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Description of spine motion during gait in normal adolescents and young adults

Solène Prost[1,2,4] · Benjamin Blondel[1,2,4] · Vincent Pomero[1] · Guillaume Authier[1] · Christophe Boulay[1,3,4] · Jean Luc Jouve[1,3] · Sebastien Pesenti[1,3,4]

Abstract

Introduction Standing radiographs allow analysis of spinal segments and their relative positioning. However, it requires a specific positioning influencing spinal alignment. Knowledge of trunk movements when walking is therefore an essential step to evaluate dynamic sagittal balance. Our objective was to define spinal junction kinematics and their correlations during gait in a healthy population.

Method This is a prospective, single-center study. Between 2015 and 2017, 25 healthy volunteers were included. The measurements were taken in a motion analysis laboratory. Several kinematic parameters were studied, including spinal junction movements in the three planes and dynamic sagittal vertical axis (Dyn-SVA). Pearson correlation coefficients were calculated to determine the interactions between the spinal junctions.

Results In the sagittal plane, the average amplitude of variation of the dyn-SVA was 25.5 cm (SD = 8.9). The average range of motion of the lumbosacral and thoracolumbar junction was approximately 3°, they operated in anti-phase during the gait cycle and were strongly correlated ($r = -0.5069$, $p = 0.01$). In the transverse plane, the anti-rotation of the upper body relative to the pelvis was mainly ensured by the opposite movements of the lumbosacral and thoracolumbar junction ($r = 0.5689$, $p = 0.003$). In the frontal plane, the lateral inclination in the lumbar region was made in the opposite direction from the pelvis toward the carrying member.

Conclusion Although there is substantial inter-subject variability, our study characterized the angular movements in the three planes of the different spinal junctions, of the pelvis and the lower limbs during a gait cycle in a healthy population.

Keywords Gait cycle · Trunk motion · Dynamic sagittal balance · Spinal junction

Introduction

Since the last decade, the analysis of spinopelvic interactions has been reported to be crucial for the understanding of spine sagittal alignment [1]. Thereby, in daily practice, full spine radiographs including the pelvis have become the gold standard for analysis of the so-called lumbopelvic complex [2–4] providing information for either pathological condition or preoperative planning. Based on this, many spinopelvic parameters have been described and after age adjustment, serve as realignment goals in spinal deformity patients [5, 6]. Recent literature has stressed the importance of fulfilling these goals to improve functional results in spine surgery [7–9].

However, conditions in which radiographs are taken may be misleading. Indeed, standard radiographs are performed in a constrained position and a restrained environment. In these conditions, radiographic spinal alignment may differ from daily life. In 2020, it was shown that in adolescents

with idiopathic scoliosis, dynamic sagittal alignment was not related to X-ray parameters, questioning the validity of sagittal alignment assessment based on radiographic measurements [10]. On the other hand, technologies such as gait analysis provide data about dynamic spinal posture and could therefore give valuable information about sagittal alignment [11].

Gait cycle is a sequence of stance and swing phases during which balance is voluntarily compromised, to provoke forward projection of the body [12]. Ducroquet et al. stressed the importance of pelvic rotation during gait and introduced the "pelvic step", described as a forward rotation of the pelvis in the transverse plane, allowing an increased step length of the ipsilateral leg during the swing phase [13]. Simultaneously, the upper part of the trunk initiates an opposite rotation, to prevent complete rotation of the pelvis [14–16]. Although the rotational motion of the trunk and pelvis is well-known, the behavior of spinal segments linking the upper trunk to the pelvis remains unknown, as well as their behavior in sagittal and coronal planes.

A specific gait analysis protocol was recently described with the ability to describe a segmental analysis of the spine [17, 18]. This protocol demonstrated significant correlations with usual radiographic parameters in adolescent idiopathic scoliosis patients [19]. Knowledge of segmental spinal motion appears crucial, to be able to understand various spinal conditions and properly adapt physical therapy or surgical treatment. Therefore, this study aimed to describe kinematic mechanisms within the spine in asymptomatic volunteers during walking, using gait analysis.

Methods

Study design

This is a prospective single-center study of asymptomatic volunteers. Inclusion criteria were as follows: no history of chronic back pain, major trauma, orthopedic condition or previous orthopedic surgery. To limit the risk of biased analysis, subjects must have been between 12 and 30 years old to be included as mature trunk parameters are acquired in adolescents from the age of 12 [20] and degenerative changes of the spine may occur from the age of 30 [21]. This study was approved by our local ethics committee, and before inclusion, informed consent was collected from every participant.

Gait protocol

Gait analysis was performed in a laboratory equipped with 6 high-res infrared cameras. Subjects were prepared with a 36-marker protocol derived from the Helen Hayes and Plug-in-Gait protocol, enhanced with four additional markers along the spine [17]. In total, six markers were used for spine description (C7, T7, T9, T12, L3, S1). Subjects were asked to walk barefoot, at a self-selected speed along a 9-m walkway. An average number of four trials were performed and the best one was kept for analysis.

