World Neurosurgery: X 18 (2023) 100165

Contents lists available at ScienceDirect

World Neurosurgery: X

journal homepage: www.journals.elsevier.com/world-neurosurgery-x

The dynamic sagittal balance: Definition of dynamic spino-pelvic parameters using a method based on gait analysis

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ARTICLE INFO

Keywords:
Dynamic sagittal balance
Spino-pelvic parameters
Gait analysis

ABSTRACT

Introduction: Evaluation of sagittal balance parameters is a standard assessment before spine surgery. However, these parameters can change during walking. We aimed to describe the behavior of spino-pelvic parameters during walking in healthy subjects.

Material and methods: Analyses were performed in 60 healthy subjects. *Static* spinal sagittal balance parameters were assessed. We performed gait analysis and we used SMART-DX 500® to analyze parameters aimed at defining *dynamic* sagittal balance, including *pelvic tilt angle* (PTA), *sagittal trunk shift* (STS), and *trunk angle* (TA). We considered rotational and obliquity movements of the pelvis, flexo-extension movements of the hip, trunk, and knees. Analyses were performed in a standing posture and during walking.

Results: PTA-cycle, PTA-stance, PTA-swing, STS-cycle, STS-stance, and STS-swing showed good-to-excellent internal reliability (ICC = 0.867; ICC = 0.700; ICC = 0.817, respectively). The parameters with the lowest variability were radiographic PI (CV = 16.53%), PTA-stance (CV = 9.55%), and PTA-swing (CV = 17.22%). PT was directly related to PTA-cycle (r = 0.534, p = .027). PI was inversely correlated with trunk flexo-extension range of motion (r = −0.654, p = .004) and dynamic PT (r = −0.489, p = .047). LL and SS were directly related to knee flexo-extension (r = 0.505, p = .039; r = 0.493, p = .045, respectively). SVA was correlated with the trunk obliquity in dynamics (r = 0.529, p = .029). PTA-cycle was directly related to trunk obliquity (r = 0.538, p = .049). STS and TA in the three phases of step were related to the kinematic parameters of the pelvis. TA was related to flexo-extension of the hip and knee.

Conclusions: Variations of dynamic spino-pelvic parameters occur during walking and modify sagittal balance from a static to a dynamic condition.

1. Introduction

The concept of “spine balance” was first presented by Dubousset in his theory of the “efficiency cone”.[1] According to this theory, the spine is balanced by the actions of agonist and antagonist muscles aiming to maintain orthostatism, both when standing upright and walking. Le Huec et al later presented a detailed description of the mechanisms regulating the sagittal balance of the spine in healthy subjects, the compensation mechanisms needed to maintain balance in pathological conditions, and the consequences of their progressive loss in advanced stages of spinal disorders.[2]

These theories changed spine surgery, which is now performed with the additional goal of restoring the sagittal balance of spine, according to the preoperative evaluation of spino-pelvic parameters that influence surgical planning. These parameters are measured using standing x-rays, and describe sagittal balance under static conditions. However, recent data suggest that sagittal balance of the spine can be more reliably described by integrating gait analysis and the measurement of spino-pelvic parameters under dynamic conditions, since they seem to change during walking.[3–5] For example, pelvic compensation demonstrated in static x-rays can fail during walking, leading to severe sagittal imbalance.[6,7] This discrepancy between static and dynamic measure has been also suggested to be a possible cause of failure of spine surgery.[8,9] To date, few studies have attempted to develop a systematic definition of dynamic sagittal balance parameters, especially under physiological

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https://doi.org/10.1016/j.wnsx.2023.100165
Received 25 August 2022; Received in revised form 23 January 2023; Accepted 24 January 2023

Abbreviations

PI	pelvic incidence
PT	pelvic tilt
SS	sacral slope
LL	lumbar lordosis
SVA	sagittal vertical axis
SD	standard deviation
3D	three dimensional
TA	trunk angle
STS	sagittal trunk shift
PTA	pelvic tilt angle
C7	seventh cervical vertebra
S1	first sacral vertebra
RoM	range of motion
ICC	intraclass correlation coefficient
CV	coefficient of variation
ASD	adult spine deformity
LSS	lumbar spinal stenosis
PJK	proximal junctional kyphosis
LI	lumbar instability
FBSS	failed back surgery syndrome
HC	healthy patients

conditions. In the present study, our first aim was to define a method for describing and measuring parameters of the physiological dynamic sagittal balance of the spine, through gait analysis in healthy subjects. We additionally investigated correlations between these parameters and the static parameters. The hypothesis was that even in the healthy subject, walking significantly influences and modifies the sagittal balance of the spine.

