Gait Asymmetry Comparison between Subjects with and without Nonspecific Chronic Low Back Pain

Dongchul Lee 1 and Paul Sung 2,*

Abstract: Individuals with chronic low back pain (LBP) report impaired somatosensory function and balance. However, there is a lack of investigation on limb motion similarities between subjects with and without LBP during gait. The aim of this study was to compare gait parameters as well as combined limb motions using the kinematic similarity index (KSI) between subjects with and without LBP. Twenty-two subjects with LBP and 19 age- and body mass index-matched control subjects participated in this study. The combined limb motions in the gait cycle of subjects with LBP were compared with those of a prototype derived from healthy subjects. The calculations resulted in response vectors that were analyzed in comparison to control-derived prototype response vectors for the normalized index at 5% increments in the gait cycle. The results of our study indicated that the KSI of the control group demonstrated higher similarities in the swing (t = 4.23, p = 0.001) and stance (t = 6.26, p = 0.001) phases compared to the LBP group. The index for the whole gait cycle was significantly different between the groups (t = 6.52, p = 0.001), especially in the mid stance and swing phases. The LBP group could have adjusted the gait patterns during these specific phases. The KSI is useful for clinical outcome measures to differentiate kinematic changes and to demonstrate quantified similarities in the gait cycle between subjects with and without LBP. It is warranted to validate the KSI for the analysis of physiological gait asymmetry using a larger sample in future studies.

Keywords: kinematic similarity index; normalization; gait cycle; low back pain; asymmetry

1. Introduction

Low back pain (LBP) is one of the most frequently reported complaints, with a 24% to 87% rate of unpredictable recurrence [1,2]. Chronic nonspecific LBP occurs for more than 3 months without a recognizable, specific pathology and is the leading cause of functional limitations [3]. However, there is a lack of understanding of the kinematic changes and compensatory motions in the gait cycle (GC) occurring in individuals with LBP.

While gait patterns are cyclical and typically characterized by low variability in healthy individuals [4,5], an implication of those challenges is that some inter-stride variability may represent a healthy state of being [6]. The parameters of three-dimensional (3D) kinematic data are useful, since they match precisely the clinical definition of the limb segments interconnected by joints [7]. These compensatory motions are reflected by altered coordination and muscular control, not only of the trunk but also of the bilateral upper and lower limbs [8–10].

Limb motions are characterized by the adaptability of postural reactions; however, the degree of kinematic similarity between individuals with and without LBP has not been carefully investigated for gait performance. It is critical to incorporate other contributions to the kinematic similarity of gait, considering how neural control of compensation adapts in response to impairments such as LBP. There are limited studies on both stability and adjustability, which poses challenges to bipedal ambulation for individuals with LBP. The kinematic similarity of gait performance between individuals with and without LBP might be explained by a sensitive index for the GC.
A similarity concept has been introduced to compare voluntary motor controls in a clinical setting [11–15]. In our study, the kinematic similarity index (KSI) represents the magnitude of the difference between pathological and normal responses, although by itself it does not depict the direction of variance from normal motions in the original studies. In our previous study, a similar concept of kinematic index was utilized based on the mathematical expression of the similarity between individuals with and without LBP [16,17]. However, this index provided a limited interpretation of kinematic variations in the GC within, as well as between, groups.

Individuals with LBP often have poor neuromuscular control, which may alter the normal postural stability of the spine [18,19]. Thus, there is a need to identify specific gait deviations in order to maintain balance and to develop effective, evidence-based strategies to improve balance control in individuals with LBP and to reduce their risk of falls. However, very limited scientific evidence of GC exists that would help identify the kinematic changes to maintain balance. In our study, the normalized KSI in the GC was used to investigate the ratio between the vector representing the kinematic changes in individuals with LBP and that representing the kinematic changes in control subjects.

