Inertial Measurement Unit-based Evaluation of Global and Regional Lumbar Spine and Pelvis Alignment in Standing Individuals With a Flat Lumbar Posture

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Abstract

Objective: The purpose of this study was to investigate the global and regional lumbar spine and pelvis postural alignment in standing individuals with a flat lumbar posture using an inertial measurement unit (IMU) system.

Methods: A total of 80 symptomatic young volunteers (25 men and 55 women in their early 20s) were recruited at Inje University in Gimhae, South Korea for this study. Participants stood in a comfortable posture for 5 seconds with IMUs on the T10, L3, and S2 level. Participants were then categorized into 3 groups according to the global lumbar lordosis (GLL) angle (T10-S2): $<20°$, $20° \leq$ GLL angle $< 30°$, and $30° \leq$ GLL angle $< 40°$. We compared the GLL and regional lumbar lordosis (RLL) angles among the 3 groups.

Results: As GLL increased, RLL angles (upper, $P = .001$; lower, $P < .001$) tended to increase, whereas the sacrum angle decreased ($P < .001$). A stepwise regression model showed that the sacrum angle was the single best predictor of GLL in standing participants. Based on IMU measurements, participants with GLL $<20°$ are considered representative of participants with a flat lumbar posture.

Conclusion: Posture measurements in a standing position conducted to assess lordosis should consider the relationship between GLL and RLL rather than GLL or RLL alone. We found that S2 was the best predictor of GLL. (J Manipulative Physiol Ther 2019;42:594-600)

Key Indexing Terms: *Posture; Standing Position; Spine*

Introduction

Spinal alignment within the sagittal plane contributes to ideal posture and functional movement of the spine.[1,2] The sagittal profile of the spine is characterized by a kyphotic thoracic spine and lordotic cervical and lumbar spinal curve, which absorb the shock of load imposed on the spinal column. Lumbar lordosis maintains efficient upright posture and influenced by pelvic anterior or posterior tilting.[1,3] Acceptable lumbar lordosis angles are suggested to be 20° to 65°,[4] and a lumbar lordosis loss or reduction is classified as a "flat back" posture. Reduced lumbar lordosis may be a clinical sign of back problems.[3,5-8] It is hypothesized that reduced lordosis alters the relationship between the line of gravity and each spinal region and may cause increased stress on muscles, ligaments, bones, and discs.[2,5-7]

A loss of normal lumbar lordosis can be caused by pathology, such as lumbar spinal stenosis, that results in forward inclination of the trunk for symptom relieving[9] and iatrogenic issues after fusion surgery attributable to distraction instrumentation into the lower lumbar spine or sacrum regions.[4] A loss of lumbar lordosis may be caused by habitual poor posture, including abnormal and deviated posture such as slump and sway posture in otherwise healthy persons.[2,10] Habitual poor posture and repeated movement in one direction during daily life activities may cause a loss of movement precision and changes in movement patterns, which may result in mechanical back pain. People with lumbar flexion movement impairment tend to reduce lumbar lordosis to a greater extent than those with lumbar extension movement impairment, and symptoms are often worsened with flexion activities and limited lumbar extension mobility.[11] Educating people who have poor posture to maintain optimal spinal postures could possibly prevent or manage pain.

The lumbar lordosis is flexible and changes in shape to achieve optimal function in people with a healthy spine.[1,2]

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Table 1. *General Characteristics of the Participants (N = 80)*

Variables	Group 1 (n = 28)	Group 2 (n = 27)	Group 3 (n = 25)	*P*
Age (y)	22.00 ± 1.94	21.56 ± 1.87	21.94 ± 3.13	.756
Height (cm)	164.88 ± 7.32	164.30 ± 6.65	166.96 ± 7.43	.376
Weight (kg)	57.66 ± 7.58	59.01 ± 8.53	61.12 ± 9.68	.348
BMI (kg/m^2)	21.28 ± 1.51	21.80 ± 2.51	21.95 ± 2.81	.537

All values are mean ± standard deviation. $P < .05$. Group 1, global lumbar lordosis (T10 relative S2 angle) <20°; group 2, 20° ≤ and <30°; group 3, 30° ≤ and < 40°.
BMI, body mass index.

