PM R XXX (2015) 1-11

www.pmrjournal.org

Original Research

Quantification of Lumbar Stability During Wall Plank-and-Roll Activity Using Inertial Sensors

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Abstract

Objective: To develop a simple method of quantifying dynamic lumbar stability by evaluating postural changes of the lumbar spine during a wall plank-and-roll (WPR) activity while maintaining maximal trunk rigidity.
Design: A descriptive, exploratory research with a convenience sample.
Setting: A biomechanics laboratory of a tertiary university hospital.
Participants: Sixteen healthy young subjects (8 men and 8 women; 30.7 $\pm$ 6.8 years old) and 3 patients (2 men 46 and 50 years old; 1 woman 54 years old) with low back pain (LBP).
Methods: The subjects performed the WPR activity with 2 inertial sensors attached on the thoracic spine and sacrum. Relative angles between the sensors were calculated to characterize lumbar posture in 3 anatomical planes: axial twist (AT), kyphosis-lordosis (KL), or lateral bending (LB). Isokinetic truncal flexion and extension power were measured.
Main Outcome Measures: AT, KL, and LB were compared between the initial plank and maximal roll positions. Angular excursions were compared between males and females and between rolling sides, and tested for correlation with isokinetic truncal muscle power. Patterns and consistencies of the lumbar postural changes were determined. Lumbar postural changes of each patient were examined in the aspects of pattern and excursion, considering those from the healthy subjects as reference.
Results: AT, KL, and LB were significantly changed from the initial plank to the maximal roll position ($P < .01$); that is, the thoracic spine rotated further, lumbar lordosis increased, and the thoracic spine was bent away from the wall by 6.9° $\pm$ 12.0°, 9.5° $\pm$ 6.5°, and 7.9° $\pm$ 4.9°, respectively. The patterns and amounts of lumbar postural changes were not significantly different between the rolling sides or between male and female participants, except that the excursion in AT was larger on the dominant rolling side. The excursions were not related to isokinetic truncal muscle power. The 3 LBP patients showed varied deviations in pattern and excursion from the average of the healthy subjects.
Conclusions: Certain amounts and patterns of lumbar postural changes were observed in healthy young subjects, with no significant variations based on gender, rolling side, or truncal muscle power. Application of the evaluation on LBP patients revealed prominent deviations from the healthy postural changes, suggesting potential clinical applicability. Therefore, with appropriate development and case stratification, we believe that the quantification of lumbar postural changes during WPR activity can be used to assess dynamic lumbar stability in clinical practice.

Introduction

Among the many causes of low back pain (LBP), mechanical factors play a most important role [1] because the lumbar spine is subject to lifelong repetitive mechanical stress. To fully understand the cause of a particular case of LBP, it is critical to understand the extent of lumbar stability, which is defined as the ability of the lumbar spine to withstand mechanical perturbation [2,3]. The concept of spine stability/instability was developed to determine whether the spine requires surgical stabilization [4,5], under the concern of risks of damage or irritation of the neural elements by physiological loads [6]. Since the concept was broadened to explain spinal pain in addition [6,7], measuring subtle spine instability remains a major challenge [8]. Researchers have focused on intersegmental motion [9], measuring excessive motion beyond normal constraints [10], or abnormal coupling patterns [11] observed between 2 adjacent vertebrae that result from applying a standardized external load or motion [12]. However, all static imaging modalities, even conventional magnetic

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http://dx.doi.org/10.1016/j.pmrj.2015.03.004

resonance imaging (MRI), are unreliable for the assessment of spinal instability [8], and no universal consensus has been reached as to the most practical, especially dynamic, method of measurement of lumbar stability [13].

Measurement of dynamic intersegmental stability requires technologically demanding methods such as videofluoroscopy [14,15] and intraoperative biomechanical testing [16,17]; although they are reliable, these methods have been shown to have limited clinical applicability. Thus, to overcome this issue, researchers have focused on measuring entire spine motions, while applying external force [18], sudden load release [19,20], or postural perturbation [21-25]. To improve clinical utility, these approaches abandon the assessment of segmental motion and measure instead the lumbar motion in aggregate, using the concept that sufficient spine stability requires involvement of all of the muscles in the torso [26,27].

The wall plank-and-roll (WPR) test is one such example of a lumbar stability assessment tool based on the principle of observing whole spine motion during postural perturbation. The test is performed to observe lumbar motion while the subject rolls to either side from the wall plank position, rotating the whole body as a single unit by activating the core muscles as instructed [2]. Although a certain amount or pattern of lumbar motion is considered representative of dynamic lumbar instability [3,28], the motion is observed visually and stability is determined subjectively. This lack of objectivity raises concern about the potential of WPR as a clinical assessment tool, and to the best of our knowledge, no research has evaluated lumbar stability during WPR testing by quantifying lumbar motion. Hence, it is unknown whether healthy people demonstrate any lumbar motion during a WPR activity and what degree of motion is considered normal.

In this study, an inertial sensor-based system was developed to test the hypothesis that healthy young adults would not have significant changes in motion and lumbar postures while performing the WPR activity with efforts to maintain maximal trunk rigidity. Furthermore, the patterns, consistencies, and amounts of changes were investigated to find any side-to-side or gender-related differences. The relationship between the amounts of postural changes and isokinetic truncal muscle power were analyzed to determine whether stronger truncal muscle power would reduce postural changes. Finally, we applied the measuring system in 3 cases of LBP to determine any differences with the controls.

