Analysis of the Sagittal Balance of the Spine and Pelvis Using Shape and Orientation Parameters

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Objective: The purpose of this study is to introduce a method to analyze and characterize the global sagittal balance of the human trunk using indexes derived from the shape and orientation of the pelvis and cervical, thoracic, and lumbar spine.

Methods: Standing lateral x-rays of a cohort of 160 asymptomatic young adult volunteers were obtained. On each radiograph, a simplified model of the spine and pelvis was created using a dedicated computer software, and the following shape and orientation variables were calculated at each anatomic level: pelvic incidence, pelvic tilt, sacral slope, cervical curvature and tilt, thoracic curvature and tilt, and lumbar curvature and tilt.

Results: Significant linear correlations were found between each single adjacent shape parameter as well as between each single adjacent orientation parameter at all anatomic levels. Significant correlations were also found between some shape and orientation parameters at the same anatomic level as well as between adjacent anatomic areas. In general, the linear correlations were stronger between shape and orientation variables at the pelvic, lumbar, and cervical areas and weaker at the thoracic level and between the thoracic and lumbar areas.

Conclusions: These results confirm that the pelvis and spine in the sagittal plane can be considered as a linear chain linking the head to the pelvis where the shape and orientation of each anatomic segment are closely related and influence the adjacent segment to maintain a stable posture with a minimum of energy expenditure. Changes in shape or orientation at one level will have a direct influence on the adjacent segment. Knowledge of these normal relationships is of prime importance for the comprehension of sagittal balance in normal and pathologic conditions of the spine and pelvis.

Key Words: spine, pelvis, human posture, sagittal balance

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In the sagittal plane, the posture of a standing human subject can be viewed as a set of mutually articulating body sections: The head is balanced on the trunk by the cervical spine; the trunk articulates on the pelvis, which in turn articulates with the lower limbs at the hip joints to maintain a stable posture and to expend a minimum of energy.

Studies of sagittal balance in volunteer human subjects in the standing position have been previously published.[1–5] These authors have used standing lateral radiographic films to characterize the spine by direct measurements of lumbar lordosis (LL), thoracic kyphosis (TK), and cervical lordosis (CL) with the Cobb angle technique. Jackson et al[3,4] have described the pelvic lordosis angle measured by the pelvic radius technique to characterize the pelvis, whereas Legaye et al[6] have proposed the pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS) angles to describe the shape and orientation of the pelvis. PI is a pelvic shape parameter that is specific and constant for each individual and has been shown to directly influence pelvic orientation as well as the size of lumbar lordosis. PI (Fig. 1) is defined as the angle between a line perpendicular to the sacral plate and a line joining the sacral plate to the axis of the femoral heads and is the arithmetic summation of SS + PT, two position-dependent variables that determine pelvic orientation in the sagittal plane. Because of this mathematical relationship between PI, SS, and PT, the shape of the pelvis as quantified by PI is a strong determinant of the sagittal orientation of the pelvis in the standing position: The greater the PI, the greater has to be SS, PT, or both.

More recently, Berthonnaud et al[7,8] have proposed a computer software designed to represent the spine and pelvis on standardized lateral standing x-rays of the trunk, using a minimum of geometric parameters describing their shape. The sagittal x-ray is first digitized, then minimum numbers of points and tangents to bone contours are recorded (14 points and 6 tangents), using technical aids provided by image processing. The representative figures of the pelvic and spinal curves are drawn automatically (see Fig. 1). The mean curve of the spine is represented as a series of arcs of circles and straight lines tangent together. The parameters characterizing the spine are directly calculated from the geometric specificities of the curves.[7–9] They depend solely on the recorded landmarks. Intra- and interobserver variations have been tested[10] and were

