INTERNATIONAL JOURNAL OF
–EXERCISE SCIENCE–

Original Research

Unilateral Posterior-Chain Training as a Perturbation Strategy for Balance Improvements in Middle-Aged Adults

Kabalkin Artiom*, Dunsky Ayelet‡

School of Human Movement and Sport Sciences, The Levinsky-Wingate Academic College, Israel

*Denotes student investigator, ‡Denotes established investigator,

Abstract

International Journal of Exercise Science 19(1): 1-13, 2026. [***https://doi.org/10.70252/IJES2026102***](https://doi.org/10.70252/IJES2026102)
Postural instability and impairments in dynamic balance are common in aging populations and are often linked to asymmetries between the supportive and non-supportive limbs. This study investigated the effects of a four-week unilateral posterior- chain resistance training program targeting the non-supportive leg on dynamic and static balance measures in middle-aged, recreationally active adults. Twenty-seven participants (ages 40–56) performed Single-Leg Romanian Deadlifts (SLRD) twice weekly, following a progressive overload model. Balance performance was evaluated using the Y Balance Test (YBT) and the Tetrax posturography at three time points: PRE (familiarization), PRE1 (before intervention), and POST (post-intervention). Initial analysis of the supportive versus non-supportive classification showed no statistically significant improvements in either the trained (non-supportive) leg or the supportive one. However, when analyzed based on left versus right leg performance, the results revealed significant improvements in posterolateral reach in both limbs, indicating direction-specific adaptations and potential bilateral transfer effects. Posterolateral reach improved significantly in both the left leg ($p = 0.008$, $\eta^2 = 0.170$) and right leg ($p = 0.022$, $\eta^2 = 0.137$), with no change in static balance. The observed gains in dynamic balance across legs suggest that unilateral posterior-chain training may improve specific components of balance, regardless of limb dominance. Findings support the idea that unilateral posterior-chain exercises can act as perturbation-like stimuli, encouraging neuromuscular adaptations that enhance overall dynamic balance. Additionally, they also highlight the importance of clear methodological approaches to limb classification when analyzing training effects in balance research.

Keywords: Postural control, aging, balance training

Introduction

Postural control is a crucial aspect of functional mobility and independence, particularly among aging populations. As people age, the integration of sensory inputs and neuromuscular coordination generally declines, leading to increased postural sway and a higher risk of falls.[1,2] In older adults, medial-lateral sway has been recognized as a significant factor contributing to

*Corresponding author: Kabalkin Artiom; archik1@gmail.com

instability, particularly in response to lateral perturbations.[3] Since falls are a leading cause of injury-related hospitalization and death among older adults,[4] identifying targeted and effective interventions remains a public health priority.

One strategy suggested for fall prevention training is perturbation-based balance training (PBT), which has demonstrated strong efficacy in improving reactive balance and reducing the risk of falls. Its practical implementation remains limited by several logistical and psychological constraints. PBT protocols typically rely on expensive, specialized equipment such as instrumented treadmills or movable platforms, in conjunction with overhead harness systems and trained personnel to safely administer high-magnitude, task-specific perturbations. These requirements introduce substantial barriers in terms of cost, infrastructure, and operational complexity, particularly in community or non-clinical settings.[5] Additionally, effective PBT delivery often demands individualized safety procedures, therapist supervision, and dynamic adjustment of perturbation intensity based on participant response and anxiety levels, further restricting scalability and accessibility.[6] Given these challenges, there is a growing need for alternative strategies that replicate the neuromuscular benefits of perturbation training while offering greater feasibility and a lower implementation burden.

Another strategy suggested for balance training focuses on lower-limb strength symmetry. This strategy is based on research demonstrating that asymmetrical components affect balance and postural control in the lower limbs.[7,8] Studies on lower-limb functionality indicate that limb asymmetries, such as reduced neuromuscular efficiency and proprioceptive deficits, can significantly impact postural control.[9,10] While the dominant leg is typically associated with skilled, precise movements, the opposite limb often exhibits lower stability and greater deficits in static and dynamic control. These differences may contribute to postural impairments and increased medial-lateral sway.[11,12]

Recent evidence suggests that single-leg training is effective in enhancing postural control in healthy adults. A systematic review by Marcori et al examining 13 trials found that unilateral balance training protocols ranging from brief sessions (10–15 minutes) to more extended interventions (up to 390 minutes) consistently improved balance performance, regardless of task complexity or progression.[13] Notably, the review documented contralateral effects, with improvements in the trained limb transferring to the non-trained limb, providing further support for asymmetrical training approaches. These gains were observed across multiple test modalities, indicating both peripheral neuromuscular and central neural (cortical) adaptations.

Current interventions, such as general balance training and strength exercises, target overall lower-limb function without distinguishing between the supportive and non-supportive roles of the legs.[11] However, limited research has explored the specific effects of targeting the non-supportive leg through resistance training to improve postural control.

The purpose of this study was to examine the effects of a 4-week unilateral posterior-chain resistance training program, targeting the non-supportive leg, on measures of static and dynamic balance in middle-aged, recreationally active adults. We hypothesized that training the non-supportive leg could function as a safe perturbation training model, potentially enhancing overall postural control.