Methods

Study Subjects

A total of 16 healthy young subjects (8 men and 8 women; mean age $\pm$ SD, 30.0 $\pm$ 2.5 years and 31.4 $\pm$ 9.6 years, respectively) were included in this study. The healthy subjects had no history of a back disorder and pain for the 12 weeks before recruitment. The exclusion criteria for the healthy subjects were no history of pain in the lower extremity below the gluteal fold, infection, fracture, or inflammatory conditions involving the spinal column or other axial joints. Fifteen of the healthy subjects were right-handed, and the remaining subject was left-handed. Three patients with LBP were also included in this study. Patient 1 was a 46-year-old man with a visual analogue scale (VAS) score of 5.6; patient 2 was a 50-year-old man with a VAS score of 4.5; and patient 3 was a 54-year-old woman with a VAS score of 4.5. None of them had pain in the lower extremity below the gluteal fold. All subjects provided informed consent. This study was approved by the review board of Seoul National University Hospital.

Experimental Setup

Two inertial sensors (ADIS16360, Analog Devices, Norwood, MA) that consisted of a tri-axis accelerometer and gyroscope were used to measure acceleration and angular velocity. To detect the orientation of the thoracic cavity and pelvis, the sensors were firmly attached to the skin over the spinous processes of the sixth thoracic vertebra, at the inferior angle of the scapula [29], and the second sacral vertebra at the midpoint between the 2 posterior superior iliac spines [30], using adhesive gel pads (StiMus Hydrogel Patch, Hurev, Wonju, South Korea) and protective tape (OPSITE, Smith & Nephew, London, UK) (Figure 1). The sensor output data were wirelessly transferred to a personal computer via a Zigbee module (EZbee M-100, Chipsen, Gwangmyeong, South Korea) at a sampling rate of 30 Hz.

WPR Test

Each subject performed the WPR activity by rolling side to side from the initial plank position (IPP) while minimizing lumbar postural changes [2]. The IPP refers to the state of the torso as it is positioned like a wooden plank leaning against a wall. The subject first stood facing a wall, approximately 40 cm away, with feet shoulder width apart. Keeping the torso straight in a single unit, the subject leaned toward the wall, placing both forearms horizontally, with the elbows flexed at 90° and the shoulders forward elevated and internally rotated. Both heels were lifted slightly to turn easily using the forefeet as pivot points (Figure 1A).

After the IPP was attained, the subject performed a rolling motion while maintaining the plank position of the torso. A 90° rotation around the longitudinal axis of the torso was performed by pivoting on both forefeet until the torso faced the left (left WPR) or right (right WPR) side to reach the maximal rolling position (MRP). While rolling to 1 side, the subject was requested to maintain the torso in a single, straight unit with the support of the contralateral forearm on the wall. The ipsilateral arm

