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Development of clinical methods for measuring geometric alignment of the thoracic and lumbar spines of wheelchair-seated persons

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Abstract—This study investigated the use of the geometric alignment of two frontal lines (the sternum and abdominal) for predicting alignment of the thoracic and lumbar spines and for measuring wheelchair-seated posture. The sternum line connects the upper sternum point and the lower sternum point. The abdominal line connects the lower sternum point and the center point between the right and left anterior superior iliac spines. I compared the alignment of these two frontal lines in 10 normal subjects by examining the positions of the spinous processes of their thoracic and lumbar spines in 16 sitting postures. Inclination of the sternum line correlated with that of the thoracic spine in both the frontal and sagittal planes; inclination of the abdominal line correlated with that of the lumbar spine in both planes as well. The length of the abdominal line was correlated with lumbar spine length, and the direction of curvature of the lumbar spine was either convex anterior or posterior.

Key words: anatomical segment lines, lumbar inclination, lumbar spine, pelvic alignment, posture-support device, seated-posture evaluation, spinal alignment, thoracic inclination, thoracic spine, wheelchair.

INTRODUCTION

Seated posture is one of the major factors in the etiology of pressure sores, and it has significant effects on the comfort, function, physiology, mobility, and cosmetic features of the spine [1–4]. Pelvic/spinal alignment is considered one of the most important variables in special seating [5].

Generally, a person's posture in a wheelchair seat is evaluated only qualitatively. Evaluation forms have been produced that researchers use to document a patient's personal information, environment of use, current positions and equipment, mat evaluations, anthropometric measurements, and evaluations of typical body postures. These forms are available from RehabCentral.com [6]. The evaluation forms classify postures of the trunk into six categories: neutral, collapsed, hyperextended, forward flexed/rounded, shortened right/left, and rotated right/left. Mat evaluation forms use three anatomical classifications to describe the trunk: total spine, lumbar space, and rib cage deformities of the total spine are also classified into three categories: straight, scoliotic, and kyphotic. The lumbar spine and rib cage are each classified into three categories: normal, flat, and lordotic, and even, forward (right and left),

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Abbreviations: AL = abdominal line, ASIS = anterior superior iliac spine, C = cervical, COF = center of fulcrum, IAL = inclination of the abdominal line, ISL = inclination of the sternum line, L = lumbar, LAL = length of abdominal line, LED = light-emitting diode, LSL = length of sternum line, SL = sternum line, Th = thoracic, 3-D = three-dimensional.

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and lower (right and left), respectively. The magnitude and rigidity of deformities of the spine are also classified into three categories: fixed, flexible, and corrects with difficulty.

Studies have reported pelvic and hip angles of seated individuals that were measured with an electromagnetic tracking device and a goniometer [7–9]. Hobson and Tooms measured seated lumbar/pelvic alignment with a radiograph series that included lateral and anteroposterior views, and these data showed differences between groups with and without spinal cord injuries [10].

Ferguson-Pell et al. used metal probes passed through an array of holes in a vertical peg-board frame to measure spinal curvature through an open-weave canvas replacement of the wheelchair backrest [11]. When developing a new backrest for wheelchairs, Parent et al. measured dorsal profiles by digitizing back shapes through holes in the seat back [12]. Similarly, when developing a new wheelchair, Sakajiri et al. measured the dorsal profiles of subjects using a special chair [13]. Reed et al. used a special laboratory seat that allowed access to the spine and simulated posture of subject in a normal automobile seat [14].

Some studies use frontal measures to describe seated posture. Fife et al. introduced the "seated postural control measure: alignment section" from a form developed at Sunny Hill Hospital for Children, Vancouver, British Columbia, Canada [15]. Researchers use this form for recording descriptive categories and numerical scores of alignment postures, including pelvic obliquity and trunk lateral shift in the anterior view and pelvic tilt and head anterior/posterior tilt in the right lateral view. Hirose et al. studied and described posture in seat-support devices with the use of stick figures [16]. The stick figures were composed of lines connecting anatomical landmarks that had been previously digitized. The study reported a number of anatomical points that were important for the measurement of postural changes, but did not include the positions of the important spinal segments.