The lack of evidence regarding reduced lumbar lordosis remains challenging for clinicians and researchers; however, a few studies have been conducted on the posture and movement of individuals with a flat back posture. Two studies suggest that there should be a separate consideration of 2 lumbar regions in evaluating lumbar spinal posture: the lower lumbar (LLx) and upper lumbar (ULx) segments.[12,13] According to these studies, functional independence between the LLx and ULx segment regions should be taken into account rather than global lumbar lordosis (GLL) angle when evaluating spinal posture, motion, and loading. Furthermore, the global lumbar spine kinematics does not accurately reflect these differences between regional lumbar spine segments. However, the GLL angle is variable and influences adjacent segments to maintain a stable posture with minimal energy expenditure; these studies did not consider the flexible GLL angle but simply compared regional lumbar lordosis (RLL) angles (LLx and ULx). Such studies are insufficient to develop an understanding of the relationship between GLL and RLL or the functional movement of participants with a flat lumbar posture.

Radiographic assessment of the lumbar spine is limited owing to clinical space and resource requirements and public health and ethical problems associated with radiation exposure. Radiographs also cannot provide extended dynamic posture information such as gait, sit-to-stand, or forward-bending motion data.[5,14] In addition, radiography is not optimal for posture assessment in pain-free individuals.

Recently, various inertial measurement units (IMU) have been developed for quantitative biomedical applications. Inertial measurement unit systems have been proven valid for trunk and hip movement measurements and reliable for analyses of trunk orientation, movement dysfunction, and biomechanical analysis; this method is commonly used to measure tilting angles relative to gravity or to other body segments. These sensors are small, wireless, portable, accurate, and easy to use, with continuous recording ability, and are thus suitable for frequent spinal curve evaluation and lordosis angle monitoring.[14-17] These advantages make IMUs useful for clinical posture and movement assessment. Therefore, the purpose of this study was to investigate the characteristics of the GLL and RLL angles in the LLx, ULx, and sacral segment regions in standing individuals with a flat lumbar posture using an IMU system.

Methods

Participants

A total of 80 asymptomatic young volunteers (25 male and 55 female participants in their early 20s) were recruited at Inje University in Gimhae, South Korea. Participants had had no surgery, traumatic injury, or history of musculoskeletal pathology during the 12 months before the study, and had no functional restrictions, respiratory or neurologic disorders, or pain in the spine or lower limbs. Table 1 lists the characteristics of all participants. Ethics approval was obtained from the Inje University Ethics Committee for Human Investigations, and written informed consent was obtained from all participants.

Measurement System

We used 3 wireless IMU systems to measure GLL and RLL. The IMU devices each consisted of 3 transmitters (model EBIMU24G, E2BOX, Seoul, South Korea), 1 receiver (39 mm × 26 mm, EBRF24G3CH; E2BOX), 3 gyroscopes, 3 accelerometers, 3 magnetometers, and Kalman filters. The transmitters were 32 mm × 21 mm × 6.5 mm and weighed 7.85 g, including the attached lithium polymer battery. The IMU sensor data were transmitted via radio frequency communication (Visual FoxPro, Microsoft Corp, Redmond, Washington) to obtain real-time orientation at a sampling frequency of 100 Hz. The sensitivities of the sensors were 250 to 2000 dps (gyroscope), 2 to 8 g (accelerometer), and 1.3 to 8.1 gauss (magnetometer). The static accuracy was <0.5°, and the dynamic accuracy was <2°.

Procedures

Before task performance, participants were asked to stand in a comfortable posture with feet slightly apart, looking ahead. The examiner marked the participant's T10, L3, and S2 spinous processes and midpoint of transmitters mounted on a plastic frame. Then the examiner attached the

