Title:

Influence of spino-pelvic and postural alignment parameters on gait kinematics.

Authors:

Joeffroy Otayek, MD, MSc [1], Aren Joe Bizdikian, MD, MSc [1], Fares Yared, MD, MSc [1], Eddy Saad[1], Ziad Bakouny, MD, MSc [1], Abir Massaad, PhD [1], Joe Ghanimeh, MD [1], Chris Labaki [1], Wafa Skalli, PhD [2], Ismat Ghanem, MD, MSc [1,3], Gaby Kreichati, MD [1,3], Ayman Assi, PhD [1,2]

Affiliations:

(1) Faculty of Medicine, University of Saint-Joseph, Beirut, Lebanon
(2) Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris
(3) Hôtel-Dieu de France Hospital, University of Saint-Joseph, Beirut, Lebanon

Corresponding author:

Ayman Assi
Laboratory of Biomechanics and Medical Imaging
Faculty of Medicine, University of Saint-Joseph in Beirut
Damascus street, BP 17-5208 - Mar Mikhaël
Beirut, Lebanon
Tel: +9611421676 – Fax: +9611421681
Email: ayman.assi@gmail.com, ayman.assi@usj.edu.lb

Acknowledgment:

This research was funded by the University of Saint-Joseph (grant FM183). The funding source did not intervene in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Highlights:

- To study the Influence of postural alignment parameters on gait kinematics
- 134 asymptomatic adults had gait analysis & postural parameters assessed on X-rays
- Increase in sagittal vertical axis is related to larger knee flexion in stance
- Increase in radiological pelvic tilt is related to reduced pelvic obliquity
- Increase in thoracic kyphosis is related to reduced hip sagittal mobility

Abstract:

Introduction: Postural alignment is altered with spine deformities that might occur with age. Alteration of spino-pelvic and postural alignment parameters are known to affect daily life activities such as gait. It is still unknown how spino-pelvic and postural alignment parameters are related to gait kinematics.

Research Question: To assess the relationships between spino-pelvic/postural alignment parameters and gait kinematics in asymptomatic adults.

Methods: 134 asymptomatic subjects (aged 18 to 59 years) underwent 3D gait analysis, from which kinematics of the pelvis and lower limbs were extracted in the 3 planes. Subjects then underwent full-body biplanar X-rays, from which skeletal 3D reconstructions and spino-pelvic and postural alignment parameters were obtained such as sagittal vertical axis (SVA), center of auditory meatus to hip axis plumbline (CAM-HA), thoracic kyphosis (TK) and radiologic pelvic tilt (rPT). In order to assess the influence of spino-pelvic and postural alignment parameters on gait kinematics a univariate followed by a multivariate analysis were performed.

Results: SVA was related to knee flexion during loading response (β=0.268); CAM-HA to ROM pelvic obliquity (β=-0.19); rPT to mean pelvic tilt (β=-0.185) and ROM pelvic obliquity (β=-0.297); TK to ROM hip flexion/extension in stance (β=-0.17), mean foot progression in stance (β=-0.329), walking speed (β=-0.19), foot off (β=0.223) and step length (β=-0.181).

Significance: This study showed that increasing SVA, CAM-HA, TK and rPT, which is known to occur in adults with spinal deformities, could alter gait kinematics. Increases in these parameters, even in asymptomatic subjects, were related to a retroverted pelvis during gait, a reduced pelvic obliquity and hip flexion/extension mobility, an increased knee flexion during loading response as well as an increase in external foot progression angle. This was associated with a decrease in the walking pace: reduced speed, step length and longer stance phase.

Keywords: gait analysis; posture; global alignment; spine; pelvis; adults

Introduction

Sagittal alignment of the human posture is known to be altered with age or in the presence of spinal deformities [1]. In order to assess sagittal malalignment, a set of radiological parameters is calculated on full body lateral radiograph that evaluate the spino-pelvic complex as well as other global alignment parameters that include more cranial segments such as the cervical spine and the head. The clinical importance of sagittal spino-pelvic and postural alignment parameters has been increasingly recognized as of late [2,3]. To begin with, normative values of spino-pelvic postural alignment parameters have been established by many authors as reference values to better evaluate subjects with spinal deformities [4–6]. It appeared that age is a major factor in the alteration of homogenous postural alignment [7,8]. Many studies have investigated the influence of spinal deformities such as adolescent idiopathic scoliosis (AIS) [9] and especially adult spinal deformity (ASD) [10] on sagittal alignment. The consideration of sagittal alignment in the treatment planning of such pathologies has been proven to be crucial [11], since its restoration has been correlated with better prognosis and better quality of life [12–15].

Gait is a component of daily life activities and plays a major role in a subject's autonomy; its alteration can affect quality of life [16,17]. Previous studies based on gait analysis have shown a significant effect of frontal as well as sagittal malalignment on gait kinematics and kinetics [18–20]. More recently, Bakouny et al. showed that even asymptomatic adults with different Roussouly sagittal alignment morphotypes may walk differently [21]. However, Roussouly types of spinal curvatures, based on sacral slope and the number of vertebrae in the lumbar lordosis [22], do not take into account the global postural alignment of the subject. Other spino-pelvic parameters such as thoracic kyphosis (TK), pelvic tilt (PT), and postural alignment, known as global alignment parameters, such as the C7 sagittal plumbline (Sagittal Vertical Axis, SVA) or the head sagittal plumbline (i.e. CAM-HA, plumbline of the center of auditory meatus to the middle of hip axis) are important in the description of the full body posture. These parameters have been shown to be highly altered in patients with spinal deformities and strongly correlated to the deterioration of quality of life [23].

However, it is still not known how these postural parameters affect gait, even in asymptomatic adults. Thus, this study aimed to assess the relationship between spino-pelvic and global postural alignment parameters and gait kinematics in asymptomatic adults with varying age.

Methods

2.1. Study design

This is a cross-sectional IRB approved study (CEHDF 285) of the relationship between spino-pelvic postural alignment and gait in asymptomatic adult volunteers. Subjects were enrolled in the study if their age was above 18 years and had no history of orthopedic surgery to either the spine, pelvis or lower limbs. The exclusion criteria were pain, including lower back pain at the time of the study or any musculoskeletal disease (scoliosis, Scheuermann's kyphosis or leg length discrepancies) or the presence of at least one radiological criteria of adult spinal deformity (based on the European and International Spine Study Groups [24–29]) or previous orthopedic surgeries. A written informed consent form was signed by each subject.

2.2. Data acquisition

For each subject the following demographic characteristics were collected: age, weight, height and sex.