Evaluation parameters

Several parameters were measured in the three planes of the space (Fig. 1).

In the coronal plane, shoulder-line and pelvis obliquity were collected. Coronal vertical axis (Dyn-CVA) was defined as the horizontal distance between the S1 marker and a line dropped from the C7 marker, in the coronal plane.

In the sagittal plane, we measured dynamic thoracic kyphosis (dyn-TK) defined as the angle between the C7-T7 and the T9-T12 lines; the dynamic lumbar lordosis (dyn-LL), defined as the angle between the T12-L3 and the L3-S1 lines; pelvic tilt (PT); and the sagittal vertical axis (dyn-SVA), defined as the horizontal distance between the S1 marker and a line dropped from the C7 marker, in the sagittal plane.

Finally, in the transverse plane, shoulder-line and pelvis rotations (SL-rotation and P-rotation, respectively) were measured, as well as the acromion-pelvis angle (APA), defined as the angle between the bi-acromial line and the line passing through the anterior superior iliac spines.

Additionally, spinal parameters were measured at the cervicothoracic (CTh), thoracolumbar (ThL) and lumbosacral (LS) junctions in the three planes of the space: coronal (lateral bending), sagittal (flexion–extension) and transverse (torsion). CTh was the relative motion of the Vertex-C7 line with regard to the C7-T12 line; ThL was the relative motion of the C7-T12 line with regard to the T12-S1 line, and LS was the relative motion of the T12-S1 line with regard to the pelvis.

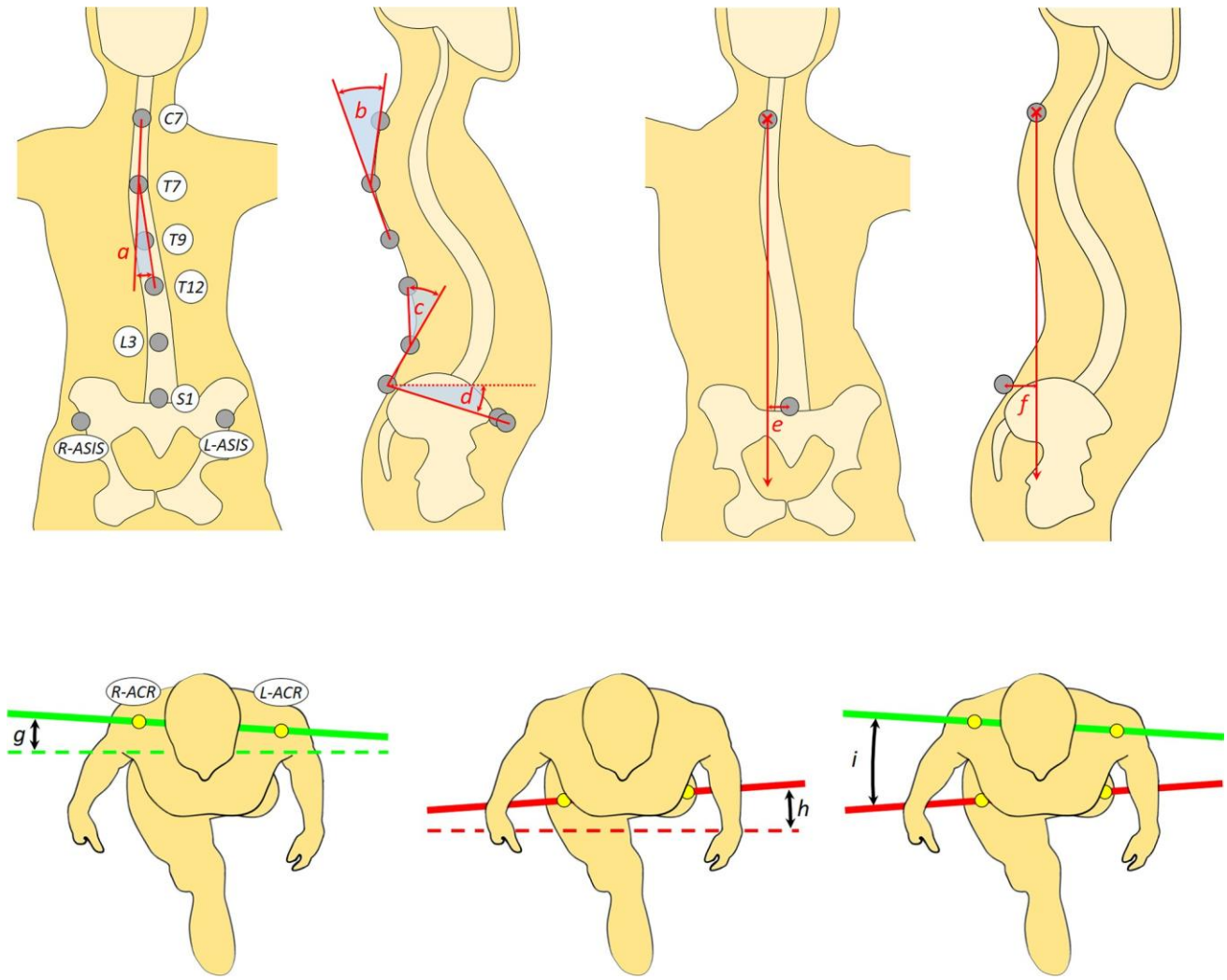


Fig. 1 Marker protocol and gait parameters. **a**: Thoracic cobb, **b**: dynamic thoracic kyphosis, **c**: dynamic lumbar lordosis, **d**: dynamic pelvic tilt, **e**: dynamic CVA, **f**: dynamic SVA, **f**: shoulder-line rotation, **g**: pelvis rotation, **h**: acromion-pelvis angle