2. Materials and methods

2.1. General data

From September to October 2020, 60 healthy young volunteers (both sexes, 19–32 years old), with no history of symptoms related to spinal disease, were included in this study. From each subject, we obtained informed consent for the following evaluations. We also obtained ethical approval from our institution's ethics committee for our study.

2.2. Radiographic recordings

For each patients, we obtained a full spine standing x-ray (EOS imaging), including femoral heads and pelvis. The *Surgimap®* software was used to calculate the spino-pelvic and global sagittal balance parameters: *pelvic incidence PI*, *pelvic tilt PT*, *sacral slope SS*, *lumbar lordosis LL*, *sagittal vertical axis SVA,* and *Roussouly classification* (Tables 1 and 2).

2.3. Instrumental evaluation

2.3.1. Kinematic recordings

This study was performed in a gait kinematic analysis lab. Recordings were obtained using the SMART-DX 500 optoelectronic motion analysis system (BTS, Milan, Italy). This system detects the movement of specific passive spherical markers (15-mm diameter) positioned on anatomical landmarks, as described by Davis et Al.[10,11]

2.3.2. Procedure

Analyses were performed in a standing posture (before walking) and during walking. Before starting formal measurements, the participants had a practice session to become familiarized with the experimental procedure. Subjects were required to walk barefoot at three different speeds (slow, normal, and fast) along a walkway of approximately 10 m in length. To avoid a potential "velocity bias", our analysis considered only the trials in which the gait speed was within the range of the patients' mean gait speed ± SD.[12–14] We acquired ten walking trials for each different speed per subject. We analyzed only the central strides of these trials, to "capture" the gait variables during steady state walking.

2.3.3. Data analysis

The trajectories of the three-dimensional markers were acquired using three-dimensional (3-D) acquisition software (*Smart Capture*; BTS, Milan, Italy), and were labeled using a frame-by-frame tracking system (*Tracklab*; BTS, Milan, Italy). All data were processed using 3D processing software (SMART Analyzer; BTS, MA, USA) (Fig. 1) and MATLAB software (Matlab R2014a, version 8.3; MathWorks, Natick, MA, USA).

2.3.4. Gait parameters

Kinematic data were normalized between the two consecutive heel strikes when reduced to 100 samples in the gait cycle using a polynomial procedure. The following time–distance parameters were considered for the statistical analysis: step length (cm) and width (cm), stance phase duration (%), swing phase duration (%), double support phase duration (%), cadence (step/min), and speed (m/sec).

Next, in the same subjects, we analyzed parameters with the intention of defining the concept of dynamic sagittal balance.[3] In particular, we analyzed three parameters calculated thanks to spherical markers positioned in anatomical landmarks (Fig. 2): trunk angle (TA), sagittal trunk shift (STS), and pelvic tilt angle (PTA). TA was defined as the angle between the vertical axis and a line connecting the spinous process of C7 to the spinous process of S1. STS was defined as the distance between the vertical lines passing through the spinous processes of S1 and C7. This parameter can be considered equivalent to the static SVA in the dynamic analyses. PTA was defined as the angle determined by the horizontal axis passing through the posterior-superior iliac spine and a line connecting the axis of the posterior-superior iliac spine to the axis of the anterior-superior iliac spine. This parameter represents the anteroposterior inclination of the pelvis and how it changes during walking, and can be considered the equivalent of the static PT in the dynamic analyses.[3] We additionally determined how these parameters changed during walking, and how they changed at different speeds. In addition to dynamic pelvis tilt, we also considered the rotational and obliquity movements of this segment. Finally, we evaluated the flexo-extension of the hip, trunk, and knees.

2.3.5. Trunk kinematics

To assess trunk kinematics, we determined the trunk and pelvis joint centers of rotation, and calculated the range of motion (RoM) of the trunk in the sagittal (flexion–extension), frontal (lateral bending), and transverse planes (rotation) during the gait cycle. these analyzes are possible by calculating the trajectories and angles determined by the passive spherical markers and analyzed by the software.

2.4. Statistical analysis

For subjects who performed at least three consecutive tests that were valid for analysis of the parameters, we evaluated the intra-subject reliability of the sagittal dynamic balance measurements, by calculating the two-way intraclass correlation coefficient (ICC) mixed for absolute concordance. ICC coefficients of >0.70 were considered an expression of good reliability. To assess the inter-subject variability of the static and dynamic parameters, we calculated the coefficients of variation (CV),

Table 1

Static sagittal balance data. Legend: LL = lumbar lordosis, PI = pelvic incidence, PT = pelvic tilt, SS = sacral slope, SVA = sagittal vertical axis.