A recent systematic review reported that a number of studies presented methodological limitations as well as inconsistent findings, including small sample sizes and gait variability level to cope with the activation patterns [20]. Another gait study also reported that no differences were found between groups for gait parameters in the subphases of the GC in older adults with and without LBP [21]. Further standardized studies are needed to clarify these controversial findings based on participants with similar characteristics. The conflicting results are related to a lack of sensitive measures when considering individual variations, including age, body mass index (BMI), and limb dominance [22].

The gait of chronic LBP subjects is characterized by more rigid and less variable kinematic coordination in the transverse plane and less tight and more variable coordination in the frontal plane [23]. It was reported that measured intersegmental trunk coordination may be more informative about changes in gait in LBP subjects. Without comparing kinematic variations within, as well as between, the groups, the numerical expression of the motions may provide a limited clinical outcome [16,17]. Ultimately, a kinematic measure, such as the similarity index (SI), may help to evaluate gait functions and to determine the similarity of combined motions. In our study, the KSI allowed the interpretation of the normalized kinematic data of a group for combined upper and lower limb motions.

Clinicians are interested in measures that quantify the effect of interventions on gait asymmetries and their functional consequences in individuals with LBP compared with control subjects. Therefore, the aim of this study was to investigate the gait parameters and kinematic changes on the bilateral upper/lower limbs by using motions and the normalized KSI in age- and BMI-matched groups. We hypothesized that (1) the gait parameters would not be significantly different between the groups and (2) the KSI based on limb motions would be different in the GC between the groups.

2. Materials and Methods

2.1. Subjects

Subjects were recruited from the community and were informed about the protocol, procedures, and potential risks of the study. Those subjects who met the study inclusion criteria signed a copy of the Institutional Review Board (0816A2 and 1225A3)-approved consent form. Subjects were eligible to participate if they: (1) were right-limb dominant, (2) were between 19 and 60 years old, (3) had a current episode of LBP that had lasted for 12 weeks or longer with or without leg pain, (4) had no serious pathology, such as nerve root compromise, and (5) had no conditions which would prevent them from standing without impaired balance.

Subjects were excluded from participation if they: (1) had a diagnosed psychological illness that might interfere with the study’s protocol, (2) had overt neurological signs, and/or (3) were pregnant. Limb dominance was determined based on the preference to
use the right limb to kick a ball and to step out first when initiating gait [22,24]. All subjects were right-handed as determined by the Edinburgh handedness questionnaire [25]. The control group was recruited based on similar characteristics as those of the individuals with LBP.

2.2. Experimental Setup

Subjects provided a signed informed consent form and completed a health questionnaire. The level of disability of the LBP group was measured by the Oswestry Disability Index (ODI), which is one of the most frequently used tools for measuring dysfunction [26]. The subjects were informed about the precautions of the study.

Standardized instructions were provided following warm-up trials to acclimatize the subjects to the environmental conditions. Each subject underwent a series of walking trials, and he/she stepped on two force plates along the way.

The modified Helen Hayes full-body reflective marker set was attached to specific sites on the subjects’ bodies with adhesive tape rings (Figure 1). Data for the kinematics and kinetics were recorded using a Motion Analysis System (Motion Analysis Corporation, Rohnert Park, CA, USA) with six infrared cameras as well as two force platforms (AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA, USA) capturing 3D full-body kinematic motions sampling at 120 Hz. The ground reaction forces were recorded at 1000 Hz. The point of initiation of gait was set so that right heel contact was recorded on the force plate following two complete strides, similar to another study [27]. While the subjects repeated the series of gait trials, the 3D kinematic and kinetic data were synchronized using the Motion Analysis system. These sampling rates influenced the recognition of gait function. A study by Fallahtafi et al. indicated that the sampling rate of 120 Hz is the minimum sampling rate that should be used to calculate spatiotemporal data for variability [28]. By reducing the sampling rate, the time increments were increased and the resolution was reduced, leading to less accurate gait event detection in the temporal domain, according to this report.

