Chapter 10

The Quantified Indices for Compensatory Patterns for Low Back Pain and Outcome Measures

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Abstract

The quantification of balance stability is valuable to a number of populations, including older adults with low back pain (LBP). Investigations into postural stability and one-leg standing should be performed to integrate balance performance using kinematic and kinetic indices. The comparison of postural control between older adults with LBP and healthy older adults might contribute to a further understanding of postural adaptations, especially when considering visual condition. The one-leg standing test would highlight the differences in kinematic and kinetic stabilities between groups. Because the eyes-closed condition results in significantly decreased spinal stability, the normalized kinematic and kinetic indices could be utilized to compare postural integration as well as proprioceptive responses. Older adults with LBP demonstrated higher lumbar spine stability in the eyes-open condition, which might be due to a possible pain avoiding strategy from the standing limb. Clinicians need to consider both kinetic and kinematic indices and visual condition when addressing lumbar spine stability. Quantified indices for compensatory patterns might provide further understanding of optimal injury prevention and rehabilitation strategies for individuals with LBP.

Keywords: low back pain, balance, kinetic, kinematic, biomechanics, postural control

1. Introduction

Low back pain (LBP) is an ailment that impacts work performance and affects up to 80% of the United States population at some point in an individual's, making it one of the most prevalent musculoskeletal conditions causing physical disability [1, 2]. LBP is a major factor in escalating health-care costs with a point prevalence of approximately 12%, a 1-month prevalence of 23%, and a 1-year prevalence of 38% [3]. One study reported that between 24 and 80% of older adults with LBP experienced recurrent episodes within 1 year [3]. As the most commonly encountered medical condition in older adults, LBP poses an even greater challenge in the health care of this population as compared to their younger counterparts.

This chapter proposes biomechanical assessments of spinal function by which to evaluate LBP. The development of a valid and reliable tool for evaluating older adults with LBP is necessary to provide a link between LBP and balance deficits. It might be helpful for clinicians to consider the potential characteristics of kinematic data, such as range of motion, velocity, and acceleration as well as kinetic data, such as ground reaction force (GRF) changes, during the one-leg standing test. This combined approach could provide a better understanding of postural stability and ground reaction forces for integrating motor control and biomechanics. Specifically, an understanding of the compensatory patterns between normalized kinematic and kinetic stability indices for spinal regions, while considering visual condition may reveal possible pain avoiding strategies from the standing limb. These would be important findings since a lack of coordination and altered postural strategy has the potential to cause musculoskeletal injuries. Individual variations between older adults might lead to different compensatory responses and should be elucidated to establish fall prevention strategies. Several studies reported that an analysis of the one-leg standing test via a motion capture system could be used to determine balance strategies in older adults with LBP [4–8]. However, a comprehensive tool for quantifying kinematic and kinetic changes during one-leg standing is still needed to enhance evidence-based practice, prevent fall injuries, and identify factors affecting proprioception and posture.

An evidence-based, quantitative approach may enhance quality of care for older adults with LBP and aid in preventing injury. Furthermore, the development of potential interventions as a result of this quantitative approach could favorably alter motor control, which plays a key clinical role in terms of musculoskeletal and neurological functioning of older adults with LBP.

2. Comprehensive balance parameters

Evidence-based intervention has stressed the importance of establishing a strong link between treatments and outcomes to both researchers and clinicians. Various studies have suggested that exercise programs are effective in the treatment of LBP [9–12]; however, most researchers fail to provide evidence favoring one exercise over another. Contradicting results might be related to poor sensitivity of the instruments, an unmatched research design, small sample sizes, and/or the lack of a valid and reliable index for standardization.

It is necessary to provide sensitive kinetic and kinematic indices for quantitative evaluation of altered postural coordination in older adults with recurrent LBP. Kinetic and kinematic data regarding spinal dysfunction and coordination may provide clinical insight into motor control and identify patterns of compensatory movements in older adults with recurrent LBP [13, 14]. Several studies have measured kinematic changes of the dominant thigh and pelvis to identify variations in balance sway compensation strategies as well as spinal alignment and core stability between older adults with LBP and control subjects [13, 15]. Another study

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reported that because active limb movements might be associated with early lumbopelvic motion, increased frequency of these movements may contribute to increased lumbar region tissue stress, potentially leading to LBP symptoms [16] since altered movements are known to decrease muscular force-generating capabilities [17, 18]. These outcome studies considered the morphological and functional implications in the neuro-musculoskeletal system.