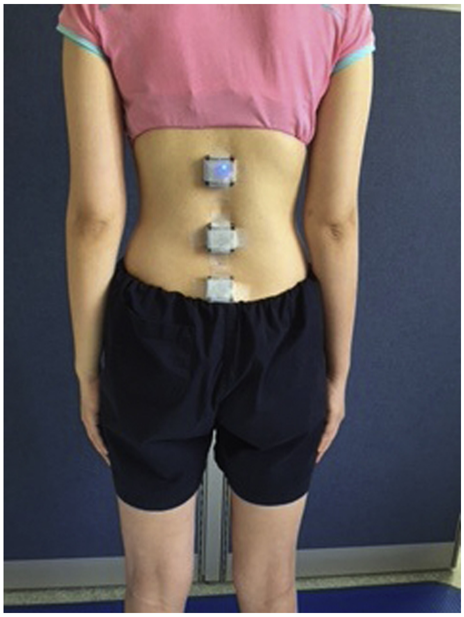

Fig 1. *Placement of the 3 transmitters on the T10, L3, and S2 spinous processes.*

marked point part of 3 transmitters mounted on a plastic frame to the T10, L3, and S2 spinous processes using Transpore medical tape (3M, Seoul, South Korea) (Fig 1). We then conducted standing posture measurements for 5 seconds, in triplicate.

Data Analysis

The T10, L3, and S2 sagittal angles were acquired during standing posture using Visual FoxPro in the Eulerian angle coordinate system (ie, in a roll−pitch−yaw angle sequence; Fig 2). All angles are reported as the mean of 3, 5-second measurements. After measurement, the participants were categorized into 3 GLL groups (T10-S2: <20°, 20° ≤ GLL < 30°, and 30° ≤ GLL < 40°). Excel 2010 (Microsoft Corp) was used to calculate mean angles from the acquired Euler data. The ULx and LLx angles were calculated between T10 and L3 and between L3 and S2, respectively.

Statistical Analysis

We used the SPSS statistical package (version 18.0 for Windows, SPSS Inc, Chicago, Illinois) to detect differences among the 3 groups by a 1-way analysis of variance. All data were tested for a normal distribution using the Kolmogorov-Smirnov test ($P > .05$) and for homogeneity of variance using Levene's test ($P > .05$). A Tukey correction was performed when making multiple comparisons. When equal variance was not observed, we performed the Tamhane correction. A stepwise multiple regression analysis (P to enter <.05, P to remove >.1) was performed to identify the best predictors of GLL angle (angle between T10 and S2) among the T10, L3, and S2 angles in standing position. The variables were assessed for outliers, and the criterion for an outlier was set at >3 standard deviations from the mean value. Before analysis, the data were examined for violation of assumptions for regression analysis, including checking for outliers, normality, homoscedasticity, independence of residuals, and linearity. The linear relationships between variables were found. No violations were found. The level of statistical significance was set at $P < .05$.

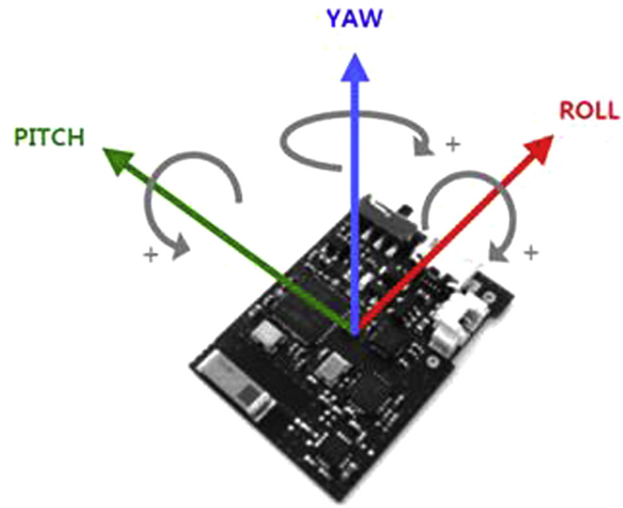

Fig 2. *Sagittal angles of T10, L3, and S2 acquired during standing posture using Visual FoxPro in the Eulerian angle coordinate system.*

Results

A total of 80 asymptomatic younger participants (25 male, 55 female) were categorized into 3 GLL angle groups: T10-S2: <20°, 20° ≤ GLL < 30°, and 30° ≤ GLL < 40°. Descriptive statistics for the RLL and GLL angles among the groups are summarized in Table 2. The ULx (T10 to L3, 2.22° ± 3.51°) and LLx (L3 to S2, 8.26° ± 5.58°) of group 1 was lower than those of group 2 (8.02° ± 6.79° and 16.09° ± 7.54°; $P = .04$ and $P < .001$, respectively) and group 3 (25.08° ± 7.65° and 20.82° ± 5.11°; $P = .001$ and $P < .001$, respectively). The LLx of group 2 was lower than that of group 3 ($P < .001$).

