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ORIGINAL ARTICLE

Postural control and trunk stability on sway parameters in adults with and without chronic low back pain

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Abstract

Background Postural sway changes often reflect functional impairments in adults with chronic low back pain (LBP). However, there is a gap in understanding how these individuals adapt their postural strategies to maintain stability.
Purpose This study investigated postural sway distance and velocity, utilizing the center of pressure (COP) and center of gravity (COG), between adults with and without LBP during repeated unilateral standing trials.
Methods Twenty-six subjects with LBP and 39 control subjects participated in the study. Postural sway ranges, COP/COG sways, and sway velocities (computed by dividing path length by time in anteroposterior (AP) and mediolateral (ML) directions over 10 s) were analyzed across three unilateral standing trials.
Results A significant group interaction in sway range difference was observed following repeated trials (F = 5.90, $p = 0.02$). For COG sway range, significant group interactions were demonstrated in both directions (F = 4.28, $p = 0.04$) and repeated trials (F = 5.79, $p = 0.02$). The LBP group demonstrated reduced ML sway velocities in the first (5.21 ± 2.43 for the control group, 4.16 ± 2.33 for the LBP group; t = 1.72, $p = 0.04$) and second (4.87 ± 2.62 for the control group, 3.79 ± 2.22 for the LBP group; t = 1.73, $p = 0.04$) trials.
Conclusion The LBP group demonstrated decreased ML sway velocities to enhance trunk stability in the initial two trials. The COG results emphasized the potential use of trunk strategies in augmenting postural stability and optimizing neuromuscular control during unilateral standing.

Keywords Low back pain · Postural sway · Center of pressure · Center of gravity · Unilateral limb standing

Introduction

Low back pain (LBP) is the second leading cause of work-related absenteeism and is clinically manifested by symptoms such as muscular tension and pain in the lumbar area to the lower limbs [1, 2]. An estimated 30% of individuals aged 60 and above have reported sustaining injuries due to falls [3]. Age-related physiological and psychosocial changes exacerbate the susceptibility to chronic LBP [4, 5].

Individuals with LBP exhibit greater postural instability signified by greater center of pressure (COP) excursions and a higher mean velocity [6]. However, other studies reported no effect of LBP on postural sway or a decreased sway in the LBP group [7]. While various investigations have examined the effect of LBP on neuromuscular control and postural stability [6, 8, 9], there remains a lack of agreement regarding compensatory postural adaptations during repeated unilateral standing balance trials.

Maintaining standing balance is essential for functional activities and can be gauged using postural sway, which mimics an inverted pendulum moving around the ankle joints [10, 11]. Clinicians commonly utilize the unilateral standing test as a fundamental balance evaluation given its cost-efficiency and adaptability in research contexts [12]. Previous studies reported postural stability using unilateral standing as a measure of postural control [13–15]. These investigations typically focus on the duration needed for center of pressure (COP) shifts during sway patterns, assuming a continued current trajectory. While these findings suggest spatial and temporal parameters of postural control in unilateral standing,

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their clinical applicability is limited without incorporating adjustments related to the center of gravity (COG) changes [16, 17]. A meta-analysis further indicated the limited sensitivity of COP measures, often neglecting the balance's temporal dimension [18]. However, there is a lack of understanding on somatosensory integrations and alterations in neuromuscular control during repeated unilateral standing trials.

Several studies extensively explored sway distances based on the COP and COG for understanding balance control mechanisms [11, 19, 20]. Their reports provided efficient motor control strategies and dynamic balance changes with COP and COG patterns. However, these findings may be limited by factors including sample size, testing conditions for balance strategies under dysfunction, and the validity of sway excursion analyses. Further investigation into potential motor learning strategies during repeated unilateral standing trials is necessary, especially when comparing individuals with and without LBP. Other postural sway parameters, such as sway distances (COP-COG) and velocity measures, may provide the need for a more targeted approach to compensatory postural sway in individuals with LBP.

The sway excursion parameters are especially prominent in the anteroposterior (AP) and mediolateral (ML) directions. These parameters need to be clarified on the utility of unilateral standing balance assessments in clinical practice, which indicate significant gaps that hinder clinical translation. However, those studies contradict previous perceptions of unilateral standing balance as a helpful tool and report crucial gaps that must be addressed in clinical assessments. There is a lack of understanding on postural control changes with LBP on the COP-COG sway excursion and velocity changes during repeated trials of unilateral standing between individuals with and without LBP. It is widely recognized that individual characteristics, such as age, body mass index (BMI), limb dominance, and gender, can influence compensatory postural stability [21, 22]. Such confounding variables might affect the generalizability of the study's outcomes [23].

Therefore, our research aimed to investigate a potential motor learning strategy related to sway excursion and velocity across three repeated unilateral limb standing trials among adults with and without chronic LBP. We hypothesized that the LBP group would show decreased sway excursion and adjusted compensatory velocity following the first unilateral standing trial.