![Figure 1. An example of marker placements for data collection during gait analysis.](image_url)

2.3. Data Processing

Kinematic data from three trials for each subject were exported and normalized to 0–100% of the GC. Before the experiment, data were collected from the unloaded platform to determine the zero offset. All kinematic data were filtered and time-synchronized in the GC. The Cortex software (Motion Analysis Corporation, Rohnert Park, CA, USA) was utilized for handling data calibration, tracking, and post-processing for the spatial-temporal measurements on each limb. Data were collected, and we tracked digital video
data using EVA 5.20 (Motion Analysis Corporation, Rohnert Park, CA, USA), which were then imported into OrthoTrac 5.2 (Motion Analysis Corporation, Rohnert Park, CA, USA) to analyze the gait parameters [29].

Reflective markers were placed in specified locations on the upper/lower limbs for the tracking of segment coordinate systems during walking trials. These markers were used to define and track a custom six-degree-of-freedom model. Markers were placed on the right and left greater trochanters of the femur, the medial and lateral femoral condyles, and the medial and lateral malleoli. Marker cluster plates were also placed on the thigh and shank [30,31]. On the left foot, markers were placed on the head of the first and fifth metatarsal heads along with three markers placed on the heel. On the right foot, the markers were placed on the most distal and dorsal points of the head of the proximal phalanx of the hallux, the head and base of the first, second, and fifth metatarsals, the most medial apex of the tuberosity of the navicular, the most medial apex of the sustentaculum tali, and the lateral apex of the peroneal tubercle; and triad markers were placed on the heel [31].

The gait speed was a function of both limbs, and the stance/swing phases (% cycle) of each limb were analyzed separately. Cadence (steps/min) was the number of steps per minute and was referred to as step rate. The gait speed (cm/s) was calculated by dividing the distance walked by the ambulation time on each limb. The stride length was the anterior–posterior distance (cm) between the same heel marker over successive foot contacts. The step width (cm) was defined as the perpendicular distance between similar points on both feet measured during two consecutive steps in the GC [16,32].

2.4. Data Computation

The KSI computation is a numerical expression of the motion’s similarity in the response vectors (RV) between subjects with and without LBP. The motions included the bilateral hips, knees, ankles, elbows, and shoulders. The SI was computed as the normalized inner product or the cosine of the solid angle between the vector representing the distribution of activity generated by subjects without LBP (prototype response vector: PRV) and that representing the distribution in subjects with LBP (RV). Thus, the index is constrained to lie between 0 and 1. As shown in Figure 2, a normalized KSI value of 1.0 designates an angle of zero between two vectors (i.e., the RV has an identical distribution of motions to the PRV) and signifies that motions in subjects with LBP are similar to those of a normal population.

The KSI tool was based on each subject who was assigned his/her own RVs, which are the set of data containing the motions for each individual. A given subject can have multiple RVs based on 3D motions for the upper and lower limbs. The PRV served as the control for the study and included only one value for a set of motion responses in the GC. The PRV is an average calculated from the RVs of the control subjects as the set of data containing the average of the motions for the control subjects.

To quantify the gait patterns, the KSI was computed from normalized motion data using the following equation (Equation (1)) for subjects with and without LBP (where i represents 3D kinematic data/channel, and x represents GC out of 100%). Previous studies reported an example of the computation of the index [11–13,15,33].

\[
KSI_x = \frac{\sum_i \text{PRV}_{x,i} \cdot \text{RV}_{x,i}}{|\text{PRV}_x||\text{RV}_x|}
\]

PRV\(_x\) = [PRV\(_x\)_1, PRV\(_x\)_1, ..., PRV\(_x\)_n] at x% in the GC

PRV\(_x\)_1: averaged value of R-Hip Rotation angles (T) from all control subjects

PRV\(_x\)_2: averaged value of R-Hip Abduction angles (F) from all control subjects

