subjects was significantly slower vis-a-vis the controls. However, there were no significant differences between the groups in stance phase and stride length between the left and right legs.

Yang, Suh, Sung and Park (17) did not find significant differences between controls and the AIS group when measuring walking speed (112 ± 2.2 cm/s and 115 ± 2.6 cm/s, respectively), stride lengths (119 ± 1.9 cm and 124 ± 2.4 cm), and cadences (111.4 ± 1.3 steps/min and 109.4 ± 1.7 steps/min). However, each group demonstrated differences in gait parameters between left and right lower extremity. More or less similar step lengths for left (58.7 ±1.0 cm) and right (59.8 ±1.0 cm) lower extremity were found in the case of the control group, while for the AIS group, the step lengths differed for the left (62.7 ± 1.2 cm) and right (61.0 ± 1.4 cm) side. Moreover, with regard to the time of the stance and swing phases as a percentage of the gait cycle, the duration was the same between the two lower extremities in each phase in the case of controls. The AIS group, on the other hand, displayed a longer stance time and a shorter swing time for the right lower extremity (62.3 ± 0.7 and 37.7 ±0.7) than for the left lower extremity (60.4 ± 0.7 and 39.6 ± 0.7).

With respect to velocity, an article by Mallau, Bollini, Jouve and Assaiante (15), noted that AIS subjects' had a velocity (median of 1,13 m/s) which was 15% lower compared to controls (median of 1,34 m/s), and stride duration (median of 1,08 s) that was 9% longer compared to control subjects (median 1,00 s). The stride length was shorter in AIS subjects (median of 1,21 m) by 9% compared to control subjects (median of 1,34 m).

Mahaudens, Thonnard and Detrembleur (13), in their study, found no significant difference for the gait parameters (speed, cadence, and stance phase) except for step length, which was reduced by 10% for AIS subjects compared with control subjects. When evaluating step initiation, one article by Bruyneel, Chavet, Bollini and Mesure (8) found that this was significantly longer in AIS subjects compared to control subjects, regardless of the step-initiation side. In AIS subjects, there was no differentiation in duration of movement between the right and left side of the limb, while in control subjects there was a difference between the right side (824 ± 126 m/s) and left side (866 ± 131 m/s) of the anterior-posterior component. In another study by Giakas, Baltzopoulos, Dangerfield, Dorgan and Dalmira (12), the statistical analysis indicated that there were no significant differences between the left and right limbs, and between the AIS and control groups for all STP variables.

4.6.2 Kinematic parameters

Kinematic parameters were measured in seven articles (9; 10; 11; 13; 14; 15; 16; 17), focusing on ROM (10), motion (15), joint angle (11; 12; 14; 15; 16; 17). In the former case, one article by Chen, Wang, Tsuang, Liao, Huang andHang (10) measured ROM to be limited in AIS subjects compared to control subjects for the pelvis in transverse plane and the spine in coronal plane, while it showed similar results for both groups of the shoulder in transverse and coronal plane, pelvis in coronal plane and spine in sagittal plane. In addition, there were no significant differences between the right and left side when analyzing ROM of AIS subjects, except ROM of the pelvis in transverse plane, which was higher in left leg cycle. The ROM of the spine in coronal plane was larger for control subjects than AIS subjects. The sagittal angular motion of the ankle, knee and hip during gait was similar for both groups of subjects.

In the context of angle, one finding by Park et al. (16) was a small hip joint angle in the AIS group (72.94° ± 2.95°) of the right foot mid-stance during a support phase compared to control subjects (78.49° ± 4.68°). From this, the authors (16) concluded that the AIS group tended to “elevate thigh segment more during walking” (p. 313). In addition, a larger trunk-tilting angle was found for the AIS group in the right foot heel strike (7.96° ± 3.21°) to the ground and the left foot toe off the ground (9.02° ± 2.61°) compared to the control group (2.85 ± 1.70 and 4.56 ± 3.00, respectively). The results implied that the AIS subjects vacillated their trunk vertically more than the control subjects did during walking. Another article by Dangerfield et al. (11) found that AIS subjects had an increased external rotation, pronation and supination of feet in comparison to control subjects.