Methods

Participants

Subjects were recruited from the community via targeted advertising campaigns. Those who met the study's inclusion criteria received comprehensive written information about the study as well as a verbal explanation of the testing procedures. Subsequently, the subjects were given the opportunity to seek clarification prior to signing a consent form approved by the Institutional Review Board (Protocol #1653.21) if they chose to participate in the study.

Inclusion criteria for the study included the following: (1) individuals aged between 50 and 75 years, (2) no experience of recent acute pain lasting for at least one month prior to data collection, (3) absence of significant pathologies, such as nerve root compromise, at the time of data collection, and (4) no medical conditions that could interfere with the ability to maintain a standing posture. Exclusion criteria included individuals who: (1) have diagnosed psychological conditions that could compromise the integrity of the study, (2) exhibit overt neurological symptoms like sensory deficits or motor paralysis, and/or (3) are in the stages of pregnancy.

Accounting for individual characteristics in dynamic standing balance is crucial for mitigating potential confounding factors that may either compromise the generalizability of the results or lead to erroneous clinical interpretations [23, 24]. In recruiting the control group, we considered anthropometric characteristics, including age, BMI, and other relevant characteristics such as limb dominance.

Experimental procedures

Upon arrival at the laboratory, subjects completed health status questionnaires that included demographic information. During the informed consent process, standardized questionnaires were administered to collect demographic data relevant to the outcome variables. The level of disability was assessed using the Oswestry Disability Index (ODI), which is comprised of ten items that gauge the extent to which back (or leg) trouble affects an individual's ability to perform daily tasks. Each item is rated on a 6-point scale, with higher scores indicating a greater level of disability [25].

The Bertec Balance Advantage® system for Computerized Dynamic Posturography with Immersion Virtual Reality (CDP-IVR) is a tool used for assessing and training balance and postural control. This system integrates several key components, which work together to provide a comprehensive balance assessment and training environment. This device has been widely utilized to assess an individual's ability to utilize somatosensory, visual, and vestibular reliance [26, 27]. The platform in the device is a force plate that

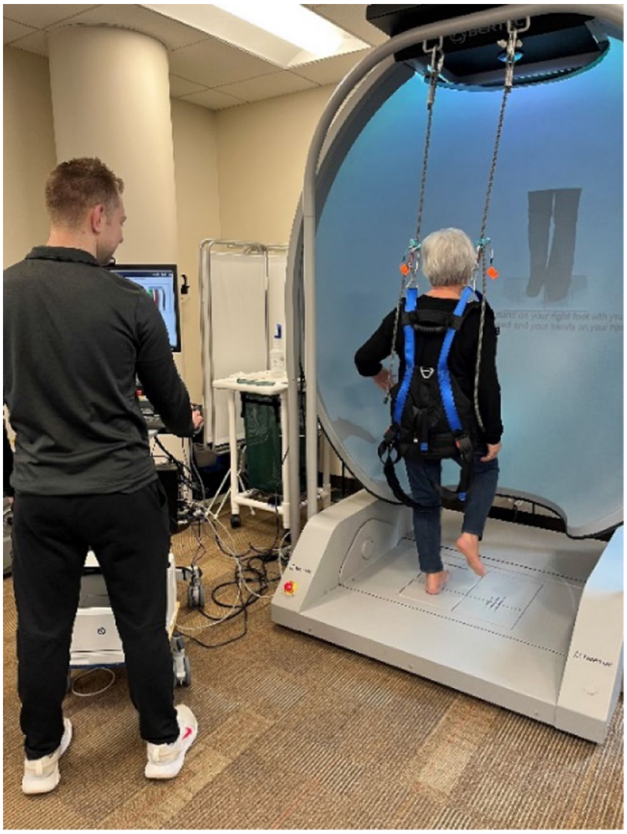

Fig. 1 The starting position of the one-leg standing test. Each subject was protected by a full-body safety harness and was instructed to remain on the dominant foot during the trial. Subjects were asked to stand barefoot on one leg for 10 s, whilst flexing the contralateral knee and hip at approximately 30° and maintaining a vertical limb position to the standing limb. This balance test was performed with a 10 s rest between trials

measures the forces exerted by a subject's feet. The platform provides real-time feedback on the COP sway and other balance-related metrics based on the subject's medial malleolus aligned with the horizontal line and the calcaneus with the AP line to ensure feet adjustments.

A standardized test protocol for unilateral standing tasks was administered, as illustrated in Fig. 1. All assessments and examinations were conducted by a licensed physical therapist. The ankle joint was aligned with the transverse rotational axis and the lateral side of the calcaneous. The y-axis indicated AP movements on the platform, while side-to-side movements on the support surface occurred along the x-axis (ML movements). The dual force plates can rotate about the x-axis, which represents the transverse axis of the ankle joint. This position acts as a reference point for the calculation of sway angles.