Subjects performed 3D gait analysis using 7 infrared MX3+ cameras (Vicon Motion Systems, Oxford, UK) using the modified Helen Hayes marker set and the Plug-in Gait model was applied [30]. Subjects were informed to walk at self-selected speed and more than 7 trials were recorded. Data were processed using Workstation® (using fill gap routine at ±10 frames and Woltring filter with a scale of 10) and the kinematics of all trials were visualized in Polygon® for consistency check. The most representative trial was selected for each subject. Angles of the pelvis, hips, knees, ankles and feet were calculated in 3D during the gait cycle. Kinematics were extracted in Excel® format and previously defined parameters, such as maximum, minimum, mean and range of motion (ROM), were calculated on the waveforms [31,32] using Matlab® (Mathworks, Natick, USA). Moreover, spatiotemporal parameters were collected: walking speed (m/s), cadence (steps/min), foot off (% of gait cycle), single support (s) and step length (m).

Following the gait analysis acquisition, subjects performed full body biplanar radiographs (EOS Imaging®, Paris, France). Subjects were instructed to stand in the standardized free standing position [33,34].

Their spines and pelvises were reconstructed in 3D using the SterEOS® software (EOS Imaging, Paris, France) and the following sagittal spino-pelvic alignment parameters were generated [35,36]: pelvic tilt, sacral slope (SS), pelvic incidence (PI), L1-S1 lumbar lordosis (LL), T1-T12 thoracic kyphosis (TK). Global postural alignment parameters were calculated using the SterEOS® postural assessment module, from which the sagittal vertical axis (SVA: plumbline of C7 to the posterior corner of the sacral plate) and the center of auditory meatus to the hip axis plumbline (CAM-HA) were collected. These parameters were represented in figure 1. Structural parameters were also calculated, such as: PI-LL (the difference between pelvic incidence and lumbar lordosis), TPA (thoracic pelvic angle: angle between the center of T1 and center of femoral heads and the middle of the sacral plate), LPA (lumbar pelvic angle: angle between the center of L1 and center of femoral heads and the middle of the sacral plate).

In the rest of this manuscript, the term “gait pelvic tilt” will be used to refer to the movement of the anterior superior iliac spines (ASIS) relative to the posterior superior iliac spines (PSIS) and is therefore a dynamic parameter, whereas “radiographic pelvic tilt” (rPT) will be used in order to refer to the radiographic definition of pelvic tilt calculated on the lateral radiograph. Note that the value of the “gait pelvic tilt” increases with anteversion and decreases with retroversion, while the value of the “radiographic pelvic tilt” increases with retroversion and decreases with anteversion.

2.3. Statistical analysis

Mean, standard deviation, minimum and maximum were calculated for spino-pelvic alignment and global postural parameters as well as gait kinematics and time-distance parameters.

In order to assess the relationship between spino-pelvic/global postural alignment parameters and gait kinematics, a univariate analysis using linear correlations was applied. Pearson’s r and p-values were reported.

Then, in order to investigate which spino-pelvic/postural alignment parameters mostly influence gait kinematics, a multivariate analysis using stepwise linear regressions was performed. Kinematic parameters were considered as dependent variables; spino-pelvic (CAM-HA, SVA, rPT, PI, LL, TK, TPA, LPA and PI-LL) and anthropometric parameters (age, weight, height and sex) as independent variables. Adjusted R^2, β and p-values were reported for each model.

Statistical analyses were performed using Xlstat® (version 2015.3.1, Addinsoft, Paris, France). The level of significance was set at 0.05.

Results

In total, 134 asymptomatic subjects (29±11 years old [18-59]; 66 females, 68 males), average weight of 71±15 Kg and height of 170±10 cm met the eligibility criteria and were included in this study.

Results of spino-pelvic alignment parameters were presented in figure 2. Briefly, the mean SVA value was -13±23 mm ranging from -67 to 37 mm. The mean CAM-HA was -26±28mm ranging from -95 to 66mm. The mean rPT value was 12±6°, ranging from -7.0 to 25°. The mean TK value was 45.6±8° ranging from 23 to 60°. In addition, the mean PI-LL was -11.8±11° ranging from -33 to 25°, the mean TPA was 6.2±6° ranging from -6.5 to 20°, the mean LPA was 3.8±6° ranging from -13 to 28°.

Gait kinematic parameters were presented in table 1 as mean and standard deviations. They were subdivided for each skeletal segment and joint separately.

Sagittal vertical axis was significantly correlated to ROM pelvic obliquity (r=-0.317), ROM hip abduction/adduction (r=-0.252) and maximum knee flexion in stance (r=0.282, figure 3). Center of auditory meatus-hip axis plumbline was significantly correlated to ROM pelvic obliquity (r=-0.263, figure 3), ROM hip abduction/adduction (r=-0.237), maximum plantarflexion in stance (r=0.176). Radiological pelvic tilt was significantly correlated to ROM pelvic obliquity (-0.211, figure 3). Thoracic kyphosis was significantly correlated to ROM pelvic obliquity (r=-0.211), ROM pelvic rotation (r=-0.197), ROM hip abduction adduction (r=-0.182), ROM knee flexion/extension (r=-0.18), maximum plantarflexion in stance (r=0.220), mean foot progression in stance (r=-0.383, figure 3), walking speed (r=-0.19, figure 3) and foot off (r=0.259). All p-values were <0.05. TPA, LPA and PI-LL were significantly correlated to ROM pelvic obliquity (r=-0.26, r=-0.20, r=-0.27, respectively). TPA was also correlated to single support (r=-0.21).

Results of the ANCOVA models were displayed in table 2. Briefly, mean gait pelvic tilt was determined (R^2 adjusted=0.09, p<0.001) by age (β=0.28), and rPT (β=-0.19). The ROM pelvic obliquity was determined (R^2 adjusted=0.37, p<0.001) by sex (β=0.49, M as reference), rPT (β=-0.30) and CAM-HA (β=-0.19). The ROM hip flexion/extension in stance (R^2 adjusted=0.13, p<0.001) was determined by age (β=0.23), height (β=-0.23) and TK (β=-0.17). Hip flexion at initial contact was determined (R^2 adjusted=0.18, p<0.001) by age (β=0.43) and TK (β=-0.17). Maximal knee flexion during stance was determined (R^2 adjusted=0.14, p<0.001) by age (β=0.27) and SVA (β=0.27). Mean foot progression in stance was determined (R^2 adjusted=0.30, p<0.001) by weight (β=-0.41) and TK (β=-0.33). Walking speed was determined (R^2 adjusted=0.03, p=0.03) by TK (β=-0.19). Foot off was determined (R^2 adjusted=0.13, p<0.001) by weight (β=0.27) and TK (β=0.22). The main results were summarized in figure 4.