Patient	Gender	Age	LL °	PI °	PT °	SS °	SVA (mm)	Roussouly classification
Pt. 1	M	30	53,6	59	24,7	34,3	−8,8	I
Pt. 2	F	29	57,9	48,3	13,2	35,1	−39,3	III
Pt. 3	M	19	54,9	59,1	30,2	28,9	−10,3	I
Pt. 4	F	27	51,5	56,4	21	35,4	−15	III
Pt. 5	F	24	82,5	71,6	14,3	57,3	−36,8	IV
Pt. 6	M	28	54,8	69,3	28,9	40,4	16,1	III
Pt. 7	M	29	61	58,9	16,3	42,5	−1,6	III
Pt. 8	M	32	47,7	49	12,4	36,5	7,8	III
Pt. 9	F	29	62,4	63,4	15,4	48	−3,3	IV
Pt. 10	F	30	61,2	47,9	8,1	39,8	−18,5	III
Pt. 11	F	30	69,2	63,6	20,9	42,7	−26,3	III
Pt. 12	F	32	43,7	36	15,6	20,4	−43,5	I
Pt. 13	F	32	68,3	55,4	16,3	39	−12,5	III
Pt. 14	F	28	66,6	60,6	7,1	53,4	−6,1	IV
Pt. 15	M	28	56,7	41,8	1,2	40,6	35,5	III
Pt. 16	M	29	59,7	44	13,1	30,9	3,7	I
Pt. 17	F	32	80,2	45,2	−2,4	47,6	−46,7	IV
Pt. 18	M	29	64,3	47,1	5,5	41,6	36,3	III
Pt. 19	M	28	57,6	48,3	13,1	35,2	−39,1	III
Pt. 20	M	30	55,1	69,3	29,1	40,2	16,3	III
Pt. 21	F	27	50,6	59	24,9	34,1	−8,6	I
Pt. 22	M	32	65,4	63,4	14,4	49	−3,5	IV
Pt. 23	F	30	44,7	49	12,6	36,4	8,1	III
Pt. 24	F	21	57,9	59,1	30,5	28,6	−10	I
Pt. 25	F	29	36,7	36	17,6	18,4	−40,5	II
Pt. 26	F	32	64,3	47,2	3,6	43,6	39,3	III
Pt. 27	M	26	53,7	69	29,6	39,4	17,1	III
Pt. 28	M	32	62,3	48,2	9,4	38,8	−19,5	III
Pt. 29	F	22	54,9	58,5	32,7	25,8	−20,4	I
Pt. 30	M	28	36,7	36,6	15,1	21,5	−30,4	II
Pt. 31	F	30	64,3	49,2	6,5	42,7	34,4	III
Pt. 32	M	23	53,7	66,9	28,6	38,3	19	III
Pt. 33	F	30	45,7	49,6	15,2	34,4	10,1	III
Pt. 34	M	32	61,3	47,6	6,8	40,8	−17,5	III
Pt. 35	M	28	69,7	63,6	19,8	43,8	−26	III
Pt. 36	M	32	60,7	47,9	9,2	38,7	−18,8	III
Pt. 37	F	26	81,2	70,2	14,1	56,1	−26,8	IV
Pt. 38	F	27	63,7	64,6	15,4	49,2	−13,3	IV
Pt. 39	F	32	59,7	58,9	16,6	42,3	12,4	III
Pt. 40	M	29	50	49	12,2	36,8	21,8	III
Pt. 41	M	30	67,3	55,2	16,5	38,7	−15,5	III
Pt. 42	F	31	60,7	44,2	13	31,2	6,7	I
Pt. 43	F	27	37,6	34,2	14	20,2	−25,5	II
Pt. 44	M	26	52,6	69,3	29,7	39,6	23,9	III
Pt. 45	F	31	49,6	56	23,7	32,3	−11,2	I
Pt. 46	M	28	61,9	51,3	14,2	37,1	−36,9	III
Pt. 47	F	22	52,7	57,5	29,8	27,7	−8,2	I
Pt. 48	M	24	53,7	58,8	22,2	36,6	−17,1	III
Pt. 49	M	25	72,5	68,4	10,2	58,2	−31,9	IV
Pt. 50	M	27	64,8	67,3	27,8	39,5	21,2	III
Pt. 51	F	29	65,3	61,2	14,4	46,8	−5,6	IV
Pt. 52	F	30	58,3	50,1	10	40,1	−16,2	III
Pt. 53	F	30	67,1	62,1	18,9	43,2	−16,2	III
Pt. 54	M	32	45,8	37,5	17,6	19,9	−37,5	I
Pt. 55	M	31	66,5	55,6	17,3	38,3	−11,3	III
Pt. 56	F	29	68,4	60,4	6,3	54,1	2,2	IV
Pt. 57	F	27	59,9	43,9	2,3	41,6	34,2	III
Pt. 58	M	30	56,5	41,9	11,8	30,1	6,3	I
Pt. 59	M	28	61,2	46,7	5,8	40,9	32,6	III
Pt. 60	M	30	65,5	63,8	14,7	49,1	−5,7	IV