Statistical a alysis

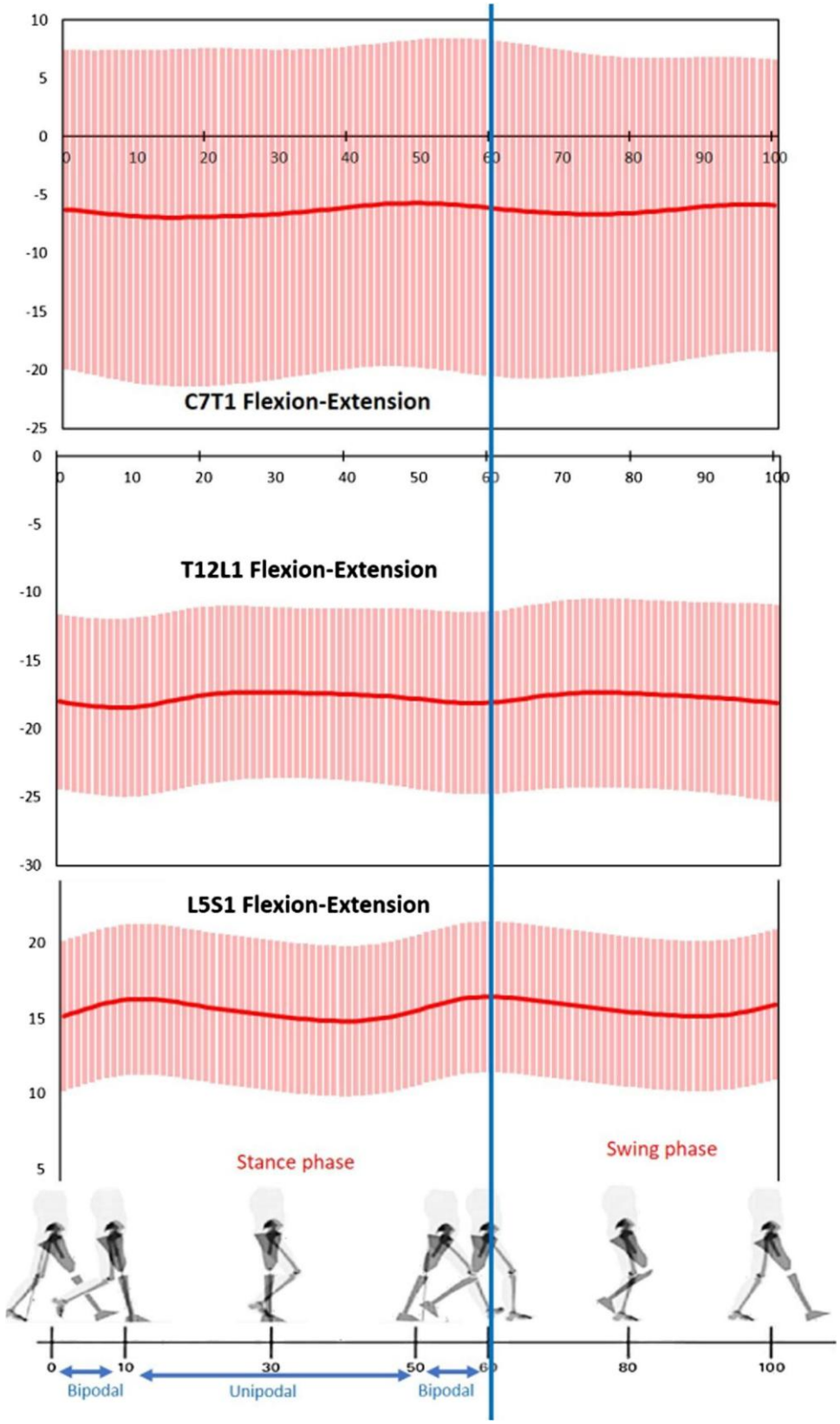
Results are presented as means (±standard deviation). By convention, data were acquired during the right gait cycle and calculated at every percentage of the gait cycle. Negative values indicate rotation toward the left side in the coronal and transverse planes and toward the back in the sagittal plane. In a secondary analysis, the average value of each parameter during a whole gait cycle was calculated, as well as the range of motion (ROM), defined as the difference between the minimal and maximal value of a parameter during the gait cycle. Interactions between spinal segments were investigated using Pearson correlation tests. Threshold for statistical significance was set à 5% (i.e., p-value < 0.05).