Discussion

The assessment of spino-pelvic postural alignment has been considered as crucial in the evaluation of patients with spinal malalignment as well as for surgical planning that aims to correct patient's alignment and to enhance quality of life. Gait is an essential factor of quality of life. It is still unknown how spino-pelvic and global postural alignment parameters are related to gait, even in asymptomatic subjects. In the current study, gait kinematics of 134 asymptomatic adults age ranging from 18 to 59 years old were shown to be partially determined by spino-pelvic and global postural alignment parameters.

The spino-pelvic parameters of our population were comparable to those of other populations published in the literature [35]. Iyer et al. established the normative values of traditional and novel sagittal alignment parameters based on age; our results were shown to be in accordance with their values [8].

Ageing has been widely shown to be a major modifier in gait kinematics and kinetics. It is already known that older adults have different gait kinematics compared to young adults when walking at self-selected speed [37]. These differences were related to the decreased walking speed seen in elderly [38–40]. Walking speed was not correlated with age in our study maybe because the maximal age in our population did not exceed 59 years. However, even with a small coefficient of determination (R^2 adjusted=0.029), a significant negative correlation was found between walking speed and TK (β=-0.19, p=0.028). This could be explained by the fact that TK is known to increase with age [8].

Age was found to have significant effects on knee kinematics in the sagittal plane during loading response and during swing: maximum knee flexion in stance (β=0.272, R^2 adjusted = 0.141, p=0.001) and maximum flexion in swing (β=0.204, R^2 adjusted = 0.105, p=0.016) were positively correlated with age. This might be explained by age related decreases in neuromuscular control [41]. These results are in accordance with other studies reporting the effect of age on gait kinematics [42].

Furthermore, hip kinematics in the sagittal plane were affected by age. In fact, ROM hip flexion/extension during stance (β=0.231, R^2 adjusted = 0.130, p=0.006), mean hip extension in stance (β=0.196, R^2 adjusted = 0.118, p=0.020), and hip flexion at initial contact (β=0.432, R^2 adjusted = 0.183, p<0.001) were shown to increase with age. This finding might join DeVita and Hortobagyi's hypothesis that older adults adopt a gait strategy with increased hip flexion, thus compensating the reduced power generation at the ankle [37].

Moreover, our results showed that increased weight might cause a decreased hip extension in stance (hip flexion: β=0.269, R^2 adjusted = 0.118), along with an attitude of external hip rotation (decreased hip internal rotation in stance: β=-0.232, R^2 adjusted = 0.234), a decreased mobility in the knee (ROM knee flexion/extension: β=-0.360, R^2 adjusted = 0.123), a more external foot progression (mean foot progression in stance: β=-0.410, R^2 adjusted = 0.301) and a longer stance phase (foot off: β=0.273, R^2 adjusted = 0.128). Part of these results are in accordance with recent studies that found that increased Body Mass Index (BMI) was associated with increased hip flexion, that might be due to differences in the location of subjects' center of mass [42,43].

While the axial-plane kinematics of the pelvis were barely affected by sex (ROM pelvic rotation: β=0.248 - M as reference, R^2 adjusted = 0.054, p=0.004), frontal-plane kinematics of the pelvis and hip presented stronger significance attributed to sex (higher adjusted R^2 and higher β coefficients). Compared to males, females had a larger ROM of pelvic obliquity in the frontal plane (β=0.488, R^2 adjusted = 0.365, p<0.001), a larger ROM of hip abduction/adduction (β=0.511, R^2 adjusted = 0.255, p<0.001) and a larger mean hip abduction/adduction (β=0.412, R^2 adjusted = 0.221, p<0.001). This was in accordance with previous studies that related these changes to anatomical and neuromuscular differences between both sexes [42].

Thus, anthropometric and demographic factors were shown to be confounding factors that affected gait kinematic parameters. Interestingly, even when including age, sex weight and height in the multivariate analysis models – thus correcting for confounding factors – the following spino-pelvic and global postural alignment parameters showed significant implications in variability of gait kinematics: SVA, CAM-HA, rPT and TK.

First, SVA was shown to determine knee flexion during stance (β=0.268, R^2 adjusted = 0.141, p=0.001). As reported by Lafage et al, SVA held the second strongest correlation with health-related quality of life (HRQOL) scores in patients with adult spinal deformity [15]. Glassman et al. also found that SVA was correlated with pain and a decrease in function measured by HRQOL outcomes [14]. Moreover, Schwab et al. used the SVA as the global alignment modifier to classify adults with spinal deformities since it has been proven to be correlated with pain and disability [44]. This emphasizes the importance of this parameter in the assessment of the global postural alignment. The findings of this study showed that asymptomatic subjects with increased SVA seem to have a larger knee flexion during loading response (figure 4). In fact, the more the SVA increases, the more the trunk has a forward inclination. It was demonstrated that an original forward or backward inclination while standing still is maintained during locomotion [36] and affects lower limbs loading patterns [45]. Therefore, postures with forward inclination of the trunk could require compensatory changes in lower limb kinematics to maintain balance during walking. Consequently, this study showed that even asymptomatic subjects that have a large SVA presented modifications in knee flexion during loading response. Thus, further increase in SVA in these subjects, either due to ageing or spinal deformities, could lead to even more flexed knees during walking, which can predispose to knee osteoarthritis (KOA) and lead to gait instability while walking at self-selected speed, as shown in previous studies [38].

Although a strong correlation is known to exist between SVA and CAM-HA ($r=0.739$, $p<0.001$- found in this study), both parameters were integrated in the multivariate analysis in order to investigate if both head and spine positions (taken into account in the CAM-HA plumbline) or only the spine position (SVA) influences gait kinematics the most.

This study showed that a more advanced head and spine position in standing (i.e. increased CAM-HA) was related to a limitation of the pelvic mobility in the frontal plane (ROM pelvic obliquity: $\beta=-0.19$, R^2 adjusted=0.365).

Moreover, subjects with increased radiographic pelvic tilt (rPT) were also found to have a retroverted pelvis during walking (mean gait pelvic tilt: $\beta=-0.185$, R^2 adjusted=0.09) and a reduced mobility in the frontal plane (ROM pelvic obliquity: $\beta=-0.297$, R^2 adjusted=0.365). Radiographic pelvic tilt in the sagittal plane is considered to be a crucial compensatory mechanism for subjects with sagittal malalignment and the maximal amount of pelvic tilt that a subject can perform is known to be limited by his maximal capacity of hip extension [15]. Moreover, rPT is an essential parameter that is used in different classifications of adult spinal deformity patients [24–29,44] and is known to be increased in this specific population whose quality of life is affected [15]. Thus, when the hip extension reserve is used, mobility of the pelvis might be limited. The results obtained in this study showed that an increased rPT is correlated to a pelvic retroversion during walking and a decrease in pelvic obliquity ROM during gait, thus affecting the mobility of the pelvis while walking.