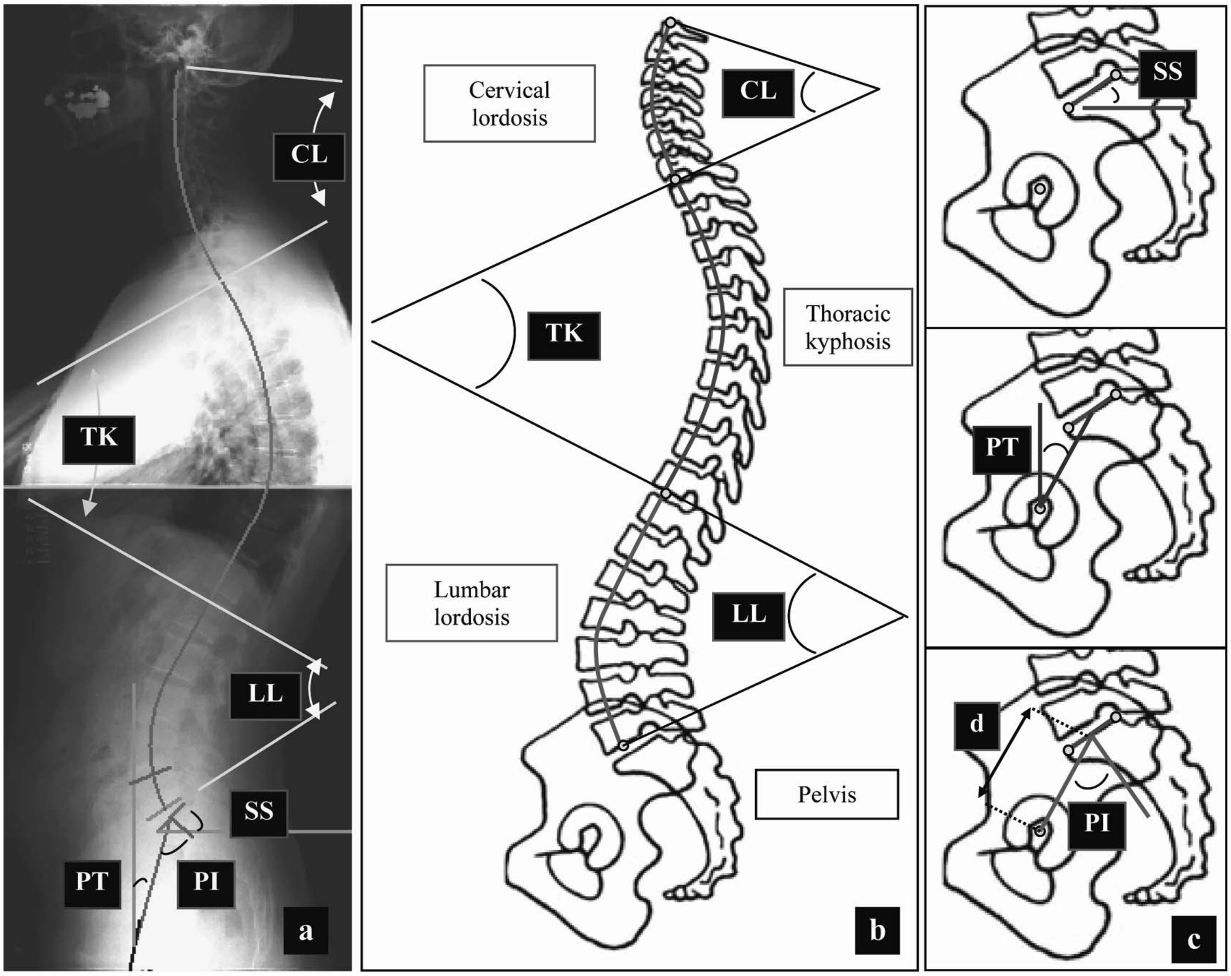

FIGURE 1. A, Sagittal X-ray of the spine and pelvis showing the simplified curve model of the spine and the shape and orientation parameters of the pelvis calculated with the dedicated computer software. B, Schematic drawings of the spine with its shape parameters (LL, TK, CL). C, Schematic drawings of the pelvis with its shape (PI, d) and orientation (PT, SS) parameters.

shown to have very little influence on the calculated data. Using this software in a prospective analysis of the sagittal profile of 100 healthy young adult volunteers, Vaz et al[11] have demonstrated that the spinal shape is closely correlated with the pelvic shape and orientation and that the spine and pelvis balance around the hip axis to position the gravity line over the femoral heads.

To our knowledge, however, there has been no study attempting to correlate shape and orientation parameters of the cervical thoracic and lumbar spine to those of the pelvis. In the sagittal plane, the body of a human subject is composed of a set of articulating body segments in which the spine and pelvis can be modeled as a series of segments supporting the head and linked together along a linear chain to maintain a stable posture. The successive links of this chain are the cervical, thoracic, and lumbar segments of the spine and the pelvis. Each of these links can be described by shape and orientation variables in the sagittal plane. The purpose of this study is therefore to introduce a simple method to characterize the global sagittal balance of the human trunk using indexes derived from the shape and orientation of these successive spine and pelvic segments and to investigate the relationship between these measurements in a cohort of normal asymptomatic adult volunteers.

MATERIALS AND METHODS

A cohort of 160 asymptomatic young adult volunteers were recruited mainly from the pool of medical and paramedical students at our institutions. All volunteer subjects were questioned by an orthopedic surgeon to rule out any history of previous spine, hip, or pelvic disorder and examined clinically to exclude any abnormal physical finding in the coronal or sagittal plane. All subjects signed an informed consent. The first 100 of these subjects have been previously reported in the study of Vaz et al,[11] and an additional 60 subjects were recently added to the cohort. The mean age of the volunteers recruited was 25.7 ± 5.5 years with a range of 20–70 years. The ratio of males to females was 0.95, with a clear predominance of males.