Table 1 Results of gait parameters in the sagittal plane

Parameter	Mean	ROM
Dyn-SVA	59.3 (±27.6)	25.5 (±8.9)
Dyn-TK	28.7 (±5.6)	4.5 (±2.6)
Dyn-LL	15.2 (±6.7)	3.3 (±2.1)
Dyn-PT	10.9 (±3.9)	3.0 (±1.1)
Cervicothoracic flexion–extension	−6.4 (±13.7)	6.3 (±3.2)
Thoracolumbar flexion–extension	−17.8 (±6.6)	3.1 (±1.8)
Lumbosacral flexion–extension	15.6 (±6.3)	3.3 (±1.6)

Except for Dyn-SVA, data are expressed in degrees (°). *Dyn-SVA* dynamic sagittal vertical axis (expressed in centimeters), *Dyn-TK* dynamic thoracic kyphosis, *Dyn-LL* dynamic lumbar lordosis, *Dyn-PT* dynamic pelvic tilt, *ROM* range of motion

Fig. 2 Spinal junctions motion in the sagittal plane during a full gait cycle



SPSS software (IBM, USA) was used to perform statistical analysis.

Results

Inclusion population

At the end of the inclusion period, 25 asymptomatic subjects were included (15 females and 10 males), with a mean age of 16.1 years (from 12.6 to 29.9 SD = 5.7) and an average body mass index of 20.0 kg/m^2 (from 15.8 to 27.8 SD = 3.3). In average, walking speed was 1.1 m/s (± 0.1), step length was 0.6 m (± 0.1) and stride length was 1.2 m (± 0.2).

Gait results

In the sagittal plane, the mean dyn-SVA value was 59.3 cm (± 27.6), corresponding to a forward tilt of the trunk during walking, with a ROM of 25.5 cm (± 8.9) (Table 1). The flexion–extension motion of spinal junctions is presented in Fig. 2 and Table 1. On average, the thoracolumbar junction was in flexion, whereas cervicothoracic and lumbosacral junctions were in extension.

In the transverse plane, mean shoulder-line and pelvis rotations were −0.9° (± 2.4°) and 0.5° (± 2.6°), respectively. Acromion-pelvis angle was 0.4° (± 4.7°). These results read as a symmetric rotation of pelvis and shoulder-line, with as much rotation to the left and the right during a full gait cycle. During the right stance phase (0–60% of the gait cycle), the pelvis was rotated toward the left at initial contact. Rotation toward the right was then initiated to allow bodyweight transfer on the right lower limb. It finally led to an anterior excursion of the center of gravity, in order to engage forward propulsion of the body. Meanwhile, the upper body rotated in the opposite direction (Fig. 3). Torsion between the upper and lower body was related to the rotation of the lumbosacral junction. Indeed, we observed opposite rotation of lumbosacral junction with regard to the pelvis, with the largest ROM at this level (8.3° at the lumbosacral junction, 3.3° at the cervicothoracic junction and 3.9° at the