Methods

Participants

To determine the minimum number of participants, a priori power analysis was conducted using the software JASP (Version 0.19.3, Apple Silicon; JASP Team, 2025) with a desired power level of 0.80, an alpha level of 0.05, and a medium-to-large effect size ($\eta^2 = 0.15$) calculated from previous studies examining postural adaptations and Y Balance Test improvements in response to unilateral balance training protocols.[14,15] Based on this analysis, a minimum of 25 participants were needed. However, to account for any potential drop-offs, 28 adults were recruited to take part in the study. As one participant was unable to complete all procedures due to personal reasons unrelated to the study, the final sample consisted of 27 participants (10 females and 17 males; 45.8 ± 4.4 and 45.3 ± 4.7 years, respectively).

All participants were healthy and regularly engaged in at least 150 minutes of moderate-intensity physical activity per week. Exclusion criteria included neurological disorders, cardiovascular issues, metabolic conditions, neuromuscular disorders, orthopedic limitations (specifically injury or surgery involving the lower limbs within the last six months), taking medications known to impair balance or neuromuscular coordination (e.g., Sedatives), or acute illness. Additionally, none of the participants were professional or semi-professional athletes, nor were they participating in high-intensity competitive sports. This research was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science*.[16] Before the study began, all participants were informed of its aims and procedures and signed an informed consent form. The Institutional Review Board at The Levinsky-Wingate Academic College approved this study (no.33-020125). It was conducted in full compliance with the ethical standards outlined in the Declaration of Helsinki. Recruitment was organized through advertisements placed at the fitness facility, on social media platforms (Facebook and Instagram), and in a local WhatsApp group.

Protocol

This study employed a single-group, repeated-measures experimental design to evaluate the effects of dynamic unilateral resistance training on postural control and balance performance in middle-aged, recreationally active adults. The study was based on three assessment time points (Figure 1): PRE, representing the baseline assessment; PRE1, the pre-intervention retest assessment conducted 14 days after routine training; and POST, the post-intervention assessment. Between PRE and PRE1, participants continued their regular training routines, which included at least 150 minutes of moderate-intensity aerobic and light resistance exercises per week. PRE1 assessments accounted for natural balance adaptations due to habitual physical activity.

Assessment.

Advanced postural analysis tools, such as the Y Balance Test (YBT) and the TETRAX posturography, enable precise measurements of sway and balance performance.[17,18] These tools offer an opportunity to assess whether unilateral interventions on the non-supportive leg can significantly enhance stability. Accordingly, dynamic and static balance performance in the current study was assessed using both the YBT and the posturography (Tetrax® system). This design enabled within-subject comparisons across multiple time points to evaluate changes in postural sway and functional balance performance.

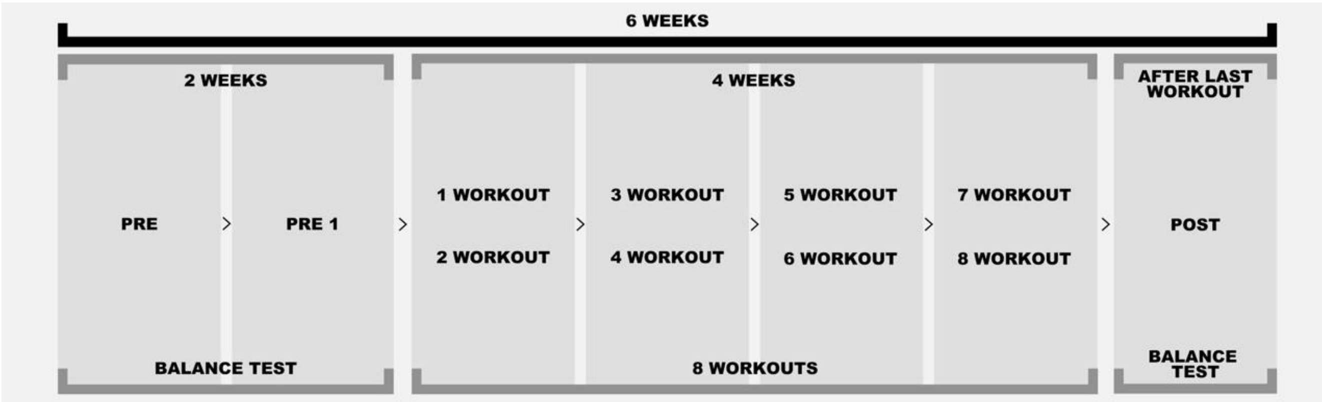

Figure 1. Experimental testing overview.

Dynamic balance assessment.

Postural control during dynamic conditions was assessed using the Y Balance Test (YBT), a standardized dynamic balance assessment tool that evaluates single-leg stance stability, neuromuscular control, and functional asymmetries. Participants are required to maintain balance on one leg while reaching with the contralateral leg in three specific directions: anterior, posteromedial, and posterolateral (Figure 2). Participants performed the test barefoot. The stance leg remained stationary on the central platform, while the reach leg extended along surface-measured metric tapes in the designated directions.

A trial was considered valid only if the participant: maintained control throughout the movement, avoided touching the ground with the reach foot, did not use the reach foot for support, and successfully returned to the starting position without shifting the stance leg. To minimize learning effects, each participant completed three practice trials per leg in each of the three directions. For the formal test, three recorded trials were performed for each direction, starting with the anterior reach, followed by the posteromedial and posterolateral directions on each leg. This sequence ensured consistency and helped reduce fatigue-related bias. Reach distances were normalized to leg length, which was measured from the anterior superior iliac spine (ASIS) to the medial malleolus, to account for individual anthropometric variation.