For each subject, left-to-right 30 × 90–cm standing lateral x-rays of the spine, pelvis, and femoral heads were obtained with the subject in a comfortable standing position, the knees fully extended, and the upper limbs resting on two arm supports. Each radiograph was digitized using a VIDAR VXR8 x-ray film scanner at 75 dpi, a process that takes around 5 minutes for an experienced user. Measurements were obtained using Sagittal OptiSoft, a dedicated software previously reported in detail.[2,3,5] This software (see Fig. 1) has been developed for the recording of digitized data, the drawing of representative curves, and the calculation of shape (LL, TK, CL, PI) and orientation (SS and PT) parameters, a process that takes 3–5 minutes for an experienced user. The results of each file can be stored for further statistical evaluation.

For the purpose of the current study, this tool was implemented with new measures of orientation of the sagittal spine at each anatomic area (Fig. 2). The spine is modeled as three distinct anatomic areas (cervical, thoracic, and lumbar), each with specific geometric characteristics. Because of the simplified representation used, the point of inflection between two different curvatures can be accurately calculated and corresponds to the junction where the curvatures change direction (see Fig. 2). The lumbar area is bound by the lower plate of L5 and by the point of inflection between the lumbar and thoracic curvatures. The thoracic area is bound by the points of inflection between the lumbar and thoracic curvatures and between the thoracic and cervical curvatures, respectively. The cervical area is bound by the lower point of inflection between the thoracic and cervical curvatures and by the upper point of the C1 vertebra (see Fig. 2). Two parameters are calculated at each anatomic area: a shape parameter corresponding to magnitude β of the curvature (LL, TK, and CL) and an orientation parameter α measuring the angular offset (or tilt) with respect to the