A full-body safety harness system, secured to an overhead bar, was worn by subjects to prevent fall injuries. Subjects stood on the Bertec Balance Advantage® system for Computerized Dynamic Posturography with Immersion Virtual Reality (CDP-IVR) with feet positioned comfortably apart (Fig. 1). The CDP-IVR allowed for the measurement of balance performance and monitoring of postural stability improvements. The initial position included standing relaxed, and each subject was asked to stand steady on the dominant foot for 10 s on the balance plate with his/her eyes open. Upon request, the subject stood on the force plate with the contralateral hip and knee flexed to approximately 30 degrees. Subjects kept their arms at their sides during initial standing, but compensatory arm movements were permitted to control dynamic standing balance.

Ground reaction force (GRF: Fx, Fy, and Fz) was recorded using the Bertec force plate at a sampling frequency of 1,000 Hz. Kinetic data were filtered and normalized based on individual body weight. The manufacturer calibrated the force plate, and a sensitivity matrix was provided to convert the voltages to forces and torques. The data were collected from the unloaded platform to determine the zero offset, and the balance changes imposed during unilateral stance balance tasks were utilized. All kinetic data were filtered using a fourth-order low-pass Butterworth filter with a 20 Hz cutoff frequency, and this cutoff frequency was selected using residual analysis and the method proposed for choosing the appropriate cut-off frequency with respect to the sampling frequency [28].

The force plate was used to determine alterations in unilateral standing on the platform. The COP/COG measures estimate a parameter associated with the displacement of the COP/COG from the central point and the velocity of the COP/COG in the AP and ML directions. Postural sway velocity parameters (COP/COG) were obtained by dividing the total length during unilateral standing. The total length of the path of movement around the COP/COG was approximated by the sum of the distances between consecutive points on the COP/COG path in ML and AP directions [29].

All subjects were able to stand the amount of time requested successfully, and the total standing time was determined until the flexed leg touched the force plate during the test protocol. Only data sets with three valid trials per subject were included in the analysis. Regarding the kinetic data, the COP and COG sway ranges (mm), as well as COP and COG sway velocity (cm/sec), on the ML and AP directions were compared. The data from the force plate were collected for the COP measures and included path length and a 95% confidence ellipse area. During unilateral standing, the whole body was situated vertically above the mathematical COG of the weightbearing surface of the foot. The force equation was utilized to calculate the force exerted by the body's COG [30]. It is the product of body weight and gravitational acceleration, mathematically expressed as: [COG force (N) = body weight (kg) × g (acceleration of gravity)].