using the formula $CV = SD/mean*100$. We evaluated the comparability between the intersubjective variability of the interrelated static radiographic and dynamic sagittal balance parameters, using Fisher's test (F) at a significance level of 95%. To assess the degree of correlation between the static radiographic parameters, static optoelectronic parameters, dynamic parameters, space–time parameters, and kinematic parameters of the trunk, pelvis, and lower limbs, we calculated Pearson's bivariate correlation coefficient at a significance level of 95%. Statistical analyses were performed using the software IBM SPSS version 20.0 and NCSS2019.

3. Results

3.1. Sample demographics

The selected sample of subjects ranged from 19 to 32 years of age, with a mean age of 28.5 ± 3 years. Of the 60 subjects, 30 were female and 30 were male (Table 1).

Table 2
Spino-pelvic radiological parameters, relative mean values and p value; Roussouly classification. Legend: SVA = sagittal vertical axis, LL = lumbar lordosis, PI = pelvic incidence, PT = pelvic tilt, SS = sacral slope.

Spino-pelvic radiological parameter	Mean value ± SD	p value
SVA, mm	−6,28 ± 22,60	0,34
LL °	58,90 ± 9,72	0,21
PI °	54,55 ± 9,92	**0,03**
PT °	15,98 ± 8,25	**0,0007**
SS °	38,56 ± 8,99	**0,05**
Roussoly classification	**N°**	**p value**
Roussoly I	4	0,42
Roussouly II	0	
Roussouly III	12	
Roussouly IV	4	

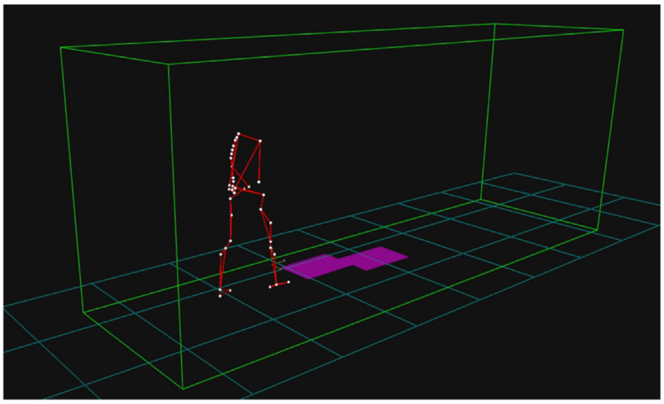

Fig. 1. 3D reconstruction of a subject through the acquisition of three-dimensional markers trajectories using a three-dimensional acquisition software.

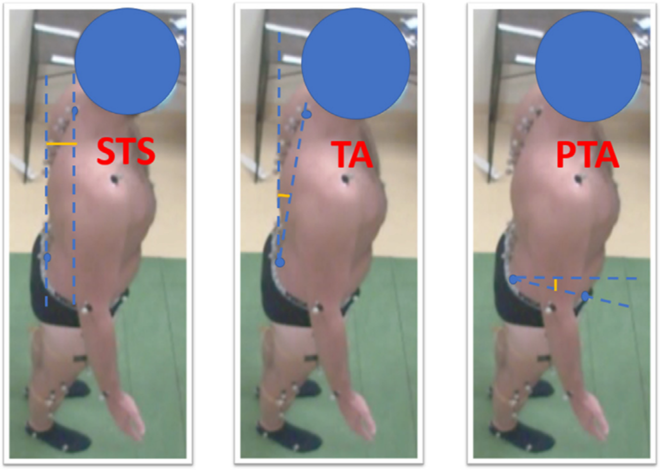

Fig. 2. The 3 dynamic parameters calculated thaks to the analysis of the movement of specific passive spherical markers, positioned on anatomical landmarks, during the dynamic study of subject. Legend: STS = sagittal trunk shift, TA = trunk angle, PTA = pelvic tilt angle.

3.2. Radiological analysis

Table 1 shows the static parameters defining the sagittal balance of each subject. Among the examined subjects, the mean lumbar lordosis (LL) was 58.90 ± 9.72°, mean pelvic incidence (PI) was 54.55 ± 9.92°, mean pelvic tilt (PT) was 15.98 ± 8.25°, mean sacral slope (SS) was 38.56 ± 8.99°, and the mean sagittal vertical axis (SVA) was −6.28 ± 22.60 mm. All patients had an SVA of <50 mm. Regarding the Roussouly classification model (Table 1), 34 subjects had a type III vertebral sagittal alignment (SS between 35° and 45°, harmonious lordotic and kyphotic curves), 12 subjects presented a type I alignment (SS of <35°, low lumbar lordosis and thoraco-lumbar kyphosis), 11 subjects presented a type IV alignment (SS of >45°, always high PI and marked sagittal curves), 3 subjects presented a type II alignment ("flat" back, SS < 35°, low PI, small angle of lumbar lordosis). These data are reported in Table 2.