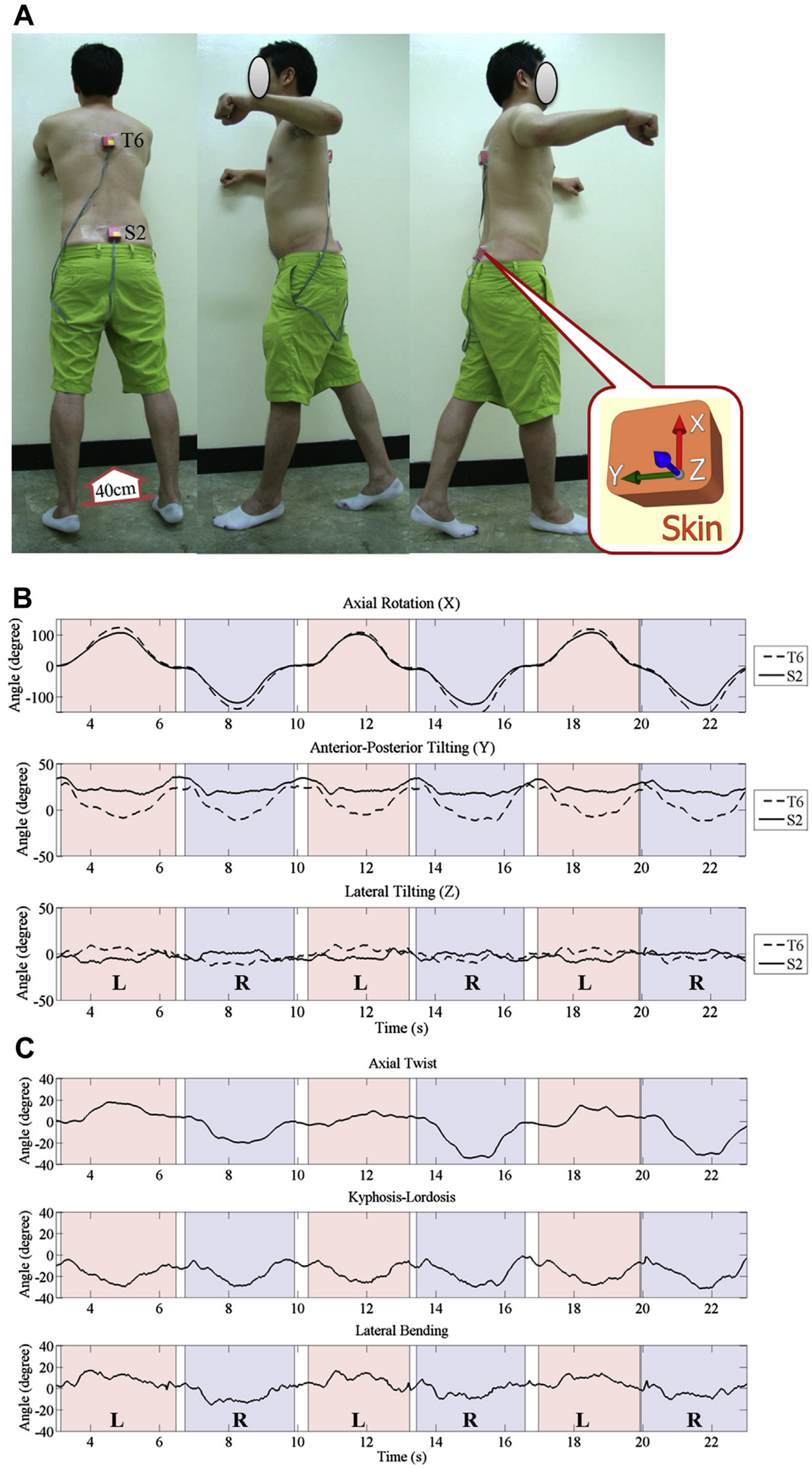

Figure 1. Postures involved in the wall plank-and-roll (WPR) activity and sensor placement. (A) Initial plank position and maximal roll position in the left and right WPR. The sensor orientations of the X, Y, and Z axes correspond to the upward longitudinal axis, mediolateral axis toward the left side, and anteroposterior axis, respectively. The inset image shows a sensor attached on the skin. (B) Typical raw data from a study subject. Axial rotation, anteroposterior tilting, and lateral tilting angles are recorded and filtered (using a Kalman filter) from the sensors on the sixth thoracic (dashed line) and second sacral (solid line) vertebrae during the WPR test. The shaded phases marked with "L" or "R" represents the left or right side WPR, respectively. (C) The relative angles between the 2 sensors are presented as axial twist (AT), kyphosis-lordosis (KL), and lateral bending (LB).

was taken off the wall, and both feet were placed in a line oriented toward the rolling side. Maintaining torso stiffness was strongly emphasized by instructing the subject not to twist, bend, or flex/extend the lumbar spine during the entire WPR motion. After reaching either side of the MRP, the subject rolled back to the IPP, thereby completing 1 round of WPR on 1 side (Figure 1B and C). Approximately 1 second after returning to the IPP, the same rolling motion was performed on the other side. The subjects chose their own comfortable rolling speeds after 10 sets of training trials. The WPR activity was performed for both sides at least 3 times.

Isokinetic Evaluation of Truncal Muscle Power

Isokinetic truncal flexion and extension power were measured by a Biodex System 4 Pro (Biodex Medical Systems, Shirley, NY) while the subject was seated on a chair, with the trunk, thigh, and feet fixed to the chair by Velcro straps. The first series of 10 sets of flexion and extension at an angular speed of 60°/s was performed against the resistance of the isokinetic device, followed by another series of 10 sets of flexion and extension at an angular speed of 90°/s. Subjects were encouraged to exert themselves as strongly as possible, and a 2-min rest period was allowed between the 2 sets at the different test speeds. The peak torques (N•m) of the flexor and extensor for both test speeds were calculated.

Data Analysis

The sensor output data of angular velocity and acceleration were merged and converted to obtain a 3-dimensional orientation using the extended Kalman filter [31]. Three orientation angles were measured for each sensor based on the rotation axes as follows: X (upward longitudinal axis), Y (mediolateral axis toward the left side), and Z (anteroposterior axis; Figure 1A and B). Lumbar posture was calculated by subtracting the angles between the thoracic and sacral sensors in each of the X, Y, and Z axes. The relative angles calculated for the X, Y, and Z axes were defined as the axial twist (AT), kyphosis-lordosis (KL), and lateral bending (LB), respectively (Figure 1C). The simple subtraction method was used instead of calculating the Cardan angles because the relative angles were expected to be substantially small, considering the in-line alignment of the 2 sensors and the nature of the WPR activity. In summary, lumbar posture is defined by 3 relative angles, namely AT, KL, and LB, and lumbar motion, a change in lumbar posture, is represented by the changes in theses angles.

The changes in the relative angles during the repeated WPR tests were divided into each cycle. A complete left or right WPR cycle was defined as the period ranging from the IPP through the MRP on either side to the point of rolling back to the IPP. The MRP time point was defined as the point at which the sacral sensor rotated maximally to the direction of rolling. Waveforms of relative angles were normalized by converting time domain into percentage of a cycle to compensate for any differences in duration for each trial. At least 3 WPR cycles for each side were obtained. The relative angles in all of the trials were ensemble averaged to determine the representative patterns for each subject (Figure 2A). To maintain consistency on both sides, the signs of the values for AT and LB during right WPR were reversed. As a result, the positive values for AT, KL, and LB represented a twist, with the thorax rotated further to the direction of rolling than the sacrum, increased kyphosis, and the thorax bent to the rolling side, respectively (Figure 2B).

To test the hypothesis that the WPR activity would not generate any significant motion, AT, KL, and LB at the IPP were compared with those at the MRP. The patterns of the lumbar postural changes, which were the directions of AT, KL, and LB changes from the IPP to the MRP, were examined, whether they were positive or negative in both sides of each subject. Figure 2 details the information on the directions of the lumbar postural changes, represented by the positive or negative signs of each relative angle. To measure the amount of lumbar postural changes, the angular excursions of the relative angles from the IPP to MRP were calculated (Figure 2A) by subtracting the angles at the IPP from those at the MRP. To represent the changes in the patterns of lumbar postural changes, the data for the subjects were averaged to generate one curve for each relative angle (AT, KL, and LB) (Figures 3 and 6). The patterns and excursions of the relative angles from the 3 LBP patients were examined for any notable differences from those in the healthy subjects.

Statistical Analysis

The relative angles (AT, KL, and LB) at the IPP and MRP were compared using the paired *t*-test to determine any significant lumbar postural changes during the WPR test. All of the angles at the IPP/MRP and angular excursions were tested for normality using the Kolmogorov-Smirnov test. The consistency of the directions of the relative angular changes from the IPP to the MRP was determined using the Fisher exact test. Differences in angular excursions according to rolling side and gender were evaluated using the Wilcoxon signed-rank test and Wilcoxon rank-sum test, respectively. Pearson correlation coefficients were calculated to determine the relationship between the number of angular excursions and isokinetic truncal muscle power. A *P* value of less than .05 was considered as statistically significant.