In an article by Mahaudens et al.(13), no significant difference between control subjects and AIS subjects was found regarding the angular pelvic displacement in the sagittal and coronal plane during gait, while the pelvic displacement in transverse plane was more externally rotated what concerns the AIS group. In one study (14), a significant reduction in vertical displacement of the shoulder (21%), pelvis (27%) and hips (28%) in the coronal plane, and hips rotation (22%) in the transverse plane were found for AIS subjects.

Yang et al.(17), measured correlation coefficients (i.e. the relationship between variables, where 1 is a perfect positive correlation and -1 is a perfect negative one) of the gait asymmetry based on angular displacement rates and found that it was smaller for the AIS group (0.42 ± 0.06) in the frontal plane compared to the control group (0.54 ± 0.05). In the sagittal plane, the AIS group and control group showed a correlation coefficient of 0.57 ± 0.06 and 0.65 ± 0.05, respectively, and in the transverse plane the scoliosis group (0.36 ± 0.06) demonstrated a smaller correlation coefficient than the control group (0.48 ± 0.05).

Another article by Chan, Wong & Goh (9) evaluated within-day repeatability of motion between AIS subjects and control subjects using coefficients of multiple correlations, a method to measure waveform similarity and variability. It was found that trunk sagittal and coronal plane motion and spinal coronal plane motion of both groups can be measured reliably, while spinal sagittal plane motion, shoulder motion in all three planes proved less reliable.

Mallau et al.(15) investigated the functional effects of idiopathic scoliosis on balance strategies during gait by studying roll stabilization strategies of the spine, locomotion, roll angular dispersions of the spine, lateral and horizontal angular dispersions, and roll and yaw stabilization of the head, shoulder and pelvis. There were few differences between the AIS group and controls, but the most important finding by the authors was decreased yaw head stabilization in AIS subjects. The yaw anchoring index (a determinant of segmental stabilization) value was near zero (where a positive value indicates stabilization in space, while a negative one indicates stabilization on the underlying anatomical segment) compared to control subjects who showed a higher positive head yaw anchoring index values.

4.6.3 Kinetic parameters

A total of six studies (8; 11; 12; 13; 14; 17) included kinematic parameters, including GRF in medial-lateral, anterior-posterior and vertical direction (8; 11; 12; 17), impulse (8), muscular efficiency through external and internal work (13; 14), kinetic energy, energy cost and oxygen consumption (13). In one article (12), the examination of GRF in the frequency domain showed significant difference in the medial-lateral component for the AIS group. The vertical and anterior-posterior components showed no significant differences between the groups. The mean frequency content for medial-lateral component on the left and right side was 49.04 Hz and 51.26 Hz, respectively, for AIS subjects, and 24.42 Hz and 22.96 Hz for control subjects. The results in this article are in line with the findings by Yang et al.(17), who demonstrated an asymmetrical gait in the medial-lateral direction in AIS subjects (correlation coefficient of 0.75 ± 0.05) compared to controls (correlation coefficient of 0.87 ± 0.02).

Research by Dangerfield et al.(11) demonstrated asymmetry in most GRF parameters of AIS subjects compared to control subjects. The reason for this was the presence of an increased right minimum vertical force and the asymmetry of the peak propulsive force. According to the authors, these results were related with the offset angle. They further argue that this might be due to the influence of the vertical torque, which may act asymmetrically through the limbs and pelvis to impact the spine and which could influence curve progression. The control subjects laced these factors of their gait cycle.

An article by Bruyneel et al. (8) calculated impulse, occurrences and force values, and found that the results in the AIS group differed from control subjects. The impulse parameter was measured before and after the single foot stance phase, and the numbers showed that the AIS group produced larger impulses on the right and left side compared to the control group. Under the stance foot, the anterior-posterior and vertical forces always increased for the AIS group while the results under the swing foot showed decreased medial-lateral impulses in the case of the AIS group compared to the control subjects.

