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Quantitative assessment of the sagittal and coronal balance of the axial skeleton using 3D motion capture

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Abstract

Introduction Sagittal and coronal balance of the body cannot be evaluated with the modern programs for musculoskeletal assessment using 3D motion capture and additional software operations are required for the measurements. **The objective** was to review information capacity and comparability of the quantitative assessments of the dynamic axial balance of the body using radiography and 3D gait analysis. **Material and methods** Comparative analysis of the information capacity of sagittal and coronal balance using radiographs and 3D gait analysis was performed in adolescents without orthopedic pathology (n = 12); untreated patients with idiopathic scoliosis (n = 53); patients with degenerative disorders of the spine (n = 15). **Results** Axial balance identified with 3D gait analysis showed dynamic measurements and depended on the posture during recording. There were no significant differences in the balance measurements in the samples in comparison with radiological findings with the medians being almost identical. Correlations between the balances were statistically significant in patients with degenerative disorders of the spine without clinical manifestations and in patients with idiopathic scoliosis without pain, and were not significant in patients with clinical and antalgic manifestations of vertebral pathology. **Discussion** Absence of statistically significant differences and close central trends in the samples indicated the comparability of the measurements in general population due to sagittal and coronal balance measured in the same patients, at different time points, in different postures and by different methods. However, significant differences in variation and a statistically significant effect of antalgic manifestations on the strength of correlation suggested that the dynamic balance measured with 3D gait analysis were more sensitive and informative to pathogenetic symptoms. **Conclusions** Algorithms for measurements of the axial balance using 3D gait analysis were comparable with radiographic findings and were much more informative and sensitive to antalgic manifestations of spinal pathology.

Keywords: motion capture, axial balance of the body, scoliosis, degenerative disorders of the spine

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INTRODUCTION

Dynamic axial balance of the spine is one of the important aspects of functional biomechanics of the spinal motion segment in clinical research [1]. The spine being balanced due to compensatory mechanisms can be imbalanced at movements that cannot be visualized in static radiography [2]. Bae J. et al. [3] reported an imbalance compensated on static radiographs can be detected during a radiological examination after walking 10 minutes. Examination of patients with pathology of the spine and the limbs normally includes collection of complaints, anamnesis, physical examination, intrascopic studies (X-ray, computed tomography and magnetic resonance imaging). In addition to standard examination, instrumentation study can be offered for quantitative and qualitative assessment of the musculoskeletal function to include stabilometry, plantography, electroneuromyography, dynamometry, a 6-minute walking test, 3D gait analysis and others [4-8]. Teleroentgenography of the spine in two projections is the most illustrative method of preoperative and postoperative assessment of spinal deformity, idiopathic scoliosis, in particular. The sagittal vertical axis (SVA) is measured as the horizontal distance between a plumb line drawn from the center of C7 and a line drawn the center of C7 to posterior superior corner of the sacrum using teleradiography of the spine in the sagittal plane. The coronal vertical axis (CVA) is classically defined as the horizontal distance measured from a vertical plumb line centered in the middle of the C7 and the center of S1 vertebrae using teleroentgenograms [9, 10, 11]. A lateral spinal radiograph is obtained with arms raised horizontally forward at 30 degrees of flexion at the shoulder resulting in less SVA shift and better functional position [12, 13]. However, a naturally relaxed standing position is functional and easy to accept, and the presence of arms on either side of the body prevents adequate radiographic imaging of the spine. Quantitative gait analysis (QGA) was initially developed as a tool for evaluating lower limb kinematics [14], the potential of the 3D gait analysis method can also make it possible to assess the dynamic balance of the axial skeleton in 3 planes and analyze compensatory mechanisms in imbalance at the gait [15-20]. Programs with an additional calculation option are required toimplement the possibilities and generate evaluation protocols [21, 22].

There are two main approaches to assessing the dynamic axial balance of the body offered [18, 23]:

– calculation of deviations and range of motion of the projection point from the marker C7 vertebra relative to the projection point from the S1 vertebra on the reference plane. The parameters has a weak ($p < 0.05$) correlation with radiological sagittal balance and a strong correlation with radiological frontal balance ($p < 0.01$) [24] in patients with idiopathic scoliosis in static (standing) position, but the relationship between radiographic findings and the dynamic parameters of SVA and CVA during walking has not been established;

– calculation of deviations and range of motion of the projection point from the C7 vertebra relative to the projection point of the COG (center of gravity) located in the projection of the pelvic plane with an offset to the center relative to the coordinate system from the midpoint of the ASIS line (anterior superior iliac spine) on the reference plane. COG was measured using magnetic resonance imaging together with a video motion capture system and was as close as possible to the anatomical position of the COG.