The research objective was to find indices that describe the spinal alignment of a wheelchair-seated person with the use of frontal body landmarks. Since the sternum is connected to the rib cage, as well as the thoracic spine, it provides a means for predicting the alignment of the thoracic spine. In addition, the anterior superior iliac spines (ASISs) are a part of the pelvis that connect directly to the lumbar spine. Researchers may be able to use these landmarks, which are located on the readily accessible frontal aspect of the body, to define anatomical segment lines, the spatial orientation of which are reliable predictors of a person's seated spinal alignment.

In summary, if a significant correlation between the orientation of the frontal sternum and abdominal lines and the alignment of the thoracic and lumbar spines can be found, the frontal lines could be used for predicting alignment of the thoracic and lumbar spines.

The frontal segment lines of interest **(Figure 1)** are defined:

- The sternum line (SL): a line between the upper sternum point and the lower sternum point.
- The abdominal line (AL): a line between the lower sternum point and the center point between the right and left ASISs.

METHODS

Measurement System

The measurement system included a three-dimensional (3-D) digitizer (FLASH POINT 3000, Pixsys, Inc., Colorado, United States), which consisted of three cameras, a 60 cm-long probe with 2 light-emitting diodes (LEDs), a

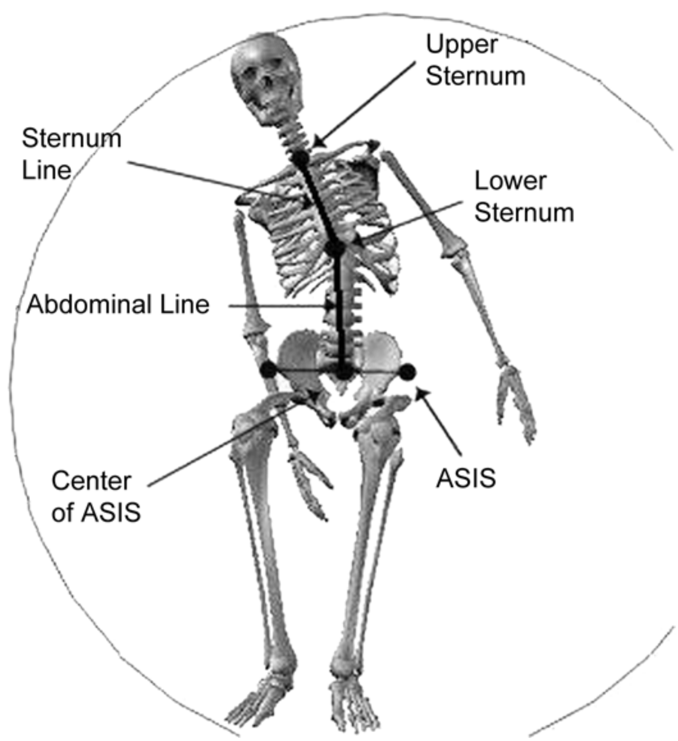

Figure 1.
Skeleton model showing frontal segment lines. Sternum line connects upper sternum and lower sternum. Abdominal line connects lower sternum and midpoint of right and left anterior superior iliac spines (ASISs).

controller, and a personal computer (to process data) (**Figure 2**). This system was selected for the following reasons:

- The probe has two LEDs so that anatomical landmarks, including the ASISs, were not obscured by the body and severe postures could be measured.
- The digitizing volume includes the user's body and posture support device (active digitizing volume: scalable 0.5 to 2 m^3).
- The digitized points are accurate (accuracy ±0.5 mm, repeatability ±0.2 mm).

The specification sheet of the system shows an accuracy of ±0.5 mm and repeatability error of ±0.2 mm. In my laboratory, repeatability was greater than ±0.1 mm and the maximum error was 1.2 mm; repeatability and error were assessed for a distance of 90 cm between two points on a ruler that is the authorized Japanese industrial standard for this system.