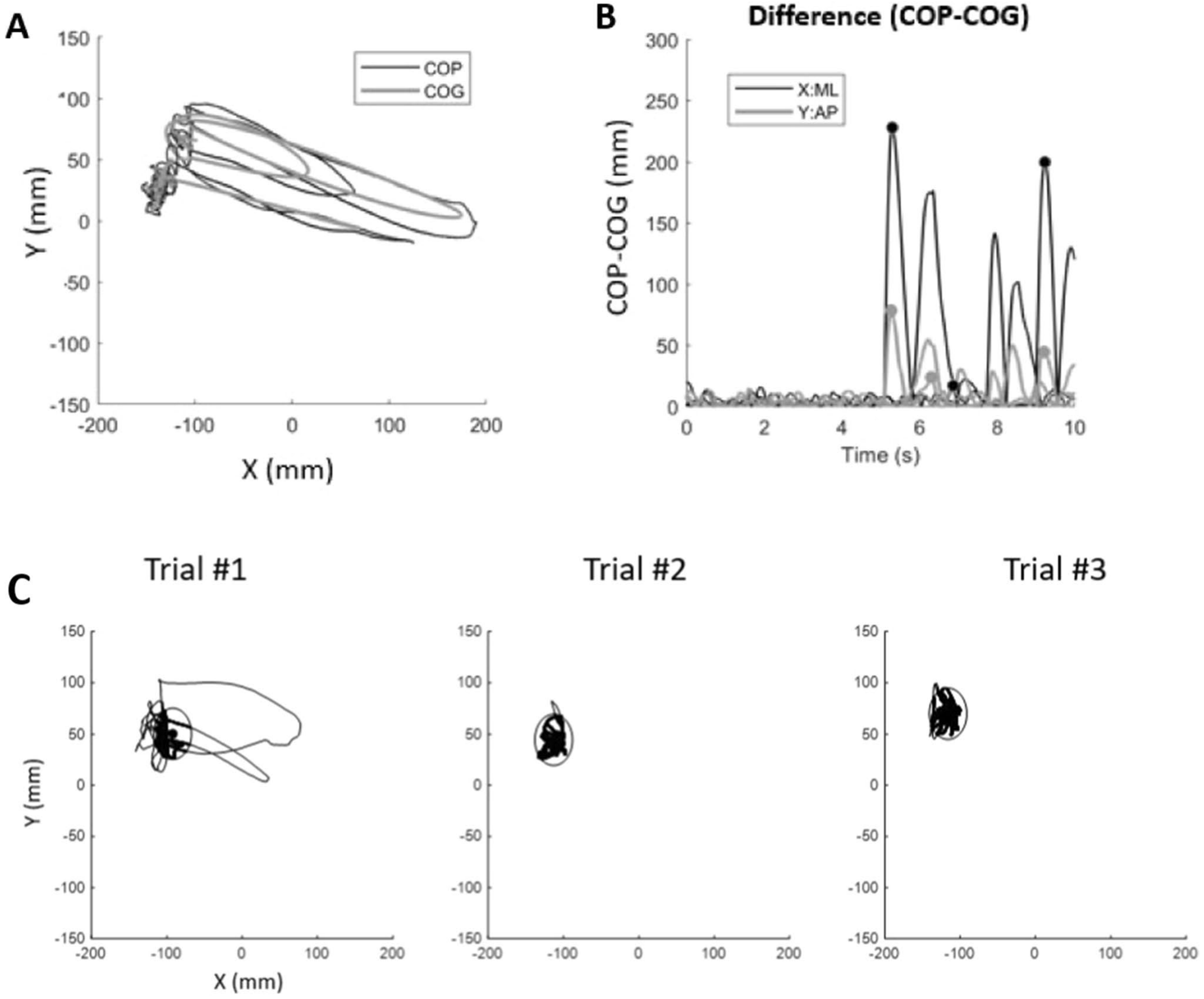

Fig. 2 Illustration of sway distance (COP–COG) during unilateral limb standing. **A**: Changes in COP (dotted line) and COG (solid line) over a 10 s period of unilateral limb standing are shown. The graph combines three repeated trials for both COP and COG. One of these trials reveals moments of instability, indicated by the crossing of COP and COG over the midline, signifying the subject's failure to maintain the stance. **B**: The 10 s difference between COP and COG during unilateral limb standing is depicted. The subject successfully maintained posture for the initial 5 s but failed to do so for the remaining duration. Maximum difference points for both x and y axes are marked (filled circle). **C**: Three trials are plotted for each direction: X (ML) and Y (AP). The subject exhibited reduced sway ranges in successive trials. COP: center of pressure; COG: center of gravity; ML: mediolateral; AP: anteroposterior

Mean and standard deviation of sway ranges and velocity changes were analyzed using linear measures root mean square (RMS) and ranges (max—min) for the AP and ML directions. The difference (COP-COG) represented the instantaneous distance between the position of the COP and the COG, independent of the effect of body weight. Figure 2 is an example of the sway distance (COP-COG), which was analyzed during 10 s of single limb standing. The repeated three trials were plotted as different lines for each X (ML direction) and Y (AP direction).

Statistical analysis

Preliminary power analyses were conducted based on the pilot data comparing groups, under the assumption of setting the type I error rate at 0.05. The effect sizes were analyzed by partial Eta-squared values (η^2p) within repeated measures analysis of variance (ANOVA) squared (small ≥ 0.01, medium ≥ 0.06, large ≥ 0.14), which was used to indicate the mean difference between groups. The independent variables included groups (subjects with and without LBP).

To investigate differences in individual characteristics between groups, an independent t-test was utilized. A mixed repeated measures ANOVA was employed to examine main and interaction effects on sway distance (COP-COG) and velocities of sway. The general linear model was applied to assess all continuous dependent variables based on a by-group factorial experimental design. For multiple comparisons, post-hoc analysis was conducted using the Bonferroni test.

In cases where demographic factors revealed group differences, these were included as covariates in the analysis. Accounting for these individual characteristics is essential for interpreting dynamic standing balance strategies. All statistical analyses were performed using SPSS version 28.0 (IBM Corp, Armonk, NY, USA).

Results

There were 26 subjects with LBP (16 female and 10 male) and 39 control subjects (20 female and 19 male) who participated in the study. There was no significant group difference on gender ($\chi^2=0.66$, p = 0.41), age (64.97 ± 9.26 for the control group vs 67.73 ± 6.57 for the LBP group; t = − 1.31, p = 0.19), or BMI (24.21 ± 5.22 for the control group vs 22.55 ± 4.41 for the LBP group; t = 1.33, p = 0.18). However, the LBP group indicated a moderate disability level based on the significantly higher ODI (3.87 ± 4.40 for the control group vs 25.62 ± 15.02 for the LBP group; t = − 8.52, $p = 0.001$) compared to the control group.

