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Postural control and leg muscle activation in athletes who underwent anterior cruciate ligament reconstruction and healthy controls: A preliminary study on acute responses to whole-body vibration

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ABSTRACT

Background: Anterior cruciate ligament reconstruction (ACL-R) restores mechanical knee stability, but neuromuscular and balance deficits often persist. Whole-body vibration (WBV) has been widely studied as a method to improve postural control and stimulate the neuromuscular system. However, the acute effects of WBV following ACL-R on postural control and muscle activation remain unclear.

Methods: Twenty-seven competitive athletes (13 ACL-R, 14 healthy athletes) underwent static and dynamic balance assessments using centre of pressure (CoP) measures synchronised with surface electromyography (sEMG) recorded in the vastus lateralis, biceps femoris, tibialis anterior, and lateral gastrocnemius muscles during single- and double-leg, in static and dynamic conditions. All participants completed a single WBV session.

Findings: Post-WBV, healthy controls showed reduced CoP sway during static single-leg ($p < 0.05$), while ACL-R participants exhibited no significant change ($p > 0.05$). In dynamic double-leg with eyes closed, ACL-R participants showed increased medio-lateral sway ($p < 0.05$). ACL-R group demonstrated reduced sEMG activity in proximal muscles (particularly biceps femoris) during double-leg ($p < 0.05$), and controls in distal muscles during single-leg tasks (tibialis anterior, lateral gastrocnemius $p < 0.05$).

Interpretation: WBV acutely influenced postural stability, improving static balance in healthy controls but increasing dynamic sway in ACL-R individuals, suggesting a recalibration of the sensorimotor set. In addition, WBV modulated biceps femoris activation in the operated leg, reducing over-activation, indicating a specific neuromuscular response. These preliminary findings highlight persistent neuromechanical alterations in ACL-R athletes and may support the potential integration of WBV exercise into rehabilitation programs designed to restore balance control.

1. Introduction

Anterior cruciate ligament (ACL) ruptures are among the most prevalent knee sports injuries (Rowe et al., 2022). Their reconstruction (ACL-R) is recommended to restore mechanical knee joint stability and pre-injury function (Jenkins et al., 2022). Nevertheless, deficiencies in postural control and knee strength frequently persist even after complete rehabilitation (Criss et al., 2021). Additionally, many individuals who undergo ACL-R may not achieve complete neuromuscular recovery, particularly in postural control, even up to 20 years after reconstruction (Stensdotter et al., 2016). ACL rupture is acknowledged as a neurophysiological dysfunction rather than a local joint injury (Criss et al., 2021; Needle et al., 2017).

Following ACL-R, early rehabilitation is essential for regaining knee stability and neuromuscular function (Criss et al., 2021). It focuses on quadriceps recovery and somatosensory pathway restoration, both of which are required for postural stability and motor control (Criss et al., 2021; Howells et al., 2011). Current protocols prioritize early full weight-bearing and accelerated strength recovery to facilitate the return to high-level sports (Jenkins et al., 2022). However, these approaches may not fully address compensatory mechanisms developed post-injury, and athletes who are ready to return to play after ACL-R still display compensatory alterations, particularly during bilateral control, compared to healthy athletes (Di Giminiani et al., 2023; La Greca et al.,

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2025a). Specifically, an enhanced activation of the biceps femoris in the operated leg may serve as an indicator of neuromuscular compensation intended to enhance knee stability (Di Giminiani et al., 2023).

While performing complex motor tasks, these modifications may increase the risk of long-term reinjury (Criss et al., 2021). These modifications are attributable to the ACL injury-related damage to periarticular soft tissues, which disrupts joint mechanoreceptors, resulting in deafferentation and altered afferent input to the central nervous system (CNS) (Needle et al., 2017). This sensory impairment compromises postural control (Howells et al., 2011), increases the demand for CNS activity to generate protective muscle activity (Palmieri et al., 2005), and induces neuroplastic changes in CNS structure and function (Needle et al., 2024). Loss of proprioceptive input from ACL mechanoreceptors (i.e. Pacinian corpuscles, Ruffini endings, Golgi organs, and free nerve endings) exacerbates joint instability and induces compensatory neuromuscular strategies, including altered muscle activation patterns and increased co-contraction (Criss et al., 2021; Di Giminiani et al., 2023). However, these compensations may reduce the ability to respond to unexpected perturbations (Needle et al., 2017), which may lead to increased postural sway in individuals considered ready to return to sport competition (La Greca et al., 2025a).