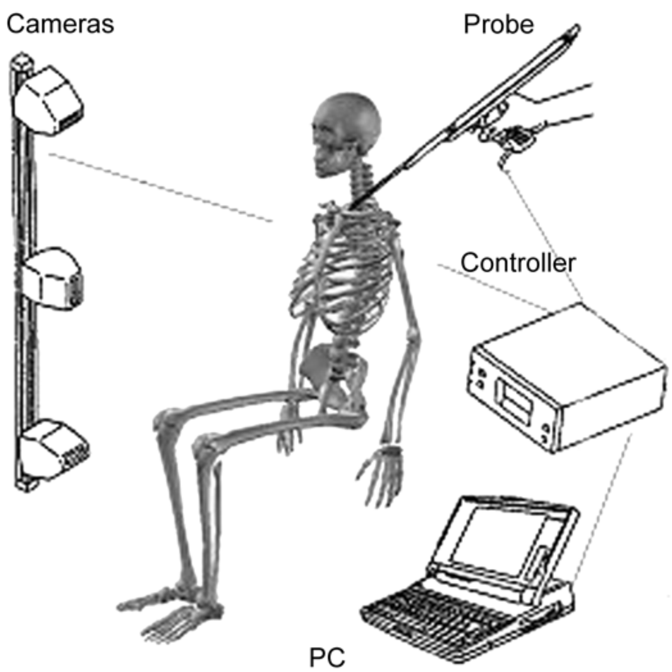

Figure 2.
Measurement system for digitizing anatomical landmarks. Positions of anatomical landmarks, indicated by probe, can be calculated from two light-emitting diode positions, which are recorded by three cameras. Controller performs decision of coordination axis, calculation of position indicated by probe, and data transfer to personal computer (PC). PC stores data and displays stick figure based on positions of anatomical landmarks.

Subjects and Measurement

Ten subjects, without spinal problems (ages 23–38, height 168–184 cm, 100% male), who were able to assume many postures in response to verbal instructions, participated in this study. I explained the purpose of the study, the safety concerns, and the privacy issues (including the use of a photograph) to all subjects; they then provided informed consent.

The subjects sat naked on a plastic foam cushion (40 cm wide, 6 cm thick) that was placed on an elevated platform (70 × 30 cm, 41.5 cm above the ground). The origin of the measurement system was 1.5 cm from the back side and on the center line of the long side of the platform. Subjects sat on the origin, aligned on the center point of their left and right ischial tuberosities. A vertical line (z-axis), a horizontal line parallel to the long side of the platform (x-axis), and a forward line from the origin (y-axis) were used to define the three planes used in the experiment (**Figure 3**). The frontal plane was composed of the y- and z-axes, the sagittal plane was composed of the x- and z-axes, and the horizontal plane was composed of the x- and y-axes.

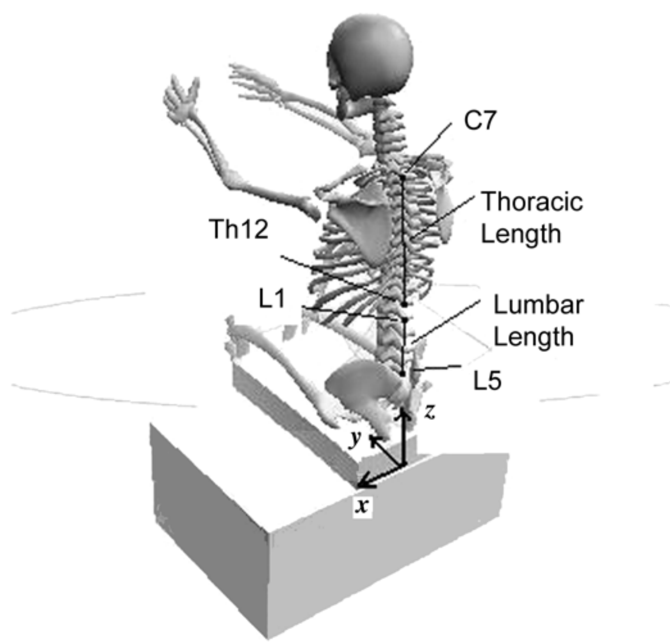

Figure 3.
Measurement system calculated thoracic length as distance between spinous processes of cervical vertebrae 7 (C7) and thoracic vertebrae 12 (Th12), and lumbar length as distance between spinous processes of lumbar vertebrae 1 (L1) and lumbar vertebrae 5 (L5). Frontal plane was composed of y- and z-axes, sagittal plane was composed of x- and z-axes, and horizontal plane was composed of x- and y-axes.