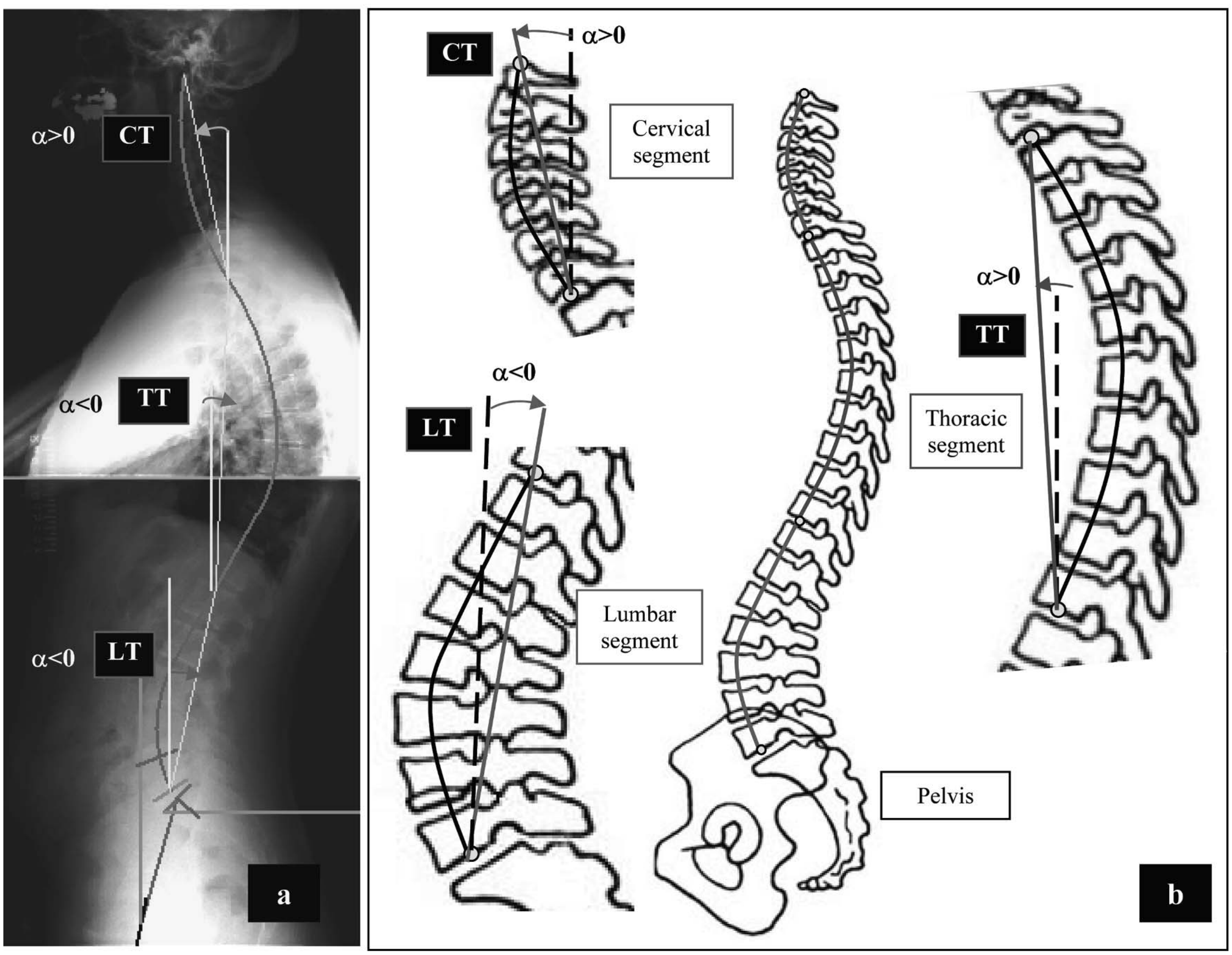

FIGURE 2. A, Sagittal X-ray of the spinal regions with their orientation (LT, TT, CT) parameters. B, Schematic drawings with the spine orientation parameters.

vertical of the line connecting the lower and upper levels of the segment, namely, lumbar tilt (LT), thoracic tilt (TT), and cervical tilt (CT). α is >0 if the region is tilted backward and <0 if it is tilted in the opposite direction. Shape and tilting parameters are automatically calculated from the recording of six points and six tangents, and the results are presented in the following manner:

Segment	Orientation Parameter α	Shape Parameter β
Lumbar	LT	LL
Thoracic	TT	TK
Cervical	CT	CL

For the pelvis, three angular parameters are calculated from eight recorded points on each radiograph: one shape parameter, PI, defined as the angle between a line perpendicular to the sacral plate and a line joining the sacral plate to the axis of the femoral heads; and two orientation parameters, SS, defined as the angle between the sacral plate and the horizontal line, and PT, defined as the angle between the vertical line and the line joining the middle of the sacral plate and the axis of the femoral heads. It is positive when the hip axis lies in front of the middle of the sacral plate. Shape and tilting parameters of the pelvis are automatically calculated from eight recorded points on each radiograph, and the results are presented in the following manner:

	Orientation Parameter		Shape Parameter
Segment	Pelvic Tilt	Sacral Slope	Pelvic Incidence
Pelvic	PT	SS	PI

All described shape and tilting parameters of the spine and pelvis were made on the lateral radiographs using the dedicated software previously mentioned. Statistical analysis was done using descriptive statistics and linear regression analysis. For each anatomic segment (cervical, thoracic, lumbar, and pelvic) and for both shape and orientation parameters, the mean values and corresponding standard deviations were calculated for the entire sample. Linear correlations between pairs of parameters (shape and/or orientation) were calculated at every level and between each level using Pearson correlation coefficients. Each couple of parameters was represented as a point in a graph expressing the value of each parameter as a function of the other one. For the entire sample, a cluster of representative points is thus obtained (Fig. 3). The level of statistical significance was set at $P = 0.01$ (99%) rather than $P = 0.05$ (95%), considering the high number of correlation tests performed.

RESULTS

Table 1 presents the mean values, the standard deviations, and the ranges obtained for each shape and orientation variable. The values for PI, SS, PT, LL, TK, and CL are similar to those published in previous studies of sagittal spinopelvic balance in adults.[1–3,5,6,11] As for the values for the proposed parameters of orientation of the spine (LT, TT, and CT), to our knowledge, there are no other values available in the literature for comparison. It should be noted that the lumbar (LT) and thoracic (TT) segments tend to be aligned vertically, whereas the cervical segment (CT) is always tilted slightly forward by an average of 24°, ranging from 10° to 45°. It is also interesting to note that there is limited variability in these orientation indexes for the spine as expressed by small standard deviations as opposed to the larger variability found for measures of spinal shape. Figure 4 displays in a graphic manner the mean values and the ranges for orientation (Fig. 4A) and shape (Fig. 4A)