Results

Changes in the Relative Angles (Lumbar Posture)

In the healthy subjects, significant changes in the relative angles were demonstrated from the angles at

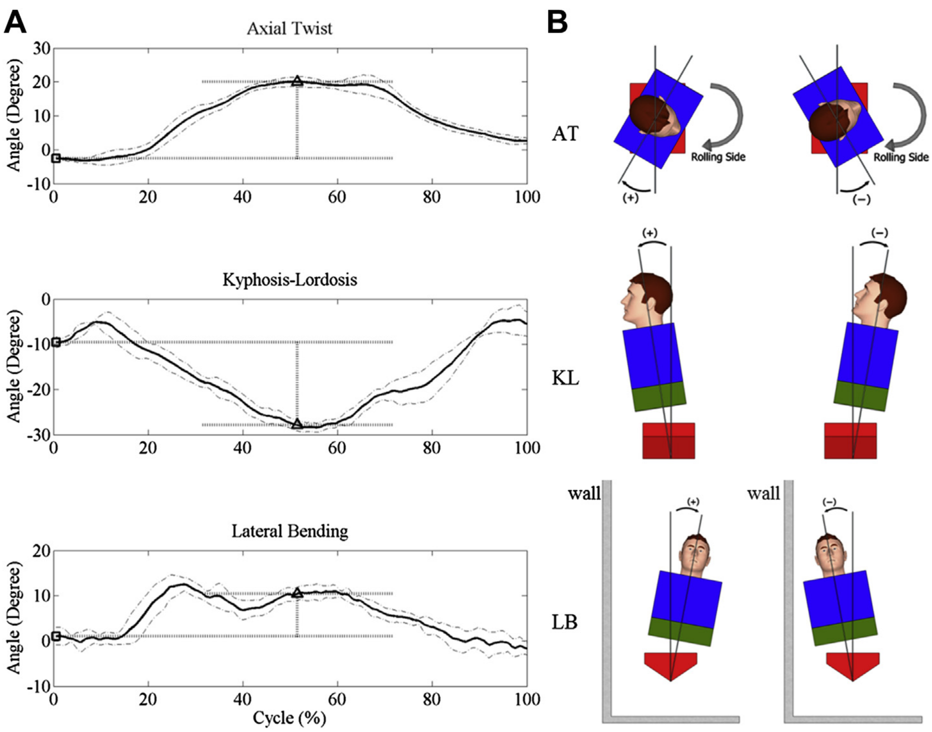

Figure 2. (A) The relative angles between the 2 sensors are averaged and presented as axial twist (AT), kyphosis-lordosis (KL), and lateral bending (LB). The upper and lower dashed curves indicate 1 standard deviation calculated from several repetitions of the subject. Excursion angle was defined as the angle difference between the initial plank position (at 0% cycle, marked as a square) and maximal roll position (near 50% cycle, marked as a triangle). (B) Schematic body diagrams are shown to illustrate the relative positions of the thorax and pelvis corresponding to the positive or negative values in AT, KL, and LB. To maintain consistency in either side of the wall plank-and-roll (WPR) test, the signs of AT and LB were reversed in the right WPR, which assigns the positive values for AT, KL, and LB to a twist with the thorax rotated further to the direction of rolling than the sacrum, increased kyphosis, and the thorax bent to the rolling side, respectively, regardless of the rolling directions.

the IPP ($-2.2° \pm 3.4°$, $-14.4° \pm 10.1°$, and $0.6° \pm 4.2°$) to those at the MRP ($4.7° \pm 10.9°$, $-23.9° \pm 10.1°$, and $8.5° \pm 5.8°$, $P = .003$, $<.001$, and $<.001$ for AT, KL, and LB, respectively). The angular excursions for AT, KL, and LB were $6.9° \pm 12.0°$, $-9.5° \pm 6.5°$, and $7.9° \pm 4.9°$, respectively (Table 1).

Patterns and Consistencies of the Changes in the Relative Angles

From the IPP to the MRP, the patterns of the angular changes in AT, KL, and LB were predominantly positive (overrotation of the thoracic spine), negative (increase in lumbar lordosis), and positive (thoracic spine bent away from the wall), respectively. These patterns were consistently observed regardless of rolling side or gender (Tables 2 and 3). The same patterns were demonstrated in the averaged curves, including both sides of the healthy 16 subjects (Figure 3).

Differences in Angular Excursion According to Rolling Side and Gender

Significant differences between sides were observed only in AT, wherein substantially larger excursion angles were observed during right WPR ($P = .015$; Figure 4) than during left WPR. No significant differences were observed in AT, KL, and LB between males and females (Figure 4).

Correlations Between Angular Excursions and Isokinetic Truncal Muscle Power

No significant correlations were observed between the angular excursions in the 3 relative angles and isokinetic truncal muscle power in the healthy subjects (Figure 5).

Patterns and Excursions of Relative Angles From 3 LBP Cases

On the AT axis, patient 2 showed a reversed pattern in angular excursion from IPP to MRP as compared to the average of the healthy subjects (Figure 6). The patterns of AT, KL, and LB of patient 3 were comparable to those from the healthy subjects; however, AT and KL were beyond the 2-SD ranges, having a taller AT with a larger excursion and downward-shifted KL (Figure 6).