Subjects were asked to assume 16 postures in accordance with verbal instructions and to hold these postures for 1 to 2 min for measurement. The relationships between the orientation of the frontal SL and AL and the alignment of the thoracic and lumbar spines were examined. The postures were selected from categories of postures of the trunk and deformities of the total spine [6]. The verbal instructions for the 16 postures were, “sit normally, straighten your back, tilt your back backward, tilt your back forward, make a slightly rounded back, make an extremely rounded back, tilt your back a little with the left side straight, tilt your back a little with the right side straight, tilt your back with the left side straight, tilt your back with the right side straight, make your back form a slight left C-curve, make your back form a slight right C-curve, make your back form a hard left C-curve, make your back form a hard right C-curve, rotate your back to the right, and rotate your back to the left.”

Nineteen points were digitized, including four abdominal anatomical points (upper and lower sternum points and right and left ASISs), twelve dorsal anatomical points, and three floor points. The twelve dorsal anatomical points included the spinous processes of the following vertebrae: cervical (C) 7; thoracic (Th) 2, 4, 6, 8, 10, and 12; and lumbar (L) 1 to 5. These points were selected because their neutral positions are known. These 16 anatomical body points were palpated and then digitized with the measurement system.

Data Processing

This study sought to (1) compare sternum inclinations with thoracic inclinations and abdominal inclinations with lumbar inclinations in seated postures and (2) compare the length of the SL with thoracic length and the length of the AL with lumbar length.

Inclinations of the sternum line (ISL) were compared with thoracic inclination, and inclinations of the abdominal line (IAL) were compared with lumbar inclination. I calculated these parameters by taking the mean of the angles (except the minimum and maximum) of two adjacent anatomical points in both the thoracic and lumbar spines. I used this method to avoid affecting errors in digitizing the anatomical points and because of the difficulty in digitizing the anatomical points when the spine is rotated. A linear, least squares, fitting technique was used to analyze these data.

The length of the sternum line (LSL) was calculated (from digitized points) as the distance between the upper sternum and the lower sternum. The length of the abdominal line (LAL) was determined (from digitized points) as the distance between the lower sternum and the center point between the right and left ASISs. The thoracic length, which is the length of a straight line connecting the spinous process of C7 with that of Th12, was calculated and statistically compared with the LSL. The lumbar length, which is the length of the straight line connecting the two spinous processes of L1 and L5, was calculated and statistically compared with the LAL.

RESULTS

Figure 4 shows digitized plots of the typical seated posture in the frontal (**Figure 4(a)**) and sagittal (**Figure 4(b)**) planes after the verbal instruction, “tilt your back with the left side straight.” All angular measurements start from the positive *z*-axis (or positive *y*-axis in the horizontal plane) and continue 360° in a clockwise direction, according to the left-hand screw rule [17]. Inclinations in the frontal plane show the same positive angles for the thoracic and lumbar spines and the SL and AL. By contrast, the inclinations in the sagittal plane are different because of the differences between frontal and dorsal profiles.

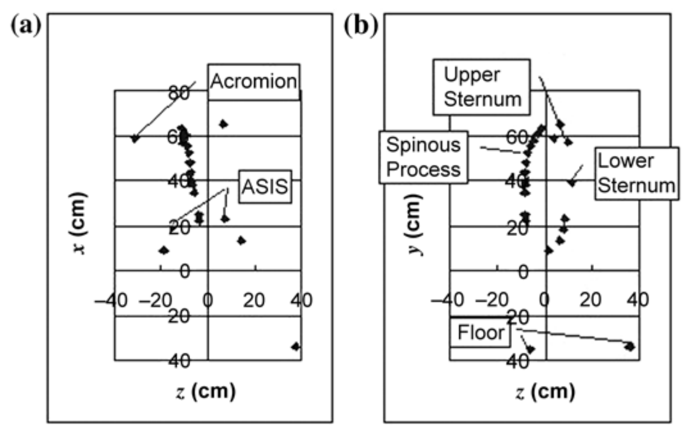

Figure 4.
(a) Frontal plane: inclination of sternum line (ISL) = 8.8°, inclination of abdominal line (IAL) = 13.1°, thoracic inclination = 11.4°, lumbar inclination = 10.5°. **(b)** Sagittal plane: ISL = –7.1°, IAL = 10.8°, thoracic inclination = 19.9°, lumbar inclination = –4.2°. Length of sternum line = 18.4 cm, length of abdominal line = 19.6 cm, thoracic length = 21.1 cm, lumbar length = 18.7 cm. All angular measurements start from positive *z*-axis (or positive *y*-axis in the horizontal plane) and continue 360° in a clockwise direction, according to the left-hand screw rule. ASIS = anterior superior iliac spine.