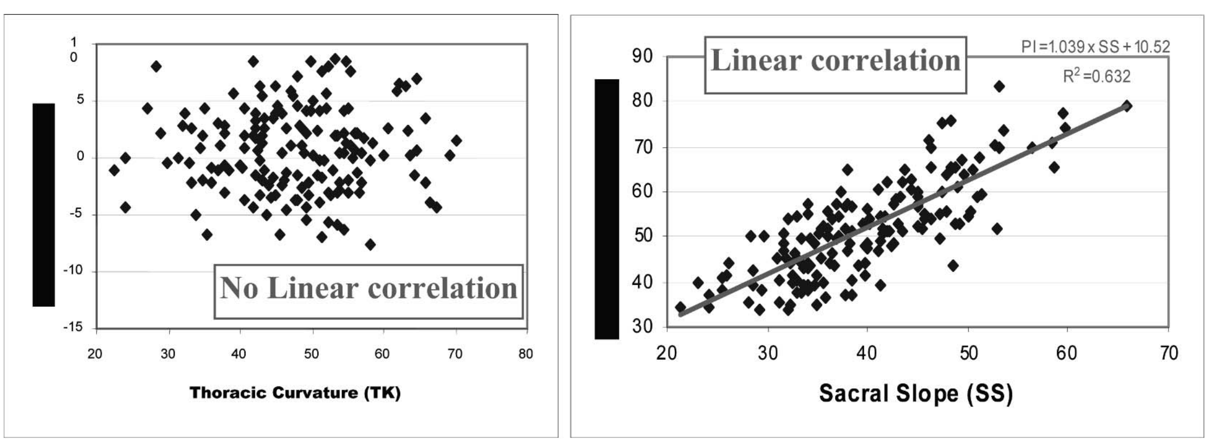

FIGURE 3. Examples of clusters of representative points between two pairs of parameters (TT vs TK, and PI vs SS). If the cluster has a significant linear shape, it is represented by its regression line and its corresponding coefficient of linear regression.

TABLE 1. Mean Values, Standard Deviations (SD), and Range Values Obtained for each Shape and Orientation Parameter

Variables	n	Mean	± SD	Range Min	Range Max
PI	160	51.80	5.32	33.7	83.7
SS	160	39.74	4.07	21.2	65.9
PT	160	12.07	3.23	−5.1	30.5
LL	160	42.69	5.39	16	71.9
LT	160	−5.85	2.34	−16.8	10.8
TK	160	47.54	4.80	22.5	70.3
TT	160	0.65	1.95	−10.8	8.8
CL	102	23.90	3.97	9.5	44.5
CT	102	20.04	2.56	9.4	32

parameters at each anatomic area from the pelvis to the head. The figure thus graphically depicts the limits within which the shape and orientation of the spine and pelvis of an asymptomatic adult should be contained. The two limits are obtained by drawing the curves corresponding to the lower and upper boundaries of tilting and shape parameters, respectively, calculated for each area of the spine. The clinical usefulness of this visual tool is illustrated in Figure 4C, in which the spine and pelvis of a subject with a grade II isthmic spondylolisthesis are clearly seen to be outside the normal boundaries for both shape and orientation.

Table 2 presents the correlations between all parameters of shape and orientation of the spine and pelvis. Significant linear correlations between pairs of parameters are explicitly shown with the values of the Pearson coefficients (r and P) at the level of significance for $P < 0.01$. Many significant linear correlations were found, but correlation levels varied from none, such as between TT and TK, to very highly significant, such as between PI and SS ($r = 0.81$, $P < 0.001$), as shown in Figure 3. Significant linear correlations were found between each single adjacent shape parameter (PI and LL: $r = 0.62$, $P < 0.001$; LL and TK: $r = 0.27$, $P = 0.008$; TK and CL: $r = 0.36$, $P < 0.001$) as well as between each single adjacent orientation parameter at all anatomic levels (SS and LTL, $r = 0.48$, $P < 0.001$; LT and TT: $r = 0.37$, $P = 0.001$; TT and CT: $r = 0.42$, $P < 0.001$). Significant correlations were also found between some shape and orientation parameters at the same anatomic level (PI and SS for pelvis: $r = 0.81$, $P < 0.001$; LL and LT for lumbar segment: $r = 0.24$, $P = 0.009$) as well as between adjacent anatomic areas (PI and LT: $r = 0.54$, $P < 0.001$; SS and LL: $r = 0.65$, $P < 0.001$; LT and TK: $r = -0.48$, $P < 0.001$; TK and CT: $r = 0.58$, $P < 0.001$).