The quantitative relationship with the radiological criterion of sagittal balance at walking and in statics is still unclear [25, 26]. Radiographical measurement of the vertical axis in the sagittal plane using the commonly used "standing, flexed shoulders" position results in the vertical axis in the sagittal plane being at least 3-4 cm posterior than the "true" sagittal vertical axis seen in functional position, and none of the radiographic positions can reproduce the real balance of the spine in a natural functional standing position [27].

The **objective** was to analyze the information content and comparability of the values of the quantitative assessment of the dynamic axial balance using radiography and 3D gait analysis.

MATERIAL AND METHODS

Comparison groups

Comparative analysis of SVA and CVA using radiography and three-dimensional gait analysis (3D GA) was performed in the groups:

– group **1**: adolescents without orthopaedic pathology ($n = 12$; 2 females and 10 males aged 11-16 years);

– group **2**: patients with idiopathic scoliosis that was not treated ($n = 53$; aged 11-20 years). With greater compensatory possibilities in the formation of an imbalance being applicable due to changes in the pelvic position and mobility of the lumbar spine, subgroups identified included: **2a** ($n = 38$; 28 females and 10 males) with clinical manifestations of pain in the lumbar spine, **2b** ($n = 15$; 13 females and 2 males) without clinical manifestations of pain in the lumbar spine;

– group **3**: patients with degenerative lesions of the spine ($n = 15$; aged 48-60 years). Subgroups identified were: **3a** ($n = 8$; 5 females and 3 males) with clinical manifestations of myelopathy/radiculopathy, **3b** ($n = 7$; 6 females and 1 male) without clinical manifestations.

Radiography of CVA and SVA

Radiography demonstrated deviation in the sagittal (SVA) and frontal (CVA) planes of the vertical axis from the middle of the C7 body in the form of a plumb line down to the posterior superior edge of the sacral body S1/middle of the sacrum. Displacement suggested a positive sagittal balance (+) anteriorly and negative sagittal balance (-) posteriorly; SVA and CVA should not exceed 40 mm [28] and 20 mm, respectively [5].

3D gait analysis of GA-CVA and GA-SVA

Radiography and CT data were used to verify the projection of 3D video analysis markers on the anatomical vertebral components. Registration of 3D gait analysis was performed using Qualisys 7+ optical cameras (8 cameras) with passive marker video capture technology. The IOR model was adopted as the basis for placing reflective markers on the body (Fig. 1).

Reflective markers 16 mm in diameter and a metal base were attached to the skin at the level of the C7 spinous process, in the jugular fossa (marker SJH) and to the pelvic points of RIPS, LIPS, RIAS, LIAS for radiographic visualization (Fig. 2). Sagittal and frontal balance was evaluated using the QTM (Qualisys) and Visual3D (C-Motion) programs with automated calculations [30].

Statistical data processing was performed using Microsoft Excel-2010 and AtteStat [31]. Normality of the distribution of SVA and CVA was assessed using radiography and gait analysis according to 3 criteria: asymmetry coefficient, kurtosis, χ^2-Fisher with a decision threshold $p = 0.1$. The SVA and CVA parameters assessed with radiography and gait analysis showed an abnormal distribution. for dependent and independent variables. Considering lack of normal distribution and the population of 7-12 individuals in groups 1 and 3 – people, the quantitative characteristics of the parameters in the sets were presented as Me (25 ÷ 75 %), and the statistical significance of differences was identified using paired and two-sample Wilcoxon tests for dependent and independent variables. For calculations, a significance level of < 0.05 was adopted.