Additionally, this study showed that a larger TK was correlated with a decreased hip mobility in the sagittal plane (ROM hip flexion/extension $\beta=-0.17$, R^2 adjusted=0.13) a decreased hip flexion at initial contact ($\beta=-0.165$, R^2 adjusted=0.183). These findings suggest that subjects with larger TK, such as in subjects with adult spinal deformities, might have their hip mobility affected. This study showed also that subjects with larger TK present with a more external foot progression ($\beta=-0.33$, R^2 adjusted=0.30), a decreased walking speed ($\beta=-0.19$, R^2 adjusted=0.03) along with a more prolonged stance phase (Foot off: $\beta=0.22$, R^2 adjusted=0.13) and a reduced step length ($\beta=-0.181$, R^2 adjusted=0.204).

Surprisingly, structural parameters were not found as significant determinants of gait parameters except for the maximal plantar flexion in stance (Table 2).

As noticed in the results of this study, several sagittal radiological parameters (SVA, CAM-HA, rPT and TK) were correlated not only to sagittal kinematics but also to frontal and axial plane kinematics such as pelvic obliquity, pelvic rotation and hip abduction/adduction. In fact, this correlation was expected since an interaction across planes is known in lower limb kinematics during gait [46]. This is usually observed in the presence of muscle weakness or spasticity causing gait abnormalities in one plane (i.e sagittal) and one joint (i.e ankle) that propagate to other joints in other planes (hip and pelvis).

The main limitation of this study is the small number of older subjects. This is due to the difficulty in finding older adults who fill the inclusion criteria, thus have no history of back pain nor have undergone any orthopeadic surgery, and do not have any spinal deformity (adult spinal deformity, vertebral compression or spondylolysthesis). Due to the inclusion/exclusion criteria, the older subjects in this study represent the higher end of the spectrum in performance and do not represent the general elderly population. This could limit this study's ability to generalize our results to the entire elderly population.

In conclusion, spino-pelvic as well as global postural alignment parameters are related to pelvic, hip, knee and foot gait kinematics as well as time-distance parameters. A more forwarded spine (larger SVA) was related to a larger knee flexion during loading response. A larger radiological pelvic tilt and a more advanced head (larger CAM-HA) were related to a limited pelvic mobility in the frontal plane during walking. A larger thoracic kyphosis was related to a reduced hip sagittal mobility, more external foot progression, a reduced walking speed and a delayed foot off. Thus, adults with spinal deformities, where increase in SVA, CAM-HA, TK and rPT are known to occur, could have their gait affected by reducing their pelvis, hips and knees mobility along with a slower pace (reduced speed, step length and longer stance phase) that might be necessary to insure stability during walking. Future studies should focus on specific alterations in gait in subjects with adult spinal deformities.

Conflict of interest: None.

References:

[1] S. Iyer, L.G. Lenke, V.M. Nemani, M. Fu, G.D. Shifflett, T.J. Albert, B.A. Sides, L.N. Metz, M.E. Cunningham, H.J. Kim, Variations in occipitocervical and cervicothoracic alignment parameters based on age: A prospective study of asymptomatic volunteers using full-body radiographs, Spine (Phila. Pa. 1976). 41 (2016) 1837–1844. doi:10.1097/BRS.0000000000001644.

[2] R. Lafage, B. Liabaud, B.G. Diebo, J.H. Oren, S. Vira, S. Pesenti, T.S. Protopsaltis, T.J. Errico, F.J. Schwab, V. Lafage, Defining the Role of the Lower Limbs in Compensating for Sagittal Malalignment, Spine (Phila. Pa. 1976). (2017). doi:10.1097/BRS.0000000000002157.

[3] B.G. Diebo, J.J. Varghese, R. Lafage, F.J. Schwab, V. Lafage, Sagittal alignment of the spine: What do you need to know?, Clin. Neurol. Neurosurg. 139 (2015) 295–301. doi:10.1016/J.CLINEURO.2015.10.024.

[4] R. Lafage, F. Schwab, V. Challier, J.K. Henry, J. Gum, J. Smith, R. Hostin, C. Shaffrey, H.J. Kim, C. Ames, J. Scheer, E. Klineberg, S. Bess, D. Burton, V. Lafage, International Spine Study Group, Defining Spino-Pelvic Alignment Thresholds, Spine (Phila. Pa. 1976). 41 (2016) 62–68. doi:10.1097/BRS.0000000000001171.