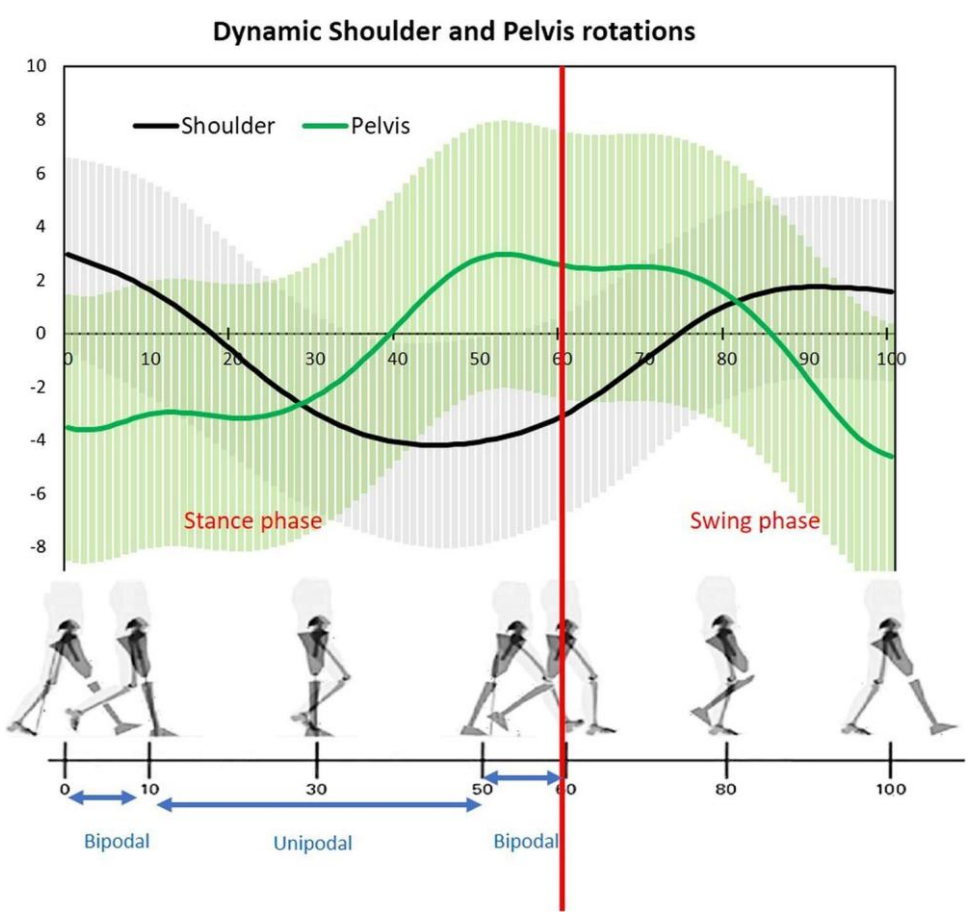


Fig. 3 Relative motion of shoulder-line and pelvis in the transverse plane during a full gait cycle

Fig. 4 Spinal junctions motion in the transverse plane during a full gait cycle

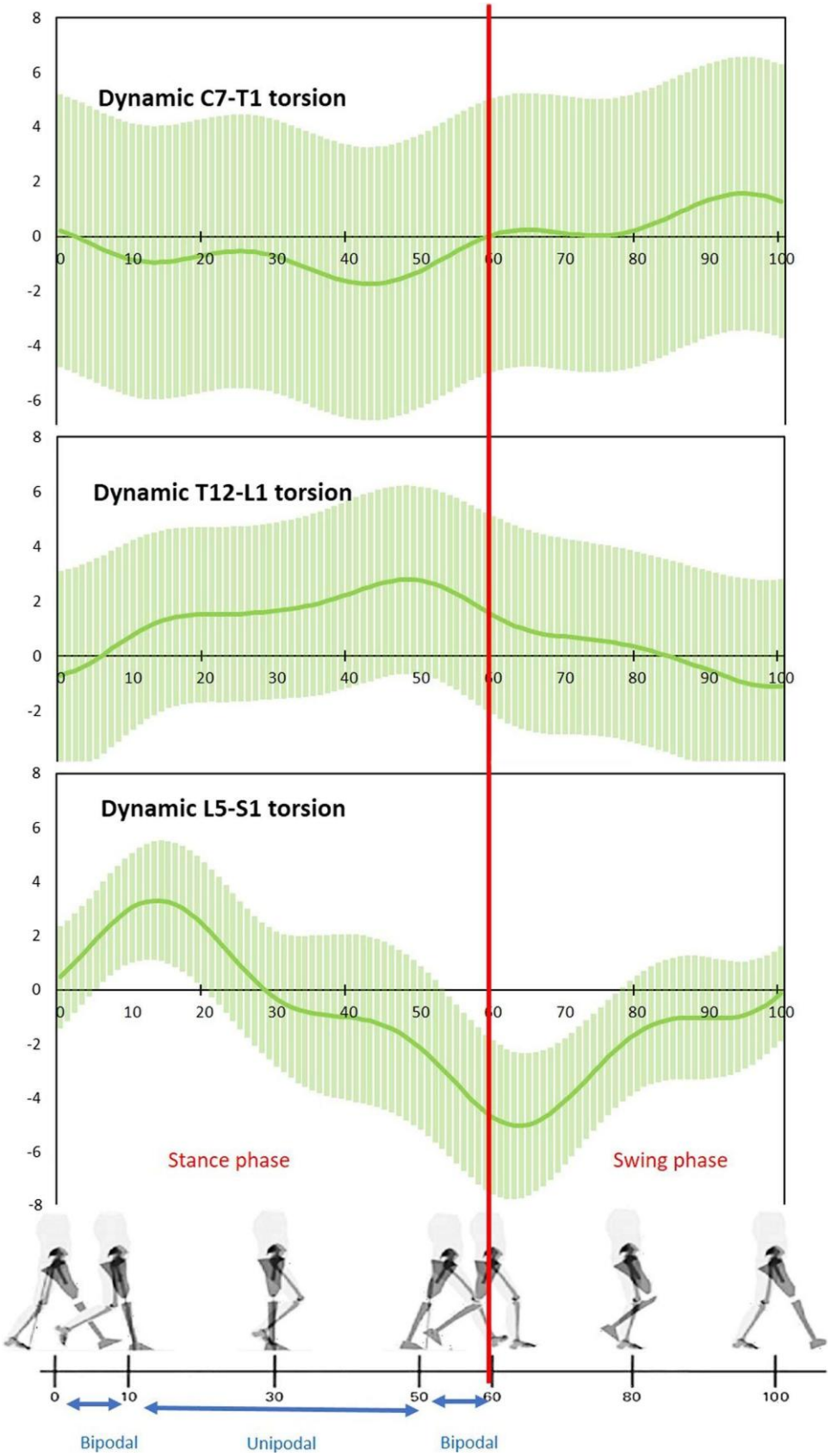


Table 2 Results of gait parameters in the transversal plane

Parameter	Mean	ROM
Dyn-APA	−0.4 (±4.7)	14.1 (±1.4)
Shoulder-line rotation	−0.9 (±2.4)	7.1 (±0.7)
Pelvis rotation	0.5 (±2.6)	7.6 (±1.6)
Cervicothoracic torsion	−0.3 (±0.9)	3.3 (±2.0)
Thoracolumbar torsion	−1.0 (±1.1)	3.9 (0.7)
Lumbosacral torsion	−0.9 (±2.3)	8.3 (±1.4)