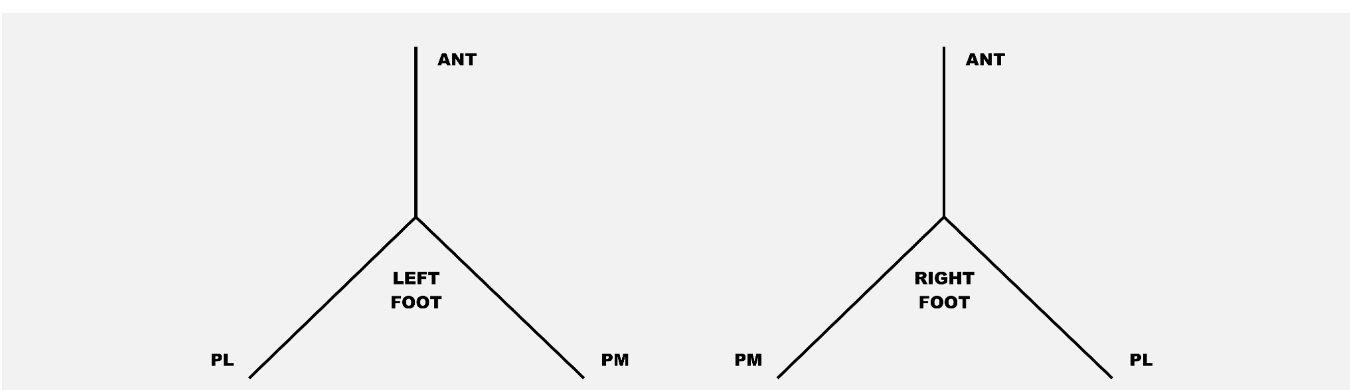

Figure 2. Y Balance Test, anterior (ANT), posteromedial (PM), and posterolateral (PL) directions.

The dynamic parameters analyzed included normalized reach distances (% of leg length) in the anterior, posteromedial, and posterolateral directions, as well as a composite score (%) calculated for each leg (averaged across the three directions) that represents an overall index of dynamic balance performance. These metrics were derived from the maximum reach distance across three valid trials per direction, collected at the PRE, PRE1, and POST assessments.

Static balance assessment.

Postural control during static conditions was assessed by using Tetrax® posturography system (Sunlight Medical Ltd., Israel), a highly sensitive force plate device designed to evaluate center of pressure (CoP) displacements. The system features four independent force platforms positioned under the heels and toes of both feet, enabling the precise measurement of vertical pressure fluctuations and sway patterns. Participants completed the assessment barefoot under eight standardized sensory conditions, each designed to challenge different components of the postural control system, including visual, vestibular, and somatosensory inputs. Each condition lasted 32 seconds and included variations such as standing with eyes open and closed on a firm surface, standing with eyes open and closed on foam, and standing with eyes closed and head rotated in four different directions. The static parameters analyzed included: Total Sway (ST), representing the total movements of CoP during the test, and, accordingly, the overall postural stability, Medial-Lateral Sway (TETLEFT) reflecting side-to-side CoP sways, and Anterior-Posterior Sway (HEEL) indicating front-to-back CoP sways.

Non-supportive leg determination.

To determine the non-supportive limb, the analysis was based on the average CoP-sway data across eight standardized positions obtained during the TETLEFT PRE and TETLEFT PRE1 assessments. If either value exceeded 50%, the left leg was classified as the supportive limb, and the right leg was identified as the non-supportive limb for intervention purposes. When sway values from PRE and PRE1 were inconsistent or inconclusive (n = 3), directional asymmetries in the Composite Score (%) from the Y Balance Test (YBT) were used to determine limb classification as follows: the leg with consistently lower composite balance performance at both PRE and PRE1 was designated as the non-supportive limb, indicating reduced dynamic control on that side. This two-step approach ensured a personalized identification of the weaker leg for targeted intervention.

Intervention Protocol.

The intervention protocol was designed to progressively strengthen the non-supportive leg, with a specific focus on postural control muscles, particularly the medial hamstrings (Semitendinosus). The intervention consisted of unilateral Single-Leg Romanian Deadlifts (SLRD), performed over four weeks, with two sessions per week, each lasting approximately 15-20 minutes. Training followed the principle of progressive overload, with both load intensity and technique monitored throughout the intervention.

Each session included a warm-up, the primary training exercise, and a cool-down. The warm-up consisted of three minutes of light cardiovascular activity (e.g., cycling or running) and two minutes of dynamic full-body exercises with a wooden stick. The primary exercise involved repetitive SLRD. During the SLRD, participants stood on the non-supportive leg, maintaining a slight knee bend (Figure 3). From this position, they flexed at the hip, lowered the upper body, and extended the contralateral leg backward, maintaining a straight line from head to heel until the torso was parallel to the ground. Participants then returned to the upright position by engaging the hamstrings and gluteus maximus of the stance leg.

The training followed a progressive overload model, with sets and repetitions increasing weekly based on body weight resistance (see Table 1 for the details of the progressive overload model). The cool-down included light walking and stretching.

Table 1. A progressive overload model, with sets and repetitions increasing weekly based on body weight resistance.