In this context, whole-body vibration (WBV) has been suggested as an alternative form of physical exercise with the potential to enhance neuromuscular function (Cardinale and Bosco, 2003; Luo et al., 2005) in healthy individuals (Krause et al., 2019a; Ritzmann et al., 2014) and specific populations, including the elderly (Bogaerts et al., 2007) and patients with neurological disorders (Krause et al., 2019b; La Greca et al., 2025b; Tankisheva et al., 2014). Additionally, it is considered a safe and effective method to accelerate rehabilitation (Fu et al., 2013). Sinusoidal oscillations transmitted by a vibrating platform provide a strong proprioceptive stimulus (Cardinale and Bosco, 2003). They quickly activate sensory pathways, such as muscle spindles (Ribot-Ciscar et al., 1998), joint mechanoreceptors (Pollock et al., 2011), and the vestibular system (Suvorov et al., 1989). Such stimulation may induce acute corticospinal changes (Rigoni et al., 2023) and hormonal responses (Di Giminiani et al., 2020; Gyulai et al., 2013), contributing to rapid adjustments in postural control (Rigoni et al., 2023).

Conflicting results have been reported in chronic studies that evaluate WBV after ACL-R. While some longitudinal interventions have reported improvements in proprioception and postural stability (Fu et al., 2013; Moezy et al., 2008), others have found no benefits despite gains in hamstring muscle strength (Pistone et al., 2016). Recent systematic reviews have confirmed heterogeneity (Qiu et al., 2022; Rowe et al., 2022) due to differences in WBV protocols, such as the use of fixed frequencies (between 20 and 50 Hz) and intervention durations (between 3 and over 12-weeks). Participant characteristics and the utilization of different assessment methodologies introduce additional variability, which restricts the comparability of studies. To better optimize training process, it is imperative to comprehend the acute neuromuscular and postural responses to WBV, given the heterogeneity and conflicting findings reported in chronic studies. At present, there is only one study that has investigated the acute effects of WBV on postural control in ACL-R (Da Costa et al., 2019). However, did not report any significant changes.

In the latter study, the applied WBV workload (~20 g) was relatively high in comparison to the values commonly reported in the literature (Cardinale and Bosco, 2003), particularly as it was imposed during a single-leg support in individuals still undergoing rehabilitation. Thus, the neuromuscular responses may have been impaired by the inhibitory afferent input (Di Giminiani et al., 2015; Roll et al., 1989), which could partially explain the absence of torque and postural sway changes that were observed. Therefore, in the current study, we implemented a progressive workload (from 0.18 g to 8.40 g) to more effectively stimulate the neuromuscular system. In addition, the neuromuscular activation was recorded in the leg muscles. The purpose of the current study was to examine the acute effects of WBV on body sway, synchronised with surface electromyographic activity of the lower limb in ACL-R athletes ready to return to sports competition and in healthy athletes. The acute effects of WBV were investigated in both static and dynamic balance conditions. We hypothesized that ACL-R athletes would exhibit altered postural sway, and changes in neuromuscular activation of the operated leg following acute exposure to WBV exercise.