[5] Z. Bakouny, A. Assi, F. Yared, A.J. Bizdikian, J. Otayek, R. Nacouzi, V. Lafage, R. Lafage, I. Ghanem, G. Kreichati, Normative spino-pelvic sagittal alignment of Lebanese asymptomatic adults: Comparisons with different ethnicities, Orthop. Traumatol. Surg. Res. (2018). doi:10.1016/j.otsr.2017.11.017.
[6] J.-M. Mac-Thiong, P. Roussouly, E. Berthonnaud, P. Guigui, Sagittal parameters of global spinal balance: normative values from a prospective cohort of seven hundred nine Caucasian asymptomatic adults., Spine (Phila. Pa. 1976). 35 (2010) E1193–E1198. doi:10.1097/BRS.0b013e3181e50808.
[7] K. Hasegawa, M. Okamoto, S. Hatsushikano, H. Shimoda, M. Ono, K. Watanabe, Normative values of spino-pelvic sagittal alignment, balance, age, and health-related quality of life in a cohort of healthy adult subjects, Eur. Spine J. 25 (2016) 2–5. doi:10.1007/s00586-016-4702-2.
[8] S. Iyer, L.G. Lenke, V.M. Nemani, T.J. Albert, B.A. Sides, L.N. Metz, M.E. Cunningham, H.J. Kim, Variations in Sagittal Alignment Parameters based on Age: A Prospective Study of Asymptomatic Volunteers using Full-Body Radiographs., Spine (Phila. Pa. 1976). (2016) 605–610. doi:10.1097/BRS.0000000000001642.
[9] J.-M. Mac-Thiong, H. Labelle, M. Charlebois, M.-P. Huot, J. a de Guise, Sagittal plane analysis of the spine and pelvis in adolescent idiopathic scoliosis according to the coronal curve type., Spine (Phila. Pa. 1976). 28 (2003) 1404–9. doi:10.1097/01.BRS.0000067118.60199.D1.
[10] O.N. Gottfried, M.D. Daubs, A.A. Patel, A.T. Dailey, D.S. Brodke, Spinopelvic parameters in postfusion flatback deformity patients, Spine J. 9 (2009) 639–647. doi:10.1016/j.spinee.2009.04.008.
[11] F. Schwab, A. Patel, B. Ungar, J. Farcy, V. Lafage, Adult Spinal Deformity — Postoperative Standing Imbalance Assessing Alignment and Planning Corrective Surgery, Spine (Phila. Pa. 1976). 35 (2010) 2224–2231. doi:10.1097/BRS.0b013e3181ee6bd4.
[12] F.J. Schwab, V. a Smith, M. Biserni, L. Gamez, J.-P.C. Farcy, M. Pagala, Adult scoliosis: a quantitative radiographic and clinical analysis., Spine (Phila. Pa. 1976). 27 (2002) 387–92. doi:10.1097/00007632-200202150-00012.
[13] F. Schwab, J.-P. Farcy, K. Bridwell, S. Berven, S. Glassman, J. Harrast, W. Horton, A clinical impact classification of scoliosis in the adult., Spine (Phila. Pa. 1976). 31 (2006) 2109–2114. doi:10.1097/01.brs.0000231725.38943.ab.
[14] S.D. Glassman, Md, K.M. Bridwell, J.R. Dimar, W.M. Horton, S.M. Berven, F. Schwab, The Impact of Positive Sagittal Balance in Adult Spinal Deformity, Spine (Phila. Pa. 1976). 30 (2005) 2024–2029. doi:10.1097/01.brs.0000179086.30449.96.
[15] V. Lafage, F. Schwab, A. Patel, N. Hawkinson, J.-P. Farcy, Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity., Spine (Phila. Pa. 1976). 34 (2009) E599–E606. doi:10.1097/BRS.0b013e3181aad219.
[16] M. Sliwinski, S. Sisto, Gait, quality of life, and their association following total hip arthroplasty., J. Geriatr. Phys. Ther. 29 (2006) 8-15 8p. http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=106348232&site=ehost-live.
[17] V. Tiffreau, F. Rannou, F. Kopciuch, E. Hachulla, L. Mouthon, P. Thoumie, J. Sibilia, E. Drumez, A. Thevenon, Postrehabilitation Functional Improvements in Patients With Inflammatory Myopathies: The Results of a Randomized Controlled Trial, Arch. Phys. Med. Rehabil. 98 (2017) 227–234. doi:10.1016/j.apmr.2016.09.125.
[18] M. Syczewska, K. Graff, M. Kalinowska, E. Szczerbik, J. Domaniecki, Influence of the structural deformity of the spine on the gait pathology in scoliotic patients, Gait Posture. 35 (2012) 209–213. doi:10.1016/j.gaitpost.2011.09.008.
[19] P. Mahaudens, X. Banse, M. Mousny, C. Detrembleur, Gait in adolescent idiopathic scoliosis: kinematics and electromyographic analysis, Eur. Spine J. 18 (2009) 512–521. doi:10.1007/s00586-009-0899-7.
[20] J.C. Paul, A. Patel, K. Bianco, E. Godwin, Q. Naziri, S. Maier, V. Lafage, C. Paulino, T.J. Errico, Gait stability improvement after fusion surgery for adolescent idiopathic scoliosis is influenced by corrective measures in coronal and sagittal planes, Gait Posture. 40 (2014) 510–515. doi:10.1016/j.gaitpost.2014.06.006.
[21] Z. Bakouny, A. Assi, A. Massaad, E. Saghbini, V. Lafage, W. Skalli, I. Ghanem, G. Kreichati, Roussouly's sagittal spino-pelvic morphotypes as determinants of gait in asymptomatic adult subjects, Gait Posture. 54 (2017) 27–33. doi:10.1016/j.gaitpost.2017.02.018.
[22] P. Roussouly, S. Gollogly, E. Berthonnaud, J. Dimnet, Classification of the Normal Variation in the Sagittal Alignment of the Human Lumbar Spine and Pelvis in the Standing Position, 30 (2005) 346–353.
[23] Y. Yamato, T. Hasegawa, D. Togawa, G. Yoshida, T. Banno, H. Arima, S. Oe, Y. Mihara, H. Ushirozako, S. Kobayashi, T. Yasuda, Y. Matsuyama, Rigorous Correction of Sagittal Vertical Axis Is Correlated With

