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Suspension Training as a Preventive Strategy: Effects on Muscle Activity, Landing Mechanics, and Balance in Female Athletes with Trunk Dominance Dysfunction

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ABSTRACT

Aims: This study aimed to determine whether a six-week progressive Total Resistance Exercise (TRX) suspension training program enhances feedback and feed-forward full-name (EMG) activity of the trunk and lumbo-pelvic muscles and leads to improved landing mechanics and dynamic balance in female athletes exhibiting trunk-dominance impairment.

Method and Materials: This study was a two-arm, assessor-blinded, randomized controlled trial. Thirty female student-athletes (aged 18–25 years) were screened with the Tuck-Jump Test (abbreviated name) for trunk-dominance impairment and randomized to either a TRX training group (intervention) or a no-intervention group (control). The intervention group completed a supervised 6-week TRX program (3 times per week). Outcome measures included feed-forward and feedback EMG activity of the transversus abdominis, external oblique, quadratus lumborum, gluteus maximus, and gluteus medius, as well as dynamic balance (Y-Balance Test) and landing mechanics as Landing Error Scoring System(LESS).

Findings: A mixed-design repeated-measures ANOVA revealed significant improvements in feed-forward and feedback muscle activity, LESS scores, and dynamic balance in the training group ($p < 0.05$). Conversely, the control group showed no significant changes ($p > 0.05$).

Conclusion: According to the results of this study, the six-week TRX suspension training program was highly effective in enhancing both anticipatory and reactive neuromuscular control in female athletes with trunk-dominance impairment. These physiological improvements translate to significant functional benefits, including safer landing mechanics and enhanced dynamic balance. Therefore, suspension training represents a valuable, evidence-based modality for injury prevention and performance optimization in at-risk athletic populations.

Keywords: Musculoskeletal System, Neuromuscular Control, Sports Injuries, Total Resistance Exercise (TRX), Landing mechanics

Introduction

Lower-extremity injuries, especially non-contact injuries such as Anterior Cruciate Ligament (ACL) tears, constitute a significant concern in high-impact, jumping, and cutting sports, particularly among female athletes (1,2). Biomechanical and neuromuscular factors, including impaired trunk control and delayed reactive stabilization, contribute to atypical loading patterns manifested as excessive knee valgus and altered jump-landing mechanics (3,4). These maladaptive movement patterns increase the risk of injury and reflect deficits in neuromuscular strategies governing both feedback (reactive) and feed-forward (anticipatory) control of the trunk and lumbopelvic region (5,6).Addressing these deficits is therefore a critical target for injury-prevention strategies. Suspension training systems, such as the Total Resistance Exercise (TRX), are gaining prominence in strength and conditioning due to their capacity to introduce instability requiring active core engagement across multiple planes (1,7,8). Recent studies demonstrate that TRX training enhances static and dynamic balance, coordination, jumping performance, and trunk control (1,9-11). TRX's emphasis on unstable support surfaces inherently challenges both feedback and feed-forward control mechanisms, potentially enhancing core muscle activity and neuromuscular responsiveness [10] These findings underscore TRX's promise for neuromuscular enhancement, yet key mechanistic evidence regarding its impact on full-body (EMG) feedback and feed-forward activation of trunk and lumbo pelvic stabilizers remains understudied. Existing literature on neuromuscular training interventions often focuses on superficial outcomes such as EMG onset times or gross measures of strength and balance [8, 10]. However, feedback (reactive) and feed-forward (anticipatory) activations of trunk musculature represent more direct indicators of motor control readiness, especially when preparing for sudden destabilization during landing tasks [12, 13]. In sports with high landing demands, these muscle activity profiles are pivotal for controlling trunk position and reducing undue distal joint loading [14, 15]. To date, no study has systematically examined whether TRX training modulates these neuromuscular activation patterns in female athletes with trunk-dominance impairments. Moreover, improvements in trunk control and EMG activity must extend beyond the lab and translate into functional and biomechanical benefits, such as improved landing mechanics and enhanced dynamic balance during sport-relevant tasks. While TRX interventions have shown efficacy in improving balance [7, 11], their downstream effects on landing mechanics and the role of feedback/feed-forward muscular activation remain unexplored in trunk-compromised athletes. Similarly, there is a lack of evidence regarding the persistence of any beneficial motor changes post-training, a crucial consideration for long-term injury prevention.