Figure 5 is a diagram illustrating the linear chain of linked anatomic areas from the pelvis to the cervical curvature and summarizing the various correlations found at and between each area for both shape and orientation variables. As there are

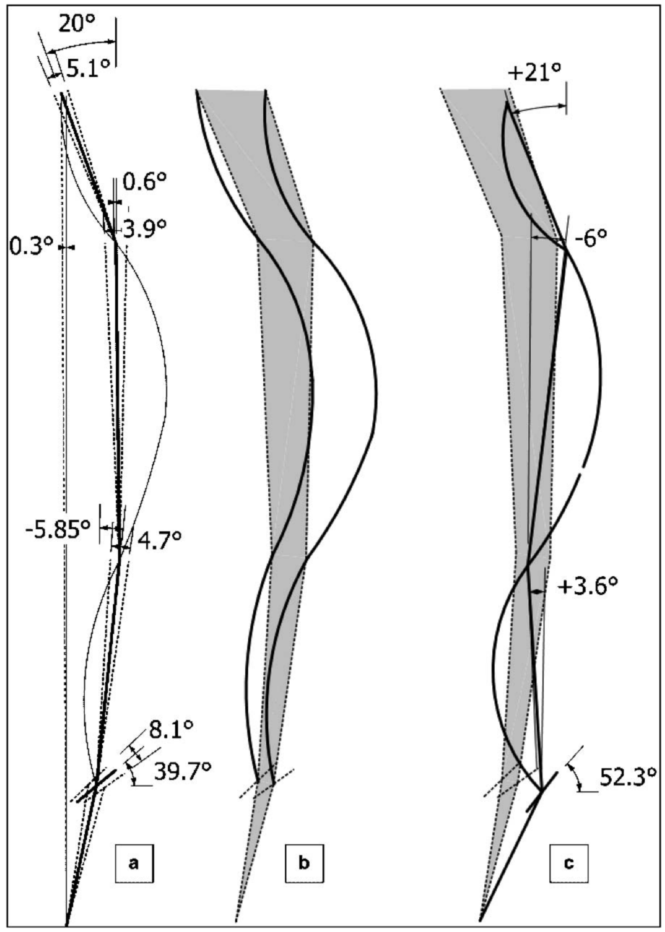

FIGURE 4. Simplified representation of the spine and pelvis illustrating the ranges of orientation parameters in normal asymptomatic adult volunteers. A, Ranges of orientation parameters of spinal and pelvic segments. Ranges for each individual segment is shown in dotted lines with the corresponding average values and ranges in numbers. B, The gray shaded area represents the limits of orientation inside which the shape of the spine and pelvis of an asymptomatic adult is contained, based on the ranges of orientation presented in figure 4a. C, Simplified representation of the spine and pelvis of a patient with a Grade II isthmic spondylolisthesis, with the gray shaded area representing the normal limits of orientation inside which the shape and pelvis of normal adults is contained. It can be clearly seen that the pelvis, a large part of the lumbar area and parts of the thoracic and cervical areas and outside these normal boundaries, indicating an abnormal orientation of the sagittal spino-pelvic unit.

two orientation variables at the pelvic level and the correlations found with other variables were stronger with the SS than with the PT, we retained only SS in the diagram for purposes of clarity. In general, it can be noted that all variables measured at the pelvic and lumbar areas were correlated and that the linear correlations were stronger between shape and orientation variables at the pelvic, lumbar, and cervical areas as well as be-

TABLE 2. Table of Significant Linear Correlations Between Couples of Parameters

	Pelvis			Spine					
Pearson	**PI**	**SS**	**PT**	**LL**	**LT**	**TK**	**TT**	**CL**	**CT**
Pelvis									
PI		0.81*	0.62*	0.62*	0.54*	X	X	X	X
SS			X	0.65*	0.48*	X	X	X	X
PT				0.21	0.27*	X	X	X	X
Spine									
LL					0.24*	0.27*	X	X	X
LT						−0.48*	0.37*	X	X
TK							X	0.36*	0.58*
TT								X	0.42*
CL									X
CT									

*Significant correlation at the level p = 0.01 (99%).

tween the pelvic and lumbar areas and weaker at the thoracic level and between the thoracic and lumbar areas. In contrast with the lumbar and pelvic levels, there were no significant linear correlations found between shape and orientation parameters at the cervical or thoracic areas.

DISCUSSION

The results of this study support the concept that the pelvis and spine of young asymptomatic adult volunteers can be considered in the sagittal plane as an open linear chain linking the head to the pelvis, in which the shape and orientation of each anatomic segment are closely related and influence the adjacent segment to maintain a stable posture with a minimum of energy expenditure. This concept implies that a change in shape or orientation at any level will effect a change on adjacent segments and will modify their shape and/or orientation. The fact that many correlations were found between variables does not, however, imply a causal relationship, except for PI, a shape variable that has been shown to be an anatomic signature describing the shape of a particular pelvis[6] and to directly influence the two orientation pelvic measures by virtue of a mathematical relationship (PI = SS + PT) as well as to directly influence the shape variable LL of the lumbar spine.[6] These correlations do indicate, however, that when one variable of shape or orientation changes as a consequence of a postural change, of a specific treatment, or of a pathologic disorder, then some variables at the same anatomic level or at an adjacent level will be affected and will change the spinopelvic balance. Knowledge of these normal relationships is of prime importance for the comprehension of sagittal balance in normal and pathologic conditions of the spine and pelvis. Our group has previously reported[11] the mean values of shape parameters in the sagittal spine as well as the shape and orientation parameters of the pelvis in a subgroup of the current cohort of asymptomatic young adults. Similar correlations were found for these parameters. This study has expanded the number of subjects in the cohort, proposes to add orientation parameters of the spine to the evaluation of spinopelvic balance, and introduces the concept of the open linear chain linking the head to the pelvis.