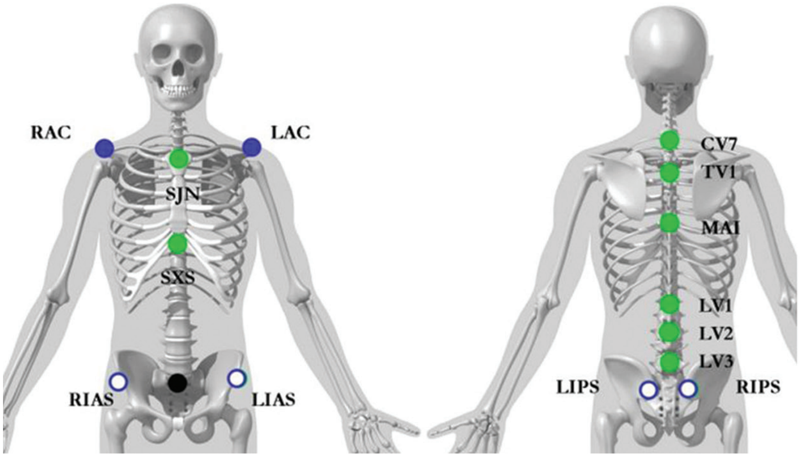

Fig. 1 Reflective markers placed on the body (IOR model) [29]: CV7, cervical vertebra; TV1, thoracic vertebra; LV, lumbar vertebra; MAI – the middle between the inferior angles of the shoulder blades; SJN, sternal jugular notch; SXS, sternum; RAC, LAC, acromial process on the right and left; RIPS, LIPS, tubercle of the superior posterior iliac spine on the right and left; RIAS, LIAS, tubercle of the superior anterior iliac spine on the right and left

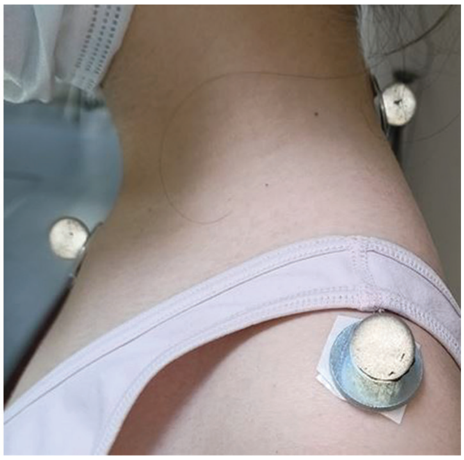

Fig. 2 Appearance of reflective markers with a 16 mm diameter and a metal base for radiographical visualization

The study was performed in accordance with ethical principles for medical research involving human subjects stated in the Declaration of Helsinki developed by the World Medical Association including amendments. Written informed consent was obtained from legal representatives of the patients for publication of the findings without identifying details.

RESULTS

The middle of the segment between the RIPS and LIPS points corresponds to the projection onto the back of the S1 vertebra (Fig. 3), and is recommended as an independent point SACR = Sacrum (the middle between RIPS and LIPS) in some models of marker placement.

C7 and the calculated point, as a landmark S1, are used to calculate the sagittal and frontal balance of the body in some biomechanical laboratories [24]. Pelvis markers in the horizontal plane are projected in the form of a trapezoid (Fig. 4). With a trapezoid, you can mathematically determine the point of intersection of the diagonals (1), the center of gravity of the trapezoid (2), the midpoint of the segment connecting the midpoints of the bases of the trapezoid (3), the center of gravity of the triangle (4). The calculated point (3) is as close as possible to the middle of the S1 vertebral body according to the marker verification on CT scan (Fig. 3).