Data are expressed in degrees (°). *Dyn-APA* dynamic acromion-pelvis angle, *ROM* range of motion

thoracolumbar junction) (Fig. 4). Rotations of the different spinal junctions are presented in Table 2.

In the frontal plane, pelvis lateral inflection peak occurred at 15% and 65% of the gait cycle. The lumbar spine responded with opposite inflection to keep the trunk vertical in the frontal plane (Fig. 5). Inflection of the different spinal junctions is presented in Table 3.

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Correlations linking the relative motion of the spinal junctions are presented in Table 4. In the transverse plane, motion at the different spinal levels was not significantly correlated, corresponding to independent moves of spinal junctions during the gait cycle. On the other hand, the lumbosacral extension was significantly correlated to thoracolumbar flexion ($r = -0.5069$, $p = 0.01$). Finally, there were significant correlations between relative motions of spinal junctions in the coronal plane (Fig. 6).

Discussion

The pelvic step was introduced by Ducroquet et al. in 1956 and describes pelvis rotation in the transverse plane [22]. This concept shed light on the pelvis, being the fundamental link for coordination between lower limbs and the trunk during gait. Since then, modern tools have been developed that allowed for accurate description and quantification of this phenomenon, as well as the relative motion of individual segments [17, 23, 24]. To the best of our knowledge, our work is the first one to go deeper into the segmental analysis of the trunk by describing the motion at different spinal junctions during gait.

In the sagittal plane, an increase of dyn-SVA corresponds to a trunk anterior tilt to promote forward propulsion of the body. Anterior tilting leads to a temporary imbalance of the trunk. Thereafter, the trunk tilts back in a less anterior position during the swing phase, to replace the center of gravity over the pelvis. In our study, the lumbosacral extension was significantly correlated to thoracolumbar flexion. The lumbosacral junction was in extension during gait as the compensation for anterior pelvic tilt. Therefore, thoracolumbar flexion was necessary to provoke anterior tilting of the trunk. On the other hand, the cervicothoracic junction was in extension but presented a great variability among our population (SD = 13.7°), reflecting the larger mobility of this segment. Higher mobility of the cervicothoracic junction allows subjects to keep a horizontal gaze when walking, which is crucial for gait stability.

In the transverse plane, our subjects presented symmetric rotations of pelvis and shoulder-line. These two segments presented opposite rotations. Considering the right gait cycle, while the pelvis rotated toward the left side to increase step length, the shoulder-line rotated in the opposite direction, as shown in Fig. 3. Our results are consistent with previous literature, this phenomenon is known as the anti-phase between trunk and pelvis [15]. Within the spine, our results suggest that trunk torsion mainly occurs at the lumbosacral level as a response to the pelvic rotation, while thoracolumbar and cervicothoracic junctions did not show great motion in the transverse plane. Once again, coordination between trunk and pelvis appears as a crucial factor for gait stability. Indeed, several authors have reported alterations of the trunk–pelvis coordination in some spinal conditions, such as chronic low-back pain or idiopathic scoliosis [25–28]. Therefore, motion analysis opens the door to physical therapy in such patients, aiming to improve transverse plane trunk motion but further research is necessary to confirm the exact implications of such disorders. We found that within the spine, the lumbosacral junction presented the largest mobility, especially in the transverse and frontal plane (Tables 2 and 3). This finding in a healthy