The stepwise regression model showed that the S2 was the best predictor of GLL, accounting for 79% of the variation in GLL during standing; the resulting model was $y = -0.79x + 8.175$, $R^2 = 0.79$ (Fig 3).

Discussion

Our primary findings are that as GLL increased, RLL angle (ULx and LLx) tended to increase, whereas the

Table 2. *Comparison of T10, L3, and S2 Angles and Relative Angles Among the Global Lumbar Lordosis Group (N = 80)*

Variables	Group 1 (n = 28)	Group 2 (n = 27)	Group 3 (n = 25)	*P*
Global (°)	12.49 ± 4.72 [b]	24.12 ± 3.17 [a,b]	36.15 ± 3.50 [a]	<.001 [c]
ULx (°)	2.22 ± 3.51 [b]	8.02 ± 6.79 [a]	11.07 ± 7.46 [a]	.001 [c]
LLx (°)	8.26 ± 5.58 [b]	16.09 ± 7.54 [a,b]	25.08 ± 7.65 [a]	<.001 [c]
T10 (°)	99.85 ± 5.09 [b]	103.29 ± 3.40 [a]	105.33 ± 4.10 [a]	<.001 [c]
L3 (°)	95.63 ± 5.94	95.27 ± 6.88	94.26 ± 6.30	.726
Sacrum (°)	87.37 ± 4.20 [b]	79.17 ± 4.90 [a,b]	69.18 ± 5.11 [a]	<.001 [c]

All values are mean ± standard deviation. Group 1, global lumbar lordosis angle <20°; group 2, 20° ≤ and <30°; group 3, 30° ≤ and < 40°. Global, T10 relative S2 angle; Sacrum, S2 angle; ULx, T10 relative L3; LLx, L3 relative S2.
LLx, lower lumbar; *ULx*, upper lumbar.
[a] Significant difference from group 1, *P* < .05.
[b] Significant difference from group 3, *P* < .05.
[c] *P* < .05.

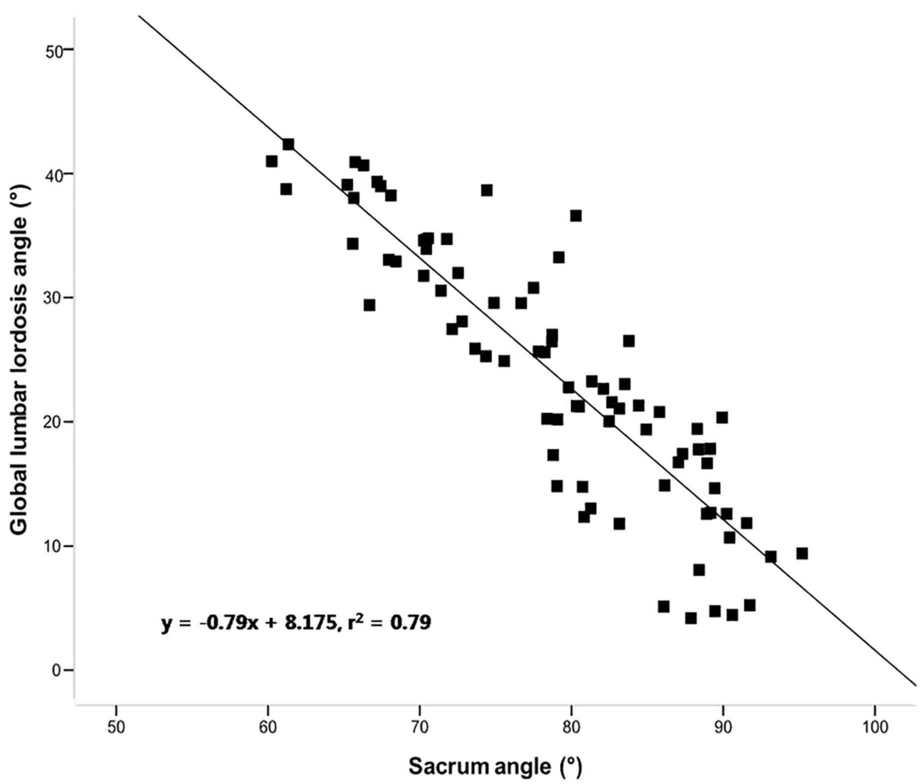

Fig 3. *Scatterplot for stepwise regression model showing that S2 was the best predictor of global lumbar lordosis.*