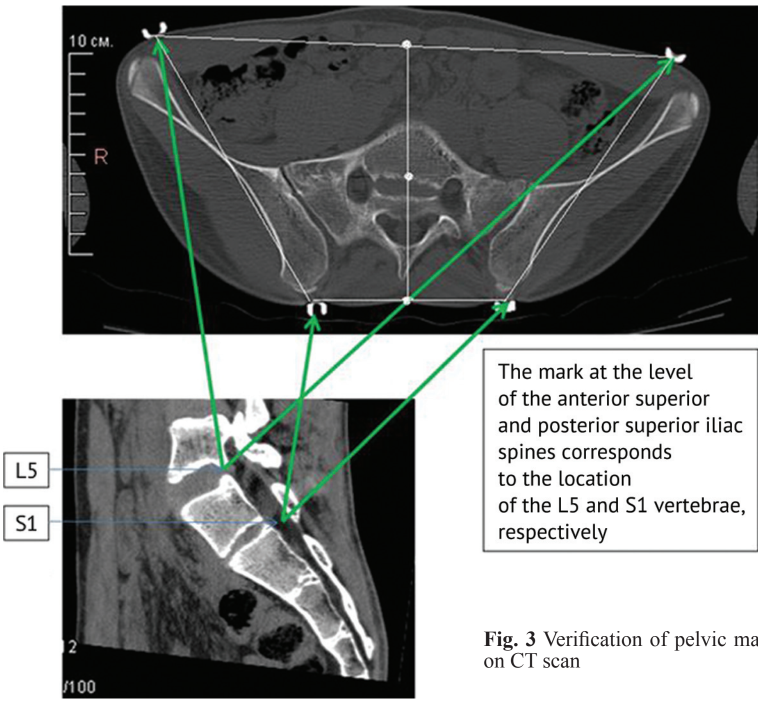

Fig. 3 Verification of pelvic markers on CT scan

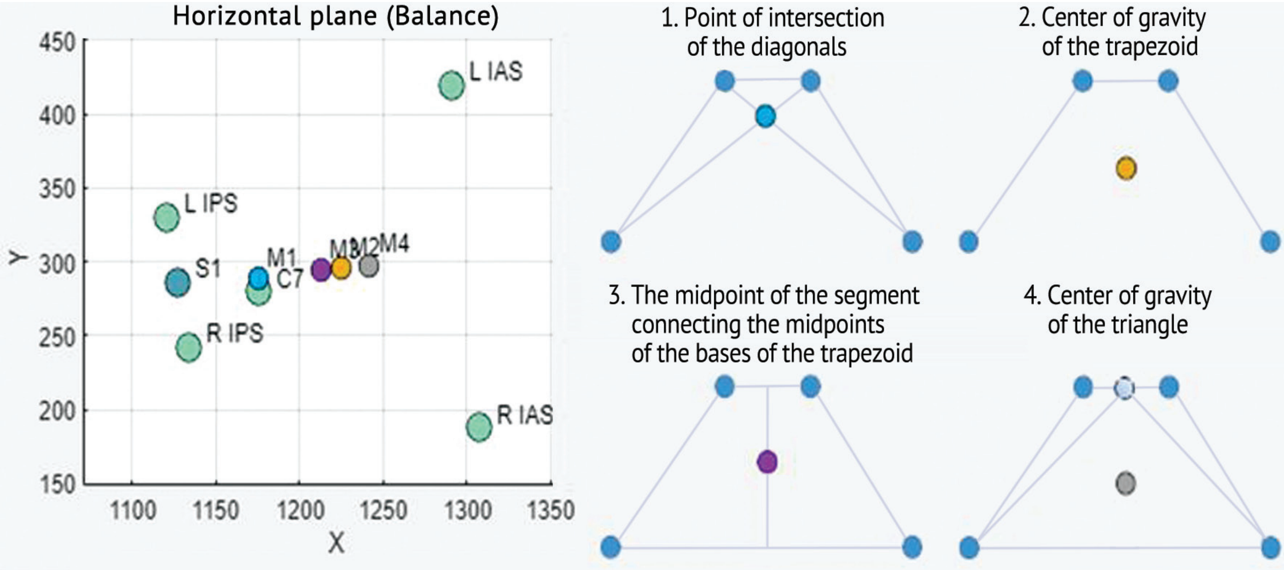

Fig. 4 Pelvic markers and C7 projected on the horizontal reference plane

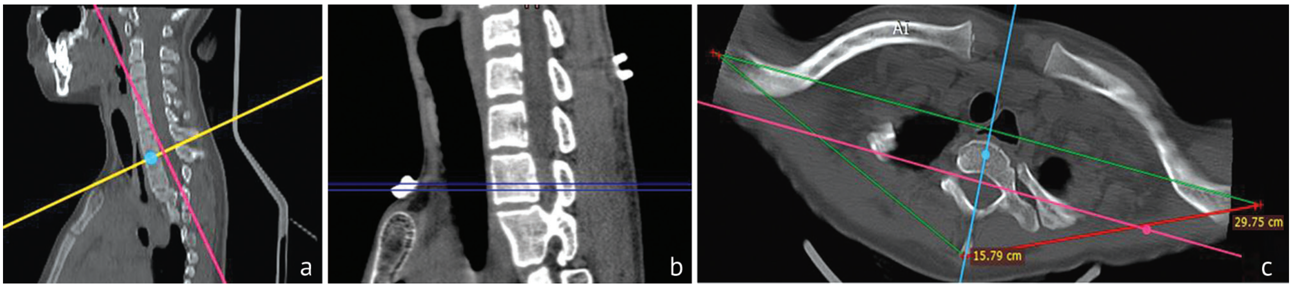

Fig. 5 Verification of C7 and SJN markers radiographs (*a, b*) and CT scan (*c*)

Verification of the C7 and SJN markers (Fig. 5) identified the C7 vertebral body as a projection of the middle of the segment between the C7 and SJH markers (jugular notch of the sternum). Parameters of SVA and CVA calculated with the method offered were determined as the projection onto the reference plane of the middle of the segment C7 and SJH (C7-SJH) and the middle of the bases of the trapezium of the pelvis (M3), as close as possible to the radiographic points for calculating the sagittal and frontal balance of the axial skeleton.