Week number	First Session	Second Session
1	2 sets 10 repetitions	2 sets 10 repetitions
2	2 sets 13 repetitions	2 sets 15 repetitions
3	3 sets 12 repetitions	3 sets 13 repetitions
4	4 sets 12 repetitions	4 sets 13 repetitions

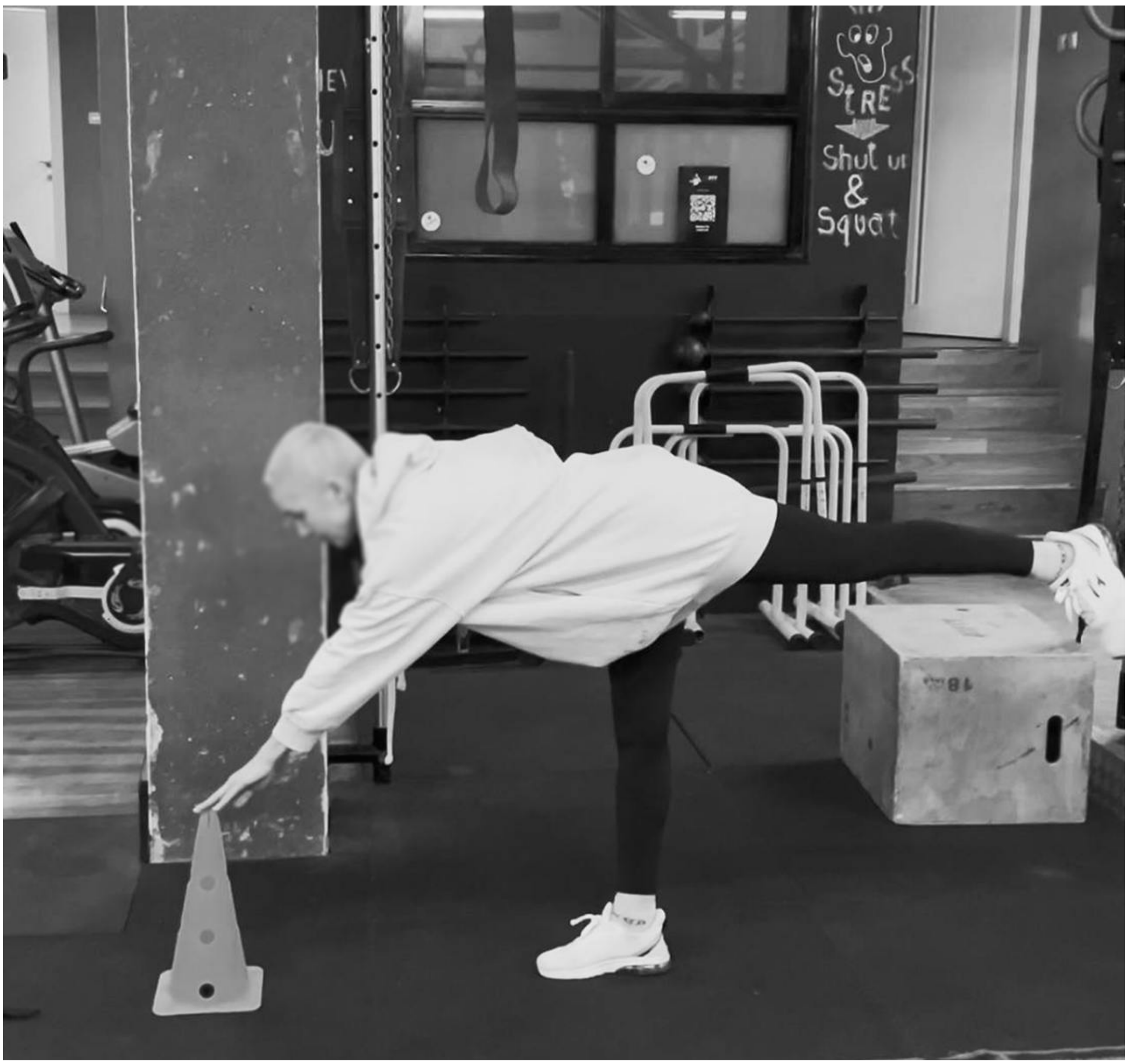

Figure 3. The Single-Leg Romanian Deadlifts (SLRD).

Statistical Analysis

Descriptive statistics (mean ± SD) were calculated for all dependent variables.
A one-way repeated-measures ANOVA was conducted to evaluate changes in balance control across three time points: before (PRE, PRE1) and after (POST) a four-week non-supportive leg resistance training intervention in two separate approaches:

1. Initial Analysis (Functional Role – Supportive vs. Non-Supportive Leg): Performance on the Y Balance Test for dynamic balance and on the Tetrax for static balance was compared separately for the trained versus untrained limbs to evaluate the specific effect of the unilateral intervention.
2. Second Analysis (Leg Side – Left vs. Right): Performance on the Y Balance Test for dynamic balance and on the Tetrax for static balance was compared separately for the left and right limbs, regardless of the intervention (trained versus untrained limb).

For all statistical tests, a probability level of $p \leq 0.05$ denotes statistical significance. All effect sizes are reported in eta-squared values. Values of 0.01, 0.06, and 0.14 represent small, medium, and large effects, respectively (19). Statistical analyses were conducted using the JASP statistical software (Version 0.19.3, Apple Silicon; JASP Team, 2025).

Results

Initial Analysis

Based on the Functional Limb Role (Supportive vs. Non-Supportive, i.e., untrained vs. trained limb). No statistically significant main effects of time (PRE, PRE1, POST) for any dynamic balance variables measured by the Y Balance Test, including anterior, posteromedial, or posterolateral reach distances in either the supportive or non-supportive leg ($p > 0.05$), were observed. Similarly, there were no significant changes in the composite Y Balance Test scores for either limb across the three time points. Additionally, static balance outcomes assessed using Tetrax posturography also showed no significant time effects for total sway, medial–lateral sway, or anterior–posterior sway in either the supportive or non-supportive leg ($p > 0.05$).