The study by Mahaudens et al. (13) observed significantly greater muscular external work to move the center of mass of the body in AIS subjects (mean 0.4 ± 0.1 j $kg^{-1}m^{-1}$) compared to the control subjects (mean 0.25 ± 0.1 j $kg^{-1}m^{-1}$). On the other hand, the control group (70%) had increase of transformation between the potential and the kinetic energy compared to the AIS group (55%). Another paper by Mahaudens and Mousny (14) showed that both the external and the internal work were reduced from 7% to 22%, depending on the severity of the scoliotic curve. Overall, a reduction of total muscular mechanical work was found in the case of AIS subjects (7% to 13%). Energy cost and oxygen consumption increased by 30% while a decrease in muscle efficiency by 29% was found without any significant difference related to the severity of the scoliosis in AIS subjects.

4.5.4 Muscle activity

Muscle activity abnormalities were found in all of the studies (13; 14; 16) conducting EMG analysis. The EMG recording during walking showed considerable prolonged duration of activation in the erector spinae (141.4 ± 27) and quadratus lumborum (146.7 ± 40) in the AIS group compared to control subjects (102.5+-33 and 109+-34, respectively) in the study by Mahaudens et al. (13). The other muscles that were under study in this research showed normal results. There were no differences in the duration of muscle activation between the convex and concave side of the scoliosis for all muscles in the AIS group. In another study (14), erector spinae, quaratus lumborum, gluteus medius and semitendinosus muscles were active during a longer proportion of the stride in AIS subjects (45% of the stride) in contrast to control subjects (35% of the stride).

A study done by Parker et al.(16), found different results for AIS subjects and control subjects mainly for the latissumus dorsi muscle, but also for biceps femoris and gluteus medius muscles. Latissimus dorsi on the right side in control subjects had greater activation (221.88%) than in AIS subjects (101.46%). Thus, the authors suggest that since the AIS subjects use less of the latissimus dorsi muscle during walking, they had limited movement of arms and upper body during gait. Although the differences were not significant due to high standard deviations, AIS subjects recorded very high muscle activation of the right gluteus medius and the right and left biceps femoris.

4.7 Summary of results

For the research questions, significant data and results from seven non-comparative (1; 2; 3; 4; 5; 6; 7) and ten comparative (8; 9; 10; 11; 12; 13; 14; 15; 16; 17) studies has been gathered and presented in the above sections. The results demonstrated, firstly, that all gait parameters show significant findings in terms of examining AIS subjects, demonstrating their value for developing further understanding of AIS. Notwithstanding, variations between results, lack of data for certain parameters and no significant relationship between gait parameters and scoliosis was also seen, which has important implications for a discussion. Secondly, the results showed that AIS subjects differ in performance compared to non-scoliosis adolescents in at least one gait parameter across all studies. This includes abnormalities in muscle activity, less economical use of the body, poorer performance in kinematic parameters and differences in STP such as step length and step initiation.

5. Discussion

5.1 Limitations and challenges of this study

This review has been concerned with being methodologically sound, but limits imposed on this study in terms of accessibility of literature has been a challenge. As a non-academic researcher, one problem was that access to certain articles required paid subscription and was therefore too expensive to access. Accordingly, bias can creep in if the search has not been exhaustive. Notwithstanding, this research has applied an explicit search strategy and endeavoured to produce a comprehensive research. To this end a combination of searching, for instance, in online databases, using search engines such as Google and Google Scholar and approaching personal contacts and experts on the field are some of the approaches that has been used. Moreover, a log of how the search process for articles has been undertaken has been kept to enhance reliability and replicability (EPPI, 2010; Rallett, Hagen-Zanker, Slater, & Duvendack, 2012; Schlosser, 2007).

Apart from that the studies differ in being non-comparative and comparative, they also vary in many other ways. This includes equipment used, variables studied, gait conditions, type of interventions on patients, sample size and selection process, gender ratio, the degree of Cobb´s angle and study designs employed. This complicates direct cross-comparison of results across studies. It also makes it harder to arrive at substantial conclusions on whether a particular aspect of the different studies is especially important to adopt for examining AIS patients or for further study (O'Mara-Eves, Thomas, McNaught, Miwa, & Ananiadou, 2015).