An example of data verification A 14-year-old patient R. diagnosed with idiopathic scoliosis.

Verification of SVA and CVA was performed using radiography and 3D gait analysis (Fig. 6). The radiograph showed CVA being shifted to the left in statics, gait analysis demonstrated the C7 projection relative to the calculated S1 being shifted to the left, and the calculated C7-SJN (as close as possible to the middle of the C7 body) relative to the M3 point (as close as possible to the S1 body) being deviated to the left. Radiographs indicated to CVA being shifted to the left by 22.3 mm, and gait analysis showed the axis being shifted to the left by 22.5 mm. Gait analysis in orthostatics showed radiological SVA being displaced anteriorly by 7 mm with SVA = 0, given the marker diameter of 16 mm being within error.

Cumulative parameters of SVA and CVA measured with X-ray and 3D gait analysis in the groups are presented in Tables 1, 2. A statistically significant difference in sagittal balance compared to the control was observed only in habitual statics and in the presence of clinical manifestations of the pathology. There were no statistically significant differences in sagittal and frontal balance in postural sets between adjusting and habitual statics, although the ranges of variation differed significantly in the sets. Comparison of CVA measurements of 3D gait analysis in patients with idiopathic scoliosis in groups, ranked according to radiographic data of vertical axis displacement in the frontal plane with CVA < 0 (tilt to the left), CVA = 0, CVA > 0 (tilt to the right) (Table 3) illustrated the differences. The sampling sets showed identical trends (Me) (differences were not greater than 2.5 mm), and the ranges of variation differed significantly, in case of R-CVA = 0, in particular.