Better ODI Outcomes After Extensive Corrective Fusion in Elderly or Extremely Elderly Patients With Spinal Deformity, Spine Deform. 7 (2019) 610–618. doi:10.1016/j.jspd.2018.11.001.
[24] C. Yilgor, N. Sogunmez, L. Boissiere, Y. Yavuz, I. Obeid, F. Kleinstück, F.J.S. Pérez-Grueso, E. Acaroglu, S. Haddad, A.F. Mannion, F. Pellise, A. Alanay, Global Alignment and Proportion (GAP) Score: Development and Validation of a New Method of Analyzing Spinopelvic Alignment to Predict Mechanical Complications after Adult Spinal Deformity Surgery, J. Bone Jt. Surg. - Am. Vol. 99 (2017) 1661–1672. doi:10.2106/JBJS.16.01594.
[25] S. Richner-Wunderlin, A.F. Mannion, A. Vila-Casademunt, F. Pellise, M. Serra-Burriel, B. Seifert, E. Aghayev, E. Acaroglu, A. Alanay, F.J.S. Pérez-Grueso, I. Obeid, F. Kleinstück, E.S.S.G. (ESSG), Factors associated with having an indication for surgery in adult spinal deformity: an international european multicentre study, Eur. Spine J. (2018) 1–11. doi:10.1007/s00586-018-5754-2.
[26] T. Fujishiro, L. Boissière, D.T. Cawley, D. Larrieu, O. Gille, J.-M. Vital, F. Pellisé, F.J.S. Pérez-Grueso, F. Kleinstück, E. Acaroglu, A. Alanay, I. Obeid, E. On behalf of European Spine Study Group, Decision-making factors in the treatment of adult spinal deformity, Eur. Spine J. 27 (2018) 2312–2321. doi:10.1007/s00586-018-5572-6.
[27] J. Yang, V. Lafage, R. Lafage, J. Smith, E.O. Klineberg, C.I. Shaffrey, G. Mundis, R. Hostin, D. Burton, C.P. Ames, S. Bess, H.J. Kim, F. Schwab, Determinants of Patient Satisfaction 2 Years After Spinal Deformity Surgery A Latent Class Analysis, (2018). doi:10.1097/BRS.0000000000002753.
[28] H.J. Kim, S. Iyer, B.G. Diebo, M.P. Kelly, D. Sciubba, F. Schwab, V. Lafage, G.M. Mundis, C.I. Shaffrey, J.S. Smith, R. Hart, D. Burton, S. Bess, E.O. Klineberg, T.I.S.S.G. International Spine Study Group (ISSG), Clinically Significant Thromboembolic Disease in Adult Spinal Deformity Surgery: Incidence and Risk Factors in 737 Patients., Glob. Spine J. 8 (2018) 224–230. doi:10.1177/2192568217724781.
[29] E.K. Miller, B.J. Neuman, A. Jain, A.H. Daniels, T. Ailon, D.M. Sciubba, K.M. Kebaish, V. Lafage, J.K. Scheer, J.S. Smith, S. Bess, C.I. Shaffrey, C.P. Ames, __, An assessment of frailty as a tool for risk stratification in adult spinal deformity surgery, Neurosurg. Focus. 43 (2017) E3. doi:10.3171/2017.10.FOCUS17472.
[30] R.B. Davis, S. Ounpuu, D. Tyburski, J.R. Gage, A gait analysis data collection and reduction technique, Hum. Mov. Sci. 10 (1991) 575–587. doi:10.1016/0167-9457(91)90046-Z.
[31] M. Benedetti, F. Catani, A. Leardini, E. Pignotti, S. Giannini, Data management in gait analysis for clinical applications, Clin. Biomech. 13 (1998) 204–215. doi:10.1016/S0268-0033(97)00041-7.
[32] H. Goujon, X. Bonnet, P. Sautreuil, M. Maurisset, L. Darmon, P. Fode, F. Lavaste, A functional evaluation of prosthetic foot kinematics during lower-limb amputee gait., Prosthet. Orthot. Int. 30 (2006) 213–223. doi:10.1016/S0966-6362(05)80254-1.
[33] R. Vialle, N. Levassor, L. Rillardon, A. Templier, W. Skalli, P. Guigui, Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects., J. Bone Joint Surg. Am. 87 (2005) 260–267. doi:10.2106/JBJS.D.02043.
[34] M.M. a Janssen, X. Drevelle, L. Humbert, W. Skalli, R.M. Castelein, Differences in male and female spino-pelvic alignment in asymptomatic young adults: a three-dimensional analysis using upright low-dose digital biplanar X-rays., Spine (Phila. Pa. 1976). 34 (2009) E826–E832. doi:10.1097/BRS.0b013e3181a9fd85.
[35] J.-M. Mac-Thiong, P. Roussouly, E. Berthonnaud, P. Guigui, Age- and sex-related variations in sagittal sacropelvic morphology and balance in asymptomatic adults, Eur. Spine J. 20 (2011) 1–6. doi:10.1007/s00586-011-1923-2.
[36] S. Leteneur, C. Gillet, H. Sadeghi, P. Allard, F. Barbier, Effect of trunk inclination on lower limb joint and lumbar moments in able men during the stance phase of gait, Clin. Biomech. 24 (2009) 190–195. doi:10.1016/j.clinbiomech.2008.10.005.
[37] P.D.E. Vita, T. Hortobagyi, N. Carolina, Age causes a redistribution of joint torques and powers during gait, (2000) 1804–1811.
[38] T.P. Andriacchi, A. Mündermann, The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis., Curr. Opin. Rheumatol. 18 (2006) 514–518. doi:10.1097/01.bor.0000240365.16842.4e.
[39] K. Blazek, J.L. Asay, J. Erhart-Hledik, T. Andriacchi, Adduction moment increases with age in healthy obese individuals, J. Orthop. Res. 31 (2013) 1414–1422. doi:10.1002/jor.22390.
[40] T.P. Andriacchi, J.A. Ogle, J.O. Galante, Walking speed as a basis for normal and abnormal gait measurements, J. Biomech. 10 (1977) 261–268. doi:10.1016/0021-9290(77)90049-5.
[41] C.A. McGibbon, Toward a better understanding of gait changes with age and disablement: neuromuscular adaptation, Exerc Sport Sci Rev. 31 (2003) 102–8. doi:10.1097/00003677-200304000-

00009.
[42] E.F. Chehab, T.P. Andriacchi, J. Favre, Speed, age, sex, and body mass index provide a rigorous basis for comparing the kinematic and kinetic profiles of the lower extremity during walking, J. Biomech. 58 (2017) 11–20. doi:10.1016/j.jbiomech.2017.04.014.
[43] F. Moissenet, F. Leboeuf, S. Armand, Lower limb sagittal gait kinematics can be predicted based on walking speed, gender, age and BMI, Sci. Rep. 9 (2019) 9510. doi:10.1038/s41598-019-45397-4.
[44] F. Schwab, B. Ungar, B. Blondel, J. Buchowski, J. Coe, D. Deinlein, C. DeWald, H. Mehdian, C. Shaffrey, C. Tribus, V. Lafage, Scoliosis Research Society—Schwab Adult Spinal Deformity Classification, Spine (Phila. Pa. 1976). 37 (2012) 1077–1082. doi:10.1097/BRS.0b013e31823e15e2.
[45] D. Kluger, M.J. Major, S. Fatone, S.A. Gard, The effect of trunk flexion on lower-limb kinetics of able-bodied gait, Hum. Mov. Sci. 33 (2014) 395–403. doi:10.1016/j.humov.2013.12.006.
[46] S. Ounpuu, K. Pierz, Gait Analysis Data Interpretation: Understanding Kinematic Relationships Within and Across Planes of Motion in Persons with Physical Disabilities, in: Instr. Course Am. Acad. Cereb. Palsy, Texas, Austin, USA, 2015.