Another challenge that is present when comparing and finding conclusions in relation to the research questions of this thesis is that the population of articles all focusing on kindred questions and themes, but few are in fact asking the same question. In this sense, to draw detailed parallels or conclusions is problematic due to the differences in study objectives in the various articles (Bartolucci & Hillegass, 2010).

5.2Gait analysis in AIS

Using the techniques of gait analysis consisting of STP, kinematics, kinetics, and EMG data, can be recognized as a useful tool for identifying asymmetries in AIS subjects during walking. In terms of STP, the most important findings indicated that the gait speed, cadence, and step length depended on the severity of scoliosis. STP were also used to measure asymmetry index without finding significant results. However, there were only three studies actually addressing and analysing the results of STP.

The results of kinematic parameters vary, but key findings were related to abnormalities in the pelvis of AIS subjects. Asymmetry in transverse plane as a torsional trunk-pelvis offset, abnormal pelvis position in sagittal plane caused by increased ROM and reduced ante version, and obliquity and rotation of the pelvis were findings that influenced other gait parameters. Many authors associated the results with the irregular limb or upper trunk data, which was also found. However, the sample sizes ranging from 10 to 24 subjects are rather small, which reduces the authors´ ability to generalize. The exception is the study by Syczewska et al. (2012), which had a larger sample size (n=63), and therefore gives support to the finding of abnormalities in the pelvis of AIS.

With reference to kinetic parameters, only one study Chockalingam et al. (2004)demonstrated a relationship between the presence of asymmetries in kinetic gait parameters and the scoliotic curve. On the other hand, most others studies also found asymmetries in kinetic parameters, but without a concrete link to the side or the magnitude of the spinal deformity. More in-depth longitudinal investigation with different curve types and magnitudes are required to substantiate or refute these findings.

Only one research study in the article population without control subjects used EMG, and found asymmetric activity of gluteus maximus and trunk muscles along the vertebral column at the lumbar and thoracic level. More studies are required using the same methods (i.e. dynamic EMG of lower extremity and trunk muscles) and preferably with larger sample size are required to draw more general results.

Gait parameters were also tested for reliability and several parameters showed high reliability among AIS subjects, although gait speed moderated the results somewhat. However, the reliability of kinetic and kinematic gait parameters was reported for only the right side in this study. Although according to a study by Steinwender et al. (2000), reliability is not significantly different between left and right leg, this nevertheless needs to be verified in subjects with AIS through further investigations.

5.3 Gait in AIS versus normal subjects

How then does the gait of AIS patients differ from adolescents without scoliosis? With respect to STP, values between controls and AIS subjects reveal few significant differences, but poorer performance in at least one parameter (either cadence, step initiation, step length, stride length, stride duration, cadence and speed) in the AIS group was observed in all the comparative studies that assessed STP. Differences were also detected when comparing left and right lower extremity within the control and AIS group.

In kinematic parameters the results showed either no significant difference between AIS individuals and non-AIS ones, decreased ROM (in pelvis in transverse plane, spine in coronal plane, hip angle, trunk tilt angle), asymmetry (in frontal and transverse plane), or reduction of angular displacement (in pelvis and shoulder transverse plane, shoulder, pelvis and hips rotation in coronal plane) in AIS subjects. One article reported increase in motion (external rotation, pronation and supination in feet) and another article noted decreased yaw head stability among AIS subjects compared to control subjects.

The results for kinetic parameters show asymmetry in GRF forces in AIS subjects, particularly in medial-lateral forces, compared to control subjects. AIS subjects have increased energy cost level and oxygen consumption and internal work and decreased muscular efficiency. External work was measured in two studies, but with contradictory results; one observing an increase in external work (Mahaudens et al. 2005), and the other (Mahaudens, Detrembleur, Mousny, & Banse, 2010) seeing a reduction in external work in AIS subjects.