Figure 5 shows regression plots of the relationships between the ISL and the thoracic inclination in each plane. In the frontal plane (**Figure 5(a)**), the graph shows a positive relationship and a straight line through the origin. In the horizontal plane (**Figure 5(b)**), the graph shows no relationship. In the sagittal plane (**Figure 5(c)**), the graph shows a positive relationship and a straight line that does not pass through the origin.

Figure 6 shows regression plots of the relationships between the IAL and the lumbar inclination in each plane. For each of the three planes, the characteristics of the relationships between the IAL and the lumbar inclination are the same as those for the ISL and the thoracic inclination (**Figure 5(a)–(c)**).

Table 1 presents, for each subject, the correlation and regression coefficients of the analysis between the ISL and the thoracic inclination and the IAL and lumbar inclination in both the frontal and sagittal planes.

The average correlation coefficients for the ISL and the thoracic inclination and the IAL and the lumbar inclination, for both planes, were between 0.86 and 0.90, respectively, which shows a high degree of association. Since the regression lines were linear, the regression coefficients of the lines were compared. The average regression coefficients were between 0.88 and 1.05. When a body leans toward one side, the results show that the ISL is the same as the thoracic inclination, in the frontal plane. In addition, the IAL is the same as the lumbar

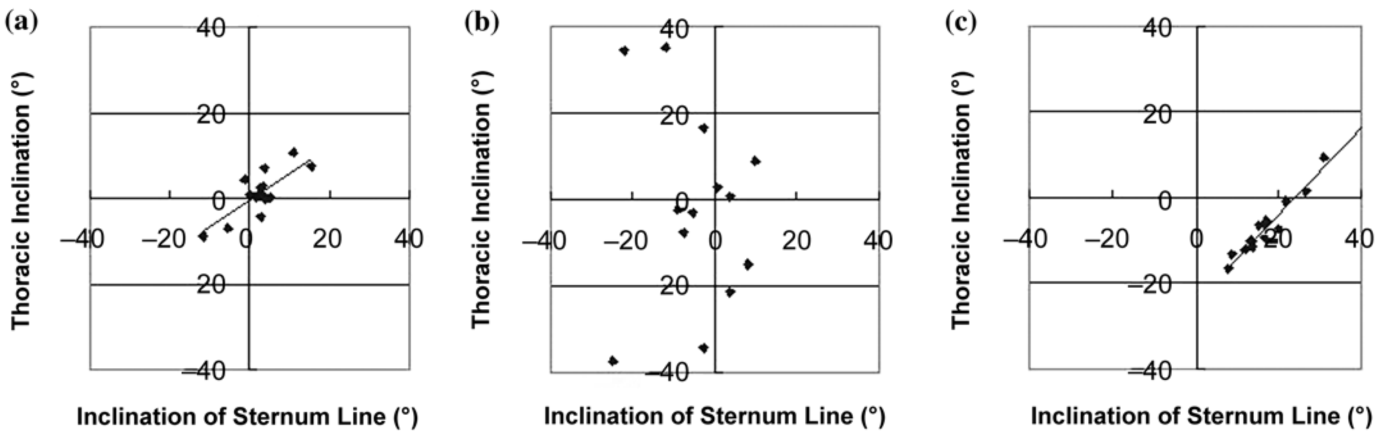

Figure 5.
Relationships in **(a)** frontal, **(b)** horizontal, and **(c)** sagittal planes between inclination of sternum line and thoracic inclination. Lines in **(a)** and **(c)** are regression lines drawn on scatter diagram.