Second Analysis: Leg Side – Left vs Right

The second analysis, conducted using anatomical leg-side classification (left vs. right), regardless of the intervention limb, showed significant improvements in dynamic balance performance, as explained below.

Dynamic Balance Assessment.

The analysis of dynamic balance assessments (using the Y Balance Test) on left leg posterolateral reach performance revealed a statistically significant time effect ($p = 0.008$, $\eta^2 = 0.170$), indicating a large effect size. Pairwise comparisons using adjusted post hoc (Holm correction) revealed that PRE (86.15% ± 4.82) vs PRE1 (87.04% ± 4.56) was not statistically significant ($p = 0.246$). However, PRE (86.15% ± 4.82) vs POST (88.59% ± 4.42) showed a significant improvement (Mean Difference = 2.44%, $p = 0.032$), and PRE1 (87.04% ± 4.56) vs POST (88.59% ± 4.42) showed a significant improvement (Mean Difference = 1.54%, $p = 0.034$). In addition, a decrease in the coefficient of variation from 0.056 at baseline to 0.050 at POST indicates a reduction in relative variability among participants (see Figure 4 for raincloud plots).

The analysis of dynamic balance assessments (using the Y Balance Test) on right-leg posterolateral reach performance also revealed a statistically significant time effect ($p = 0.022$, $\eta^2 = 0.137$), suggesting a moderate-to-large effect size. Post hoc pairwise comparisons with Holm correction demonstrated that PRE (85.42% ± 5.28) vs PRE1 (85.56% ± 5.06) was not statistically significant ($p = 0.891$). However, both PRE vs POST (87.76% ± 4.99) (Mean Difference = 2.34%, $p = 0.034$) and PRE1 vs POST (Mean Difference = 2.20%, $p = 0.034$) showed statistically significant improvements in reach performance. In addition, the coefficient of variation decreased from 0.062 at baseline to 0.057 post-intervention, suggesting a reduction in inter-individual variability and a more consistent performance pattern across participants (see Figure 5 for raincloud plots).

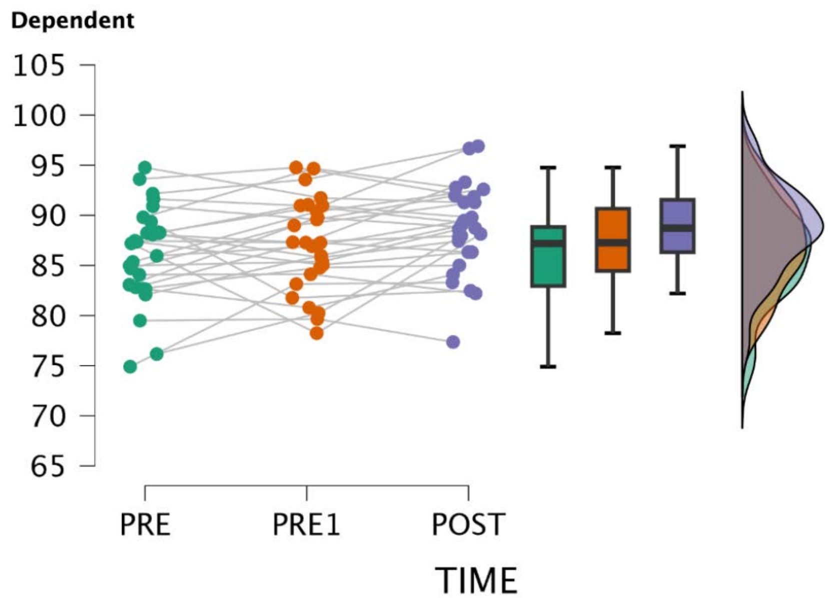

Figure 4. Raincloud plots. Left leg.

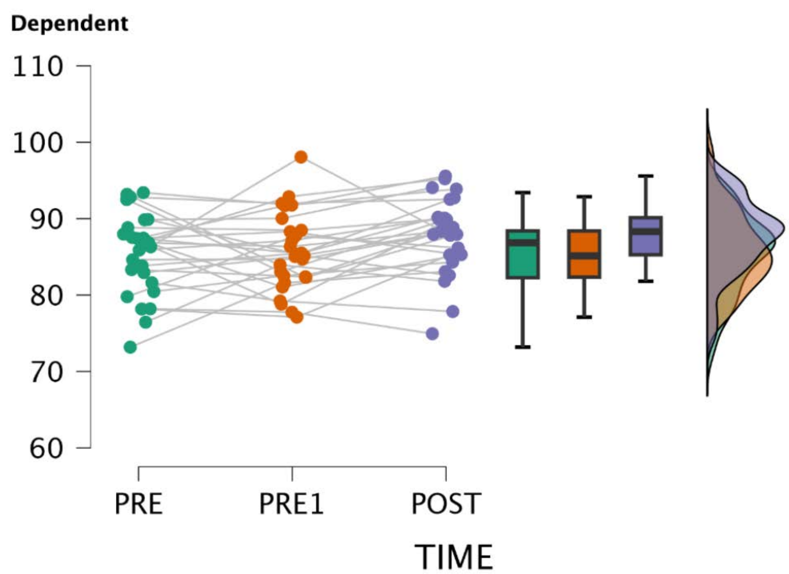

Figure 5. Raincloud plots. Right leg.