3.3. Movement analysis during walking

Table 3 presents the anthropometric characteristics of the sample.

3.4. Intra-subject reliability and inter-subject variability

Dynamic sagittal balance parameter values were reported as the average of the parameters recorded on the gait cycle of the left and right foot. Table 4 presents the mean values of each analyzed index, standard deviations, variation coefficients, and intraclass correlation coefficients of the dynamic parameters. The dynamic parameters PTA-cycle, PTA-stance, PTA-swing, STS-cycle, STS-stance, and STS-swing showed good-to-excellent internal reliability (ICC = 0.867; ICC = 0.700; and ICC = 0.817, respectively). The measured parameters with the lowest variability among the subjects were the radiographic PI (CV = 16.53%), PTA measured during standing (CV = 9.55%), and PTA-swing (CV = 17.22%).

3.5. Correlation between radiographic and optoelectronic parameters

PT was directly correlated with PTA-cycle (r = 0.534, p = .027) (Fig. 3). The intersubjective variability between these two parameters was not significantly different (F = 1.17, p = .751). We identified no other significant correlations between radiographic and optoelectronic parameters (measured during standing) and dynamic sagittal balance parameters.

3.6. Correlation between radiographic and kinematic parameters

PT was directly correlated with the duration of the stance phase (r = 0.501, p = .040), and inversely correlated with the duration of the swing phase (r = −0.507, p = .038). PI was inversely correlated with the trunk flexion-extension RoM (r = −0.654, p = .004) and with dynamic pelvic tilt (r = −0.489, p = .047). LL and SS were each directly correlated to knee flexion-extension (r = 0.505, p = .039; r = 0.493, p = .045, respectively). SVA was related to the trunk obliquity in the dynamic setting (r = 0.529, p = .029).

3.7. Correlation between dynamic parameters of sagittal balance and kinematic parameters

Table 5 presents the correlations between dynamic parameters of the

Table 3
Anthropometric characteristics of subjects.

Anthropometric characteristics	Mean value ± SD
Age (yy)	28,50 ± 3,00
Weight (Kg)	64,61 ± 16,34
Height (cm)	168,33 ± 9,79
Pelvis width (cm)	22,69 ± 2,36
Right pelvis height (cm)	9,14 ± 2,10
Left pelvis height (cm)	9,17 ± 2,06
Right knee width (cm)	10,44 ± 1,30
Left knee width (cm)	10,39 ± 1,27
Right ankle width (cm)	7,22 ± 0,81
Left ankle width (cm)	7,25 ± 0,81
Right leg length (cm)	88,06 ± 4,82
Left leg length (cm)	88,03 ± 4,77

Table 4
Sagittal balance parameters (dynamic and static), variability between subjects, intra-subject reliability. Legend: SVA = sagittal vertical axis, LL = lumbar lordosis, PI = pelvic incidence, PT = pelvic tilt, SS = sacral slope, PTA = pelvic tilt angle, TA = trunk angle, STS = sagittal trunk shift.

Sagittal balance parameters (dynamic and static)	Mean value ± SD	CV (%)	ICC
PTA_cycle°	26,12 ± 9,44	36,13	**0,867**
PTA_stance°	16,43 ± 5,29	32,21	**0,7**
PTA_swing°	16,56 ± 2,85	17,22	**0,817**
TA_cycle°	9,05 ± 14,08	155,55	0,526
TA_stance°	6,67 ± 11,57	173,53	0,6
TA_swing°	4,17 ± 5,37	128,80	0,638
STS_cycle (mm)	0,8 ± 0,8	101,45	**0,953**
STS_stance (mm)	0,6 ± 0,4	57,40	**0,948**
STS_swing (mm)	0,8 ± 0,9	119,77	**0,907**
PTA_standing°	71,47 ± 6,82	9,55	
STS_standing (mm)	0,4 ± 0,2	47,02	
TA_standing°	4,73 ± 2,22	46,91	
LL °	58,90 ± 9,72	16,53	
PI °	54,55 ± 9,92	18,11	
PT °	15,98 ± 8,25	60,05	
SS °	38,56 ± 8,99	22,00	
SVA (mm)	−6,28 ± 22,60	−257,10	