The one-leg standing test was developed in order to investigate dynamic postural steadiness (**Figure 1**). Clinicians often use the one-leg standing test to assess movement performance and to observe biomechanical deficits. It provides a sensitive analysis of postural stability, considering 40% of human gait movement occurs during one-leg stance [19, 20]. The one-leg standing test examines the ability of the subject to perform spinal load transfers and to optimize pelvic girdle stability while also detecting relative innominate bone motion [21]. A kinematic analysis of the body regions and the kinetic analysis from the force plate during the one-leg standing test could be useful in enhancing the understanding of the role of core spine activity during the test. As shown in **Figure 1**, the core spine model is a reference model for trunk motion used in motion analysis. It compares specific three-dimensional kinematic data to the motion of the lumbar spine [13]. This measure of integrated spinal stability might allow for the development of motor control strategies in older adults with LBP since reaction forces from the platform reflect oscillations in forces about the foot needed to maintain balance [7, 14, 20].

The kinetic and kinematic changes in three-dimensional trunk motion could also be compared to reflect standing balance contributions to postural control [7]. A lack of coordination of the

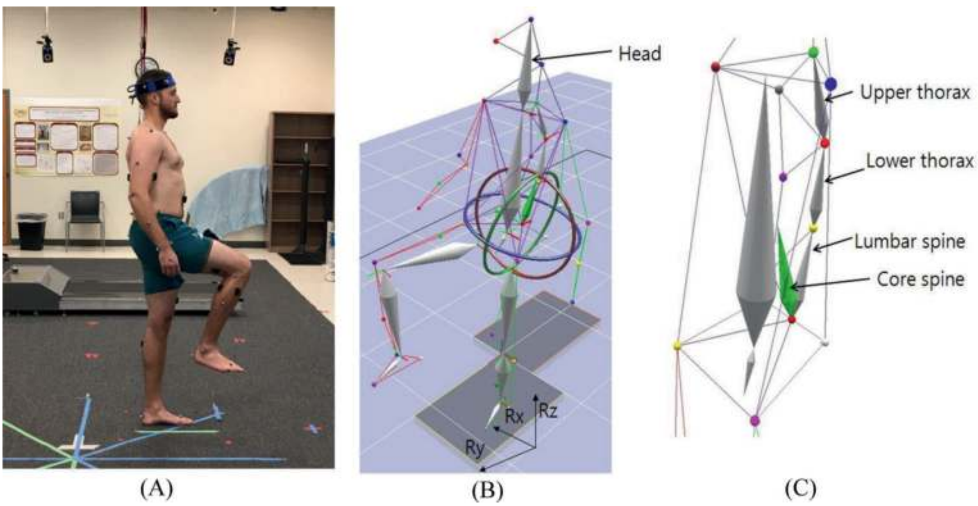

Figure 1. One-leg standing balance test (A). The subject was asked to stand on a single leg with the contralateral hip and knee flexed 90° for 30 s. During the test, the subject maintained postural stability while kinetic and kinematic data were collected. In order to quantify the data, each segment was calculated as the amount of rotational displacement side-to-side (Rx), back-and-forth (Ry), and up-and-down (Rz) away from a mean value (B). The core spine model was utilized as a reference to compare specific three-dimensional spine motions including the lumbar spine and the lower and upper thoracic spines (C).

lumbar spine may cause musculoskeletal injuries, and altered coordination of the postural reaction might lead to compensatory responses to prevent injuries [14, 22, 23]. Quantifying postural compensation may lead to a better understanding of spinal movement patterns due to a fear of falling in order to clarify the relationship between kinematic and kinetic changes in older adults with recurrent LBP.

The normalized kinematic index of the lumbar spine was calculated based on the three-dimensional rotation angle (*Rxyz*) and relative standing index between control and recurrent LBP groups. The ratio between standing duration and requested duration could be compared with the corresponding older adults' *Rxyz* values. The analysis time window excluded the initial transition time (5 s) from standing with bilateral legs to maintaining single, dominant leg standing.

3. Postural deficits and integrated balance performance

Fear of falling is a major health concern among older adults and has even been reported in those who have no history of falls [24, 25]. The presence of fear of falling was defined as "low perceived self-efficacy at avoiding falls during essential, nonhazardous activities of daily living" [26]. Fear of falling risk drastically increases with age and is known to affect quality of life in older adults, especially for women who fear that falling contains potentially serious outcomes [27–29]. These studies indicated that fear of falling in older women is a common and persistent complaint that is caused mainly by impairments of balance and mobility. The results for balance problems or fear of falling imply that early intervention might be important in the prevention and rehabilitation of balance deficits.