Bridging this gap is essential. If TRX can meaningfully enhance core-feedback/feed-forward activation and improve biomechanical and balance outcomes, it would validate its inclusion in field-applicable, time-efficient injury-prevention programs tailored for female athletes in high-risk sports such as volleyball and basketball. Hence, a mechanistic investigation using EMG metrics of feedback and feed-forward activity, coupled with objective biomechanical and balance measures, is both timely and impactful. This study aims to determine whether a six-week progressive TRX suspension training program enhances feedback and feed-forward EMG activity of trunk and lumbopelvic muscles, leading to improved landing mechanics and dynamic balance in female athletes exhibiting trunk-dominance impairment.

Method and Materials

This investigation was a two-arm, assessor-blinded, randomized controlled trial with repeated measures at baseline (pre-intervention and immediately post-intervention. A total of 30 female student-athletes (age 18–25 years) from university basketball and handball teams were recruited to participate. Participants were required to have at least three consecutive years of sport participation (≥ two sessions/week) and a Body Mass Index (BMI) of 18–25 kg/m^2. Exclusion criteria included a history of lower-extremity or trunk surgery, musculoskeletal/ neurological disorders, or low-back pain within the previous 12 months and participation in TRX or other neuromuscular injury-prevention programs within the past year [1, 10]. All participants provided written informed consent.

For screening and randomization, potential participants were screened for trunk-dominance impairment using the Tuck-Jump Test (TJT). Two independent raters analyzed video-recorded tuck jumps, classifying participants with impairment if they failed to land at the take-off marker, did not achieve approximately parallel thigh position at peak jump, or exhibited interruptions/ compensatory movements during the 10-second sequence [16, 17]. Based on sample size calculations using a priori power analysis (G*Power 3.1), a required sample size of 26 was determined, and accounting for a 15% attrition rate, the final recruitment target was set at 30 participants. After baseline assessments, participants were randomized to either a TRX suspension training group (intervention group) or a no-intervention (control group) using a blocked randomization sequence. Outcome assessors and the data analyst remained blinded to group allocation.

For laboratory procedures and measurements, testing occurred at baseline and post-intervention. The standardized test battery included anthropometric measurements (height, mass), Maximum voluntary isometric contraction (MVIC) collection for EMG normalization, the Y-Balance Test (YBT), a Landing Error Scoring System (LESS) assessment, and single-leg drop-landing trials with synchronized EMG and foot-switch recording. A standardized 10-minute warm-up preceded all test batteries.

For EMG data collection and processing, bipolar Silver/Silver Chloride (Ag/AgCl) surface electrodes were placed on the Transversus Abdominis (TA), External Oblique (EO), Quadratus Lumborum (QL), Gluteus Maximus (GMax), and Gluteus Medius (GMed). Maximal Voluntary Isometric Contractions (MVICs) were collected for each muscle to normalize EMG data. The EMG signals were amplified, band-pass filtered (20–450 Hz), notch filtered (50/60 Hz), and full-wave rectified. The Root Mean Square (RMS) envelope was then calculated to determine EMG amplitude, which was normalized to %MVIC for between-subject comparisons [10, 18]. The definition of the variables and the test are as follows.

For EMG Metrics, Feed-forward (anticipatory) activation was operationalized as the mean normalized RMS (%MVIC) in the 200 ms immediately before initial foot contact (pre-activation window). Feedback (reactive) activation was quantified as the normalized RMS (or integrated EMG, iEMG) in the 0–250 ms window following initial contact (reactive window) [18]. These windows are widely used in landing and perturbation studies and reflect anticipatory and early reactive neuromuscular control [18, 19].

For Single-leg drop landing task, Participants completed single-leg drop landings from a 40-cm platform onto a foot switch. Procedure: stand on the platform with the non-test leg flexed, arms on the iliac crests, step off forward from the box, and land on the test (dominant) leg at the center of the foot-switch, stabilize, and hold for 3 s. Five trials were performed, so the average of the three best, valid trials (without loss of balance or extraneous movement) was used for analysis [10, 18].

For Landing Error Scoring System (LESS),The LESS was administered per established protocol: a forward jump from a 30-cm box to a landing target located at 50% of participant height, followed by a maximal rebound. Two cameras (frontal and sagittal) recorded trials; three valid trials were captured and scored offline by two blinded raters. Inter-rater agreement was checked and disagreements resolved by consensus [1, 20].