Fig. 5 Spinal and pelvis motion in the frontal plane during a full gait cycle

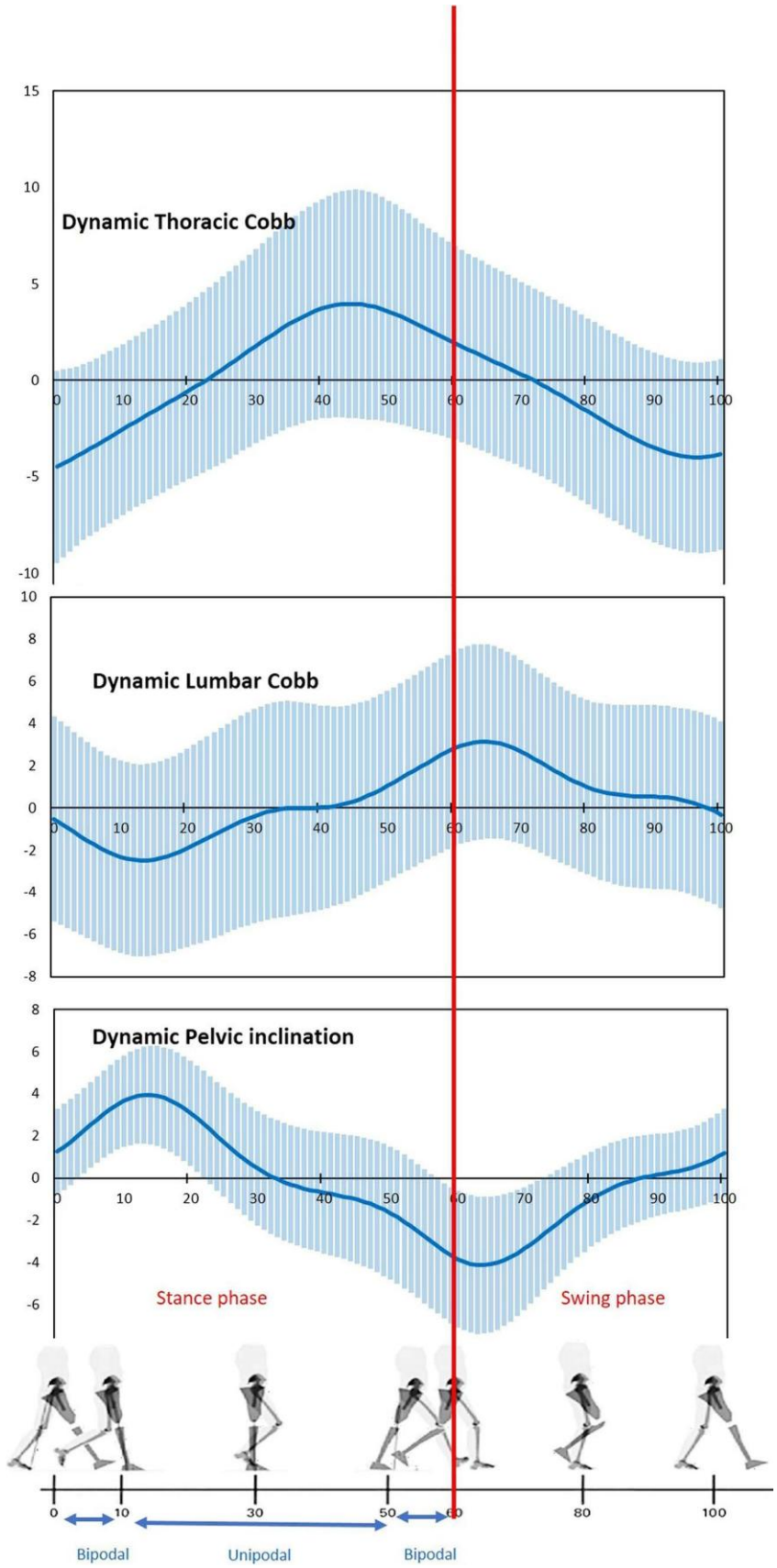

Table 3 Results of gait parameters in the frontal plane

Parameter	Mean	ROM
Dyn-CVA	−0.1 (±0.1)	3.0 (±0.0)
Shoulder-line obliquity	0.1 (±2.8)	4.9 (±2.3)
Pelvis obliquity	−0.2 (±2.3)	8.1 (±1.4)
Dyn-Thoracic Cobb	−0.1 (±2.8)	8.5 (±1.5)
Dyn-Lumbar Cobb	0.3 (±1.6)	5.6 (±1.0)
Cervicothoracic inflection	−0.6 (±1.0)	2.7 (±1.2)
Thoracolumbar inflection	0.4 (±0.4)	1.2 (±0.3)
Lumbosacral inflection	0.2 (±4.3)	12.4 (±1.6)

Except for Dyn-CVA, data are expressed in degrees (°)*Dyn-CVA* dynamic coronal vertical axis (expressed in centimeters), *ROM* range of motion

population raises serious concerns about rotational behavior of the spine in patients undergoing extended spinal fusion including the lumbosacral junction. Indeed, torsion of the trunk at this level will therefore not be possible anymore and will probably occur at a more proximal level, leading to decreased step length. In 2014, Wu et al. [29] studied the rotational behavior of the trunk with artificially increased stiffness. They reported consistent results, with a decrease of trunk–pelvis coordination associated with compensatory increased pelvis–leg phase, finally leading to decreased step length. Upper trunk and upper limbs rotation being mandatory during gait, it is likely that lumbosacral junction stiffness will lead to compensatory increased rotation at the thoracolumbar and cervicothoracic junctions, as the head must remain straight to assure gait stability.

In the frontal plane, the motion of spinal junctions was significantly correlated at every level. While thoracolumbar and lumbosacral junctions moved in the same direction, there was an opposite inclination of the cervicothoracic junction. This contra-rotation of the cervicothoracic junction appears as a compensatory mechanism, to keep a horizontal gaze.

Conclusion

In conclusion, our work is the first one to describe motion within the spine during normal gait. Our results allow a better understanding of biomechanical behavior of the spine during daily-life activities and could help to understand pathological mechanisms in patients with spinal conditions or after spinal fusion.