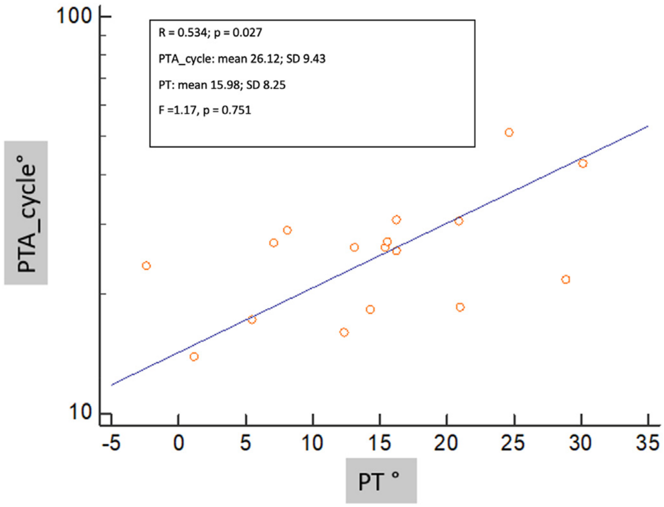

Fig. 3. correlation between PT and PTA_ cycle. Legend: PT = pelvic tilt, PTA = pelvic tilt angle, r = Pearson correlation, F = Fisher test.

sagittal balance and kinematic parameters of the gait. PTA-cycle was directly correlated with the duration of the stance phase (r = 0.626, p = .002), duration of the double support (r = 0.620, p = .008), and trunk obliquity (r = 0.538, p = .049), and was inversely correlated with the duration of the swing phase (r = −0.646, p = .005). STS and TA in the three phases of gait were related to the kinematic parameters of the pelvis. Finally, TA was correlated with the flexion-extension of the hip and knee joints.

4. Discussion

The concept of sagittal balance of the spine has revolutionized the treatment of spine diseases.[2] However, despite ample literature on static sagittal balance,[2,15–17] little has been written about its dynamic condition. Recently, the importance of studying *overall* sagittal balance during gait has been internationally recognized. Notably, a spine that is balanced but compensated on static radiographs can become unbalanced when set in motion.

In a recent three-dimensional gait analysis study in patients with degenerative lumbar kyphoscoliosis, Shiba et al[3] demonstrated that the loss of the overall sagittal alignment is underestimated on static radiographs. Indeed, as soon as the subject starts walking, anterior imbalance occurs or increases due to a failure in compensation phenomena. During gait, the hip extensor muscles alternately contract, and thus no longer contribute to static pelvic retroversion. In another recent study, Kim et al[6] compared static radiographic spino-pelvic parameters with values obtained via gait analysis among patients with ASD or lumbar spinal stenosis (LSS). They found that patients with severe positive sagittal imbalance during walking can experience failure in pelvic compensation, which was correlated with the radiological parameter SS. These studies were prompted by observations that, although *sagittal balance* knowledge has improved clinical and neurological outcomes in spine surgery, a non-negligible percentage of spine surgeries still fail, resulting in an important degree of morbidity.

Sebaaly et al[8] recently performed a multicenter study to evaluate the incidence of mechanical complications—such as proximal junctional kyphosis (PJK), failed back surgery, etc.—in patients undergoing surgery for ASD, with the aim of restoring the physiological shape of the spine through a therapeutic algorithm based on Roussouly classification.[18] Mechanical complications occurred in 30.4% of patients. Among the 66% of patients who came back to a "normal shape" according to Roussouly classification, the mechanical complication rate was 22.5%. Among the remaining 34% of patients, the complication rate was 46.8%. This study demonstrated the occurrence of mechanical complications even when paying attention to spino-pelvic parameters. In another report, Kwan et

Table 5
Correlation between dynamic sagittal balance parameters (TA, STS, PTA) and kinematic parameters. Legend: TA = trunk angle, STS = sagittal trunk shift, PTA = pelvic tilt angle, DS = double support, r = Pearson correlation.

Sagittal balance parameters (dynamic)		Pelvis obliquity	Pelvis tilt (PTA)	Pelvis rotation	Hip flex-extension	Knee flex-extension
TA_cycle	**r**	0,973**	0,875**	0,941**	0,729**	0,658**
	p value	0,000	0000	0,000	0001	0,004
TA_stance	**r**	0,966**	0,846**	0,959**	0,696**	0,676**
	p value	0,000	0000	0,000	0002	0,003
TA_swing	**r**	0,936**	0,805**	0,933**	0,799**	0,666**
	p value	0,000	0000	0,000	0000	0,003
STS_cycle	**r**	0,665**	0,639**	0,639**		
	p value	0,004	0006	0,006		
STS_stance	**r**	0,899**	0,903**	0,877**		
	p value	0,000	0000	0,000		
STS_swing	**r**	0,968**	0,900**	0,932**		
	p value	0,000	0000	0,000		
		Stance duration	**Swing duration**	**DS duration**	**Trunk obliquity**	
PTA_cycle	**r**	0,626**	−0,646**	0,620**	0.538**	
	p value	0,007	0005	0,008	0049	

al[9] analyzed the non-neurological complications within the Scoli-RISK-1 prospective study that was released in 2016.[19] They found a mechanical complication rate of 21.3%. Other studies confirm these data.[20,21] These studies, as well as clinical experience, highlight that mechanical complications have a multifactorial origin. Increasing evidence indicates that the concept of dynamism of the sagittal balance of the spine can no longer be ignored with regards to spine surgery.