The development of sensitive tools that can quantify loss of balance is paramount to improving quality of life in older adults. It is essential to perform biomechanical and functional analyses of the most representative kinematic and kinetic variables obtained from specific tasks, including the one-leg standing test. Since the control of spinal function might include excitability in the motor pathway with fearful aspects of pain syndromes, the combined kinematic analysis based on spinal regions and kinetic indices from a force plate may provide comprehensive postural integrity strategies to reduce the risk of injury.

Previous studies support the idea that older adults with LBP have reduced proprioceptive sensation on position-reposition accuracy and have a higher prevalence of balance deficits [30–32]. Several other studies focusing on typical movement patterns in older adults with LBP identified increased postural sway and decreased lumbar spine motion [33, 34]. It has been reported that individuals with LBP demonstrate significantly decreased postural stability during one-leg standing and other clinical balance tests [7, 8, 14]. However, the results of these studies lacked an understanding of three-dimensional dynamic variables over time during one-leg standing. Further, most clinical outcome studies are still not convincing in their measurements, and implications of functional activity need to be further investigated [35, 36]. For example, center of pressure (COP) displacement may provide useful information in quantifying standing postural stability as well as predicting dynamic balance [37]. However, the COP provides limited information, as it is only a two-dimensional quantity.

Before one can quantify balance deficits, however, one must first understand their origins and the factors that directly or indirectly impact them. The assessment and classification of balance deficits due to spinal disorders have been carried out in different ways. Patients have been classified according to the injured or painful structure using imaging techniques (i.e., magnetic resonance imaging, computed tomography, and myelography). However, a pathologic-anatomic diagnosis is established in only 10–15% of all patients with disorders of the lumbar region [1]. Additionally, there is great variation in the reported prevalence of balance deficits in older adults, which is associated with multiple factors, including poor health characteristics [38, 39]. Gender, age, body mass index (BMI), time since initial pain onset, and quality of life warrant further investigation for a complete understanding of the role of these factors in providing comprehensive tools to prevent fall injuries. Therefore, valid and reliable measurement tools for balance deficits that account for physiological and socioeconomic factors would be important for clinicians to develop rehabilitation and injury prevention strategies.

The quantification of balance deficits based on three-dimensional kinematic and kinetic indices is valuable to a number of populations, including older adults with LBP. It is generally accepted that individuals with LBP possess altered postural control as well as less-refined proprioception [15, 40, 41]. Previous research has shown that control groups demonstrated significantly longer standing duration in the eyes-open condition [7, 13]. Due to decreased proprioception, the pain-avoiding strategies implemented by the LBP group may be more evident. When proprioception is limited, the differences in standing duration may explain the proprioceptive capability between groups [42]. The normalized kinematic index could be utilized to compare postural integration based on visual input as well as proprioceptive responses. This compensatory pattern needs to be further investigated for optimal injury prevention and the development of effective rehabilitation programs.

Studies have also reported poor coordination of balance performance in individuals with LBP; however, there is a lack of understanding about the individual kinetic and kinematic characteristics of trunk motion in older adults with balance deficits. Recent studies have been performed to evaluate the role of core stability in older adults with LBP [43–45], as kinematic changes of the trunk are compensated for by postural alignment and core spine stability [13, 15]. Further, a comprehensive investigation to determine postural steadiness might be helpful to understand the control of postural segments, including the trunk, pelvis, and lower extremities, during one-leg standing. The ability to adjust postural steadiness as a function of these regions is critical for activities of daily life, as increased balance sway was related not only to spinal motion but also to dynamic functional capacity in older adults with LBP [46]. Therefore, a change in postural steadiness might be related to an increase in kinetic stability [7], which reduces dynamic functional capacity in the trunk, pelvis, and lower extremities.

Older adults with LBP demonstrated differences in lumbar spine stability, possibly due to a pain avoidance strategy and compensation from the standing limb [7]. However, it is not clear how the kinematic chain reaction might change for whole body control mechanisms during one-leg standing. Therefore, the normalized kinematic stability index of the body regions (thorax, pelvis, and bilateral thighs, shanks, and feet) and one-leg standing duration might contribute to an integrated understanding of postural steadiness in older adults with LBP.