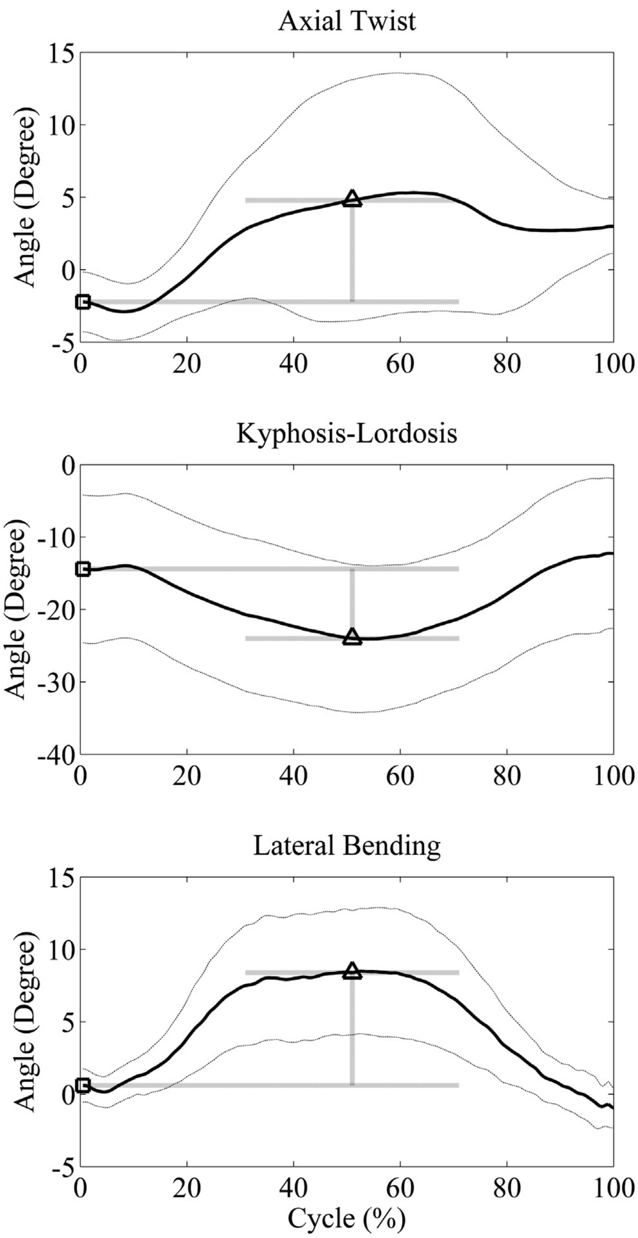

Figure 3. Averaged relative angles (solid lines) of the 16 healthy subjects during the wall plank-and-roll (WPR) test. The dashed curves represent 1 standard deviation in all of the participants. The excursion angle was defined as the angle difference between the initial plank position (at 0% cycle, marked as a square) and maximal roll position (near 50% cycle, marked as a triangle).

Discussion

Relative angles between the thoracic spine and sacrum, regarded as lumbar posture, were measured in 16 healthy young subjects (male-to-female ratio, 8:8) and 3 patients with LBP (male-to-female ratio, 2:1) during WPR activity. Significant lumbar postural changes were observed despite maximal effort to prevent them. The amounts of lumbar postural changes (ie, excursions of relative angles) did not significantly differ in relation to rolling side or gender, except that of AT, which was larger on the dominant rolling side. The changes were not related to isokinetic truncal muscle power. Most of the subjects demonstrated common lumbar motion patterns (over-rotation of the thoracic spine relative to the sacrum, increased lordosis, and lateral bending of the thoracic spine away from the wall). These common motor patterns were similar in both genders and on both WPR sides. Each LBP patient showed specific deviations in patterns and/or excursions as compared to the healthy subjects. To the best of the authors' knowledge, this is the first report to demonstrate statistically significant and patterned lumbar motions in WPR activity even when the subjects were instructed to keep their trunks rigid.

Table 1
Axial twist (AT), kyphosis-lordosis (KL), and lateral bending (LB) at the initial plank and maximal roll positions and angular excursions between the 2 positions

	AT	KL	LB
IPP	−2.2 ± 3.4	−14.4 ± 10.1	0.6 ± 4.2
MRP	4.7 ± 10.9	−23.9 ± 10.1	8.5 ± 5.8
Excursion	6.9 ± 12.0	−9.5 ± 6.5	7.9 ± 4.9
P value	.003	<.001	<.001

Data are expressed as mean ± SD values (in degrees [°]). *P* values were computed to compare angles between IPP and MRP using paired *t*-tests.
IPP = initial plank position; MRP = maximal roll position; Excursion = angular excursion from IPP to MRP (subtracting angles at IPP from angles at MRP).

WPR Test for Measurement of Dynamic Spinal Stability

Quantification of truncal motions during WPR activity in this study was used to assess the ability of a subject to maintain spine stability under the challenging condition of a WPR activity. Notably significant lumbar postural changes were observed, even though the healthy young subjects performed the WPR activity with maximal efforts to maintain truncal rigidity. This finding implies that the WPR activity involved significant perturbation of the spines in healthy young subjects. Thus, it is crucial to elucidate whether there are certain

Table 2
Relationships between the rolling sides and directions of the angular changes for each relative angle

	AT		KL		LB	
	Lt	Rt	Lt	Rt	Lt	Rt
Directions of changes						
Positive	10	14	1	1	15	15
Negative	6	2	15	15	1	1
P value	.22		1		1	

P values were determined using the Fisher exact test.
AT = axial twist; KL = kyphosis-lordosis; LB = lateral bending; Lt = left WPR; Rt = right WPR.

Table 3
Relationships between gender and directions of the angular changes for each relative angle

	AT		KL		LB	
	Male	Female	Male	Female	Male	Female
Directions of changes						
Positive	12	12	0	2	15	15
Negative	4	4	16	14	1	1
P value	1		.48		1	

P values were determined using the Fisher exact test.
AT = axial twist; KL = kyphosis-lordosis; LB = lateral bending.

representative patterns and intensities in the lumbar spine motion in response to the perturbation provoked by the WPR activity.