sacrum decreased (anterior tilt). Furthermore, the sacrum was the single best predictor of GLL (R^2 = 0.79) in standing participants.

Previous studies have described flat lumbar posture as vertical alignment of the thoracolumbar and lumbar angles or hypokyphotic thoracic and hypolordotic lumbar regions.[3,18] Based on previous studies, the normal range is generally accepted to be approximately 20° to 65°, based on Cobb's angle.[1,4,19] Vialle et al[1] reported that mean value of lordosis angle in 300 asymptomatic participants is 43 ± 13.6° (13.6° to 69° and 20 to 70 years), and Endo et al[19] demonstrated that mean value of lordosis angle in 50 asymptomatic volunteers is 33.32° ± 11.25° (4°-64° and 23-47 years). However, it is difficult to define a flat back because the normal range based on Cobb's angle is too broad, and age also affects the angle of the spine. Boulay et al[20] showed the incidence influence on pelvis and spine orientation; a low incidence (<44°) decreases the sacral slope, and the GLL is flattened. However, it remains difficult to define reduced lumbar lordosis based solely on skin surface measurements, and the IMU system was recently suggested as an appropriate tool for the clinical evaluation of posture.[16,18] In the current study, the participants in group 1 had lower GLL (12.49° ± 4.72°) and RLL angles (ULx, 2.22° ± 3.51°; LLx, 8.26° ± 5.58°). These results are consistent with those of previous studies based on skin surface measurements. Sorensen et al[7] measured GLL and RLL using a 3-dimensional motion capture system and reported that the mean GLL angle of participants in their early 20s during standing was 21.0°. Other researchers[21,22] reported that the baseline GLL angle of participants in their 20s during upright standing was 20°. Based on previous studies, we consider participants with a GLL angle <20° (group 1) to be representative of participants in their 20s with a flat lumbar posture.

Interestingly, as the GLL angle increased, the RLL angle increased significantly and the LLx angle tended to be higher than the ULx angle. These results indicate that GLL angle was affected more by the LLx angle than the ULx angle, possibly due to anatomical variation. Our results are supported by those of several previous studies that examined segmental lordosis in the standing position using radiologic or magnetic resonance imaging methods.[23-25] The mean segmental lordosis of asymptomatic adult volunteers measured in these studies demonstrated that roughly two-thirds of GLL angulations occurred at the L4-5 and L5-S1 segments; therefore, lordosis measurements should include L5-S1 motion and be performed while standing to better assess balance.[23,24] Been et al[25] also reported that the L5 segment accounted for about 40% of the GLL angle, whereas the L1 segment was responsible for only 5%. However, in contrast to the findings of our study, Mitchell et al[12] found that the ULx angle was greater than the LLx angle. The values for other segments were not reported; however, the authors suggested that the participants were standing in a sway posture. Sway posture is clinically recognized as a characteristic of posterior displacement of the trunk relative to the pelvis, long thoracic kyphosis, reduced lumbar lordosis, posterior pelvic tilt, and extended hip and knee joints.[26] We conclude that the reason for this difference in our findings was the posture of the standing participants, and that measurements in the standing position should consider GLL and RLL rather than either GLL or RLL alone. In addition, younger healthy flat lumbar posture participants tend to have higher LLx angles than ULx angles.

In the current study, the S2 angle was the single best predictor of GLL ($R^2 = 0.79$) in the standing position. It has become apparent that the shape of the pelvis and its contribution to sacral slope strongly influence the value of lumbar lordosis in a single individual.[2] The sacral bone plays an important role in determining the acquisition of spinal curvature to achieve the most economic position. Boulay et al[20] reported that <44° of participants exhibited a low sacral slope and flattened lordosis; this is a new standard for flat back measurements and supports our results.