Several studies have used the one-leg standing test to investigate postural control using different outcome variables [7, 13, 47]. The one-leg standing test can be divided into two phases: the dynamic phase and the static phase. The dynamic phase is defined as a rapid decrease of force variability during the first 5 seconds (s) of the test. The static phase is defined as the maintenance of a certain level of force variability. One study, which investigated the first 5 s of a 25 s duration test (dynamic phase), concluded that the first few seconds of the one-leg standing test pose the greatest challenge to postural steadiness [48]. They concluded that if participants were unable to perform one-leg standing for at least 5 s, they were at an increased risk for injurious falls. Other studies have investigated the static phase. High variability during the first 5 s of the static phase of the one-leg standing test was reported, which could potentially be caused by muscular or postural adjustments [7, 14]. Based on these findings, it might be possible to analyze the first 5 s increments of the static and dynamic phases of postural stability to discover different aspects of sensorimotor function that older adults with LBP use to enhance pain-avoiding strategies.

It has been reported that impaired back muscle function may lead to an inability to adopt postural control strategies focused on increasing strength and self-efficacy in older adults with LBP [49, 50]. These studies suggested that impaired back muscle function may lead to an adaptation of postural control strategies with the primary purpose of preventing pain and decreasing mobility of the painful region. By contrast, longer one-leg standing duration in the control group can be explained by enhanced motor learning due to greater ability to perform functional activities and implement more functional postural control strategies.

Other studies supported the reorganization of trunk muscle representation at the motor cortex in individuals with recurrent LBP [51, 52]. Their results suggest that this reorganization is associated with deficits in postural control, which persist after the training effect takes place as LBP becomes chronic or recurrent. Eventually, these learned strategies become automatic defense mechanisms to prevent pain and further injury [15, 52].

4. Kinetic and kinematic indices

The stability index was developed with two parameters—relative standing time and relative standstill time [14]. The relative standing time was defined as a ratio between the successful standing time and the requested standing time. The successful standing time was measured as the total standing time before the subject failed to maintain stability, allowing the non-dominant, lifted limb to touch the force plate. The relative standstill time was defined as a ratio between the sum of standstill time and successful standing time. The standstill time was the summation of the temporal segments, where the three-dimensional rotation of the tested axis was below threshold (5°).

In **Figure 2**, the distribution of the normalized standing time was plotted with the corresponding relative kinematic index for the core spine model between the control group and the recurrent LBP group. The data obtained from five subjects were selected as examples

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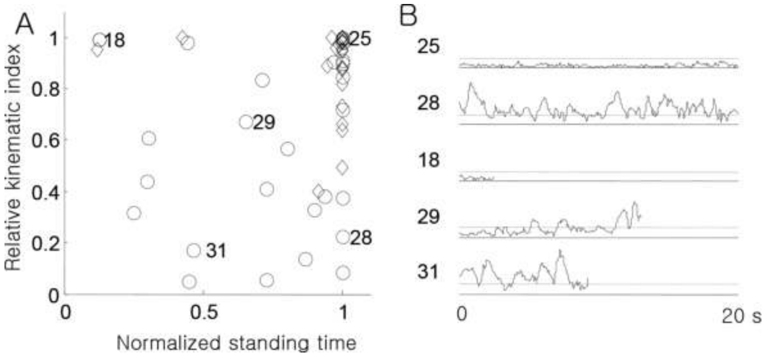
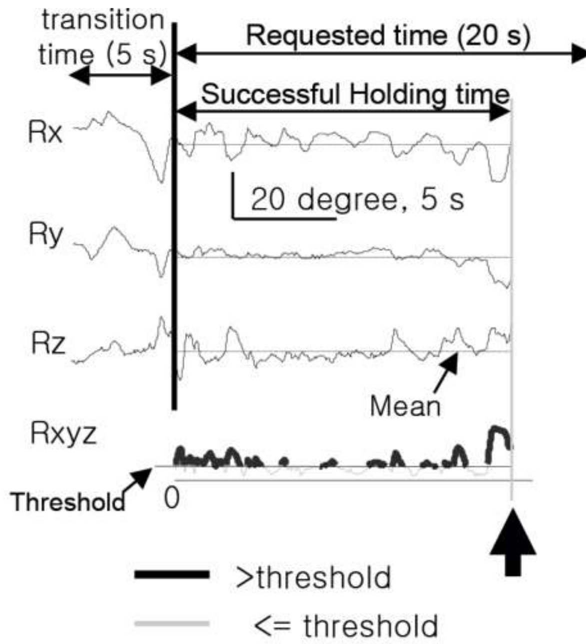


Figure 2. A: Distribution of normalized standing time (x-axis) and relative kinematic index (y-axis) of body regions and corresponding three-dimensional angle (Rxyz) from control group (diamond) and LBP group (open dot). B: Examples of Rxyz traces from A. Subject 25 had stable and long duration, while subject 28 had unstable long duration. Subject 18 had short duration with stable balance and subject 31 had relatively short duration with unstable balance. Subject 29 had longer duration and more stable balance than subject 31. Threshold (dot) and baseline (solid) are plotted for each trace.

of the normalized standing time, and the relative kinematic index was compared with the corresponding subjects' *Rxyz* values. The analysis time window excluded the initial transition time (5 s) from the test [14].