Patterns and Amounts of Lumbar Postural Changes During WPR Activity

The results of this study demonstrate that predominant patterns in lumbar postural changes occurred from the IPP to the MRP regardless of gender and WPR side. Although a complete understanding of the underlying mechanisms of these typical motor patterns may not be possible at this point, plausible assumptions can be generated for future investigation. The most frequently observed change was the increase in lumbar lordosis at the MRP. Because the WPR activities required a dynamic transition from the stable initial position to the unstable rotated position, the participants might have engaged their back extensor muscles to achieve higher stability, thereby increasing lumbar lordosis [18,32,33]. Lateral bending of the thoracic segment relative to the sacrum occurred consistently at the MRP in most of the healthy participants, which might have been the result of an interaction between the lateral bending torque due to leaning and the participants' efforts to stabilize the core muscles [22,34,35]. The larger range of axial rotation in the thoracic segment than in the sacrum seems natural because of the constraints on the sacrum by the feet planted on the floor. To confirm the mechanisms underlying these typical motor patterns of lumbar posture, further research studies that measure muscle activities during WPR activity and/or that adopt graded perturbations in terms of leaning angles, rotating speed, and/or width of the supporting base should be conducted.

The angular excursions in the 3 relative angles (ie, AT, KL, and LB) were similar between male and female participants. There might not have been gender-related differences in motor patterns to keep the lumbar spine stable from the perturbation incurred by the WPR activity. The differences in excursions according to rolling side were not meaningful either, except those of AT. The larger AT excursion on the dominant rolling side might be attributed to the weaker and less stable supporting arm, which is the nondominant arm in the case of the dominant rolling side.

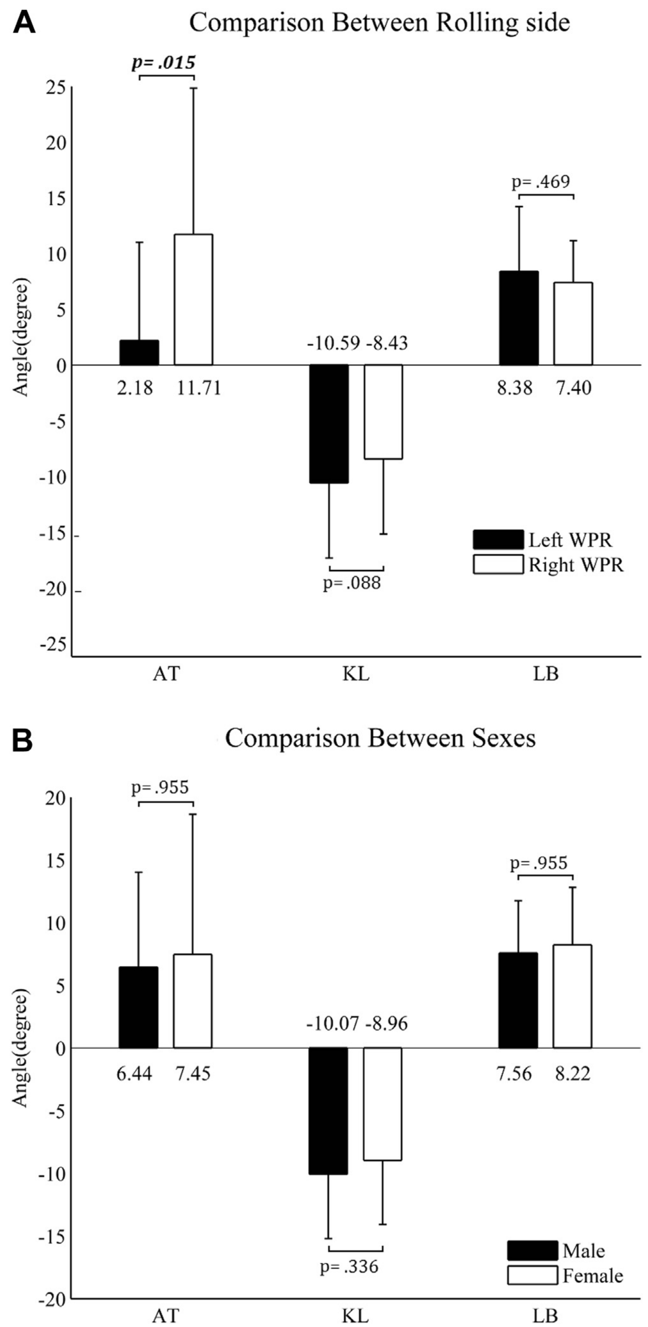

Figure 4. Comparison between the excursion angle according to (A) rolling side and (B) gender. A statistically significant mean difference was observed only in the axial twist (AT) between the left and right wall plank-and-roll (WPR) test.

In summary, the amounts of lumbar motions quantified by excursions of lumbar postural changes fell within certain ranges regardless of gender or rolling side. The motion patterns characterized by the directions of the postural changes were also similar between male and female participants and between rolling sides. These findings suggest the presence of specific patterns and intensities when the lumbar spines of the healthy young subjects responded to the perturbation from the WPR