Discussion

This study examined the effects of a four-week unilateral posterior-chain resistance training program on both dynamic and static balance in middle-aged adults. Although no significant changes were found in the dynamic or static balance of the trained (non-supportive) limb following the intervention, significant improvement was revealed when examining the overall effect of unilateral training (with the non-supportive limb targeted). Notably, significant improvements were seen in the posterolateral reach direction of the YBT in both legs. The results showed broader bilateral improvements in dynamic balance following unilateral posterior-chain training, indicating this training method can induce systemic neuromuscular adaptations that enhance the contralateral balance.

These findings align with the contralateral effect discussed in the systematic review by Marcori et al,[13] suggesting that, despite the intervention targeting only the non-supportive limb, both legs exhibited significant improvements in posterolateral reach performance. This may indicate that the observed gains were not the result of isolated muscular adaptations in the trained leg but rather reflect a bilateral transfer effect likely driven by neural mechanisms. Previous literature has attributed such interlimb transfer to increased efficacy of motor pathways and enhanced interhemispheric communication via the corpus callosum, facilitating improved motor control in the untrained limb as well.[20] Additionally, trunk stability may have served as a common performance during the Y Balance Test. Since both limbs rely on the same central mechanisms to stabilize the pelvis and spine during unilateral stance and reaching, improvements in core control could have enhanced functional balance on both sides, regardless of which side was trained.[21] These findings highlight the systemic nature of adaptations induced by posterior-chain training under unilateral load.

Sun et al propose two primary neural mechanisms that may account for the bilateral improvements observed in the present study, despite training being applied to only one limb.[22] The first, known as the cross-activation model, suggests that unilateral training elicits neural adaptations in both the active and resting motor cortices, mediated by transcallosal pathways. This leads to enhanced motor output on both sides of the body, even in the absence of direct muscular activation in the untrained limb.[22] The second mechanism, known as the bilateral access model, suggests that motor memories formed during unilateral practice are stored in a way that enables shared access between the cerebral hemispheres. This allows the untrained limb to reproduce motor strategies learned during training, thereby aiding bilateral functional improvements. In this study, both models provide plausible explanations for the symmetrical gains in posterolateral dynamic balance after unilateral SLRD training.

The fact that improvements in dynamic balance in the current study were observed only in the posterolateral reach performance after the unilateral training protocol may be explained by the principle of neuromuscular specificity, which accounts for the direction-specific effects. The Single-Leg Romanian Deadlift (SLRD), chosen as the main training exercise, closely mimics the biomechanical and neuromotor requirements of the posterolateral vector of the YBT. Both activities demand significant activation of the Gluteus medius and deep trunk muscles to maintain trunk alignment and balance during single-leg support.

Importantly, successful execution of the posterolateral reach also places high demands on the medial hamstrings, especially the Semitendinosus, which helps stabilize the hip joint and regulate eccentric force during lateral and posterior displacement of the center of mass.[7,23] Since these demands are mainly controlled by central postural strategies rather than limb-specific strength, repeated practice of the SLRD may improve neuromuscular coordination patterns accessible to both limbs, leading to bilateral enhancements in posterolateral dynamic balance.

Furthermore, dynamic postural control depends on robust core stability, which enhances intersegmental coordination and the transfer of trunk stiffness during complex limb movements.[24,25] In a recent study, Mavaeian et al found that core stabilization training significantly improved knee joint proprioception in athletic groups, emphasizing the role of central trunk control in sensorimotor function at distal joints.[24]

Given the biomechanical demands shared by core stabilization exercises and unilateral posterior-chain movements like the SLRD, it is plausible that the intervention served a dual purpose by providing both a proprioceptive stimulus and a postural control challenge. These effects likely fostered central neuromuscular adaptations, contributing to the bilateral improvements in dynamic balance observed in the current study, regardless of which limb was directly trained.

Regarding the directional demands of posterolateral reach in the YBT, proprioceptive acuity at the ankle joint is critical, particularly as the center of mass is dynamically displaced to the maximal edge of the posterolateral part above the supporting base. This movement may function as a form of self-induced perturbation, challenging the postural control system to make rapid anticipatory and reactive adjustments. Previous studies have indicated that interventions enhancing ankle proprioception, such as the balance-intensive SLRD, are positively associated with improved performance in the posterolateral vector.[1] The SLRD, performed unilaterally and under progressively increasing load, introduces perturbation-like stimuli that activates the posterior chain and core muscles. These conditions mimic those in external perturbation paradigms, such as slip-recovery protocols, which have been shown to induce rapid neuromuscular adaptations in balance-related muscle synergies.[14,17] These adaptations likely occur at a central or system level rather than being limited to the trained limb, and may also explain the bilateral improvements in posterolateral reach observed in this study.

Despite significant gains in posterolateral reach performance, the absence of improvement in the posteromedial direction reinforces the principle of directional specificity in balance adaptations. Although both vectors are measured within the same test framework, they rely on distinct neuromuscular and biomechanical requirements. According to Nelson et al, posteromedial reach performance is primarily influenced by hip flexion, ankle dorsiflexion, and ankle external rotation, as well as by combined hip and knee extensor and hip abductor moments.[26] In contrast, posterolateral reach is more dependent on hip flexion and contralateral pelvic rotation, with performance driven primarily by the hip extensor moment. These distinctions suggest that while both directions engage sagittal-plane hip mechanics, the posteromedial vector involves greater multi-joint coordination, particularly in the frontal and transverse planes. Accordingly, the SLRD, designed to target the posterior chain, including the Semitendinosus, Gluteus medius, and trunk extensors, is biomechanically better suited to improve posterolateral performance. Its movement pattern and loading characteristics are not sufficiently specific to elicit the complex, multi-planar demands required for improvement in the posteromedial direction.