All articles that measured muscle activity found abnormalities. Prolonged duration of activation was found in erector spinae, quadratus lumborum, gluteus medius and semitendinosus in AIS subjects compared to control subjects. These findings were observed across several studies and strengthen the notion that AIS patients use excessive muscular activity in contrast to healthy subjects, due to the scoliosis. The only exception to this pattern, was found in the study by Park et al. (2012), which detected less activity of latissimus dorsi on the right side in the AIS group compared to controls. AIS subjects also recorded very high muscle activation of the right gluteus medius and the right and left biceps femoris in one study.

It can be concluded that adolescents with scoliosis differ in gait performance compared to non-scoliosis adolescents in different parameters. However, one general caveat with the results is that small sample sizes are used in most studies, which may give a larger variance of results. Although this may be related to applying very strict inclusion criteria, there is a need to conduct studies with a larger dataset. Hence, it may be more appropriate to consider the results individually rather than to make generalizations concerning the different gait pattern between healthy and scoliotic subjects (Bartolucci & Hillegass, 2010; Brink, Van der Walt, & Van Rensburg, 2006; Carlson & Morrison, 2009).

5.4 Limitations of gait analysis

For gait assessment to be valid and effective method for examining spinal deformities such as AIS, issues of variability, accuracy and interpretation of results must be enhanced. According to Kirtley (2006), it can be argued whether current gait analysis procedures and technology meet these specifications. This is supported by Simon (2004) who asserts that gait parameters such as kinetics may sometimes be calculated based on assumptions and not the data measured. This critique also applies to EMG, which measures accurately muscle activation, but do not generate internal forces of muscles, joints and bones.

Furthermore, the overt observational approach, used in the articles selected for this thesis sets limits for gait analysis. This is because it does not accurately capture *de facto* day-to-day pattern of activity of the study objects. The subjects under assessment may change their behaviour, and subsequently affect their gait, when they know they are being observed. They may present their ´ideal self´ instead of their ´true self´ (Holigrocki, Kaminski, & Frieswyk, 1999). Thus, it is argued that gait analysis evaluate only potential gait ability and only at a certain point in time. Functional variability exist in every step, walk and from time to time. Another problem is inter-observer variability in the interpretation of data between physicians and institutions. Although gait data, per se, is objective, subjective interpretations reduces reliability (Simon, 2004; Skaggs et al., 2000). Then again, few research tests are perfectly free for errors and random variation.

5.5 Practical and clinical use of gait analysis

Gait analysis is not yet applied in clinical settings to make a medical diagnosis. Rather its current role is primarily in providing quantitative data to help prescribe a treatment plan and evaluate its outcome (Simon, 2004). The gait analysis system consists mainly of using a standard set of instruments (motion system, EMG, and force platforms) to produce a set of relevant data. However, the cost and spatial requirement (such as for walkways, camera placements etc.) of these systems are significant, and they are not suitable to use outside laboratory environments (Chao; 2012; Tong & Granat, 1999).

Moreover, the gait analysis process is a time-consuming one and requires the involvement of a team of at least two professional individuals (a bioengineer and a skilled physiotherapist) and the part-time efforts of a clinician, who are all specialized in the gait field and possess high-levels of interpretation skills. Hence, gait analysis is viewed as ineffective and resource-intensive. This does not, however, deflate its perceived value, but has implications mainly for the clinical productivity of the laboratory itself. The balance between these issues must improve if gait analysis is to gain in acceptance as an effective method. Future research in gait analysis should therefore also be devoted to efficacy, results and resource-effectiveness of this method (Simon, 2004).

Using the naked eye, also known as observational gait assessment (OGA), is usually the only method of gait assessment available in a clinical setting (Kirtley, 2006). It is also more effective in clinical use compared to instrumented gait assessment (Toro et al., 2003). However, the limitations of OGA are that the results are not permanently recorded, the eye cannot capture high-speed events, it is only possible to spot movements (and not forces), and it depends mostly on the skill of the individual observer (Whittle, 2007). Thus, the main problem with OGA is that it is subjective in nature, leading to issues of poor validity, reliability and specificity, which instrumental gait is better at achieving (Toro, Nester, & Farren, 2003).