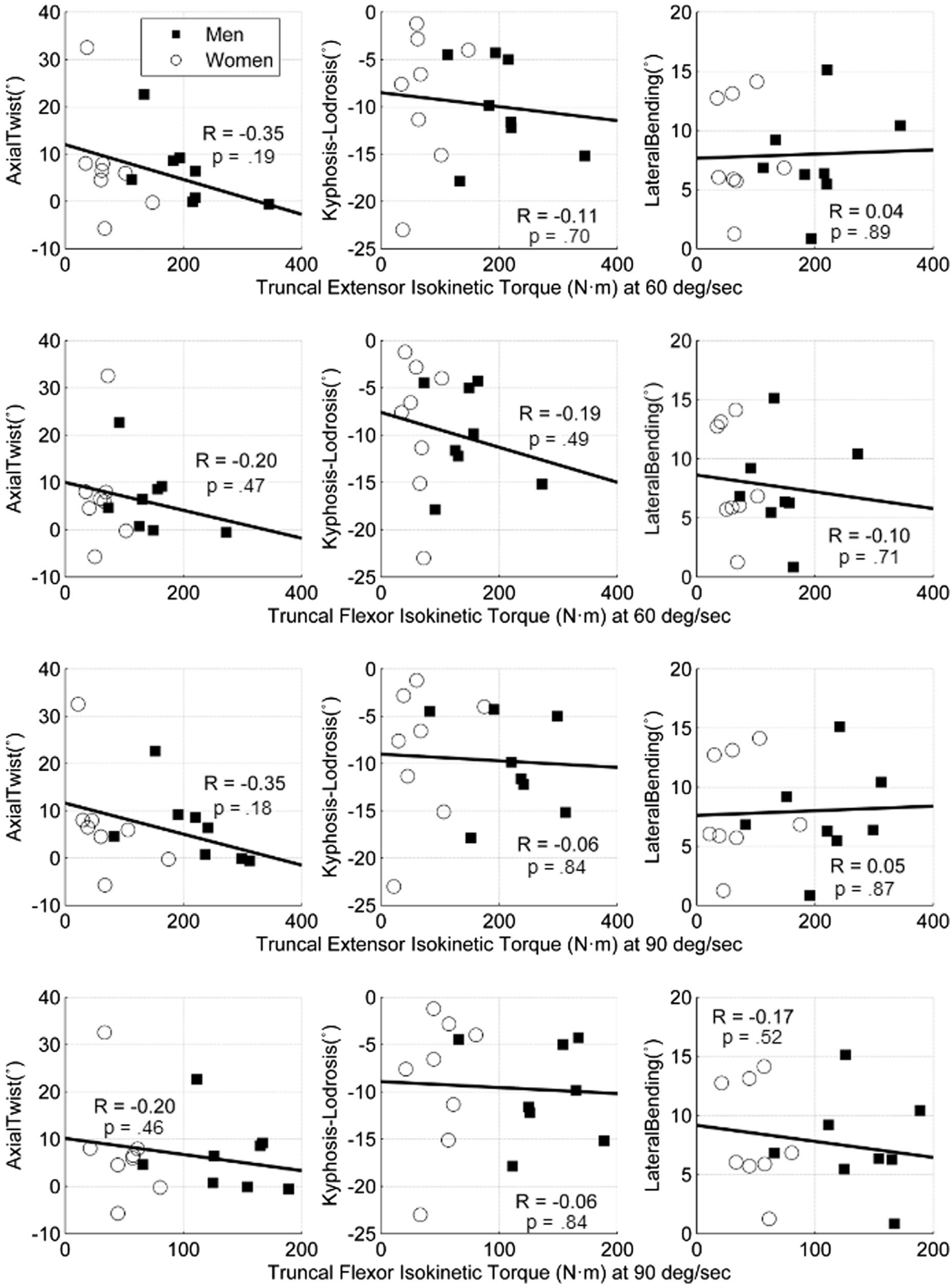

Figure 5. Scatter plots demonstrating the correlations between the excursion angles (axial twist, kyphosis-lordosis, and lateral bending) and isokinetic peak torques of the truncal extensor and flexor at 60°/s (upper 6 plots) and 90°/s (lower 6 plots). Pearson correlation coefficients between each angle and truncal torque are presented on each plot, along with the lines of best fit. Filled squares represent men, and hollow circles represent women.