Further support for the principle of direction-specific adaptation is provided by Zhang et al, whose findings confirm that training-induced improvements in dynamic balance within one diagonal plane do not reliably transfer to other planes of movement.[27] This reinforces the idea that adaptations observed in the posterolateral direction are likely specific to the biomechanical and neuromotor demands of that movement vector, rather than to generalized balance improvement (e.g., the posteromedial vector, which was not improved in the current study). Similarly, Kruchio reported that posteromedial reach tasks require more complex joint interactions, particularly between ankle dorsiflexion and knee valgus restraint, which are not sufficiently stimulated by posterior-chain-dominant exercises such as the SLRD.[28] Together, these findings suggest that the lack of improvement in posteromedial reach is not surprising, and that unilateral interventions may require targeted multi-planar strategies to improve all aspects of dynamic balance comprehensively.

In contrast to the improvements observed in dynamic balance performance, the present study found no significant changes in static balance following the four-week unilateral training intervention. This outcome is consistent with findings by Kibele and Behm, who reported no group differences in static sway following seven weeks of resistance training under stable or unstable conditions, despite improvements in muscular strength and dynamic balance measures.[29] These results support the notion that static balance assessments may be less sensitive to neuromuscular adaptations resulting from dynamic, short-duration training protocols. Unlike dynamic tasks that challenge coordination, proprioception, and reactive control under movement, static sway measures primarily capture low-velocity postural regulation, which may require longer or more proprioceptively enriched interventions to show measurable change. A second possible explanation for the lack of significant findings in the static balance tests is the relatively low postural challenge posed by the bipedal stance. Picoli et al reported that measures of postural sway complexity, including burstiness, memory, and local variation in CoP zero-crossings, were significantly lower in bipedal compared to unipedal conditions.[15] These results suggest that bipedal stance creates less temporal variability and presents a lower neuromuscular challenge, which limits its effectiveness in detecting subtle balance changes that may occur from dynamic, asymmetrical training protocols.

Taken together, these factors suggest that while static balance assessments offer valuable insights, they may be less suited to capturing early-phase functional changes in response to targeted, unilateral interventions.

It should be noted that this study has several limitations to consider when interpreting the findings: first, participants were already resistance-trained, limiting generalizability to untrained populations. Second, the relatively brief training period may have limited the potential to observe broader or longer-lasting balance adaptations. Third, no EMG or functional assessments were used to verify muscular activation. Thus, the role of different muscles in improving dynamic balance remains theoretical. Lastly, proprioceptive improvements were discussed but not directly assessed at the ankle or knee.

Although there are limitations, the results of the current study support the idea that the SLRD functions not only as a posterior-chain strengthening exercise but also as a form of perturbation-like resistance training. The unilateral stance, reduced base of support, and load placement challenge the sensorimotor system in a way that mimics destabilizing stimuli, eliciting anticipatory postural adjustments, core stabilization, and neuromuscular coordination that closely resemble the adaptations observed in structured perturbation paradigms.[29]

Moreover, consistent with the phenomenon of cross-transfer effect, the bilateral improvements observed in dynamic balance despite training only one limb suggest that central neural adaptations occurred. These include enhanced interlimb coordination, corticospinal activation, and core-mediated force transmission, as supported by Duong et al.[6] The SLRD likely contributed to these bilateral gains by simultaneously stimulating core musculature and requiring integrated trunk-limb control across both sides of the body.

Acknowledgements

The authors would like to thank all participants for their dedicated involvement in this study. No external funding was received for this project, and the author declares no conflicts of interest.

References

1. Alizamani S, Ghasemi G, Lenjan Nejadian S. Effects of eight-week core stability training on stable and unstable surfaces on ankle muscular strength, proprioception, and dorsiflexion in athletes with chronic ankle instability. *J Bodyw Mov Ther*. 2023;36:135–141. https://doi.org/10.1016/j.jbmt.2023.04.005

2. Maki BE, McIlroy WE. Postural control in the older adult. *Clin Geriatr Med*. 1996;12(4):635-658. https://doi.org/10.1016/S0749-0690(18)30193-9

3. Melzer I, Kurz I, Oddsson LIE. A retrospective analysis of balance control parameters in elderly fallers and non-fallers. *Clin Biomech*. 2010;25(10):984-988. https://doi.org/10.1016/j.clinbiomech.2010.07.007

4. Centers for Disease Control and Prevention. Facts About Falls. 2024. Accessed April 30, 2025. https://www.cdc.gov/falls/data-research/facts-stats/index.html

5. McCrum C, Bhatt TS, Gerards MHG, et al. Perturbation-based balance training: principles, mechanisms and implementation in clinical practice. *Front Sports Act Living*. 2022;4:1015394. https://doi.org/10.3389/fspor.2022.1015394

6. Hezel N, Sloot LH, Wanner P, et al. Feasibility, effectiveness and acceptability of two perturbation-based treadmill training protocols to improve reactive balance in fall-prone older adults (FEATURE): protocol for a pilot randomized controlled trial. *BMJ Open*. 2023;13(9):e073135. https://doi.org/10.1136/bmjopen-2023-073135

7. Dadfar M, Seidi F. The effects of self-myofascial release on hamstring and gastrocnemius muscles using foam roll on postural sway, knee proprioception, and dynamic balance in recreationally active females. *Int J Athl Ther Train*. 2022;27(5):227–233. https://doi.org/10.1123/ijatt.2021-0043