PRV\(_x\)_3: averaged value of R-Hip Flexion angles (S) from all control subjects

PRV\(_x\)_n: averaged value of nth channel from all control subjects

RV\(_x\) = [RV\(_x\)_1, RV\(_x\)_2, ..., RV\(_x\)_n] at x% in the GC

RV\(_x\)_1: R-Hip Rotation angle (T) from a test subject
RVx_2: R-Hip Abduction angle (F) from a test subject  
RVx_3: R-Hip Flexion angle (S) from a test subject  
RVx_n: nth channel from a test subject  

|PRVx| = magnitude of the PRVx vector  
|RVx| = magnitude of the RVx vector

PRVx= [PRVx_1, PRVx_1, … PRVx_n] at x% in the GC  
PRVx_1: averaged value of R-Hip Rotation angles (T) from all control subjects  
PRVx_2: averaged value of R-Hip Abduction angles (F) from all control subjects  
PRVx_3: averaged value of R-Hip Flexion angles (S) from all control subjects  
PRVx_n: averaged value of nth channel from all control subjects

RVx= [RVx_1, RVx_2, … RVx_n] at x% in the GC  
RVx_1: R-Hip Rotation angle (T) from a test subject  
RVx_2: R-Hip Abduction angle (F) from a test subject  
RVx_3: R-Hip Flexion angle (S) from a test subject  
RVx_n: nth channel from a test subject

Figure 2. An example of the KSI computation. The left column shows the angular motion measurement of the individual joints in the GC. The dark lines represent the averages of the control subjects. Subject A with LBP demonstrated good matching with the prototype in certain joints (R knee S, but mismatch in R hip S), and subject B with LBP showed the opposite direction in L ankle abduction. On the right panel, Equation (1) explains the principle of computing the KSI. (KSI: kinematic similarity index, R: right, L: left, GC: gait cycle, S: sagittal plane, F: frontal plane, T: transverse plane with all 24 channels (12 for each side), LBP: low back pain).

2.5. Statistical Analysis

Statistical analyses were completed using IBM Statistics 22 (IBM SPSS, Armonk, NY, USA). Normality of the joint kinematics, gait parameters, and SI data was assessed. The coefficient of variability was confirmed in order to check the homogeneity of the samples. It was also ensured that the values obtained for the joint kinematics and gait parameters were analyzed between groups using Cohen’s d test to characterize the effect size. The benchmarks for a small, medium, and large effect size were 0.2, 0.5, and 0.8 [34]. Analyses were performed, and tests were considered significant and meaningful if \( p < 0.05 \) and \( d > 0.8 \). For all statistical tests, type I error rate was set at 0.05.

3. Results

There were 22 subjects with LBP and 19 age- and BMI-matched control subjects without LBP, who participated in the study. There was no group difference in age or BMI, while there was a difference for gender. The ODI for the LBP group (21.18 ± 5.60%) indicated a moderate level of disability (Table 1). The gait parameters were compared; however, there was no significant group difference. In addition, the stance and swing
phases for the dominant and non-dominant limbs were not significantly different between the groups (Table 2).

Table 1. Summary of subjects’ demographics and bivariate relationship between groups.

| Variable            | Control Group     | LBP Group      | Statistic       | p     |
|---------------------|-------------------|----------------|-----------------|-------|
| Number (female/male)| 19 (10/9)         | 22 (8/14)      | Chi-square = 1.09 | 0.35  |
| Age (years)         | 27.58 ± 9.13      | 28.91 ± 12.80  | t = 0.37        | 0.71  |
| BMI (m/kg²)         | 19.29 ± 3.08      | 18.06 ± 4.13   | t = 1.06        | 0.29  |
| ODI (%)             | 1.79 ± 2.70       | 21.18 ± 5.60   | t = −12.37      | 0.001 *|

Mean ± Standard deviation, LBP: low back pain, BMI: body mass index, ODI: Oswestry Disability Index, *p < 0.05.