2. Methods

2.1. Participants

Twenty-seven regional/national level athletes (skiers, soccer, rugby, volleyball, and basketball players) voluntarily participated in this study. Participants formed two groups: 13 individuals with ACL-R (3 females; age: 24.5 ± 2.7 years; height: 1.78 ± 0.09 m; body mass: 77.0 ± 10.3 kg; BMI: 24.1 ± 2.2 kg/m^2; leg dominance: 11 right, operated leg is dominant: 9), and 14 matched healthy controls (HC) (3 females; age: 25.4 ± 3.4 years; height: 1.77 ± 0.06 m; body mass: 77.9 ± 14.7 kg; BMI: 24.8 ± 4.1 kg/m^2; leg dominance: 12 right). Sample size estimation was performed a priori using G*Power 3.1.9.4 (Heinrich Heine-Dusseldorf University, Düsseldorf, Germany), based on previous study (La Greca et al., 2025a). Assuming a large effect size (ES), $\alpha = 0.05$, power $(1-\beta) = 0.80$, the required simple size was estimated to be 24 participants. All ACL-R participants had undergone unilateral surgery using a semitendinosus/gracilis graft and completed a full rehabilitation protocol (6–9 months). Inclusion criteria were complete functional recovery (≥6-month post-surgery) and full return to sport competition. Rehabilitation was conducted in a NHS-affiliated centre according to the indications of Beynnon et al. (2005). For the HC group, inclusion criteria required no previous ligament or meniscal injuries. Exclusion criteria for both groups included current or previous neurological injuries, neuromuscular disorder, herniated disks, arrhythmias, epilepsies, or comorbidities affecting motor function. Participants were instructed to avoid strenuous activity and alcohol for at least 24 h before testing and tobacco or caffeine for at least 3 h.

2.2. Experimental procedure

A two-group parallel design with repeated measures was used. Assessments were conducted at the Biomechanics Laboratory of the University of L'Aquila. The study was approved by the Internal Review Board (Protocol n 33/2022), and all participants provided written informed consent. Each participant attended two laboratory sessions. During the first session, participants were familiarised with experimental procedures, including postural control assessments (double-leg and single-leg) and the isometric half-squat position required for the WBV exercise, performed in the second session. The second session, performed 48 h later, involved the experimental protocol (Fig. 1). Postural control was assessed in random order under different conditions (single-leg and double-leg, static and dynamic) while bilateral sEMG activity of leg muscle was recorded. After the initial assessment, participants completed seven sets of WBV exercise, followed by an immediate post-intervention postural control reassessment under the same conditions in a new random order. Testing was performed between 9:30 and 11:30 a.m. to minimise circadian rhythm effects.

2.3. Postural control assessment

Postural control was assessed by measuring body sway during upright standing using a force platform (Muscle-Lab 4000e, Ergotest Technology, Langesund, Norway). A standardised visual reference was provided by white walls placed 1.50 m in front and to the sides of the platform, and a red square (1 cm^2) positioned at eye level. Body sway was evaluated under randomised conditions: double-leg (static and dynamic) with open eyes (OE) and closed eyes (CE); single-leg (static and dynamic) with OE only. During OE conditions, participants were instructed to fixate on the red square. Foot placement was marked on the

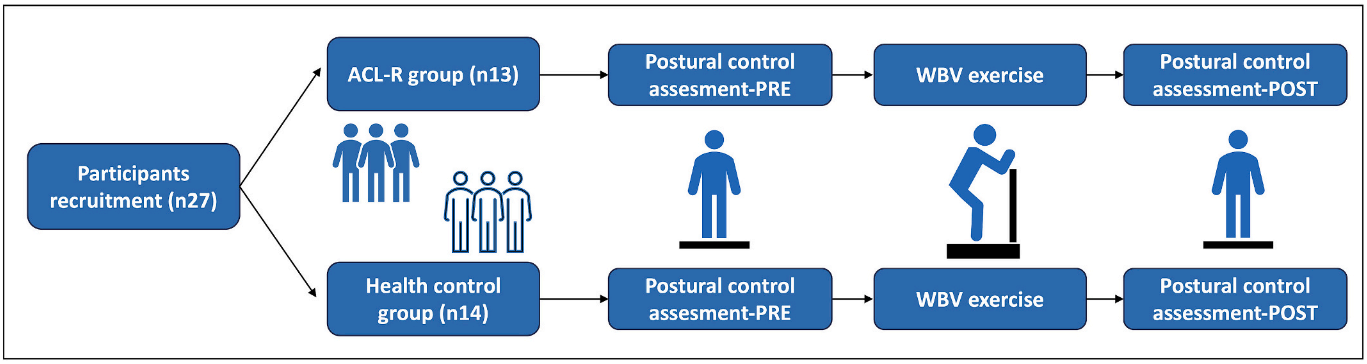

Fig. 1. Flow diagram of the experimental procedure.