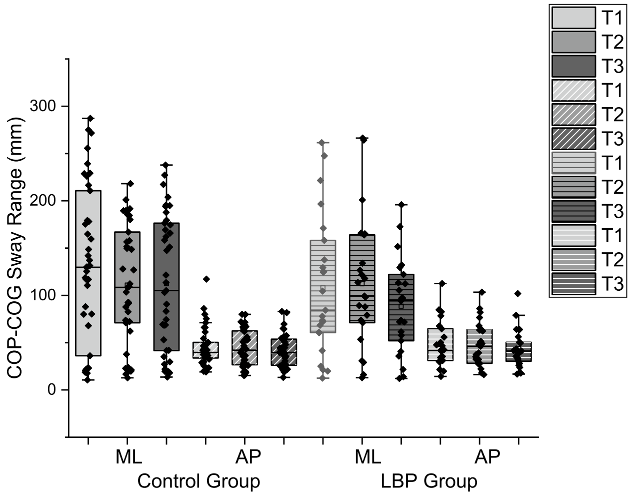

Fig. 3 Postural sway range (COP–COG) for unilateral limb standing trials between groups. The results of mixed repeated measure ANOVA indicated a significant difference of sway directions (F = 155.14, $p = 0.001$, $\eta^2 p = 0.71$). There was a significant group interaction with repeated trials (F = 5.90, $p = 0.02$, $\eta^2 p = 0.09$). COP: center of pressure, COG: center of gravity, T: standing trial, LBP: low back pain, ML: mediolateral, AP: anteroposterior

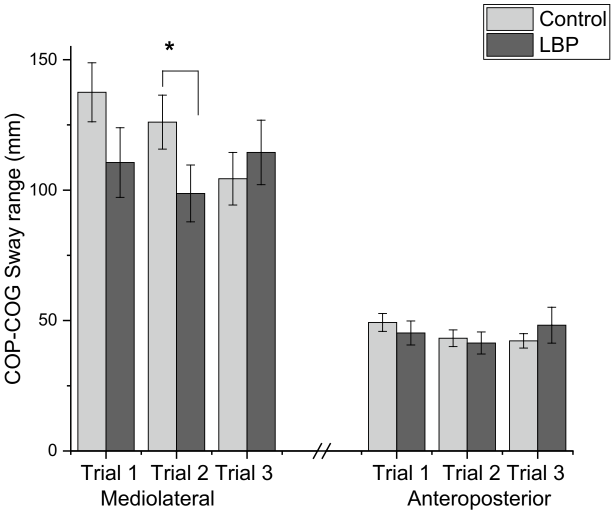

Fig. 4 The sway range (COP-COG) during repeated unilateral standing trials. A significant interaction effect between groups and repeated trials was observed (F = 5.90, $p = 0.02$, η^2p = 0.08). In the second trial, there was a significant decrease in mediolateral sway within the LBP group (t = 1.76, $p = 0.04$). COP: center of pressure, COG: center of gravity, LBP: low back pain, ML: mediolateral, AP: anteroposterior

As shown in Fig. 3, the sway ranges (COP-COG) were analyzed during three trials of dominant limb standing between groups, and the results of mixed repeated measure ANOVA indicated a significant difference of sway directions

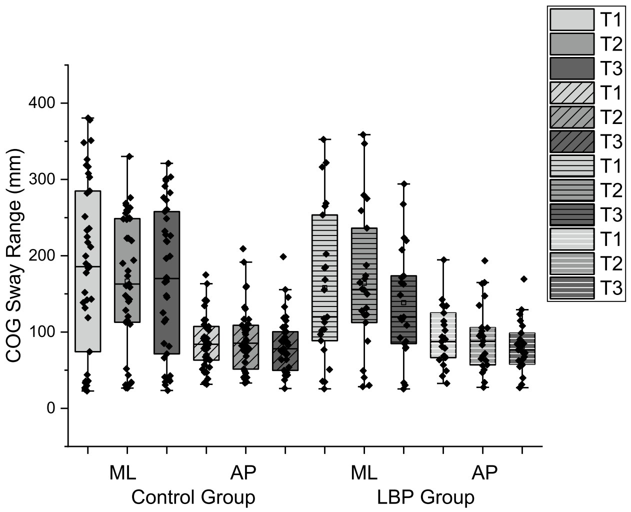

Fig. 5 The group comparison of the center of gravity (COG) between directions in repeated trials. The results from the mixed repeated measure ANOVA revealed a significant difference in the main factor of directions (F = 151.61, $p = 0.001$, η^2p = 0.71). The groups demonstrated significant interactions with repeated trials (F = 5.79, $p = 0.02$, $\eta^2 p = 0.08$) as well as a three-way interaction on directions x trials (F = 4.28, $p = 0.04$, $\eta^2 p = 0.06$). T: standing trial, LBP: low back pain, ML: mediolateral, AP: anteroposterior

(F = 155.14, p = 0.001, η^2p = 0.71). In Fig. 4, there was a significant group interaction with repeated trials (F = 5.90, p = 0.02, η^2p = 0.09). The second trial in the mediolateral direction showed significantly increased sway in the control group (t = 1.76, p = 0.04).