The geometric balance of the chain formed by the pelvis and spine can be estimated visually (see Fig. 4A) and mathematically (see Table 1), through the angular offsets or tilts, with respect to the vertical, of the lines representing the different anatomic regions. It can been observed that in standing subjects harmoniously balanced, the value of the orientation of each region (CT, TT, LT) is low and varies little (small standard deviation), indicating that the spine in an asymptomatic subject is balanced in such a way that its constitutive regions are oriented close to the vertical with minimal variability. The cervical segment is usually in a slight forward tilt averaging 20°, whereas the thoracic segment is vertical and the lumbar segment is in slight backward tilt averaging 6° (see Table1).

The simplified representation of the spine and pelvis displayed in Figure 4 and derived from the ranges of values obtained in the cohort for orientation (Fig. 4A) and shape (Fig. 4B) of the spinopelvic unit provides a simple tool to visualize the upper and lower limits of a normal sagittal spinopelvic posture. It can be used by clinicians to assess whether the spinopelvic unit of an individual affected by a pathologic disorder lies between these boundaries and is thus within normal limits or to assess the results of a treatment such as bracing or surgery on the spinopelvic balance (see Fig. 4C).

Likewise, Figure 5 provides a visual tool to better understand the complex relationships found in this study between shape and orientation variables at different levels. It can be