force platform to ensure consistent positioning. In double-leg the forefeet were externally rotated (∼30°), with an intermalleolar distance

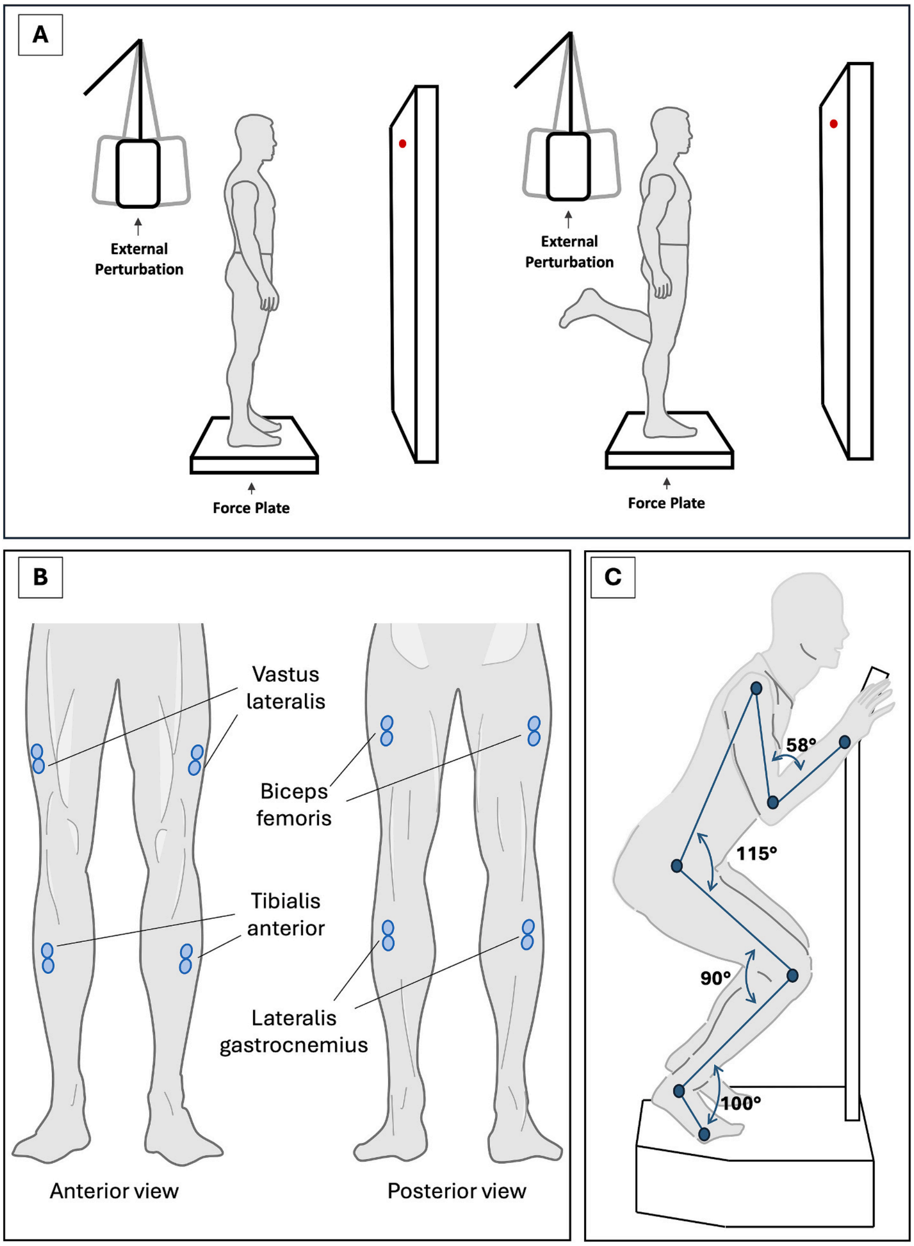

Fig. 2. Experimental setup. (A) Assessment of body sway in dynamic upright standing conditions double-leg and single-leg; (B) Placement areas for sEMG electrodes on the muscles of the lower limbs; (C) Body position assumed by the participant on the vibration platform.