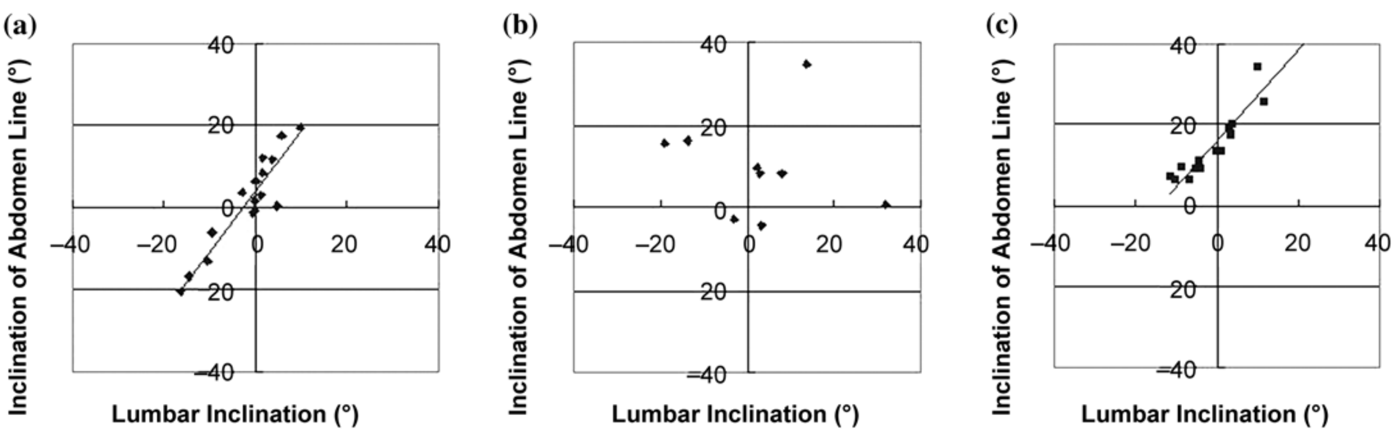

Figure 6.
Relationships in **(a)** frontal, **(b)** horizontal, and **(c)** sagittal planes between inclination of abdominal line and lumbar inclination. Lines in **(a)** and **(c)** are regression lines drawn on scatter diagram.

Table 1.
For each subject, correlation and regression coefficients for analyses between inclination of sternum line (ISL) and thoracic inclination and between inclination of abdominal line (IAL) and lumbar inclination, in frontal and sagittal planes.

Subject	ISL vs. Thoracic Inclination				IAL vs. Lumbar Inclination			
	Frontal Plane		Sagittal Plane		Frontal Plane		Sagittal Plane	
	r	*b*	*r*	*b*	*r*	*b*	*r*	*b*
1	0.91	0.88	0.99	0.83	0.78	0.91	0.64	0.87
2	0.94	1.18	0.88	1.04	0.82	0.91	0.94	1.12
3	0.88	0.95	0.98	0.95	0.91	0.89	0.76	0.68
4	0.94	0.88	0.97	0.97	0.75	1.26	0.78	1.14
5	0.99	1.02	0.96	0.82	0.69	0.79	0.91	0.79
6	0.94	1.16	0.90	1.08	0.92	1.16	0.93	1.24
7	0.87	0.84	0.73	0.67	0.94	1.05	0.96	1.08
8	0.87	0.85	0.71	0.63	0.94	1.05	0.97	1.10
9	0.82	0.64	0.97	1.03	0.94	1.45	0.96	1.13
10	0.87	0.91	0.88	0.78	0.91	1.00	0.93	0.97
Mean	0.90	0.93	0.90	0.88	0.86	1.05	0.88	1.01

r = Pearson's correlation coefficient   *b* = regression coefficient

inclination because the regression lines of the frontal plane in **Figures 5(a)** and **6(a)** show an inclination of 45° through the origin. In the sagittal plane, the variation of the ISL is the same as the thoracic inclination and the variation of the IAL is the same as the lumbar inclination. This is because the regression lines show an inclination of 45°, but do not pass through the origin. A typical relationship between LSL and thoracic length shows no correlation, with the LSL remaining constant and thoracic length changing (**Figure 7(a)**). A typical relationship between the LAL and lumbar length shows only a moderate inverse relationship (**Figure 7(b)**).

Table 2 presents the correlation and regression coefficients for analyses of the LAL and lumbar length and LSL and thoracic length, for each case. The correlation coefficients of the LSL with thoracic length ranged between 0.26 and –0.49, which indicates no relationship. The correlation coefficients of the LAL with abdominal length ranged from –0.81 to –0.93 (mean = –0.87), which shows a strong negative correlation. The regression coefficients of the relationship between LAL and lumbar length ranged from –1.33 to –3.73 (mean = –2.4).