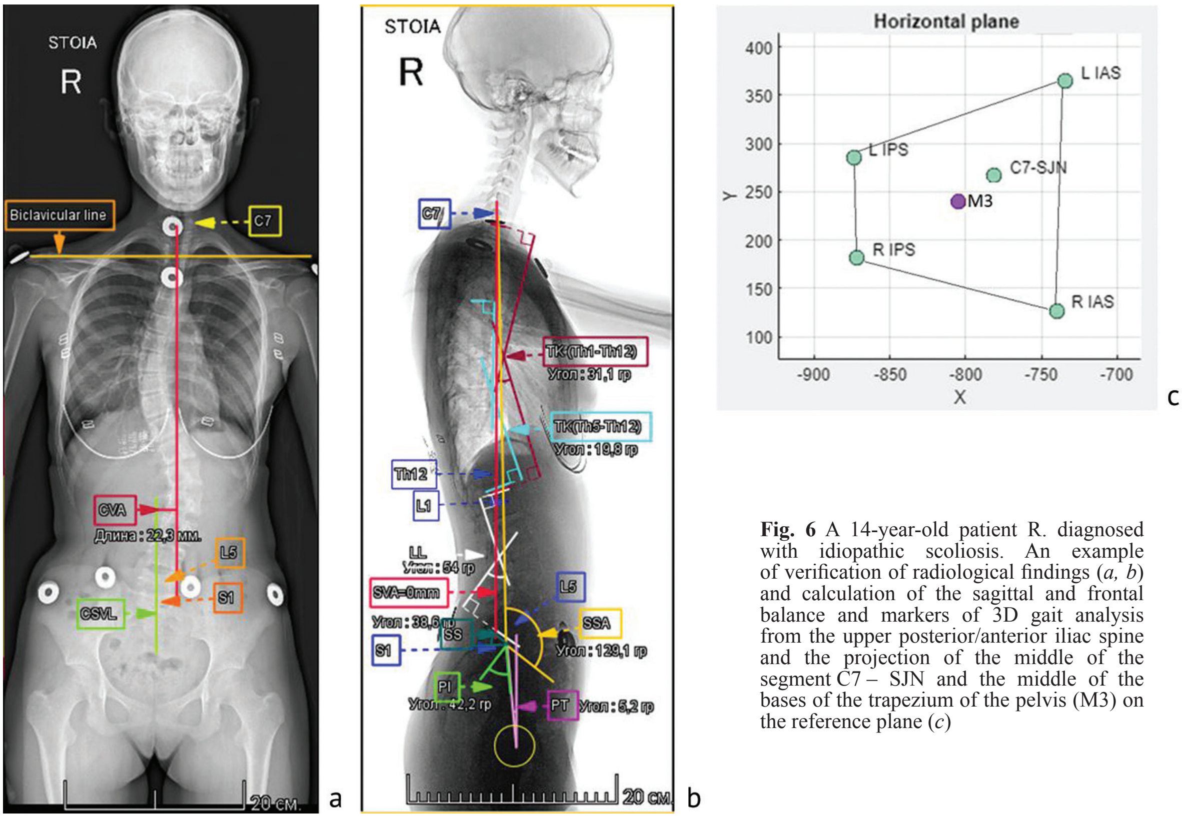

Fig. 6 A 14-year-old patient R. diagnosed with idiopathic scoliosis. An example of verification of radiological findings (*a, b*) and calculation of the sagittal and frontal balance and markers of 3D gait analysis from the upper posterior/anterior iliac spine and the projection of the middle of the segment C7 – SJN and the middle of the bases of the trapezium of the pelvis (M3) on the reference plane (*c*)

Table 1

Cumulative parameters of axial sagittal balance SVA (mm) according to radiography (R) and 3D gait analysis (GA) (Me (25 ÷ 75%), n, number of observations)

Groups	Axial sagittal balance parameters			
	R-SVA, mm, adjusting statics	GA SVA, mm, habitual statics	GA SVA at the gait, mm	GA SVA range at the gait, mm
Group 1, n = 12	0.0 ± 40.0 [20]	-11.0 (-14.5 ÷ -7.7)	-16.9 (-24.1÷-6.0)	41.1 (36.6÷52.0)
Group 2a, n = 38	0.0 (-40.0 ÷ 0.0)	4.0 (-2.8 ÷ 11.6) P = 0.0046	17.0 (-2.4 ÷ 27.9)	37.0 (29.5 ÷ 43.4)
Group 2b, n = 15	0.0 (-39.0 ÷ 7.0)	-1.0 (-15.4 ÷ 7.6)	-8.0 (-12.6 ÷ 8.7)	34.0 (28.1 ÷ 41.6)
Group 3a, n = 8	73.0 (52.5 ÷ 106.5)	92.1 (50.9 ÷ 161.1) P = 0.00027	128.5 (88.1 ÷ 194.6)	49.8 (31.8 ÷ 50.5)
Group 3b, n = 7	11.0 (4.0 ÷ 104.5)	63.6 (6.35 ÷ 66.95) P = 0.0144	86.5 (11.6 ÷ 155.8)	54.9 (38.8 ÷ 59.4)

Note: p, significant differences from measurements in group 1 shown (the norm).

Table 2

Cumulative parameters of axial frontal balance CVA (mm) according to radiography (R) and 3D gait analysis (GA) (Me (25 ÷ 75%), n, number of observations)

Groups	Axial frontal balance parameters			
	R-CVA, mm, adjusting statics	GA CVA, mm, habitual statics	GA CVA at the gait, mm	GA CVA range at the gait, mm
Group 1, n = 12	0.0 ± 20.0 [2]	4.1 (0.6 ÷ 6.9)	4.2 (1.4 ÷ 7.5)	24.2 (20.9 ÷ 32.2)
Group 2a, n = 38	0.0 (-5.0 ÷ 0.0)	-6.0 (-11.7 ÷ 13.0)	-8.0 (-18.8 ÷ 4.77)	19.0 (16.1 ÷ 23.2)
Group 2b, n = 15	0.0 (0.0 ÷ 0.0)	9.0 (-3.65 ÷ 19.1)	2.0 (-7.55 ÷ 14.2)	19.0 (15.8 ÷ 23.9)
Group 3a, n = 8	10.0 (0.0 ÷ 33.0)	15.3 (3.3 ÷ 23.6)	8.5 (0.4÷30.9)	46.7 (40.0÷62.6) **P^1 = .0049**
Group 3b, n = 7	0.0 (-30.0 ÷ 25.0)	-1.1 (-13.8 ÷ 10.0)	10.6 (-10.1÷25.1)	23.6 (19.3÷24.6) **P^2 = 0.0172**

Note: p^1, significant differences from measurements in group 1 shown (the norm); p^2, significant differences between group 3a and group 3b