Figure legends:

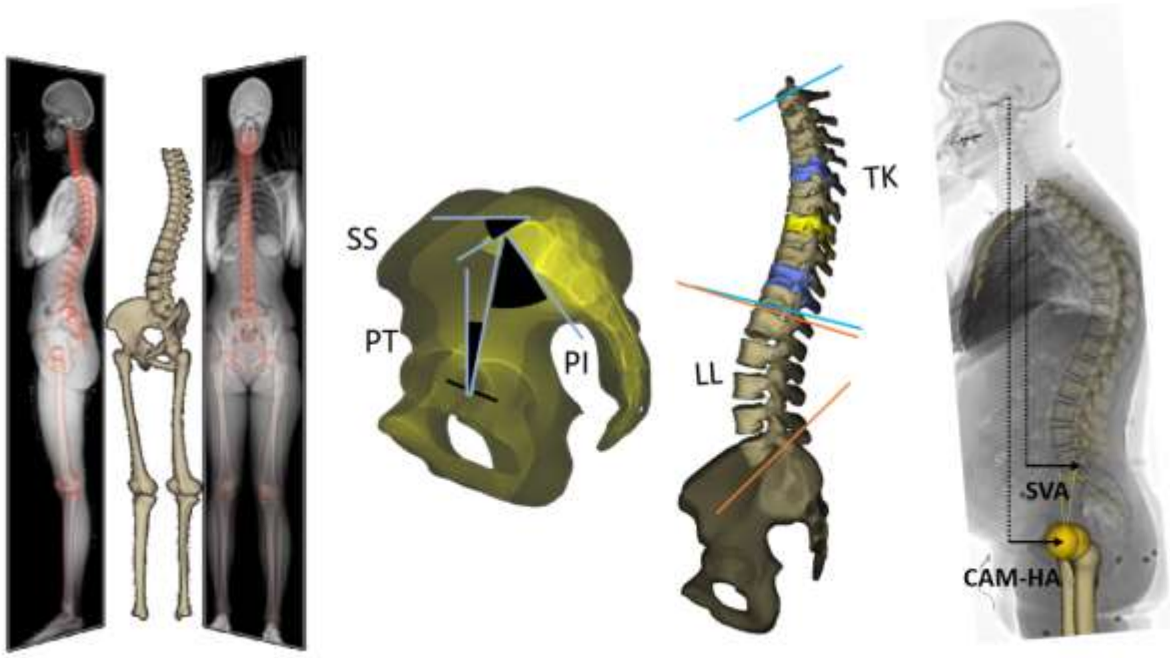

Figure 1: Sagittal spino-pelvic and global postural alignment parameters: pelvic tilt (PT), sacral slope (SS), pelvic incidence (PI), L1S1 lumbar lordosis (LL), T1T12 thoracic kyphosis (TK), sagittal vertical axis (SVA), center of auditory meatus to hip axis plumbline (CAM-HA).

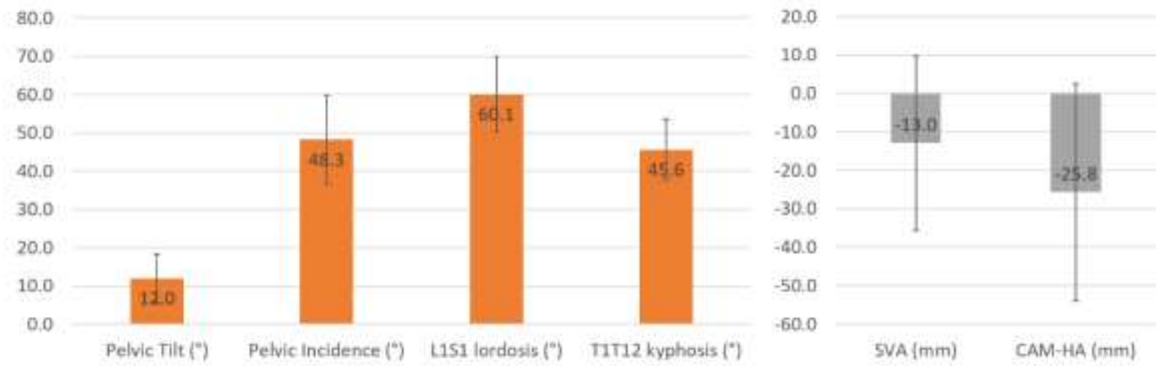

Figure 2: Means and standard deviations for sagittal spino-pelvic and global postural alignment parameters in 134 asymptomatic adults.

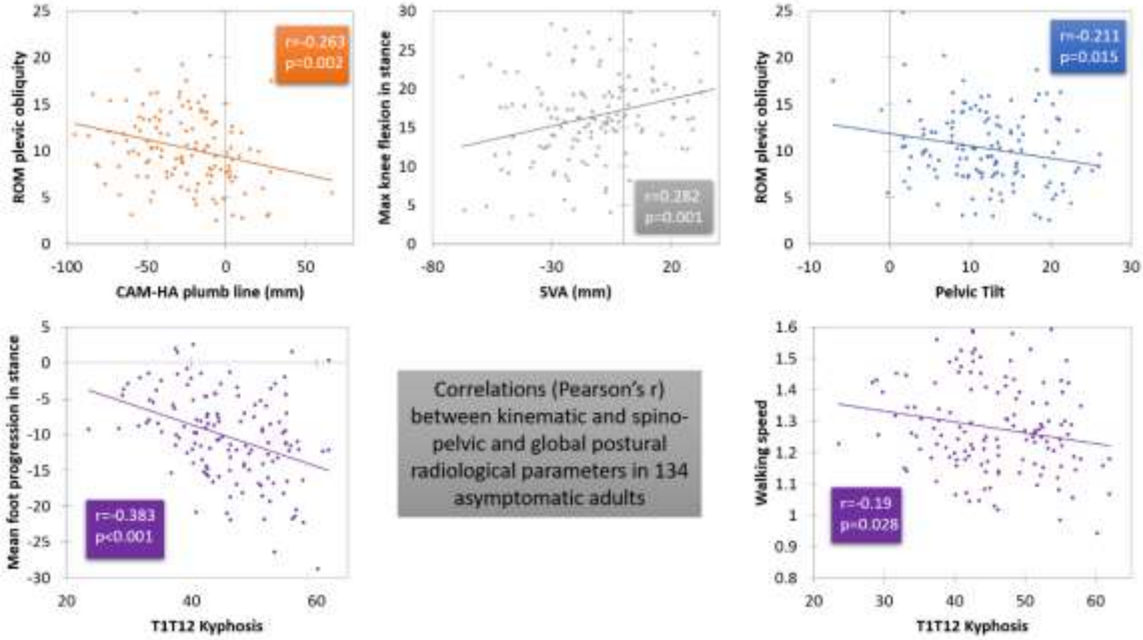

Figure 3: Correlations (Pearson's r) between kinematics and spino-pelvic and global postural parameters.