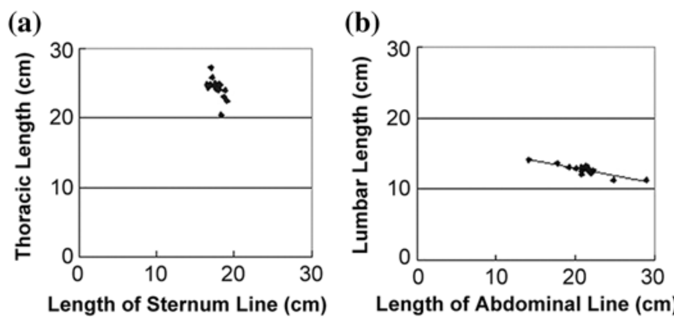

Figure 7.
Relationship between **(a)** thoracic length and length of sternum line and **(b)** lumbar length and length of abdominal lines obtained from all postures from a subject. Line in **(b)** is a regression line drawn on scatter diagram.

DISCUSSION

The accuracy of the anatomical positions I used in this study was influenced on three levels, namely error from the measurement system, error from variation in the positions of the anatomical points between subjects [18], and error from movement of the subjects when the postures were measured. Maltais et al. reported the accuracy of measuring the positions of anatomical landmarks to evaluate seated postures, and they showed that measurements of the positions of the upper sternum (suprasternum notch), lower sternum (xyphoid process), and ASISs have less variability when compared with those of the great trochanter and the iliac crest [19]. The center of movement that occurs during flexion and extension of the thoracic and lumbar spines is known as the instantaneous axis of rotation and is not a spinous process [20]. Bryant et al. reportedly estimated the positions of the centers of the vertebral bodies of the thoracic and lumbar spines, in the sagittal plane, by measuring the skin profile with high precision [21].

Lateral flexion of the spine occurs with rotation [20], but the degree of rotation is very small [22]. Geometrically, the vertebral body and the spinous processes are in the same position in the frontal plane. Furthermore, the sternum and the vertebral bodies and spinous processes of the thoracic spine move together because the thorax consists of a shell structure [23]. **Table 1** shows high correlations between the ISL and the thoracic inclination; the regression coefficients of ~0.9 show that movement of the sternum is highly associated with that of the thoracic spine. This same trend is seen in the relationship between the IAL and the lumbar inclination.

The ISL and IAL were each compared with the thoracic and lumbar inclinations. The results showed high correlations between inclinations of skin profiles in the thoracic and lumbar spines and inclinations of the SL and the AL, in the frontal and sagittal planes. Furthermore, the ISL and the thoracic spine as well as the IAL and the lumbar spine covary.

Researchers can, therefore, use the SL and the AL to predict inclinations of the thoracic and lumbar spines, in the frontal and sagittal planes. However, in the horizontal plane, there is no relationship between the SL and the AL and the thoracic and lumbar spines. Because the SL and the AL are connected between the ends of the spinous process of the thoracic and lumbar spines, respectively, they cannot be used to predict the position of the thoracic and lumbar spines in the horizontal plane.

The LSL remained constant despite changes in the thoracic length, because the SL is associated with a single bone, the sternum. However, the relationship between the LAL and lumbar length showed a linear correlation with a gentle inclination. The changes in the LAL were greater in the lumbar region.

These results can be explained by the movement of two levers, each having a center of fulcrum (COF) and two tip points **(Figure 8)**. This movement is similar to that of the thorax in the sagittal plane during respiration [19]. The upper lever is composed of a lower sternum point, the L1 vertebral body as the COF, and the L1 spinous process. The lower lever is composed of a midpoint of the ASISs, the L5 vertebral body as the COF, and the L5 spinous process. For the upper lever, the length between the lower sternum point and the L1 COF is longer than that between the L1 COF and the spinous process in L1. This relation-

Table 2.
For each subject, correlation and regression coefficients for analyses of abdominal and lumbar line lengths and sternum and thoracic line lengths.