Table 2. Difference of gait parameters between the groups.

| Variable          | Control Group     | LBP Group      | 95% CI (Lower/Upper) | Statistic | p     |
|-------------------|-------------------|----------------|----------------------|-----------|-------|
| Cadence (steps/min) | 113.35 ± 13.24 | 110.58 ± 5.31 | −4.09/9.63          | t = 0.82  | 0.42  |
| Speed (cm/s)      | 125.84 ± 23.84    | 123.17 ± 13.49| −10.55/15.89        | t = 0.41  | 0.68  |
| Stride length (cm)| 131.93 ± 18.07    | 132.88 ± 12.09| −10.92/16.26        | t = −0.18 | 0.85  |
| Step width (cm)   | 10.56 ± 2.65      | 10.09 ± 3.80   | −1.79/2.73          | t = 0.42  | 0.67  |
| Stance D (% cycle)| 60.20 ± 4.38      | 61.16 ± 2.01   | −3.28/1.35          | t = −0.84 | 0.41  |
| Swing D (% cycle) | 39.79 ± 4.38      | 38.83 ± 2.00   | −1.35/3.28          | t = 0.84  | 0.41  |
| Stance ND (% cycle) | 61.28 ± 2.89 | 60.11 ± 1.54   | −0.41/2.75          | t = 1.50  | 0.14  |
| Swing ND (% cycle)| 38.88 ± 1.54      | 39.88 ± 1.54   | −2.75/0.41          | t = −1.50 | 0.14  |

Mean ± Standard deviation, LBP: low back pain, CI: confidence increment, D: dominant side, ND: non-dominant side.

As indicated in Table 3, the KSI (t = 6.52, p = 0.001, Cohen’s d = 1.43) and the standard deviation (SD) of SI (t = −7.62, p = 0.001, Cohen’s d = 1.53) were significantly different between the groups. There was also a significant difference for the KSI of the stance phase (t = 6.26, p = 0.001, Cohen’s d = 1.40) and the KSI of the swing phase (t = 4.23, p = 0.001, Cohen’s d = 1.11). The results of our study indicated that the LBP group demonstrated greater variability based on the SD than the control group in the GC.

Table 3. Comparison of the overall KSI and stance/swing phases between the groups.

| Variable                | Control Group     | LBP Group      | 95% CI (Lower/Upper) | Statistic | p     |
|-------------------------|-------------------|----------------|----------------------|-----------|-------|
| KSI                     | 0.99 ± 0.01       | 0.91 ± 0.05    | 0.05/0.10            | t = 6.52  | 0.001 **|
| SD of SI                | 0.01 ± 0.01       | 0.06 ± 0.03    | −0.07/−0.04          | t = −7.62 | 0.001 **|
| KSI of stance phase     | 0.99 ± 0.01       | 0.90 ± 0.05    | 0.06/0.11            | t = 6.26  | 0.001 **|
| KSI of swing phase      | 0.98 ± 0.01       | 0.92 ± 0.06    | 0.03/0.08            | t = 4.23  | 0.001 **|

Mean ± Standard deviation, LBP: low back pain, CI: confidence increment, KSI: kinematic similarity index, **p < 0.01.

The normalized KSI data were obtained from the groups at each 5% increment of the GC (Figure 3). The average of the KSIs analyzed for a whole GC in the control group (0.99 ± 0.01) was higher than that of the LBP group (0.91 ± 0.05), which supports that the prototype represented similar patterns within the group. The largest difference between the groups was observed at 10–30% (midstance) and 80–90% (terminal swing) of the GC. However, the SD of the KSI was less than 0.01 in the control group.
The KSI, therefore, differentiated kinematic changes between groups. Thus, sub-
jects with LBP were limited to adjust their limb motions characterizing their gait, although decreased variability in the control group was evident. The KSI, therefore, differentiated kinematic changes between groups.