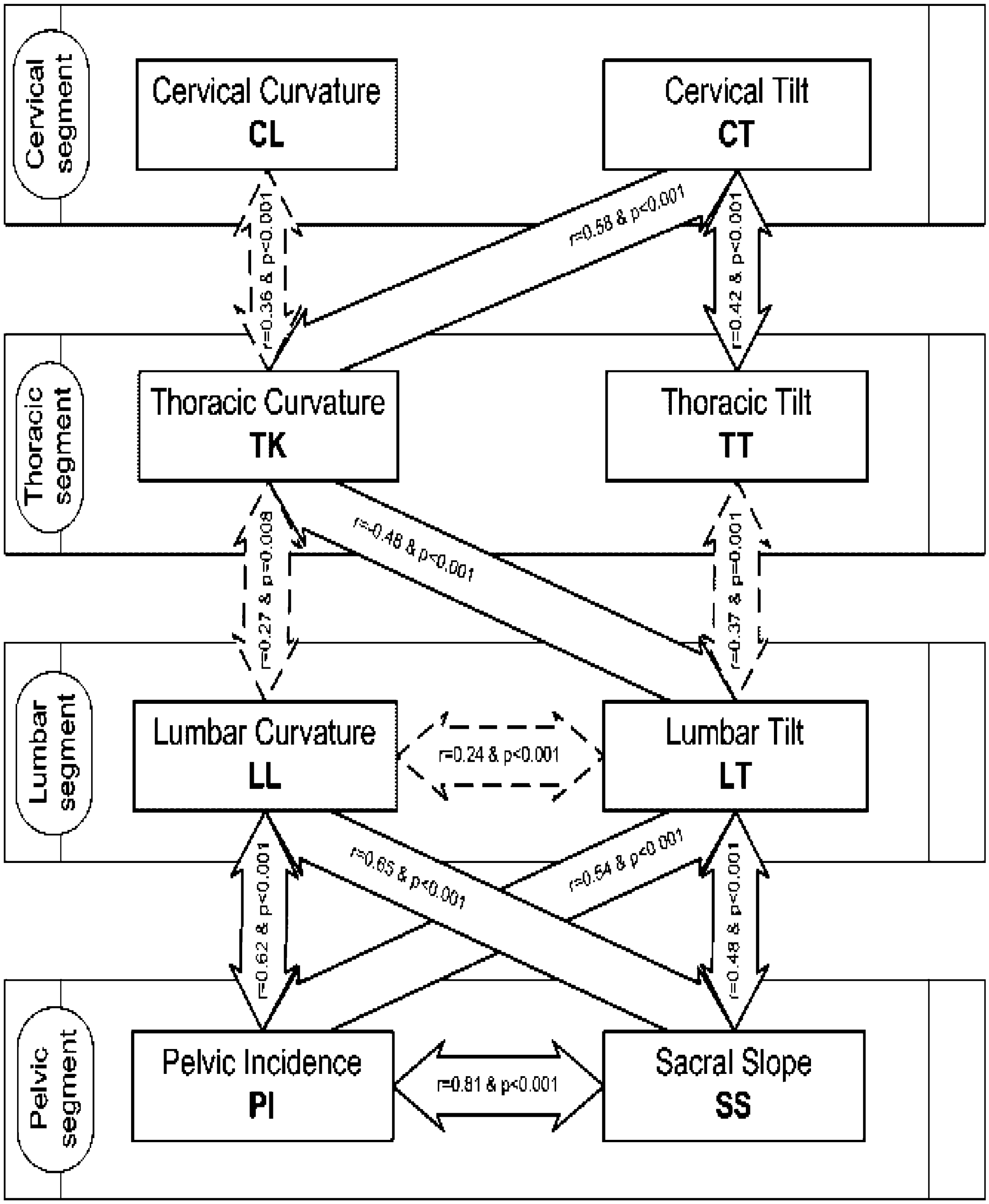

FIGURE 5. Diagram illustrating the linear chain of linked anatomical areas from the pelvis to the cervical curvature. The shape and orientation parameters of the adjacent areas are displayed at the left and right side of the diagram. Significant linear correlations are represented as arrows connecting two different parameters of the same nature (shape or orientation) or of different nature. Arrows in full lines indicate a strong clinical correlation (r > 0.4) and in dotted lines a weaker but statistically significant correlation (0.2 < r < 0.4, p < 0.01).

seen that all parameters at the pelvic and lumbar levels are strongly correlated, as well for the correlations between shape and tilt parameters for a same segment as for the relationship between the pelvic and lumbar segment, that is, relations between shape parameters, orientation parameters, and cross-relationships. The same phenomenon is observed at the junction between the thoracic and cervical segments, but the corresponding correlation coefficients are smaller. There is weak correlation between lumbar and thoracic segments. A possible explanation for this observation is that the stronger correlations between shape and orientation parameters are more likely to occur at the highly mobile areas of the spine, namely, the lumbar and cervical areas. The less mobile thoracic spine does not appear to react and compensate as easily to changes in shape or orientation of the pelvis, lumbar, or cervical spine. This information brought by the correlations between shape and orientation parameters along the spine should be used to better understand the mechanisms of normal sagittal spinopelvic balance.

All shapes and orientations of pelvic and lumbar segments are significantly correlated and influence each other: A surgical change of the PI will have effects on both curvature and orientation of the lumbar segment. Similarly, a change in PT or in the SS will act directly on the lumbar curvature and its orientation.

The linear correlation between shape and orientation is very strong at the pelvic area but weaker at the lumbar area and nonsignificant at the thoracic and cervical areas. We think this is because there is a well-demonstrated geometric relationship between shape and orientation at the pelvic level (PI = SS + PT), a relationship that is not present at other levels of the spine, thus explaining the weaker or absent correlations. Another possible explanation could be a size effect or type II error. This is much less likely as our sample size is fairly large, but we are currently accumulating more volunteers to exclude this possibility. We believe that a problem with the accuracy of the system is not a likely explanation, as a previous study done with this measurement system has demonstrated that the intra- and interobserver variations are very small and have very little influence on the calculated data.[10]

The concept presented is a research tool that will need to be further validated with comparisons between normal and affected individuals with spine or pelvic diseases that can alter the shape and/or orientation of the trunk in the sagittal plane. The results provide a basis from which sagittal spinopelvic balance in pathologic disorders of the spine and pelvis can be evaluated, but they should be used only for young adult male subjects between 20 and 40 years of age, which constitutes most of the cohort studied. Mean values for shape and orientation variables may be different in an older age group or in a cohort with a predominance of females. It would also be interesting to evaluate these parameters in children and adolescents, as results for shape parameters of spinopelvic balance have been shown to vary according to age and sex.[12] Diagrams such as the one presented in Figure 4 could serve as a simple template to establish if the normal sagittal spinopelvic balance of a particular individual is affected or not by a disease and to evaluate the effect of a treatment of such a disorder.

CONCLUSION

In conclusion, the evidence presented supports the concept that the spinopelvic balance in the sagittal plane can be considered as an open linear chain linking the head to the pelvis where the shape and orientation of each successive anatomic segment are closely related and influence the adjacent segment. Changes in shape or orientation at one level will have a direct influence on the adjacent segment. Knowledge of these normal relationships is of prime importance for the comprehension of sagittal balance in normal and pathologic conditions of the spine and pelvis.

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