Subject	Abdominal vs. Lumbar		Sternum vs. Thoracic	
	r	*b*	*r*	*b*
1	–0.86	–2.60	0.21	0.24
2	–0.89	–1.90	–0.47	–1.16
3	–0.83	–1.84	–0.09	0.04
4	–0.93	–3.16	–0.22	–0.02
5	–0.85	–1.33	0.31	0.05
6	–0.88	–2.15	–0.49	–0.53
7	–0.89	–2.41	–0.14	–0.20
8	–0.81	–2.25	0.01	0.27
9	–0.90	–3.73	0.26	0.07
10	–0.90	–2.59	0.15	0.08
Mean	–0.87	–2.40	–0.05	–0.12

r = Pearson correlation coefficient *b* = regression coefficient

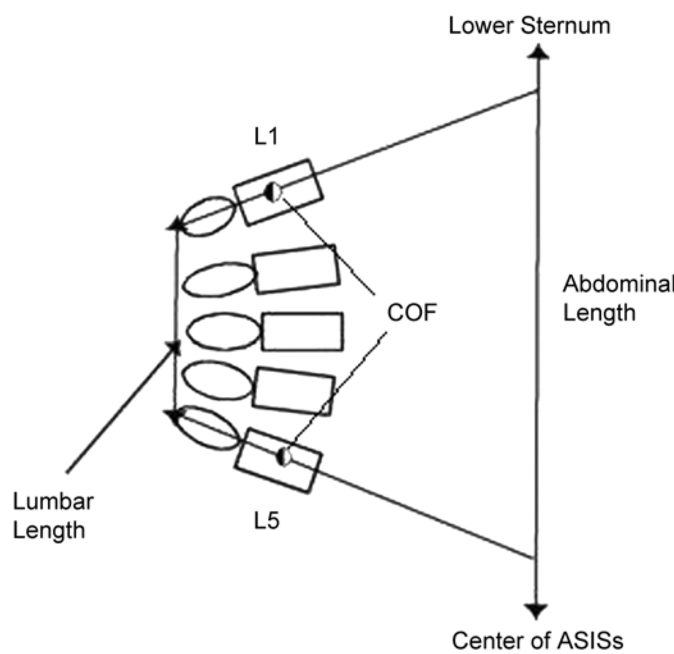

Figure 8.
View of lower spine demonstrates relationship between lumbar length and abdominal length in sagittal plane and lever system. ASISs = anterior superior iliac spines, COF = center of fulcrum, L1 = lumbar vertebrae 1, L5 = lumbar vertebrae 5.

ship is the same for the distances between the midpoint of the ASISs and the L5 COF, and the L5 COF and the L5 spinous process in the lower lever. When the lever rotates at a constant degree in the COF, the LAL is longer than the lumbar length. When the AL extends, the lumbar length shortens by virtue of the lever mechanism. This lever model demonstrates the inverse relationship between the LAL and lumbar length, which is shown in **Figure 7(b)**.

Anatomically, as a vertebra extends, its spinous process approaches the next lower spinous process [14]. Kapandji [20] introduced clinical assessment of the range of movement of the thoracolumbar column by measuring, with a tape, the distance between the spinous processes of C7 and the first sacral vertebrae during extension and flexion [19]. When the lumbar length shortens compared with the neutral position, the curve of the lumbar region becomes convex anterior. When the LAL shortens, the curve of the lumbar region becomes convex posterior, when compared with the neutral position. When the LAL lengthens, it becomes convex anterior. Stewart stated that abdominal compression [4], which can occur while a patient is in a fixed position, can exacerbate a hiatus hernia, an occurrence that can be both uncomfortable for the patient and cause eating difficulties. This may explain why a patient's lumbar region becomes convex posterior and the LAL decreases. However, use of the LAL exclusively for evaluation of the lumbar spine is difficult because the LAL becomes longer when the sternum and pelvis rotate in the opposite directions.

This article has shown that the SL and AL can be used as indices for prediction of the 2-D alignment of the thoracic and lumbar spines, and for evaluation of patients' postures in a wheelchair as well as on a mat [24], from the frontal side.

CONCLUSION

I have suggested two indices for measuring geometric alignment of the thoracic and lumbar spines for users of wheelchairs and posture-support devices. These are an SL connecting the upper and lower sternum point and an AL connecting the lower sternum point and midpoint of the right and left ASISs. Using experimentation and relating the results to the literature, I confirmed that the inclinations of the two anatomical lines, in the sagittal and frontal planes, are the same as that of the thoracic and lumbar spines.

The LSL provided no information about the alignment of the thoracic spine. The LAL was correlated with the lumbar length. The LAL provided some information about the alignment of the lumbar spine.

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