of ~1.5 cm. In single-leg the supporting foot was positioned at the centre of the platform, while the contralateral leg was flexed at 90° (femur–tibia axis). Each trial lasted 30 s, with participants standing still and arms relaxed alongside the body. Dynamic conditions were induced by controlled perturbations delivered to the upper back using a pendulum system individualised to each participant's height (Fig. 2A) (Di Giminiani et al., 2024; La Greca et al., 2025b). The mass of the pendulum was about 3.5% of the participants' body mass. This system has demonstrated high to excellent reliability (ICC 0.70–0.95) (La Greca et al., 2025a). Force plate data were collected at 100 Hz, and body sway was quantified by centre of pressure (CoP) displacement. Medio-lateral (M-L) and anterior-posterior (A-P) CoP displacements were analysed. In static conditions, data from the full 30-s trial were considered. In dynamic conditions, perturbations were applied to capture the responses occurring within the first seconds after perturbation onset (Colebatch et al., 2016), three 1.5-s time windows were extracted, each triggered by the onset of the change in ground reaction force induced by the perturbation. Postural sway data were synchronised with surface electromyography (sEMG) signals recorded from the leg muscles.

2.4. Synchronised sEMG activity

The sEMG was recorded using triode electrodes (T3402M, Thought Technology Ltd., Montreal, Canada) from the vastus lateralis, biceps femoris, tibialis anterior and lateralis gastrocnemius muscles (Fig. 2B). Signals were collected bilaterally from the operated leg (OL) non-operated leg (N-OL) in the ACL-R group, and from dominant leg (DL), non-dominant leg (N-DL) for CG. Electrodes were placed according to SENIAM guidelines (Hermens et al., 2000). To minimise skin impedance (<5 kΩ), the skin was shaved, lightly abraded, and cleaned with alcohol. Electrodes and cables were secured with an elastic band (Flexa Elast, Pic Solution, Pikdare S.p.A.) to reduce motion artefacts. Raw EMG signal were acquired using the Muscle Lab 4000e system (Ergotest-Innovation, Porsgrunn, Norway), preamplified, and band-pass filtered (voltage supply ±5 VDC; input impedance 2 GΩ; common-mode rejection rate 100 dB; input noise level 3 μV_{CC} at 1 kHz; output impedance ≤10 Ω; output voltage ±4 V; gain at 100 Hz: 1000; band-pass filter 8–1200 Hz, 3 dB cut-off). The raw EMG was converted to an RMS signal using a hardware circuit network that computed the true root-mean-square level according to the standards (International Society of Electrophysiology and Kinesiology, **https://isek.org/resources/**). The RMS conversion circuit had a frequency response (typically) of ±3 dB, a bandwidth 450 kHz, an averaging constant 100 ms, conversion accuracy of ±0.5%. The RMS signal was sampled at 100 Hz using a 16-bit A/D converter. The $sEMG_{RMS}$ values were normalized for each muscle its own $sEMG_{RMS}$ peak recorded during the no-vibration condition (isometric position on the plate without vibration) for each participant (Di Giminiani et al., 2015). The sEMG data were analysed using the same windows adopted for body sway analysis: the entire 30-s trial for static condition and three 1.5-s windows at perturbation onset for dynamic conditions.

2.5. Whole-body vibration intervention

The participants assumed an upright isometric high-squat position with raised heels and a forward-tilted trunk (elbow angle = 58°, hip angle = 115°, knee angle = 90° and ankle angle = 100°) (Fig. 2C) (Di Giminiani et al., 2013) on a vertical vibrating platform (Bosco System, Nemes Lsb, Rieti, Italy). Participants were allowed to lightly place their hands on the bar for safety in case of balance loss; however, they were instructed not to apply gripping force or use the bar for weight support. Each participant performed seven WBV trials under the following condition: isometric (0.0 g), 0.18, 0.30, 1.10, 1.90, 5.70 and 8.40 g, (g is the Earth's gravitational field; 9.81 $m \cdot s^{-2}$). Each trial lasted 30-s, with 2-min of rest between trials. Foot positions were marked on the platform to ensure consistent placement across trials.