For Y-Balance Test (YBT), Dynamic balance was assessed with the Lower-Quarter YBT in the anterior, posteromedial, and posterolateral directions. Reach distances were normalized to limb length, Anterior Superior Iliac Spine (ASIS) to medial malleolus). After three practice trials, three test trials were performed, and the maximum reach for each direction was used to compute the composite reach score (%) per standard methods [1, 7]. For TRX training intervention, Participants in the experimental group completed a supervised TRX suspension training program 3×/week for 6 weeks (non-consecutive days). Each session followed a consistent format: 10-minute standardized warm-up, 15–20 minutes of TRX exercises, and a 5-minute cool-down/stretch [7, 9]. Two familiarization sessions preceded baseline testing to ensure proficiency and reduce learning effects (Table1).TRX sessions employed a TRX full name (PRO3) Suspension Trainer (mounted ~2.5 m above ground). Exercises targeted trunk feed-forward and feedback control, lumbopelvic stability, and lower-limb functional strength. Progression followed Frequency, Intensity, Time, and Type (FITT) principles across 5–6 difficulty levels: increase instability (single-leg), increase range/time, or add dynamic/ball-based perturbations as participants achieved mastery. Certified trainers supervised all sessions; adherence and perceived exertion (Borg's, Rate of perceived exertion (RPE) were recorded. Participants missing two consecutive sessions were counseled; missing >2 sessions could be cause for exclusion per the protocol (Table 2)

In this study, control groups were asked to maintain their usual daily activities and refrain from initiating any new structured core, balance, or resistance programs during the study period. Weekly check-ins were performed to verify compliance. All training and testing were supervised by a licensed corrective exercise specialist. Participants reported any pain, dizziness, or adverse events; these were documented and assessed. Serious adverse events prompted immediate medical referral and review by the research team. To perform statistical analysis, demographic characteristics were compared using independent t-tests. Data were checked for normality (Shapiro–Wilk). Between-group × time effects were analyzed using mixed (group × time) repeated-measures ANOVA. Effect sizes were determined using eta-squared. Analyses were performed in SPSS v26 (IBM); significance was set at $p < 0.05$. Sample-size re-estimation was not planned; missing data were handled with intention-to-treat and multiple imputation if >5% of data were missing.

Table 1- Movement Levels for Total Resistance Exercise (TRX) Protocol

Movement Type	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
(A) Squat	Squat	Squat-ankle plantar	Fixed squat-ankle plantar			
(B) Hamstring	Hamstring	Hamstring-abduction	Hamstring curl	S.L. hamstring		
(C) Lunge	Forward lunge	Forward lunge	S.L. lunge	S.L. lunge with the ball		
(D) Single leg squat	S.L. squat	S.L. squat with leg swing	S.L. squat to lateral			
(E) Jump landing	Squat jump	Squat jump F-B	Squat jump with Ball	S.L. squat Jump	S.L. squat Jump F-B	S.L. squat jump with ball
(F) Cutting	Squat jump	S.L. squat jump R-L	S.L. squat jump with the ball			

F-B :Forward-Backward; R-L :Right-Left; S.L :Single Leg

Table 2- Total Resistance Exercise (TRX) Session Protocol

Session	Movement Type and Difficulty Levels (Sets × Seconds)
1	A1 (3×30), B1 (3×25), C1 (3×25)
2	A1 (3×30), B1 (3×25), C1 (3×25)
3	A1 (3×35), B1 (3×30), C1 (3×35)
4	A2 (3×35), B2 (3×30), C2 (3×35)
5	A2 (3×35), B2 (3×30), C2 (3×35)
6	A3 (3×35), B3 (3×30), C2 (3×35)
7	A3 (3×35), B3 (3×30), C3 (3×35), D1 (3×25)
8	B4 (3×25), C3 (3×35), D1 (3×25), D2 (3×20), E1 (3×20)
9	B4 (3×25), C3 (3×40), D1 (3×30), D2 (3×25), E1 (3×25)
10	C4 (3×40), D2 (3×30), E1 (3×25), E2 (3×25), E3 (3×25)
11	C4 (3×45), D2 (3×30), E2 (3×25), E3 (3×25), E4 (3×25), F1 (3×30)
12	C4 (3×45), E2 (3×30), E3 (3×30), E4 (3×25), E5 (3×25), F1 (3×20)
13	E3 (3×35), E4 (3×30), E5 (3×20), E6 (3×35), F1 (3×20), F2 (3×20)
14–18	E4 (3×30), E5 (3×25), E6 (3×25), F1 (3×40), F2 (3×20), F3 (3×25)

Findings

Demographic information for the subjects, including age, height, weight, and body mass index (BMI), is reported for each group in Table 3.

Table 3- Results of the independent t-test for comparing demographic characteristics at baseline.