Based on skin surface measurements, the degree of lumbar lordosis decreases when posterior sacral tilt increases in the standing position,[27] and increases in lumbar lordosis lead to decreases in sacral tilt (anterior tilt) angles. Because the lumbar spine is associated with the pelvis through the kinematic lumbopelvic link, anterior and posterior pelvic tilting can lead to lumbar extension and flexion, respectively.[2,28] In this study, the S2 angle showed sacrum posterior tilt (close to 90°). The sacrum slope according to the IMU measurements was unknown; however, sacrum posterior tilt led to a reduction in GLL because GLL increased as sacral slope became more vertical, demonstrating a reciprocal association between sacrum orientation and lumbar lordosis characteristics. Thus, we suggest that the S2 value is the best single indicator of GLL in skin surface measurements.

Limitations

First, our participants consisted only of asymptomatic healthy young participants. Thus, our findings cannot be generalized to the entire population, patients with low back pain, or people with other postures such as sway-back posture. Second, we performed measurements in a static standing posture, not during sitting or dynamic activity; thus, we did not consider changes to the GLL and RLL angles during functional movement. Third, we did not consider hip position. Hip motion compensates hyperextension or hypoextension to increase comfort during standing. This compensation influences GLL and RLL. Finally, although the lowest activity levels for most muscles were observed in the flat posture, we did not consider trunk muscle condition in posture assessment. Future studies should investigate the connection between GLL and RLL angles during dynamic activities such as sitting to standing and forward bending in flat back subgroups. Despite these limitations, this study offers new reference information about reduced lumbar lordosis based on IMU (skin surface) measurements.

Conclusion

Based on IMU system measurements, we consider that young participants with a GLL angle <20° (group 1) are representative of a flat lumbar posture. Posture measurements in a standing position conducted to assess lordosis should consider the relationship between GLL and RLL rather than GLL or RLL alone. Furthermore, S2 was the best predictor of GLL.

Funding Sources and Conflicts of Interest

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Contributorship Information

Concept development (provided idea for the research): S.S.
Design (planned the methods to generate the results): S.S.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): W.Y.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): S.S.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): S.S.
Literature search (performed the literature search): S.S.
Writing (responsible for writing a substantive part of the manuscript): S.S.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): S.S., W.Y.

Practical Applications

- Based on IMU system measurements, participants with a GLL angle <20° were representative of a flat lumbar posture.
- Posture measurements in a standing position conducted to assess lordosis could consider the relationship between GLL and RLL rather than GLL or RLL alone.
- The S2 was the best predictor of GLL in this study.