Table 3

Cumulative parameters of the frontal balance of CVA (mm) measured with radiography and 3D gait analysis in patients with idiopathic scoliosis, ranked by groups according to the nature of the displacement of the vertical axis in the frontal plane (Me (25 ÷ 75%); n, number of observations)

Groups	Axial frontal balance parameters			
	R-CVA, mm, adjusting statics	GA-CVA, mm, habitual statics	GA-CVA at the gait, mm	GA CVA range at the gait, mm
R-CVA < 0, n = 12	-21.0 (-27.0 ÷ -17.0)	-18.7 (-36.4 ÷ -11.7)	-21.2 (-28.9 ÷ -11.35)	18.2 (15.6 ÷ 25.0)
R-CVA = 0, n = 34	00 (00 ÷ 00)	2.3 (-8.3 ÷ 13.3)	-2.8 (-13.3 ÷ 6.3)	19.0 (15.6 ÷ 22.4)
CVA > 0, n = 7	19.0 (16.0 ÷ 21.0)	21.0 (12.1 ÷ 26.3)	19.45 (8.55 ÷ 26.1)	21.3 (15.6 ÷ 23.17)

Despite the fact that the sagittal and frontal balance was measured in orthostatics in the same cohort of patients, but at different times in different positions and by different methods, the absence of statistically significant differences in the samples indicated to the calculated data belonging to the general population. A correlation analysis of CVA and SVA radiological findings and 3D gait analysis was performed to determine the degree of interdependence between the parameters in patients of groups 2 and 3. If the correlation analysis of the measurements of GA-CVA and GA-SVA 3D gait analysis and radiological R-CVA and R-SVA showed a strong and statistically significant correlation between R-SVA – GA-SVA, $r = 0.774$, $p < 0.05$, $n = 7$ and R-CVA – GA-CVA, $r = 0.856$, $p < 0.01$, $n = 7$ in patients of group **3b** (no clinical symptoms of myelopathy/radiculopathy) no statistically significant correlation was found in patients of group **3a** (the presence of clinical symptoms of myelopathy / radiculopathy): R-SVA – GA-SVA, $r = 0.422$, $n = 8$, R-SVA – GA-SVA, $r = 0.259$, $n = 8$. Correlation analysis of the measurements of GA-CVA and GA-SVA 3D gait analysis and radiological R-CVA and R-SVA demonstrated a statistically significant relationship between R-SVA – GA-SVA, $r = 0.659$, $p < 0.01$, $n = 15$ in patients of group **2b** (with severe frontal impairment of axial biomechanics and in the absence of clinical pain in the lumbar spine), and no significant correlation between the frontal parameters R-CVA – GA-SVA, $r = 0.0811$, $n = 15$. No statistically significant correlation was observed between the parameters of the axial balance according to gait analysis and radiography in group **2a** (with a pronounced frontal impairment of axial biomechanics and in the presence of clinical pain syndrome in the lumbar spine) even in the representative sample set R-SVA – GA-SVA, $r = 0.018$, $n = 39$ and R-CVA – GA-CVA, $r = 0.299$, $n = 39$.

DISCUSSION

Benchmarks for calculating GA-SVA and GA-CVA being approximate to RG-SVA and GA-CVA were identified using CT scans, teleroentgenograms, and 3D gait analysis with the program for calculations being corrected during gait analysis. Half the length of the segment connecting the midpoints of the bases of the trapezium formed by the projections of the pelvic points RIPS, LIPS, RIAS, LIAS (Fig. 4) and the midpoint of the segment between markers C7 and SJN (Fig. 5) appeared to be the optimal points for measuring GA-SVA and GA-CVA. The examination protocol using 3D gait analysis demonstrated the calculated parameters GA-SVA and GA-CVA as projections onto the floor plane of the middle of the segment C7 and SJH (C7-SJH, close to the C7 vertebral body) and the middle of the bases of the trapezium of the pelvis (point M3, close to the body vertebra L5).

The GA-SVA and GA-CVA parameters calculated in the group of healthy adolescents in orthostatics showed no significant differences from the normal radiological measurements reported in the literature, and there was a tendency for the body to tilt backwards (negative SVA values up to -15 mm). The range of fluctuations at the gait averaged to 41 mm in SVA and to 25 mm in CVA and was within the normal limits according to radiography in statics (SVA: 0.0 ± 40 mm, CVA: 0.0 ± 20 mm). The median values of GA-SVA and GA-CVA at the gait showed no significant differences from those measured in orthostatics.