Table 4 Correlations linking motion of the spinal junctions

	Correlation coefficient (r)	*p*	Linear regression
Frontal plane			
Cervicothoracic vs Thoracolumbar	−0.4737	0.017	−0.1x + 0.4
Cervicothoracic vs Lumbosacral	−0.7056	< 0.001	−0.3x
Thoracolumbar vs Lumbosacral	0.5689	0.003	1.2x−0.3
Sagittal plane			
Cervicothoracic vs Thoracolumbar	−0.397	0.049	−0.2x−19
Cervicothoracic vs Lumbosacral	0.2616	0.207	–
Thoracolumbar vs Lumbosacral	−0.5069	0.010	−0.5x + 7
Transversal plane			
Cervicothoracic vs Thoracolumbar	−0.2045	0.327	–
Cervicothoracic vs Lumbosacral	0.0595	0.778	–
Thoracolumbar vs Lumbosacral	−0.1043	0.620	–

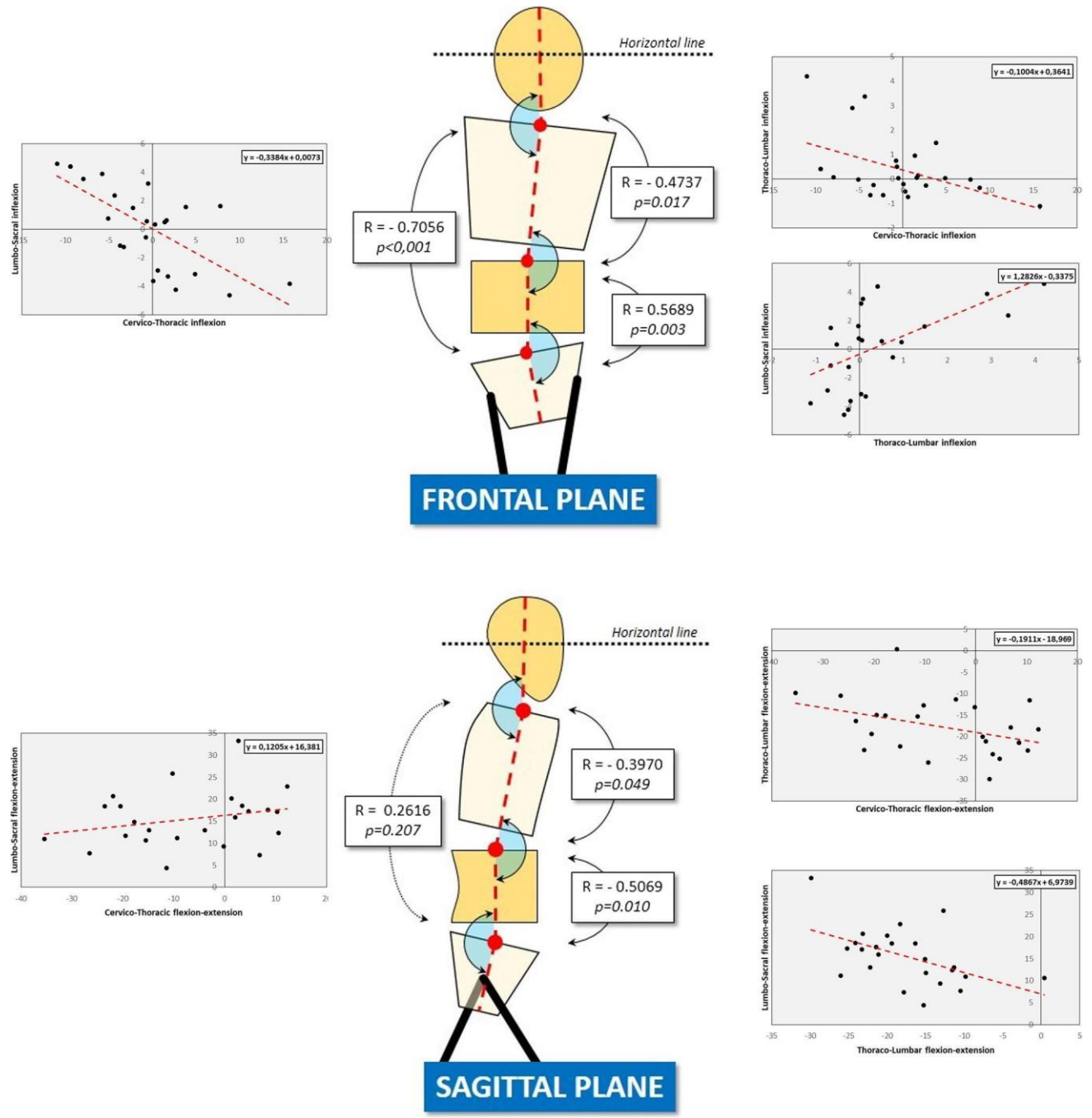

Fig. 6 Correlation analysis of motion at the different spinal junctions in frontal and sagittal planes

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