The COG sway range was analyzed by a mixed repeated measures ANOVA, which was conducted to explore the main and interaction effects (Fig. 5). The results indicated that the groups demonstrated significant interactions with repeated trials (F = 5.79, p = 0.02, η^2p = 0.08) as well as a three-way interaction on directions x trials (F = 4.28, p = 0.04, η^2p = 0.06). Regarding the COP sway range in Fig. 6, the results indicated that there was a significant group interaction on repeated trials (F = 4.39, p = 0.04, η^2p = 0.06). The COP sway velocity changes were also analyzed during repeated unilateral standing between groups (Fig. 7). There were significant interactions observed between groups across repeated trials (F = 4.39, p = 0.04, η^2p = 0.06) as well as sway directions (F = 122.74, p = 0.001, η^2p = 0.66).

As shown in Fig. 8, however, a significant interaction for COG sway velocity changes was observed. There was a significant difference in directions (F = 151.61, p = 0.001, η^2p = 0.71), and significant group interactions on both directions and repeated trials (F = 4.28, p = 0.04, η^2p = 0.04), as well as for repeated trials (F = 5.79, p = 0.02, η^2p = 0.08), were detected. The LBP group demonstrated reduced ML sway velocities during the first (5.21 ± 2.43 for the control group, 4.16 ± 2.33 for the LBP group; t = 1.72,

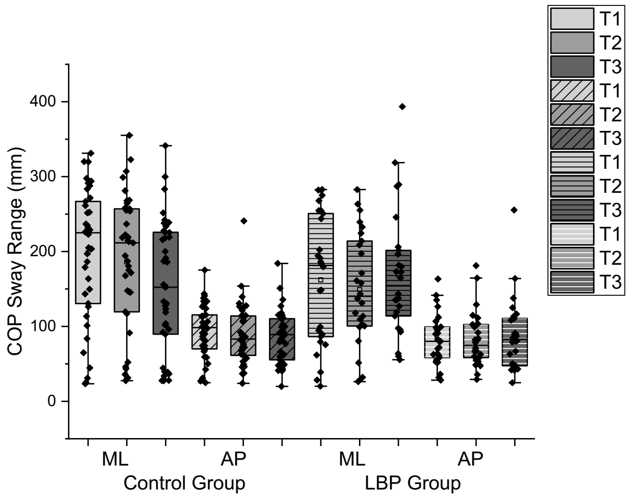

Fig. 6 The center of pressure (COP) for directions on repeated trials between groups. The results of mixed repeated measures ANOVA indicated that the main factor, directions, was significantly different (F = 122.75, *p* = 0.001, η^2p = 0.66) between groups, and there was a significant group interaction on repeated trials (F = 4.39, *p* = 0.04, η^2p = 0.06). T: standing trial, LBP: low back pain, ML: mediolateral, AP: anteroposterior

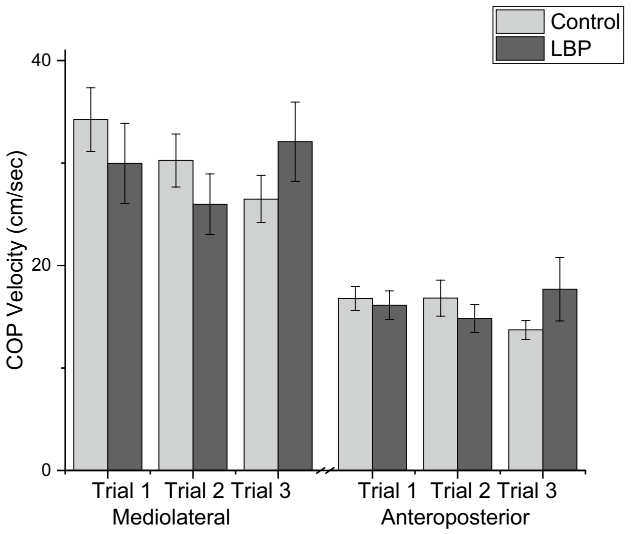

Fig. 7 The center of pressure (COP) sway velocity during repeated unilateral standing trials. A significant interaction effect was observed between groups across repeated trials (F = 4.39, *p* = 0.04, η^2p = 0.06). Furthermore, a significant distinction was observed in the directions of sway (F = 122.74, *p* = 0.001, η^2p = 0.66). However, no significant interaction effects were found between the groups in relation to sway directions (F = 0.33, *p* = 0.57, η^2p = 0.01) or between the directions and trials (F = 1.01, *p* = 0.31, η^2p = 0.02). COP: center of pressure, COG: center of gravity, LBP: low back pain, ML: mediolateral, AP: anteroposterior