8. Wang FC, de Pasqua V, Delwaide PJ. Age-related changes in fastest and slowest conducting axons of thenar motor units. *Muscle Nerve*. 1999;22(8):1022-1029. https://doi.org/10.1002/(SICI)1097-4598(199908)22:8<1022::AID-MUS3>3.0.CO;2-F

9. Hill MW, Wdowski MM, Rosicka K, Kay AD, Muehlbauer T. Exploring the relationship of static and dynamic balance with muscle mechanical properties of the lower limbs in healthy young adults. *Front Physiol*. 2023;14:1168314. https://doi.org/10.3389/fphys.2023.1168314

10. Swash M, Fox KP. The effect of age on human skeletal muscle: Studies of the morphology and innervation of muscle spindles. *J Neurol Sci*. 1972;16(4):417-432. https://doi.org/10.1016/0022-510X(72)90048-2

11. Benjuya N, Melzer I, Kaplanski J. Aging-induced shifts from a reliance on sensory input to muscle co-contraction during balanced standing. *J Gerontol A Biol Sci Med Sci*. 2004;59(2):M166-M171. https://doi.org/10.1093/gerona/59.2.M166

12. Lubetzky-Vilnai A, Kartin D. The effect of balance training on balance performance in individuals poststroke: A systematic review. *J Neurol Phys Ther*. 2010;34(3):127-137. https://doi.org/10.1097/NPT.0b013e3181ef764d

13. Marcori AJ, Monteiro PHM, Oliveira JA, Doumas M, Teixeira LA. Single leg balance training: a systematic review. *Percept Mot Skills*. 2022;129(2):232–252. https://doi.org/10.1177/00315125211070104

14. Krause A, Freyler K, Gollhofer A, et al. Neuromuscular and kinematic adaptation in response to reactive balance training: a randomized controlled study regarding fall prevention. *Front Physiol*. 2018;9:1075. https://doi.org/10.3389/fphys.2018.01075

15. Picoli T, Santos DA, Nakamura FY, Batista LA. Characterizing postural sway signals by the analysis of zero-crossing patterns. *PLoS One*. 2022;17(1):e0262737. https://doi.org/10.1016/j.physa.2022.127160

16. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. *Int J Exerc Sci*. 2019;12(1):1-8. https://doi.org/10.70252/EYCD6235

17. Newton RA. Validity of the multi-directional reach test as a practical measure for limits of stability in older adults. *J Gerontol A Biol Sci Med Sci*. 2001;56(4):M248-M252. https://doi.org/10.1093/gerona/56.4.M248

18. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther*. 2006;36(12):911-919. https://doi.org/10.2519/jospt.2006.2244

19. Richardson JTE. Eta squared and partial eta squared as measures of effect size in educational research. *Educ Res Rev*. 2011;6(2):135-147. https://doi.org/10.1016/j.edurev.2010.12.001

20. Lee M, Carroll TJ. Cross education: Possible mechanisms for the contralateral effects of unilateral resistance training. *Sports Med*. 2007;37(1):1-14. https://doi.org/10.2165/00007256-200737010-00001

21. Duong A, Wójcicki TR, Carnes AJ. The effects of unilateral resistance training on muscular strength, power, and measures of core stability in resistance-trained individuals. *Int J Strength Cond*. 2022;2(1):1–11. https://doi.org/10.47206/ijsc.v2i1.145

22. Sun L, Wang Y, Luo L, Yang Y, Luo J. Cross-education mechanisms and clinical rehabilitation research: A literature review. *Qual Sport*. 2024;35. https://doi.org/10.12775/QS.2024.35.56330

23. Leavey VJ, Sandrey MA, Dahmer G. Comparative effects of 6-week balance, gluteus medius strength, and combined programs on dynamic postural control. *J Sport Rehabil*. 2010;19(3):268–287. https://doi.org/10.1123/jsr.19.3.268

24. Mavaeian Z, Mir Mohsen S, Shadmehr A, Malmir K. The effect of core stabilization exercises compared to balance training on proprioception and dynamic balance in healthy female amateur soccer players: A randomized controlled trial. *Arch Rehabil*. 2025;25(4):864–889. https://doi.org/10.32598/RJ.25.4.3881.1

25. Wilson M. The effect of a core stability, gluteus medius, and proprioceptive exercise program on dynamic postural control in netball players [master's thesis]. University of the Free State; 2014.

26. Nelson RK, Silva DM, Ford KR. Kinematic and kinetic predictors of Y Balance Test performance. *J Biomech*. 2021;118:110301. https://doi.org/10.26603/001c.21492

27. Zhang W, Chen X, Xu K, et al. Effect of unilateral training and bilateral training on physical performance: A meta-analysis. *Front Physiol*. 2023;14:1128250. https://doi.org/10.3389/fphys.2023.1128250

28. Kruchio NA. An Investigation of the Relationship Between the Y-Balance Test and the Sit-to-Raise Test in a Sample of Active Healthy Adults: A Cross-Sectional Correlation Design [master's thesis]. Auckland University of Technology; 2016

29. Kibele A, Behm DG. Seven weeks of instability and traditional resistance training effects on strength, balance, and functional performance. *J Strength Cond Res*. 2009;23(9):2443–2450. https://doi.org/10.1519/JSC.0b013e3181bf0489

30. Wang Y, Pai YC, Bhatt T. Neuromuscular mechanisms of motor adaptation to repeated gait-slip perturbations in older adults. *Sci Rep*. 2022;12:19302. https://doi.org/10.1038/s41598-022-23051-w