Starting from this evidence, we previously investigated the spatial and temporal profile of muscle activation during walking in patients with lumbar instability (LI) and with *failed back surgery syndrome* (FBSS), comparing their results with those from a control group of healthy patients (HC).[22,23] Patients with LI exhibited a series of electromyographic abnormalities in terms of left-right symmetry and spatiotemporal activation and modulation on the segment involved in the instability. In contrast, patients with FBSS showed electromyographic abnormalities in all spinal muscles, regardless of the segment involved, and these were related to the disease severity. Moreover, FBSS patients exhibited decreased gait balance. This methodological approach suggested how evaluation of the functional status of the spine might potentially enable verification of whether surgery, and which surgical procedure, could preserve or improve spinal muscle function during gait.

The majority of the available studies on this topic involve patients with a spinal disease. However, we feel that it is essential—as was the case for defining the *static* sagittal balance—to possess physiological reference parameters in order to completely understand the pathological ones. Therefore, in our present study, we aimed to develop a system for definition of the *dynamic* sagittal balance of the spine, and to standardize parameters to clearly define it in healthy subjects.

The majority of cases in our population presented a Roussouly type III spine, which is unsurprising as it was a healthy population.[24] Examining correlations between the analyzed radiographic and kinematic parameters revealed that LL and SS correlated with the knee kinematics, SVA with the trunk kinematics, and PI with trunk kinematics and dynamic pelvic tilt. In particular, LL and SS showed positive correlations with the degree of knee flexion-extension, such that increases of these two angles were associated with an increased angle of movement of this joint. This is an interesting association for further exploration. In a recent study, Kim et al[6] observed that patients with ASD showed increased minimum flexion angles of the knee and hip during walking, confirming the principle of compensation in sagittal imbalance.[17] We also found that SVA was related to increased inclination of the trunk in dynamics. This result is not surprising since a higher SVA is an index of increased trunk obliquity, and of a greater propensity to lean forward.[2]

Interestingly, we found that PI was negatively correlated with dynamic pelvic tilt and trunk flexion-extension RoM. This means that higher PI values corresponded to decreased dynamic pelvic tilt and, therefore, to decreased pelvis anteversion and decreased forward trunk imbalance. This seems to confirm the findings of Barrey et al,[24] who suggested that subjects with a low PI had a greater predisposition to develop certain degenerative spine diseases. Moreover, this finding represents an interesting starting point for future studies regarding the possibility of creating a model to define the degree of variability and the RoM of compensation mechanisms during walking, starting from the spino-pelvic parameters.

Radiographic parameters exhibited an association with the kinematics of the step, but not with space–time parameters. Indeed, only PT showed a correlation—exhibiting a direct association with the duration of the stance phase and inverse association with the duration of the swing phase. With regards to the parameters studied with the aim of defining a model of dynamic sagittal balance (i.e. PTA, STS, and TA), PTA and STS were found to be the most reliable in the three phases of gait. In terms of the relationship between radiographic and optoelectronic parameters, the PTA of the gait cycle was found to be correlated with the radiographic PT, and both were similarly correlated to the space–time parameters of stance and swing duration. Furthermore, these two parameters showed comparable intersubjective variability. This means that higher PT values (and therefore greater pelvic retroversion) would be associated with increased PTA (and therefore greater pelvic anteversion) during walking. This is remarkable because it proves that even in a healthy subject with a physiological and greater pelvic retroversion (Roussouly types I and II), there is a greater tendency to pelvis anteversion during walking. In the setting of pathology, this mechanism can lead to a significant sagittal imbalance due to failure of the compensation mechanisms, as demonstrated in various studies.[3–7] Therefore, PTA is an essential parameter. It is also significantly correlated with trunk obliquity, which tends to increase with increased pelvis anterior leaning in healthy subjects. It will be important to further investigate how the dynamic pelvic tilt in healthy subjects modifies the lumbar lordosis during walking,[25] and how hip and lumbar muscle compartment fatigue influences PT.[26]