2.6. Statistical analysis

Statistical analyses were performed using the Statistics and Machine Learning Toolbox in MATLAB (R2024b; MathWorks, Natick, MA, USA). Data normality was assessed using the Shapiro-Wilks's W test. As variables were not normally distributed, non-parametric tests were applied. Baseline anthropometric differences between groups were analysed using the Mann-Whitney *U* test. Within each group, acute effect of WBV exercise on body sway and synchronised sEMG activity were analyses using the Wilcoxon signed-rank test (two-tailed). Between-groups differences in pre–post change scores (Δ%) were analysed using the Mann–Whitney U test to compare the magnitude of acute WBV effects. No significant differences were found in baseline anthropometric variables (age, height, body mass, BMI), confirming that the groups were well-matched. Statistical significance was set at $\alpha = 0.05$. Effect size was calculated as $r = z/\sqrt{N}$. and interpreted as small at $r < 0.3$, moderate at $0.3 < r < 0.5$, and large at $r > 0.5$ (Cohen, 2013).

3. Results

3.1. Static balance measures

Following WBV, no significant changes in body sway path (A-P and M-L CoP displacement) were observed in ACL-R group across all condition ($p > 0.05$). Conversely, healthy athletes exhibited a significant reduction in M-L and A-P sway during the single-leg non-dominant condition ($p = 0.006$, ES = 0.73; $p = 0.030$, ES = 0.58, respectively) (Table 1).

Between-group comparisons of pre-post change scores (Δ%) revealed no statistically significant differences ($p > 0.05$). Nevertheless, a moderate between-group effect size was observed for static M-L sway during single-leg on the non-operated leg/non-dominant leg (ES = 0.38), reflecting a greater sway reduction in the HC group (Table 2).

3.2. Dynamic balance measures

After WBV, the ACL-R athletes showed a significant increase in M-L CoP displacement during double-leg with CE ($p = 0.027$, ES = 0.59). No significant changes were observed in the healthy athletes across condition ($p > 0.05$) (Table 1).

Between-group comparisons of the pre-post changes scores (Δ%) for dynamic balance parameters revealed no significant differences ($p > 0.05$). However, a moderate between-group effect size was observed during the single-leg dynamic condition in the A-P direction on the non-dominant leg (ES = 0.34) (Table 2).

3.3. Neuromuscular response during static balance

In the ACL-R athletes, WBV acutely reduced the biceps femoris sEMG activity in the operated leg during double-leg with CE ($p = 0.041$, ES = 0.55) and OE ($p = 0.033$, ES = 0.57) (Fig. 3). A reduction in vastus lateralis sEMG activity was also observed during the double-leg CE condition ($p = 0.015$, ES = 0.65) (Supplementary Table S1). In the HC athletes, vastus lateralis sEMG activity decreased in the dominant leg during the double-leg CE condition ($p = 0.033$, ES = 0.57). Moreover, during single-leg condition, significant reductions were observed in tibialis anterior ($p = 0.028$, ES = 0.59) and lateral gastrocnemius ($p = 0.047$, ES = 0.53) sEMG activity of the non-dominant leg (Supplementary Table S2).

Between-group comparisons of pre-post change scores (Δ%) for sEMG activity during static tasks showed no statistically significant differences ($p > 0.05$) (Supplementary Table S3).

3.4. Neuromuscular response during dynamic balance

In the ACL-R athletes, biceps femoris sEMG activity was significantly

Table 1
Body sway path values (mean ± SD) during static conditions, pre- and post-WBV exercise, in anterior cruciate ligament reconstruction (ACL-R) and healthy controls.