A sampling clinical observation showed identical SVA and CVA measurements during markers verification using radiographic findings and 3D gait analysis within the error of the marker size (16 mm). Comparison of GA-CVA and R-CVA measured in patients with idiopathic scoliosis using radiographic findings of vertical axis displacement in the frontal plane with R-CVA = 0, R-CVA < 1.0 (tilt to the left), R-CVA > 1.0 (right slope), showed no significant difference between summarized parameters of GA-CVA and R-CVA. The median values of GA-CVA at the gait showed no significant differences from measurements in statics regardless of the trunk lean in the frontal plane and severity of pain. The range of variation was in compliance with the values of healthy peers (Table 3).

Whereas the evidence of a statistically significant effect of pain and functional disorders on the sagittal balance in spinal pathology was reported in the literature [32] with the antalgic manifestations to be detected in natural orthostatics using measurements of the axial balance by definition, the sagittal spinal balance did not appear to be correlated with gender in both populations [33, 34, 35] and the aspect was not examined in our series. The degree of correlation between GA-SVA and R-SVA measured in patients with idiopathic scoliosis and degenerative spine conditions was significantly affected by clinical and antalgic manifestations of the pathology in our series. A strong correlation was observed between measurements of the sagittal and frontal balance in patients with degenerative spine conditions and the sagittal balance in patients with idiopathic scoliosis in the absence of clinical symptoms and pain, and no statistically significant correlation was found between the parameters in the presence of clinical symptoms and pain syndrome. It can be concluded that the natural posture in orthostatics is closer to the adjusting posture in radiography. The summarized values of GA-SVA measured in patients with idiopathic scoliosis in orthostatics were not statistically different from the normal R-SVA and GA-SVA measurements. The median values of GA-SVA at the gait and in the norm showed no significant differences from those measured in statics with the range of SVA fluctuations in the sample being 34 mm and withing normal limits (Table 1).

Since the sagittal and frontal balance was determined in orthostatics in the same patients, but at different times in different postures and by different methods, the absence of statistically significant differences and the proximity of the central tendencies in the samples indicated the comparability of the measurements and their adjunct to the general population. Significant differences in variation and a statistically significant effect of antalgic manifestations on the strength of correlation suggested that the dynamic balance measured with gait analysis was more sensitive and informative to pathogenetic symptoms.

The forward trunk lean was statistically significant in habitual orthostatics in scoliotic patients according to GA-SVA measures ($p = 0.0046$, $n = 38$) with a slight increase at gait with the median being greater by 13 mm. The overall range of SVA fluctuations in the median values was 37 mm and within normal limits (Table 1). The severity of discrepancy between standing posture and sagittal balance during walking is mainly determined by the severity of the pathology in patients with idiopathic scoliosis [36]. Patients with degenerative spine conditions displayed more forward trunk lean. Gait analysis in orthostatics showed significantly impaired sagittal balance in the presence and absence of pain with the median measuring 92 mm and 64 mm, respectively, in the samples (Table 2). The forward trunk lean was greater by 22 mm during walking with the range of fluctuations in the sagittal balance tending to increase as compared to controls with no statistically significant differences recorded. There were no significant differences in GA-CVA measured in orthostatics and during walking in subgroups 3a and 3b compared with the norm but the frontal range of GA-CVA increasing significantly in patients with severe pain ($p = 0.0049$, $n = 8$) (Table 2). The extended range of frontal balance CVA is consistent with the literature data: patients with a severe condition exhibited more trunk sway, increased lower extremity neuromuscular activity, and decreased spine neuromuscular activity ($0.331 < r < 0.716$, $p < 0.05$) [37].

CONCLUSION

The natural posture in orthostatics was shown to be closer to the adjusting posture at radiography in the absence of pain and clinical manifestations of the pathology with a statistically significant correlation being recorded between measurements of GA-SVA – R-SVA and GA-CVA – R-CVA. Patients suffering from pain and those of the representative sample showed no statistically significant correlation between the measurements. Three-dimensional gait analysis in orthostatics and during walking is an independent research dynamically exploring motor function of the musculoskeletal system and the core postural components in the form of axial balance values. The results of the gait analysis performed for healthy individuals showed the values of variation in the measurements of the sagittal and frontal balance during walking being within the normal limits measured radiographically in orthostatics (SVA ± 40 mm, CVA ± 20 mm). Calculation algorithms for axial balance based on 3D gait analysis were comparable with radiographic data and were much more informative and sensitive to antalgic manifestations of spinal pathology.

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