Our results demonstrated that STS and TA were closely related to the pelvis kinematics (dynamic tilt, rotation, obliquity), and that TA also positively correlated with the hip and knee flexion-extension. Thus, increased TA is associated with increases in dynamic pelvic tilt and in the degree of knee flexion-extension, as a physiological compensatory mechanism. However, in our study, TA was not found to be reliable (ICC<0.70). Therefore, it is necessary to ascertain whether this low reliability was due to the population sample, or to low intrinsic reliability of the parameter itself. In contrast, STS presented with high reliability, and a close correlation with the pelvis kinematics. In fact, STS and dynamic pelvic tilt increase together, and are both greater in patients with a high PT in the upright position, i.e. in patients with greater physiological pelvic retroversion. Shiba et al[3] previously described this trunk imbalance during walking in patients with spinal deformity. Our present study demonstrated that this also occurs in healthy subjects, and is closely related to dynamic pelvic tilt. Overall, PTA and STS are the most reliable parameters for our purpose.

The present findings suggest that further studies will be important for definition of the dynamic sagittal balance of the spine. This will be possible through the creation of a mathematical model to obtain the expected theoretical dynamic spino-pelvic values based on the static radiological values in healthy subjects. Such values would be useful in the analysis of compensatory mechanisms for maintaining equilibrium. Such a protocol could be created through the application of multivariate linear regression models integrating both *static* and *dynamic* parameters. This would allow us to derive dynamic theoretical reference values for use in the study of spinal degenerative disease and of ASD, leading to more accurate analyses in comparisons between healthy subjects and people showing a sagittal imbalance in both static and dynamic settings. All of this could be useful in the planning of surgery in patients with sagittal *imbalance*. It would allow us to account for changes in compensation mechanisms that may occur during walking, and to "know" the real correction angle that should be achieved to reduce the risk of surgical failure.

Our present study also confirms the relevance of compensation mechanisms in maintaining dynamic sagittal balance, explaining the need to preserve them. This would support the consideration of minimally invasive spinal procedures, which spare the muscular system of the spine, as the present and the future of spinal correction surgery, since they have a lower impact on the aforementioned compensation mechanisms.

The present study had some limitations. First, the number of analyzed subjects was relatively small. A larger sample will be needed to develop a mathematical model. It will also be necessary to understand how lordosis changes during walking, and in relation to the other radiological and dynamic spino-pelvic parameters. Additionally, real-time electromyographic monitoring (EMG) of the activity of the back muscles during walking will be necessary to clarify their roles in dynamic sagittal balance in healthy subjects.

Furthermore, in the present study the accuracy of kinematic parameters is certainly lower than that of radiographic ones.

Finally, the kinematics of the extremities will have to be systematically integrated into the study of the dynamic sagittal balance in order to fully understand the weight of compensation mechanisms occurring at this level.

5. Conclusions

In healthy subjects, the dynamic spino-pelvic parameters, as well as the kinematic parameters of the trunk and knee joint, are closely related to the radiological spino-pelvic parameters. Moreover, variations of these parameters are important during walking, and modify sagittal balance from a static to a dynamic condition. Further studies are needed to create a mathematical model to determine theoretical reference values for use in the study of vertebral pathology, and to be considered in analyses of compensatory mechanisms for maintaining balance. Furthermore, further studies will be needed to determine the correlation between changes in the static/dynamic sagittal balance between healthy subjects and pathological subjects.

Credit author statement

Conception and design of study: Miscusi Massimo, Di Bartolomeo Alessandro, Raco Antonino acquisition of data: Di Bartolomeo Alessandro, Scafa Anthony Kevin, Chiarella Vito, Giugliano Marco, Castiglia Stefano Filippo, Serrao Mariano analysis and/or interpretation of data: Miscusi Massimo, Di Bartolomeo Alessandro, Castiglia Stefano Filippo, Varrecchia Tiwana, Serrao Mariano, Raco Antonino.Drafting the manuscript: Miscusi Massimo, Di Bartolomeo Alessandro, Scafa Anthony Kevin, Ricciardi Luca, revising the manuscript critically for important intellectual content: Miscusi Massimo, Di Bartolomeo Alessandro, Raco Antonino.Approval of the version of the manuscript to be published (the names of all authors must be listed): Miscusi Massimo, Di Bartolomeo Alessandro, Scafa Anthony Kevi, Ricciardi Luca, Chiarella Vito, Giugliano Marco, Castiglia Stefano Filippo, Varrecchia Tiwana, Serrao Mariano, Raco Antonino.

Acknowledgements

All persons who have made substantial contributions to the work reported in the manuscript (e.g., technical help, writing and editing assistance, general support), but who do not meet the criteria for authorship, are named in the Acknowledgements and have given us their written permission to be named. If we have not included an Acknowledgements, then that indicates that we have not received substantial contributions from non-authors.

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