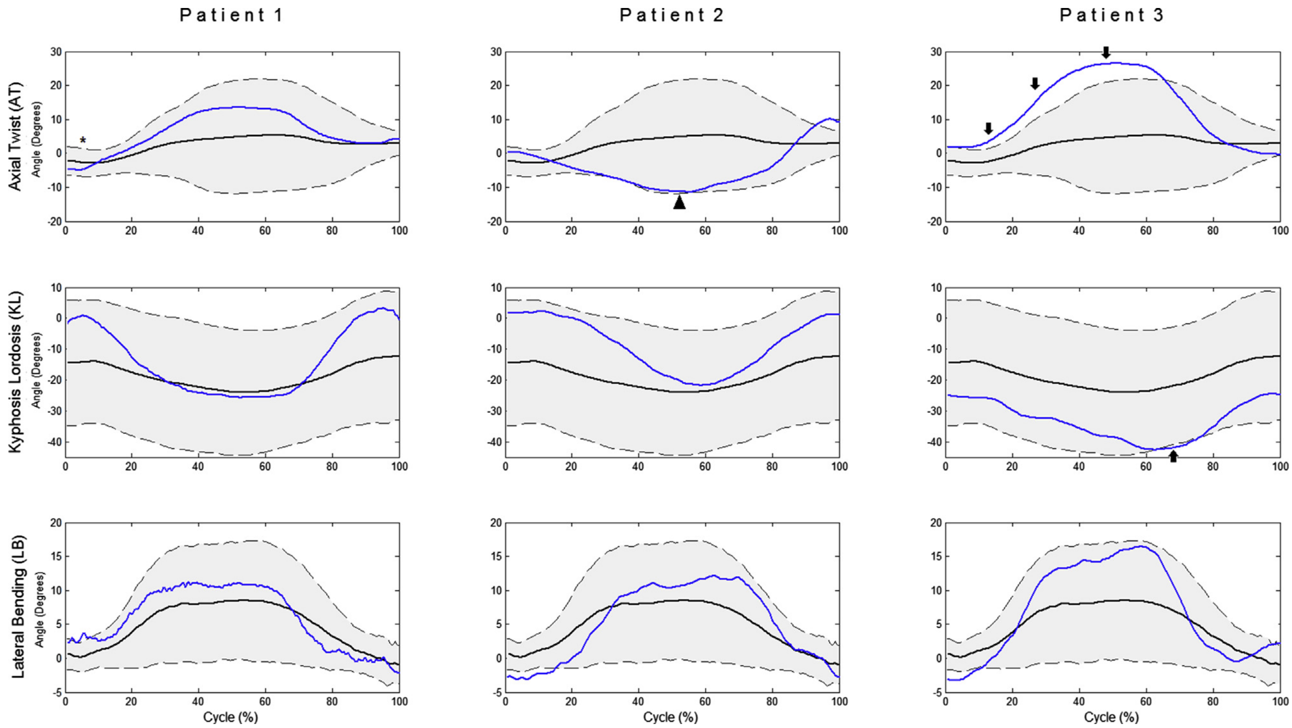

Figure 6. Relative angles (solid lines) of 3 axial low back pain (LBP) patients shown over averaged relative angles (dashed dotted lines) of the healthy subjects with 2 standard deviations (dotted lines). Patient 2 (middle column) showed a reversed axial twist (AT) (upper row) pattern (arrowhead) compared to the normal data. The axial twist (AT) and kyphosis-lordosis (KL) of Patient 3 (right column) was beyond the normal ranges near the maximal rolling position (MRP; arrows). *Note that 2 standard deviations are plotted here in gray, whereas in Figure 3 only 1 standard deviation is plotted.

activity. By cumulating large-scale data on the patterns and excursions of lumbar motion, the quantitative WPR test may then be validated as a useful tool for the evaluation of dynamic spinal stability.

Relationship Between Amounts of Lumbar Postural Changes and Truncal Muscle Power

Considering that truncal muscles are mostly responsible for lumbar stability [22,32,35], the authors hypothesized that a subject with stronger truncal muscles would have higher lumbar stability, that is, fewer changes in lumbar posture during rolling activities. However, no significant relationships were found in the results, disproving the hypothesis. This finding may be related to the fact that the extent of truncal muscle activity required to stabilize the lumbar spine during normal daily activities is far lower than the maximal voluntary contraction [22,35]. Because the perturbation exerted to the lumbar spine by the WPR test was mild, the angular excursions (ie, the amount of lumbar postural changes) did not correlate with the maximal truncal muscle power tested by the isokinetic device in this study. Although the small sample size could have affected the lack of correlation, this finding may indicate that lumbar spine stability could not be determined by measuring the maximal muscle power.

Angular Excursions and Patterns of LBP Patients During WPR Activity

It would be of interest to interpret changes in relative angles, AT, KL, and LB in clinical perspective. Interestingly, in patient 2, the values of AT during the whole cycle were within normal ranges. However, in the healthy subjects the pattern was exactly reversed, showing that the pelvis rotated faster than the thorax while the thorax moved faster, which may implicate faulty motor control to cause rotational instability in dynamic conditions. The generally downward shifted KL is of note in patient 3. She might have had fixed hyperlordosis or spasmodic paraspinal muscles to keep the lumbar spine in abnormally increased lordosis. The deviations in pattern and excursion manifested in the 3 anecdotal LBP cases suggest potential clinical applicability of the quantitative WPR.

Study Limitations

The sample size used in this study was relatively small to determine the normal values of lumbar postural changes during WPR activity. However, the objective of this study was not to establish normative values but rather to test whether any lumbar motions were detectable by an inertial sensor system. Further studies should be conducted to collect normal values of different population groups and of various symptomatic groups before this approach could be used in clinical fields. In terms of LBP analysis, there could be several more potential patho-mechanisms other than those described for each patient. It is beyond the scope of this study to apprehend the underlying patho-mechanisms of abnormal patterns and excursions in LBP patients, because we need far more information on different aspects such as nature of LBPs, anatomical structures responsible for them, and patterns of muscle activation, to name a few. Furthermore, whereas the 3 LBP patients were on average 50 years old, the average age of the 16 healthy subjects was 31 years. Therefore, aging may have contributed to the differences between the 2 groups found in this study, and the differences may not have been solely attributable to LBP. Multiple layers of research with stratification of cases with sufficient information should be done before the WPR test could acquire clinical utility.

Using an inertial sensor system that had relatively lower accuracy and lack of positional information, instead of a traditional optoelectronic motion analysis system, might have been another limitation of this study [36]. Tracking spinal motion using an optoelectronic system is challenging. The lack of bony landmarks in the back areas made it difficult because at least 3 noncollinear markers are required to obtain 3-dimensional information on position and rotation. Recent advancements in inertial sensor systems provide a good opportunity for spine kinematic analysis because a single inertial sensor, such as a small, lightweight electronic device, can measure the 3-dimensional orientation of a solid segment with few time and space constraints. In clinical practice, simpler and shorter data processing methods are more advantageous than optical motion analysis systems [8,9]. Their advantage may enable continuous or repeated monitoring of spinal posture in future applications.

In conclusion, using an inertial sensor system, lumbar postural changes were quantitatively analyzed by determining the 3-dimensional relative angles between the thoracic spine and pelvis in healthy subjects to find significant amounts and patterns of the lumbar postural changes during WPR, including over-rotation of the thoracic spine relative to the sacrum, increase in lordosis, and lateral bending. The application of this system on 3 axial LBP cases was feasible and revealed prominent deviations from the healthy postural changes, suggesting potential clinical value of the quantitative WPR by delineating small but abnormal lumbar motions in comparison to normal physiologic motor patterns. Hence, quantification of lumbar motion during WPR activity might be validated as a useful assessment tool for lumbar stability if large-scale normal and pathological data become available in the future.

Acknowledgments

The authors thank Dr. Sung Pill Kim for the assistance in the application of the Kalman filter algorithm. The authors also gratefully acknowledge the support of Seoul National University Hospital and the National Research Foundation of Korea (NRF), which is funded by the Ministry of Science, ICT and Future Planning.

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The authors acknowledge the support of Seoul National University Hospital (grant 0320110030) and the National Research Foundation of Korea (NRF), which is funded by the Ministry of Science, ICT and Future Planning (grants NRF-2005-2001287 and NRF-2014-050669).

Submitted for publication June 9, 2014; accepted March 7, 2015.