Variable	Control Group	Intervention Group	p-value
Age (years)	22.3 ± 2.1	22.5 ± 2.2	0.68
Height (cm)	168.5 ± 5.2	169.1± 5.4	0.47
Weight (kg)	65.1 ± 7.3	66.2 ± 7.5	0.32
BMI (kg/m^2)	23.4 ± 2.1	23.6 ± 2.2	0.56

cm (Centimeter), kg (Kilogram), BMI (Body Mass Index)

Independent t-tests revealed no significant differences in demographic characteristics between groups. Data normality was confirmed using the Shapiro-Wilk test. To assess the training effect, a mixed-design repeated measures ANOVA was conducted. Results indicated a significant improvement in feedforward and feedback muscle activity, as well as landing mechanics and dynamic balance, in the intervention group ($p < .05$). Conversely, the control group showed no significant change in any of the aforementioned variables between pre- and post-tests ($p > .05$) (Table 4).

Table 4) Mean and standard deviation of variables in the two groups at pre-test

Muscle	Variable	Control group		Intervention group	
		Pre	Post	Pre	Post
TA	F-F	89.1 ± 9.6	92.5 ± 10.2	87.5 ± 10.4	109.1 ± 11.5
	F-B	106.4 ± 8.5	103.2 ± 7.3	105.5 ± 8.1	119.4 ± 10.1
EO	F-F	67.3 ± 6.3	70.2 ± 9.1	65.5 ± 8.5	76.9 ± 7.4
	F-B	93.3 ± 6.2	95.1 ± 5.5	96.2 ± 6.8	108.4 ± 7.6
QL	F-F	72.4 ± 8.2	70.6 ± 7.4	72.1 ± 9.1	83.8 ± 9.6
	F-B	84.2 ± 4.8	86.2 ± 7.3	83.5 ± 5.7	97.4 ± 6.8
G-Max	F-F	110.4 ± 12.1	106.8 ± 13.7	107.7 ± 11.1	124.9 ± 13.1
	F-B	119.8 ± 12.4	121.7 ± 8.8	124.3 ± 9.5	138.2 ± 9.3
G-Med	F-F	104.8 ± 10.3	99.8 ± 12.6	103.3 ± 11.7	121.7 ± 12.8
	F-B	123.5 ± 10.1	125.8 ± 12.5	120.9 ± 9.3	135.7 ± 11.1
Less		13.3 ± 2.4	13.8 ± 3.1	12.8 ± 3.4	6.6 ± 3.9
DB		69.2 ± 5.2	73.1 ± 5.8	70.6 ± 4.3	82.9 ± 4.7

TA: Transversus Abdominis); EO: External Oblique; QL: Quadratus Lumborum; G-Max: Gluteus Maximus; G-Med Gluteus Medius; F-F: Feed Forward; F-B: Feed Back; LESS: Landing Error Scoring System; DB: Dynamic Balance

Table 5) Mixed-design ANOVA results

Muscle		Time (P-value)	Group (P-value)	Interaction (P-value)	Effect Size (Control – Intervention)
TA	FF	≤≤0.001	≤0.001	≤0.001	0.029 - 0.211
	F-B	≤≤0.001	≤0.001	≤0.001	0.008 - 0.187
EO	F-F	0.003	≤0.001	≤0.001	0.011 - 0.199
	F-B	≤0.001	≤0.001	≤0.001	0.041 - 0.213
QL	F-F	0.005	≤0.001	≤0.001	0.015 - 0.308
	F-B	≤0.001	≤0.001	≤0.001	0.018 - 0.263
G-Max	F-F	≤0.001	≤0.001	≤0.001	0.022 - 0.211
	F-B	≤0.001	≤0.001	≤0.001	0.017 - 0.231
G-Med	F-F	≤0.001	≤0.001	≤0.001	0.018 - 0.215
	F-B	≤0.001	≤0.001	≤0.001	0.029 - 0.155
Less		0.011	≤0.001	0.031	0.014 - 0.167
DB		≤0.001	≤0.001	0.017	0.015 - 0.195

TA: Transversus Abdominis); EO: External Oblique; QL: Quadratus Lumborum; G-Max: Gluteus Maximus; G-Med Gluteus Medius; F-F: Feed Forward; F-B: Feed Back; LESS: Landing Error Scoring System; DB: Dynamic Balance

Discussion

This study aimed to investigate the effects of suspension training on feedforward and feedback muscle activity, landing mechanics, and dynamic balance in young female athletes. The results demonstrate that a six-week suspension training intervention significantly improved all measured variables in the training group, while the control group showed no significant changes. These findings affirm that suspension training effectively enhances neuromuscular control, postural stability, and movement efficiency, aligning with previous research that highlights the efficacy of suspension training modalities for motor learning and injury prevention [7, 8, 10, 21].