Nonetheless, there are still some practical ways to achieve a sound gait assessment, which are more suitable for clinical use, if advanced equipment and sufficient space is not available (Whittle, 2007). Firstly, with respect to spatial requirements, a corridor or gym (or even outdoors if the ground permits) can be used so long as the length is around five metres and width is around three metres (Codamotion, n.d). This should be adequate to capture most gait cycles, although the longer the walkways are, the better. Treadmill-based gait assessment also brings about benefits such as smaller measurement space and that several gait cycles can be acquired. However, a limitation is that the adapting of the individual gait to normal walking, which is harder for those with a disability (Stoia & Toth-Tascau, 2011).

Secondly, measurement of the gait parameters can be carried out by the use of some simple tools. A mobile phone camera and a stop-clock would be sufficient to assess simple STP (Kirtley, 2006). This would also allow the clinician or therapist to store the information for in-depth analysis and comparison purposes. Wearable sensors such as gyrosensors, accelerometer, foot switches and goniometers can be used to measure characteristics of kinematic and kinetic parameters (Tao, Liu, Zheng & Feng 2012).Surface EMG can be used to record muscle activation in a cost-effective manner (Kasman & Wolf, 2002). Ultimately, the clinician can decide on the appropriate technology-level for a gait analysis, taking into account economic and capacity-related factors. Generally, the more advanced the system, the better quality of objective data can be obtained (Whittle, 2007).

5.6 Gait analysis before and after intervention in AIS

As mentioned earlier, gait analysis is also used routinely for treatment planning and long-term follow-up monitoring (Kaufman, 1998). It is imperative to examine patients before and after an intervention to determine the level of improvement (Giakas, 1996). For those with progressive scoliosis, treatment such as spinal fusion surgery and orthotic treatment such as bracing is required to correct and stabilise the scoliosis, while at the same time trying to keep intact segmental spinal mobility (Mahaudens et al., 2010). For the latter treatment, a study by Mahaudens, Raison, Banse, Mousny, & Detrembleur (2014), found that the scoliotic curve was partly corrected. The authors further observed an increase of pelvis and hip motion, leading to an improvement of muscular mechanical work during gait. For the former treatment, studies such as the one by Mahaudens et al. (2010) found improvements in the gait and mechanical parameters, including for step length, cadence and mechanical work.

Despite these results, according to Giakas et al. (1996), AIS patients may never emulate normal gait. It is known that brace can only maintain, but not cure scoliosis. Meanwhile, surgery involves the implantation of metal rods into the spine, which stiffens and restricts the spine and, as a result, body functions differently to emulate the gait of healthy adolescent (Danielsson & Nachemson, 2001; Engsberg, Lenke, Uhrich, Ross, & Bridwell, 2003).

For future research, to determine if a realignment of the spine following treatment on AIS consistently modifies gait patterns is an interesting topic subject to a systematic review.

6. Conclusion

This endeavour has attempted to undertake a systematic review of the evidence-based research concerning the effectiveness and validity of gait analysis in examining adolescents with idiopathic scoliosis, and how the gait of adolescents with idiopathic scoliosis differ from adolescents without scoliosis. It has tried to be methodologically sound, but limits such as accessibility to articleshave beena challengeto which the best of efforts have been made to mitigate.

It is evident that gait analysis is a valid method for exploring the consequences of AIS during walking. However, the evidence base is diverse, inconclusive and there is still a lack of substantial research on the topic. Furthermore, AIS individuals show a different gait pattern than non-AIS individuals. Yet, the ability to generalize these findings is low due to methodological reasons and the results must be considered individually. It is suggested that further research tries more replications of the same methodologies applied in the literature on gait and AIS, but modifying the study characteristics, such as increasing the sample size, to establish whether the results hold water in different contexts. There is a need for accumulation of parallel findings from similar, but not identical studies to give a better convergence of results, and hence generality (Gast, 2009; O’Mara-Eves et al., 2015).

Future research in gait analysis should also be devoted to efficacy and resource-effectiveness of this method. From a health practitioner’s point of view, although gait analysis is still considered inefficient method, some practical ways to achieve a reasonable gait assessmenthave been suggested by this study.

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