The second hypothesis stated that the KSI based on limb motions would be signifi-
cantly different in the GC between groups. We accepted this hypothesis since the overall KSI, as well as the swing and stance phases, increased significantly in the control group compared with the LBP group. Thus, subjects with LBP were limited to adjust their limb motions characterizing their gait, although decreased variability in the control group was evident. The KSI, therefore, differentiated kinematic changes between groups.

The variance of the KSI itself at each GC is shown in Figure 3. The control group demonstrated variations of the kinematic data, and the variations of SD at each 5% increment of the GC were larger from 10% to 30% of the GC. These variations indicated the control group demonstrated higher similarities in the swing and stance phases than the LBP group. The overall KSI in the GC was significantly different between the groups, especially during the midstance and terminal swing phases.

The results of the SD of the KSI also indicated that the variability of the index sign-
ificantly decreased in the control group. Previous studies support our results that the normalized KSI, based on motions, is sensitive, reliable, and valid in comparison with other measurements [11,14,15]. These studies support our results that the normalized KSI, based on motions, provides a sensitive measure to differentiate individuals with and without LBP. Therefore, the development and use of the KSI could provide an effective means to quantify functional outcomes in rehabilitation.

The second hypothesis stated that the KSI based on limb motions would be signifi-
cantly different in the GC between groups. We accepted this hypothesis since the overall KSI, as well as the swing and stance phases, increased significantly in the control group compared with the LBP group. Thus, subjects with LBP were limited to adjust their limb motions characterizing their gait, although decreased variability in the control group was evident. The KSI, therefore, differentiated kinematic changes between groups.

The variance of the KSI itself at each GC is shown in Figure 3. The control group demonstrated variations of the kinematic data, and the variations of SD at each 5% increment of the GC were larger from 10% to 30% of the GC. These variations indicated that the control group demonstrated a wider variance in the GC, which indicated large variabilities of kinematic data at the end of the stance and swing phases compared with the beginning of each phase. When the PRV was compared to that of the LBP group, however, the difference was shown at the midstance and swing phases. These results indicated that the LBP group might have modified their walking patterns at specific phases, and the KSI provided a sensitive detection of the differences.

The normalized KSI can be useful for determining which data deviate the most from those of control subjects. Individual variations (ex. Age, height, and gender) in the groups, as well as confounding factors of the gait parameters (ex. Faster or slower speeds), may

---

**Figure 3.** The Kinematic Similarity Index (KSI) values of the groups were compared at each 5% increment during gait analysis. (*p < 0.05).
provide a different PRV. However, it would be necessary to build a database to evaluate other variations or gait parameters.

It has been reported that altered postural control might be a consequence of diminished proprioceptive input that leads to compensatory strategies to avoid pain or injury in individuals with LBP [8,35,36]. The results of our study confirmed that the decreased variability in the control group was based on the SD of the KSI. Thus, subjects with LBP were less capable of adapting their upper and lower limbs to the optimal motions during walking. Gait must be adequately rhythmic and sufficiently adaptable to accommodate destabilizing demands. It is generally accepted that gait patterns are cyclical and typically characterized by low variability in healthy adults [4]. An implication is that some inter-stride variability may represent a healthy state. Those variabilities in healthy individuals occurred in recurring gait cycles, and there is evidence in physiological systems that loss of complexity represents a pathological state [35]. The KSI, therefore, differentiated the kinematic changes in the LBP group, as the control group demonstrated significantly increased similarity in the GC.

Although the gait parameters were not significantly different between the groups, the proximal limb stability may enhance movement accuracy similar to the control group. Consequently, the compensatory limb’s motions resulted in increased motion variability and reduced coordination of limb motions, especially in the midstance and swing phases in the LBP group.