Therefore, the rotational angular displacements were more important than translations during the test. The operational definitions for the terms utilized in this study are included as follows:

- Normalized kinematic index from spinal regions: The rotational angles of the specific spinal regions (core spine model, lumbar spine, lower thorax, and upper thorax) were calculated between two adjacent joints in three dimensions and then combined to quantify the normalized kinematic stability index. As shown in **Figure 3**, the angular displacement of the lumbar spine was calculated from the average, and then, temporal summation of the data was used to calculate the normalized kinematic index for each spinal region.
- Normalized kinetic index from force plate: The older adults stood upright on the non-dominant leg for 20 s on a force plate surface with the dominant hip and knee flexed to approximately 90°, first with their eyes open and then with their eyes closed. The summation of ground reaction forces was computed in the same way as the kinematic index, with the average value subtracted to have each force plane average. Therefore, the normalized kinematic and kinetic changes for postural stability were compared for the balance test under different visual conditions. The kinematic and kinetic data were normalized so that various individual differences might be fairly compared between groups. For reliability, the intra-class correlations were calculated to determine the force plate measures taken. The intra-class correlation coefficients of type (3, 1) were used to determine the degree of test-retest reliability, ranged from 0.85 to 0.98, and were interpreted as excellent according to Shrout and Fleiss [53].



$$Rxyz = \sqrt{(R_x - R_{x\_mean})^2 + (R_y - R_{y\_mean})^2 + (R_z - R_{z\_mean})^2}$$

Figure 3. The rotation angle of the core spine computed from kinematic markers. For computing stability index, initial transition time (5 s) was excluded. Out of 25 s requested holding time, successful holding time (duration) was measured as the total duration until subject fail to stand on one leg (large arrow). The kinematic stability was measured as the square root sum of axial angle subtracted from its own mean value during successful holding time (see equation).

- The dynamic postural steadiness index (DPSI): The DPSI (4) was based on the kinetic data, which was calculated for three principal directions and was reported as a sensitive measure index. The DPSI is a composite of the medio-lateral steadiness index (MLSI; 1), anterior-posterior steadiness index (APSI; 2), and vertical steadiness index (VSI; 3), which are mean square deviations assessing fluctuations around a zero point, rather than standard deviations assessing fluctuations around a group mean. The stabilization time was also determined as an objective postural control measure by using three indices of analysis based on the resultant GRF. The MLSI and APSI assessed the fluctuations from a zero point along the frontal and sagittal planes of the force plate, respectively. The VSI assessed fluctuation of the subject's body weight to normalize the vertical scores for standardization of the vertical GRF along the transverse plane of the force plate. This measure allowed comparison of individuals with different body weights (mass).

$$\text{MLSI} = \sqrt{\left[\frac{\Sigma\,(0-x)^2}{\text{number of data points}}\right]} \tag{1}$$

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$$\text{APSI} = \sqrt{\left[\frac{\Sigma(0-y)^2}{\text{number of data points}}\right]} \quad (2)$$

$$\text{VSI} = \sqrt{\left[\frac{\Sigma(\text{body weight}-z)^2}{\text{number of data points}}\right]} \quad (3)$$

$$\text{DPSI} = \sqrt{\left[\frac{\Sigma(0-x)^2+\Sigma(0-y)^2+\Sigma(\text{body weight}-z)^2}{\text{number of data points}}\right]} \quad (4)$$

The outcome measures included one-leg standing time, DPSI (composite of MLSI, APSI, and VSI), and stabilization times. In this way, postural stability might be quantified during the one-leg standing test with the underlying premise that dynamic postural stability depends on lower limb kinematics.

5. Applications for the balance indices

The normalized kinematic stability index for specific portions of the body was compared with the kinetic stability index from the force plate.

As shown in **Figure 4**, a threshold was determined as 10 Newtons for the normalized kinetic stability. Although the value might not be the optimal quantity, the results would not be significantly different if neighboring values were selected.