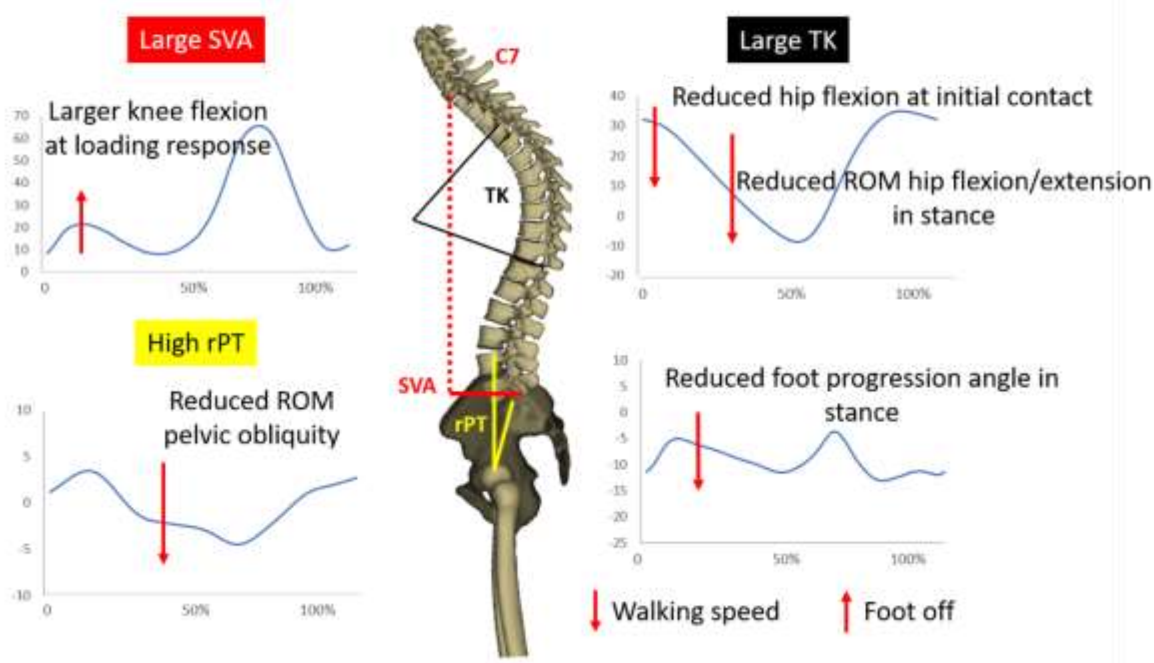

Figure 4: Influence of spino-pelvic and postural alignment parameters (SVA, PT and rPT) on gait kinematics.

Table 1: Gait kinematics in 134 asymptomatic subjects as mean and standard deviation.

	Gait kinematics	Mean	Standard deviation
Pelvis	Mean pelvic tilt	11.4	5.8
	ROM pelvic tilt	3.4	1.2
	Mean pelvic obliquity	-0.1	1.6
	ROM pelvic obliquity	10.3	4.0
	Mean pelvic rotation	0.0	2.7
	ROM pelvic rotation	12.5	4.5
Hip	ROM hip flexion/extension in stance	42.0	4.6
	Max hip extension in stance	-7.4	7.0
	ROM hip flexion/extension	43.6	4.6
	Mean hip flexion/extension	16.4	6.6
	Hip flexion at initial contact	34.2	7.2
	ROM hip abduction/adduction	14.0	4.0
	Peak hip abduction in swing	-8.0	3.0
	Mean hip abduction/adduction	-0.4	2.9
	Mean hip internal/external rotation	0.9	8.7
	Mean hip internal/external rotation in stance	0.7	9.3
Knee	Max knee flexion in stance	16.4	5.6
	Max knee extension in stance	2.5	5.0
	Max knee flexion in swing	62.3	5.6
	Knee extension at initial contact	4.2	4.7
	ROM knee flexion/extension	61.2	5.1
	Mean knee flexion/extension	20.6	4.2
Ankle & foot	Max dorsiflexion in stance	17.3	3.5
	Max plantarflexion in stance	-8.5	5.6
	Max dorsiflexion in swing	9.5	3.4
	ROM dorsi/plantar flexion	29.4	5.8
	Mean dorsi/plantar flexion	6.2	2.7
	Mean foot progression angle in stance	-10.3	6.1
	ROM foot progression angle in stance	9.2	3.2
Time-distance parameters	Walking speed	1.3	0.1
	Cadence	115.5	9.1
	Foot off	60.8	1.7
	Single support	0.4	0.0
	Step length	0.7	0.1

ROM: Range of Motion; Max: Maximum.

Table 2: Multivariate analysis results: effect of demographic and postural alignment parameters on gait kinematics.

	Gait parameters (dependent variables in the ANCOVA models)	R^2 adjusted	Demographic and Postural alignment parameters as determinants of gait (independent variables in the ANCOVA model)																					
			Age		Weight		Height		Sex (M as reference)		SVA (mm)		CAM-HA (mm)		Pelvic Tilt		T1T12 kyphosis		Pelvic Incidence		TPA		LPA		PI-LL	
			β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value	β	p value
Pelvis	Mean pelvic tilt	0.089	0.284	0.001											-0.185	0.028										
	ROM pelvic obliquity	0.365							0.488	<0.001			-0.19	0.02	-0.297	<0.001										
	ROM pelvic rotation	0.054							0.248	0.004																
Hip	ROM hip flexion/extension in stance	0.13	0.231	0.006			-0.228	0.007									-0.17	0.04								
	Max hip extension in stance	0.118	0.196	0.02	0.269	0.002																				
	ROM hip flexion/extension	0.125					-0.362	<0.001																		
	Mean hip flexion/extension	0.101	0.328	<0.001																						
	Hip flexion at initial contact	0.183	0.432	<0.001													-0.165	0.039								
	ROM hip abduction/adduction	0.255							0.511	<0.001																
	Mean hip abduction/adduction	0.221	0.222	0.005					0.412	<0.001																
	Mean hip internal/external rotation in stance	0.234	-0.396	<0.001	-0.232	0.003																				
Knee	Max knee flexion in stance	0.141	0.272	0.001							0.268	0.001														
	Max knee flexion in swing	0.105	0.204	0.016	-0.319	<0.001																				
	ROM knee flexion/extension	0.123			-0.36	<0.001																				

Ankle & foot	ROM dorsi/plantar flexion	0.141				0.384 <0.001								
	Max plantar flexion in stance	0.137				-0.254 0.003				0.192 0.021	0.289 0.001	-0.37 0.001		
	Mean foot progression in stance	0.301		-0.41 <0.001						-0.329 <0.001				
Time-distance	Walking speed	0.029								-0.19 0.028				
	Cadence	0.209			-0.463 <0.001									
	Foot off	0.128		0.273 0.001						0.223 0.007				
	Step length	0.204			0.447 <0.001					-0.181 0.022				

ROM: Range Of Motion; Max: Maximum; TPA: thoracic pelvic angle; LPA: lumbar pelvic angle; PI-LL: pelvic incidence-lumbar lordosis.