The most significant finding was the concurrent improvement in feedforward and feedback muscle activity across the lumbopelvic and hip musculature, including the TA, EO, QL, G-Max, and G-Med. From a physiological perspective, enhanced feedforward control reflects a more efficient anticipatory recruitment of stabilizing muscles [22, 23]. The continuous instability and variable load vectors inherent to suspension training likely refine the central nervous system's ability to pre-program motor commands, thereby improving the proactive recruitment of core and hip stabilizers before a postural perturbation or impact [24]. For instance, the improved feedforward activity of the TA and EO is critical for pre-stabilizing the trunk, which is essential for athletes in sports requiring landing and cutting maneuvers [25, 26]. This is consistent with a meta-analysis by Bao et al., which found that unstable training significantly increased feedforward trunk muscle activation compared to stable-surface training, underscoring its role in joint protection and movement efficiency [27].

Furthermore, the significant enhancement of feedback muscle activation highlights improved reactive neuromuscular control. This is a critical adaptation as it reflects a more rapid and effective response to unexpected joint or postural disturbances [28]. The rich proprioceptive input from suspension training forces the sensorimotor system to process afferent information from muscle spindles and mechanoreceptors more efficiently and translate it into precise efferent motor commands [8, 29]. Improved feedback stabilization is a cornerstone of injury prevention, as delayed feedback activation has been implicated in the mechanisms of non-contact injuries such as ACL sprains [30]. A systematic review by Winter et al. supports this, showing that proprioceptive-rich training environments lead to superior improvements in feedback muscle activity [31].

The concurrent improvements in landing mechanics and dynamic balance underscore the functional benefits of these neuromuscular adaptations [1]. The reduced LESS scores in the training group indicate a safer landing strategy with better alignment and force attenuation [21]. This biomechanical improvement is a direct consequence of the enhanced neuromuscular control [1]. Improved activation of the gluteus medius and maximus helps control hip adduction and internal rotation during landing, a key factor in mitigating knee valgus collapse, a primary risk factor for ACL injury [32, 33]. This finding aligns with previous studies that linked enhanced hip and core muscle strength to improved landing mechanics and reduced injury risk [4, 34, 35]. Similarly, the significant improvement in dynamic balance further supports the efficacy of suspension training in developing functional stability. The continuous challenge to equilibrium during suspension exercises requires synchronized contributions from the vestibular, visual, and proprioceptive systems, thereby improving coordination and joint stability[1].

Conclusion

This study provides strong evidence that suspension training enhances both feedforward and feedback muscle activity of the lumbopelvic and hip musculature, leading to improved landing mechanics and dynamic balance. These neuromuscular and biomechanical adaptations are tightly interlinked, with anticipatory activation setting the foundation for stable movement and reactive activation ensuring rapid corrections during perturbations. Together, these mechanisms foster safer and more efficient motor strategies, directly contributing to injury prevention and performance optimization in female athletes. Suspension training, therefore, represents a valuable addition to both preventive and rehabilitative exercise programs, offering comprehensive benefits that extend beyond strength development to encompass neuromuscular coordination, postural stability, and functional resilience.

Our findings have significant practical implications. Suspension training is a highly effective, cost-efficient, and portable modality that can be easily integrated into warm-up routines or as a complementary training program for athletes in high-risk sports. Coaches and athletic trainers can use this tool to enhance neuromuscular control and reduce injury risk. For rehabilitation professionals, the dual benefit of improving both anticipatory and reactive neuromuscular strategies makes suspension training particularly valuable in the late stages of rehabilitation following lower limb injuries.

While this study provides robust evidence, it is essential to acknowledge certain limitations. The sample size was relatively small and limited to young female athletes, which may limit the generalizability of the findings to other populations, such as male athletes or non-athletes. Additionally, the six-week intervention period was short, and the long-term retention of these training effects remains unknown.

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Authors' Contribution

All authors contributed equally to the conception and design of the study, data collection and analysis, interpretation of the results, and drafting of the manuscript. Each author approved the final version of the manuscript for submission

Conflicts' of Interest

The authors declared no conflict of interest.

Ethical Permission

This study was approved by the Sport Sciences Research Institute of Iran (approval code: SSRI.REC-2302-2093). All participants provided written informed consent before participation.

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