References

1. Vialle R, Levassor N, Rillardon L, Templier A, Skalli W, Guigui P. Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. *J Bone Joint Surg Am*. 2005;87(2):260-267.
2. Neumann DA. *Kinesiology of the Musculoskeletal System*. New York, NY: Mosby; 2010.
3. Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine (Phila Pa 1976)*. 2005;30(3):346-353.
4. Potter BK, Lenke LG, Kuklo TR. Prevention and management of iatrogenic flatback deformity. *J Bone Joint Surg Am*. 2004;86A(8):1793-1808.
5. Smith A, O'Sullivan P, Straker L. Classification of sagittal thoraco-lumbo-pelvic alignment of the adolescent spine in standing and its relationship to low back pain. *Spine (Phila Pa 1976)*. 2008;33(19):2101-2107.
6. Lee CS, Lee CK, Kim YT, Hong YM, Yoo JH. Dynamic sagittal imbalance of the spine in degenerative flat back: significance of pelvic tilt in surgical treatment. *Spine (Phila Pa 1976)*. 2001;26(18):2029-2035.
7. Sorensen CJ, Norton BJ, Callaghan JP, Hwang CT, Van Dillen LR. Is lumbar lordosis related to low back pain development during prolonged standing? *Man Ther*. 2015;20(4):553-557.
8. Been E, Kalichman L. Lumbar lordosis. *Spine J*. 2014;14(1):87-97.
9. Farrokhi MR, Haghnegahdar A, Rezaee H, Sharifi Rad MR. Spinal sagittal balance and spinopelvic parameters in patients with degenerative lumbar spinal stenosis; a comparative study. *Clin Neurol Neurosurg*. 2016;151:136-141.
10. Claus AP, Hides JA, Moseley GL, Hodges PW. Thoracic and lumbar posture behaviour in sitting tasks and standing: progressing the biomechanics from observations to measurements. *Appl Ergon*. 2016;53:161-168.
11. Van Hoof W, Volkaerts K, O'Sullivan K, Verschueren S, Dankaerts W. Comparing lower lumbar kinematics in cyclists with low back pain (flexion pattern) versus asymptomatic controls-field study using a wireless posture monitoring system. *Man Ther*. 2012;17(4):312-317.
12. Mitchell T, O'Sullivan PB, Burnett AF, Straker L, Smith A. Regional differences in lumbar spinal posture and the influence of low back pain. *BMC Musculoskelet Disord*. 2008;18(9):152.
13. Burton K. The ratio of upper lumbar to lower lumbar sagittal mobility related to age, sex and low back trouble. *Eng Med*. 1987;16(4):233-236.
14. Wong WY, Wong MS. Trunk posture monitoring with inertial sensors. *Eur Spine J*. 2008;17(5):743-753.
15. Bauer CM, Heimgartner M, Rast FM, Ernst MJ, Oetiker S, Kool J. Reliability of lumbar movement dysfunction tests for chronic low back pain patients. *Man Ther*. 2016;24:81-84.
16. Bauer CM, Rast FM, Ernst MJ, et al. Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement. *J Electromyogr Kinesiol*. 2015;25(5):782-790.
17. Yun WS, Kim H, Ahn JH, Park YB, Park YJ. Individual characteristics of reliable lumbar coupling motions. *Eur Spine J*. 2015;24(9):1917-1925.
18. Claus AP, Hides JA, Moseley GL, Hodges PW. Is 'ideal' sitting posture real?: measurement of spinal curves in four sitting postures. *Man Ther*. 2009;14(4):404-408.
19. Endo K, Suzuki H, Nishimura H, Tanaka H, Shishido T, Yamamoto K. Sagittal lumbar and pelvic alignment in the standing and sitting positions. *J Orthop Sci*. 2012;17(6):682-686.
20. Boulay C, Tardieu C, Hecquet J, et al. Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis. *Eur Spine J*. 2006;15(4):415-422.
21. Dunk NM, Callaghan JP. Lumbar spine movement patterns during prolonged sitting differentiate low back pain developers from matched asymptomatic controls. *Work*. 2010;35(1):3-14.

22. Kim MH, Yoo WG, Choi BR. Differences between two subgroups of low back pain patients in lumbopelvic rotation and symmetry in the erector spinae and hamstring muscles during trunk flexion when standing. *J Electromyogr Kinesiol*. 2013;23(2):387-393.
23. Jackson RP, McManus AC. Radiographic analysis of sagittal plane alignment and balance in standing volunteers and patients with low back pain matched for age, sex, and size A prospective controlled clinical study. *Spine (Phila Pa 1976)*. 1994;19(14):1611-1618.
24. Meakin JR, Gregory JS, Smith FW, Gilbert FJ, Aspden RM. Characterizing the shape of the lumbar spine using an active shape model: reliability and precision of the method. *Spine (Phila Pa 1976)*. 2008;33(7):807-813.
25. Been E, Barash A, Marom A, Kramer PA. Vertebral bodies or discs: which contributes more to human-like lumbar lordosis? *Clin Orthop Relat Res*. 2010;468(7): 1822-1829.
26. Pezolato A, de Vasconcelos EE, Defino HL, Nogueira-Barbosa MH. Fat infiltration in the lumbar multifidus and erector spinae muscles in subjects with sway-back posture. *Eur Spine J*. 2012;21(11):2158-2164.
27. Levine D, Whittle MW. The effects of pelvic movement on lumbar lordosis in the standing position. *J Orthop Sports Phys Ther*. 1996;24(3):130-135.
28. Page P, Frank C, Lardner R, eds. *Assessment and Treatment of Muscle Imbalance: The Janda Approach*. Champaign, IL: Human Kinetics; 2010.