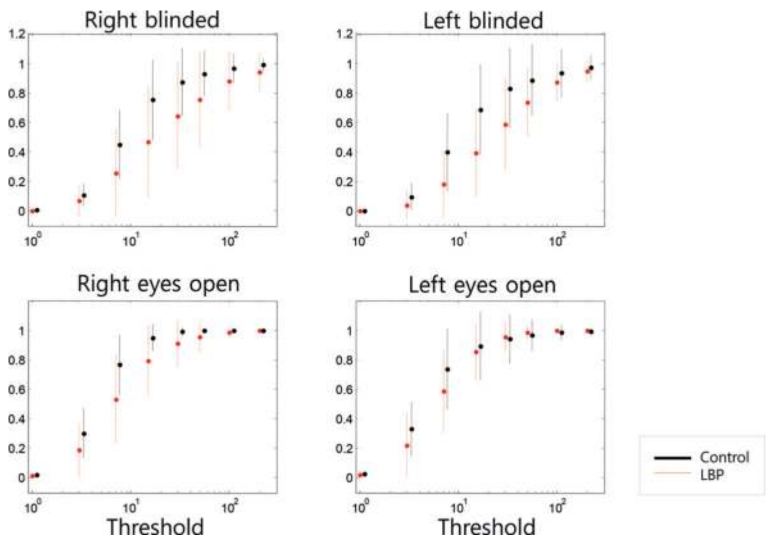

Figure 4. The change of threshold on normalized kinetic stability for the force platform between groups based on visual input. A threshold of approximately 10 Newtons could separate the LBP group from the control group.

A recent review article indicated that there are no evidence-based guidelines currently available to assess spinal instability [54, 55]. Their summary indicated that both spinal stability and mobility concepts represent a new frontier in the study of the painful degenerative spine. The development of new rehabilitation strategies for LBP based on information regarding the kinematic and kinetic stability indices could help restore the normal function of spinal segments and protect the adjacent segments. Previous studies also reported that postural steadiness, including trunk coordination, is a foundational necessity to prevent early mechanical deterioration of the entire body [8, 14, 56]. Postural steadiness has been used to characterize the dynamics of the postural control system associated with maintaining balance [57]. However, the compensatory function of postural steadiness needs to be implemented within the whole body to prevent recurrence of pain and further injuries.

6. Clinical implications

It is important to investigate the effects of an intervention in terms of its musculoskeletal or neurological link with the cardiovascular and integumentary systems during human motion. Although some therapeutic interventions have demonstrated benefits, researchers have not quantified or characterized the results yielded by specific non-surgical interventions [9–12].

The one-leg standing test could be utilized to quantitatively assess postural steadiness in a static position and to investigate various balance disorders in older adults with LBP. The test has been utilized in clinical settings, in which patients perform the test with their eyes open, standing unassisted on one leg. The test is timed in seconds from the time one foot is lifted off the floor to the time when it touches the ground [7, 58].

Other balance and gait abilities were assessed using the Berg Balance Scale [59], the functional reach test [60], the timed up and go test [61], the 10-m walking test [62], and the timed single leg stance test [8]. The performance values established in this study help make the single-limb stance test (eyes open and eyes closed) a reliable, readily available, and easy to perform "bedside" examination tool for balance testing [63]. The quantified performance scores based on the age and the degree of pain across a sample will aid clinicians in understanding the specific level of performance for the clinical outcome measures.

Therefore, it is evident that nonsurgical spine research, as well as other fields of clinical research, should enhance the quality of clinical efforts and develop effective interventions for individuals suffering from LBP. It is important to develop a sensitive tool for evaluating baseline disability and the effectiveness (or detriment) of clinical treatment strategies for individual patients. However, the COP provides limited information on body reactions. Conversely, the combined three-dimensional kinetic analyses from GRF with specific sensitive thresholds, as well as kinematic index analyses, provide more accurate and meaningful data, which could allow for the development of new and more effective intervention strategies for treating LBP [14].

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7. Conclusion

The quantification of balance deficits based on kinematic and kinetic indices is valuable to a number of populations, including older adults with LBP. The comparison of postural control based on the normalized kinematic and kinetic stabilities during the one-leg standing test might contribute to a further understanding of postural adaptations that occur as a result of chronic LBP. The compensatory pattern need to be investigated to allow for optimal injury prevention and the development of effective rehabilitation programs.

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Conflicts of interest

None of the authors has any financial or personal conflicts of interest in relation to the submission, other people, or any organizations.

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