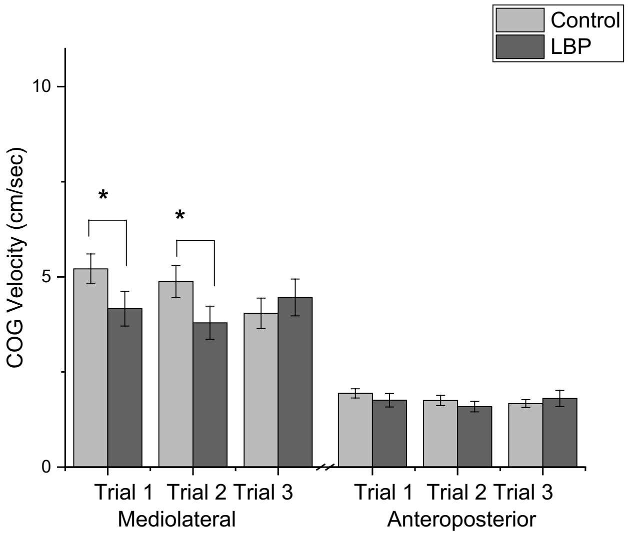

Fig. 8 Variability in center of gravity (COG) sway velocity during repeated unilateral standing trials. A significant difference in directions was detected (F = 151.61, *p* = 0.001, η2*p* = 0.71). In the mediolateral direction, the LBP group exhibited significantly reduced sway velocities during both the first (t = 1.72, *p* = 0.04) and second (t = 1.73, *p* = 0.04) trials. However, no significant group interactions were found in directions (F = 1.32, *p* = 0.25, η2*p* = 0.02). COG: center of gravity, LBP: chronic low back pain

p = 0.04) and second (4.87 ± 2.62 for the control group, 3.79 ± 2.22 for the LBP group; t = 1.73, p = 0.04) trials.

Discussion

Our study compared changes in sway excursion and velocity during three repeated unilateral limb standing trials between groups. The results of our study indicated a significant group interaction in the sway distance difference (COP-COG) with repeated trials. Furthermore, the results demonstrated alterations in COG and COP sway distances to a complex interplay of biomechanical and neuromuscular factors. These factors collectively contribute to the adaptive postural strategies shown in the LBP group.

We analyzed group interaction for the COG and COP separately. There was a significant group interaction between directions and repeated trials on COG changes; however, there was no group interaction on COP changes. These results are supported by a potential hip strategy, as the COP indicated the LBP group is unable to initiate and control a hip strategy [8, 31]. A pattern of trunk control indicates a deficit of postural control and is hypothesized to result from altered muscle control and proprioceptive impairment. These reports affirmed the context-dependent nature of postural responses, particularly in the eyes open condition.

The Bertec force plates are the 'gold standard' for balance testing, and the plates have been shown to exhibit moderate to very high reliability across a range of postural sway measures [32]. In general, COG is the point at which the distribution of body mass is balanced, while COP refers to the point of application of the GRF vector. These parameters are essential indicators of postural stability, and they often become compromised in the LBP group. However, alterations may be indicative of compensatory strategies for COP to maintain balance or to avoid pain. These changes could be related to a redistribution of load across the spinal structures, potentially leading to altered biomechanics and motor control. The sway in COP could reflect these changes and serve as a valuable assessment tool for evaluating the effectiveness of interventions aimed at restoring optimal balance and motor control.

Changes in COG could reflect adaptations in neuromuscular control to minimize pain or discomfort, especially following repeated trials. These adaptations may include hip and trunk strategies aimed at keeping the COG within the base of support, thereby maintaining balance while reducing load on the lumbar spine. This strategy highlights the clinical relevance of repeated trials for understanding balance deficits and motor control strategies. It has been suggested that individuals may employ a "tight control strategy," characterized by minimized spinal segment mobility and co-contraction of the trunk and lower limbs, to enhance kinematic and kinetic stability [12, 33]. This strategy may be particularly relevant for the LBP group as a potential pain-avoidance mechanism during dominant limb standing. In our study, examining sway ranges and velocity changes for both COG and COP provided a more comprehensive view of postural control mechanisms that are affected by or contribute to chronic LBP. Understanding these factors could provide important insights into targeted fall prevention strategies to enhance both balance and pain management in the LBP group.

Our hypothesis was that the LBP group would exhibit reduced sway excursion performance and compensatory velocity following the first unilateral standing trial compared to the control group. We partially accepted this hypothesis, as the results indicated a significant group interaction in sway distance difference following repeated trials in both directions and trials for COG sway velocity. The LBP group demonstrated reduced ML sway velocities during the first and second trials; however, there was no group difference in the third trial due to a potential compensatory response. Another study partially supported our results that older adults with LBP had poorer postural responses in delayed reaction, more significant displacement, and longer path length than older, healthy controls [34]. The LBP group was associated with a significantly larger area of COP, higher velocity of COP sway in the AP and ML directions, and longer path length in the AP direction than the control group [17].