The KSI, taking into consideration all kinematic data/channels, is a sensitive tool that might be utilized for the early detection of functional outcomes of gait dysfunction. The reduced variability of kinematic changes resulted in an increased KSI in the control group. Other studies reported that compensatory motions during gait provide the necessary stability and prevent potential injuries by integrating optimal trunk and limb coordination [36,37]. The KSI tool is valuable, as multiple factors in motor control may explain the considerable between-subject variance of this measure, since the LBP group demonstrated altered 3D motions in the upper and lower limbs during walking.

Although our study was not intended to compare the theoretical rationale for these differences, the LBP group could display motor control disturbances in trunk and limb muscle activation. For example, pain intensity was negatively correlated with step and stride length as well as cadence and velocity [38,39]. The higher degrees of stride-to-stride variability, as our results indicated, represented increased fluctuations in dynamic thoracic and pelvic oscillations in the LBP group [40]. Another study also supports our results that the pressures on the plantar surface were unequally distributed in the chronic LBP group in the midstance phase of the GC [41]. An altered foot contact may be used to avoid pain or to compensate for the limited mobility of the lower limbs during walking.

There are possible reasons for the gait asymmetry in the LBP group compared with the control group, as the KSI was different in the midstance and swing phases while walking. The proximal limb and/or core muscle stability might be critical to enhance movement accuracy to values similar to those of subjects without LBP [42–44]. Consequently, the compensatory limb motions resulted in increased motion variabilities and reduced smoothness of limb motions, especially in the midstance and swing phases in the LBP group.

The chronic LBP group was also characterized by more rigid and less variable kinematic coordination in the transverse plane during gait [23]. These biomechanical differences may result in reduced motion in other planes [45].

There are several limitations in our study. First, individual variations, including a possible leg length discrepancy within the groups, may make it difficult to generalize the results of our study. However, the demographic factors were not statistically different between the groups. Second, it is possible that instrumental problems may have affected the data. For example, the accuracy in placing markers on the skin could be slightly different due to varied soft tissue thickness of the upper and lower limbs. However, the accuracy of marker placement was carefully ensured to mitigate this possibility.
The KSI measure might be utilized to analyze gait dysfunction for rehabilitation strategies [33]. Specifically, KSI differences between the examined groups were apparent during the loading response of the limb and during the midstance and terminal swing phases of the GC. Group differences were evident and were related to the moderate level of pain, although pain did not prevent the subjects from standing without impaired balance. The KSI provides a sensitive measure that begins at midstance when the heel leaves the ground and ends with toe-off at the end of the stance phase, as well as in the terminal swing phase.

5. Conclusions

As the KSI measurements detected gait deviations, the LBP group may have adjusted their gait patterns. Further studies are warranted to compare whole-body motions, including trunk and limb motions, for gait control.

Author Contributions: Conceptualization, D.L. and P.S.; methodology, D.L. and PS.; validation, D.L. and PS.; formal analysis, D.L. and PS.; investigation, D.L. and PS.; resources, D.L. and PS.; data curation, D.L. and PS.; writing—original draft preparation, P.S.; writing—review and editing, D.L. and PS.; visualization, D.L.; supervision, P.S.; project administration, PS. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (20100003019).