In the context of motor learning, the repeated unilateral standing trials revealed interactions on sway range (COP-COG), indicating potential adaptations in motor control. The LBP group demonstrated reduced ML sway velocities in the initial two trials. This reduction suggests an adaptive strategy for enhancing trunk stability, potentially compensating for impaired neuromuscular control mechanisms. The interaction effects on the COG underscore this adaptation, highlighting a shift toward improved trunk stability, despite the neuromuscular challenges in the LBP group. Although our study did not measure electromyography reactions, this observed response could be attributed to novel experiences and delayed trunk reactions associated with coordination issues in the lower limb muscles [35].

Moreover, the LBP-related dysfunction involves reestablishing neural connections [36], as another study proposed that a persistent "tight control strategy" may be specifically targeted by reducing muscle excitability and co-contraction while increasing movement variability in motor control [37]. The postural responses observed across repeated trials, particularly the sway excursion adjustments, are crucial for fall prevention strategies in the LBP group. These compensatory reactions merit further exploration to understand the causal links between repeated trials and motor control strategies. Further studies are warranted to provide insights into these dynamics, shedding light on the motor learning processes in the LBP group.

Our results further revealed that the LBP group exhibited a significant decrease in sway distance differences exclusively during the second trial of unilateral standing in the ML direction. These results are not aligned with existing literature indicating that older adults with sagittal imbalance display diminished trunk proprioceptive input and postural instability. Previous studies have emphasized that sideways falls are prevalent and account for more than 95% of hip fractures [38, 39], suggesting that inadequate momentum control may be a contributing factor to postural imbalance or falls.

Our results indicated a significant group interaction on COG sway velocity differences on repeated trials, and the groups demonstrated a significant three-way interaction on direction and trial. In contrast, no significant three-way interaction emerged for the COP sway velocity for direction and trial, although a significant group interaction was found for both repeated trials and directions. These results enhance our clinical understanding of neuromuscular control in ML sway distance, underscoring the significance of fine-tuning postural sway in the ML direction for effective postural control. Furthermore, the optimal allocation of somatosensory resources could be pivotal in achieving better postural stability.

Our findings align with existing research, emphasizing the critical role of limb preference in both motor development and functional task performance [40]. In our study, all participants were right limb dominant, which is a factor that likely influenced postural reaction during repeated dominant limb standing. This study's protocol highlights the multidimensional aspect of human laterality, which can give rise to performance asymmetry. This limb preference suggests an inherent aspect of motor development that mitigates performance asymmetry, given the importance of limb dominance in executing functional tasks that require stability and mobility control.

In a clinical context, limb dominance is accounted for across various components of motor learning. Postural adjustments in movement patterns are expected to alleviate fear and enhance confidence in dynamic standing balance, ultimately reducing sway distance to prevent fall-related injuries. If differences in sensorimotor control are the underpinning factors for limb dominance, it would be reasonable to anticipate variations in postural control during unilateral standing tasks. Our results indicated that the initial trial did not reveal significant group differences in sway distances. This could be attributed to the novelty of the experience and potential coordination issues with the lower limb muscles, as musculoskeletal pain in the LBP group depends on reconnecting neuromuscular control with the rest of the body. However, the results of COG velocity indicated that the LBP group demonstrated significantly delayed reactions due to possible chronic pain.

In postural sway dynamics, studies reported how the COG changes within an individual's stability limit [41, 42]. It was expected that the LBP group may experience compromised somatosensory and visual information, which affects postural orientation. The vertical direction of the body in the upright standing position is maintained by keeping the body's COG upright by a dynamic interplay of visual, vestibular, and somatosensory control systems [43]. Those subjects with LBP may have restrictions within the musculoskeletal system to cause dysfunction in muscle synergies, which is expressed by an increase in the angular velocity of the COG.

The COP mechanisms contributed to corrections of the COG acceleration, but their results were indicated only in the initial phases of the first trial. Based on repeated standing trials, our study protocol may have implications for adaptative strategies to minimize fall incidence in the LBP group. It would be beneficial to expand upon the concept of proprioceptive reweighting. This altered reweighting process involves a neurological mechanism that dynamically modulates the reliance on proprioceptive inputs from different body segments, thereby optimizing the regulation of standing balance [44, 45].

Our study acknowledged several limitations that warrant consideration. These include the potential for fatigue accumulation, the duration of the trials, anthropometric differences among participants, and the inherent variability in unilateral standing, all of which could impact the data. Understanding of motor learning could offer more detailed insights into the intricacies of neuromuscular control. Future research could benefit from subgroup analyses to provide more nuanced insights into intra- and inter-individual variability.

Conclusion

The LBP group exhibited reduced ML sway velocities during the first and second trials. The significant interaction effects on the COG suggest an enhancement in trunk stability despite compromised neuromuscular control mechanisms.

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Declarations

Conflict 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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