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of Korea University (protocol numbers: 0816A2; date of approval 22 January 2012 and 1225A3; date of approval 12 June 2012).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank WH Park at Korea University and Emily Hosmer at Central Michigan University for their technical assistance in data collection and their contributions to the study.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Pengel, L.; Herbert, R.D.; Maher, C.; Refshauge, K.M. Acute low back pain: Systematic review of its prognosis. BMJ 2003, 327, 323. [CrossRef]
2. Stanton, T.R.; Henschke, N.; Maher, C.; Refshauge, K.; Latimer, J.; McAuley, J. After an Episode of Acute Low Back Pain, Recurrence Is Unpredictable and Not as Common as Previously Thought. Spine 2008, 33, 2923–2928. [CrossRef]
3. Deyo, R.A.; Dworkin, S.F.; Amtmann, D.; Andersson, G.; Borenstein, D.; Carragee, E.; Carrino, J.; Chou, R.; Cook, K.; Delitto, A.; et al. Report of the NIH Task Force on Research Standards for Chronic Low Back Pain. Phys. Ther. 2015, 95, e1–e18. [CrossRef]
4. Hollman, J.H.; Kovash, F.M.; Kubik, J.J.; Linbo, R.A. Age-related differences in spatiotemporal markers of gait stability during dual task walking. Gait Posture 2007, 26, 113–119. [CrossRef]
5. Bailey, C.A.; Porta, M.; Pilloni, G.; Arippa, F.; Pau, M.; Côté, J.N. Sex-independent and dependent effects of older age on cycle-to-cycle variability of muscle activation during gait. Exp. Gerontol. 2019, 124, 110656. [CrossRef] [PubMed]
6. Hollman, J.H.; Watkins, M.K.; Imhoff, A.C.; Braun, C.E.; Akervik, K.A.; Ness, D.K. Complexity, fractal dynamics and determinism in treadmill ambulation: Implications for clinical biomechanists. Clin. Biomech. 2016, 37, 91–97. [CrossRef] [PubMed]
7. An, K.N.; Chao, E.Y. Kinematic analysis of human movement. Ann. Biomed. Eng. 1984, 12, 585–597. [CrossRef] [PubMed]
8. Lamoth, C.J.; Daffertshofer, A.; Meijer, O.G.; Beek, P.J. How do persons with chronic low back pain speed up and slow down?: Trunk–pelvis coordination and lumbar erector spinae activity during gait. Gait Posture 2006, 23, 230–239. [CrossRef]
9. Callegari, B.; Saunier, G.; Duarte, M.B.; da Silva Almeida, G.C.; Amorim, C.F.; Mourey, F.; Pozzo, T.; da Silva Souza, G. Anticipatory Postural Adjustments and kinematic arm features when postural stability is manipulated. PeerJ 2018, 6, e4309. [CrossRef] [PubMed]
10. Sung, P.S.; Leininger, P.M. A kinematic and kinetic analysis of spinal region in subjects with and without recurrent low back pain during one leg standing. Clin. Biomech. 2015, 30, 696–702. [CrossRef]
40. Vogt, L.; Pfeifer, K.; Portscher, M.; Banzer, W. Influences of Nonspecific Low Back Pain on Three-Dimensional Lumbar Spine Kinematics in Locomotion. Spine 2001, 26, 1910–1919. [CrossRef] [PubMed]

41. Anukoolkarn, K.; Vongsirinavarat, M.; Bovonsunthonchai, S.; Vachalathiti, R. Plantar Pressure Distribution Pattern during Mid-Stance Phase of the Gait in Patients with Chronic Non-Specific Low Back Pain. J. Med Assoc. Thai. = Chotmaihet thangphaet 2015, 98, 896–901.

42. Lee, T.-R.; Kim, Y.H.; Sung, P.S. A comparison of pain level and entropy changes following core stability exercise intervention. Med. Sci. Monit. 2011, 17, CR362–CR368. [CrossRef] [PubMed]

43. Willson, J.; Dougherty, C.P.; Ireland, M.L.; Davis, I.M. Core Stability and Its Relationship to Lower Extremity Function and Injury. J. Am. Acad. Orthop. Surg. 2005, 13, 316–325. [CrossRef] [PubMed]

44. Hodges, P.W. Core stability exercise in chronic low back pain. Orthop. Clin. N. Am. 2003, 34, 245–254. [CrossRef]

45. Sjolander, P.; Michaelson, P.; Jaric, S.; Djupsjöbacka, M. Sensorimotor disturbances in chronic neck pain—Range of motion, peak velocity, smoothness of movement, and repositioning acuity. Man. Ther. 2008, 13, 122–131. [CrossRef] [PubMed]