Variables	Pre	Post	p	ES
ACL-R athletes				
Static Double-leg OE M-L (mm)	308.8 ± 104.4	314.56 ± 96.4	0.893	0.04
Static Double-leg OE A-P (mm)	550.3 ± 186.3	611.9 ± 158.1	0.893	0.04
Static Double-leg CE M-L (mm)	338.7 ± 114.6	366.86 ± 96.4	0.146	0.39
Static Double-leg CE A-P (mm)	658.4 ± 226.3	611.9 ± 158.1	0.455	0.20
Static Single-leg operated leg M-L (mm)	850.2 ± 165.1	888.2 ± 312.5	0.388	0.23
Static Single-leg operated leg A-P (mm)	1145.5 ± 409.2	1144.9 ± 589	0.638	0.13
Static Single-leg non-operated leg M-L (mm)	867.7 ± 133.2	877.8 ± 198.2	0.388	0.23
Static Single-leg non-operated leg A-P (mm)	1194.7 ± 314	1179.8 ± 311.2	0.735	0.09
Dynamic Double-leg OE M-L (mm)	102.8 ± 54.7	143.1 ± 56.8	0.146	0.39
Dynamic Double-leg OE A-P (mm)	362.5 ± 74.9	386.2 ± 96.8	0.305	0.27
Dynamic Double-leg CE M-L (mm)	111.5 ± 48.6	175.3 ± 48.5	0.027*	0.59
Dynamic Double-leg CE A-P (mm)	385.6 ± 88.1	415.0 ± 122.3	0.542	0.16
Dynamic Single-leg operated leg M-L (mm)	130.7 ± 36.5	147.0 ± 48.8	0.191	0.35
Dynamic Single-leg operated leg A-P (mm)	316.6 ± 59.9	350.6 ± 90.9	0.060	0.50
Dynamic Single-leg non-operated leg M-L (mm)	124.2 ± 27.9	130.2 ± 35.4	0.497	0.18
Dynamic Single-leg non-operated leg A-P (mm)	308.3 ± 87.9	314.8 ± 91.5	0.988	0.01
Healthy controls				
Static Double-leg OE M-L (mm)	242.6 ± 56.1	240.4 ± 63.3	0.391	0.23
Static Double-leg OE A-P (mm)	350.6 ± 145.9	324.5 ± 121.3	0.670	0.11
Static Double-leg CE M-L (mm)	271.7 ± 81.2	317.6 ± 87.6	0.062	0.50
Static Double-leg CE A-P (mm)	422.4 ± 176.2	470.1 ± 163.1	0.345	0.25
Static Single-leg dominant leg M-L (mm)	930.2 ± 245.4	855.6 ± 175.05	0.216	0.33
Static Single-leg dominant leg A-P (mm)	1005.6 ± 335.4	889.7 ± 266.5	0.080	0.47
Static Single-leg non-dominant leg M-L (mm)	940.4 ± 214.4	822.1 ± 219.1	0.006*	0.73
Static Single-leg non-dominant leg A-P (mm)	1082.7 ± 318.9	950.7 ± 281.6	0.030*	0.58
Dynamic Double-leg OE M-L (mm)	86.6 ± 58.9	89.1 ± 60.6	0.463	0.20
Dynamic Double-leg OE A-P (mm)	271.1 ± 198.2	271.2 ± 180.5	0.326	0.26
Dynamic Double-leg CE M-L (mm)	107.9 ± 70.0	111.3 ± 84.7	0.424	0.21
Dynamic Double-leg CE A-P (mm)	269.0 ± 178.4	269.8 ± 209.4	0.626	0.13
Dynamic Single-leg dominant leg M-L (mm)	108.8 ± 42.4	118.5 ± 56.8	0.245	0.31
Dynamic Single-leg dominant leg A-P (mm)	303.8 ± 244.3	269.2 ± 186.7	0.542	0.16
Dynamic Single-leg non-dominant leg M-L (mm)	117.6 ± 55.5	110.7 ± 62.6	0.808	0.06
Dynamic Single-leg non-dominant leg A-P (mm)	261.4 ± 139.1	264.2 ± 181.4	0.952	0.02

Abbreviations: anterior cruciate ligament reconstruction (ACL-R); open eyes (OE); closed eyes (CE); medio-lateral (M-L); anterior-posterior (A-P); * Significant difference between pre- and post-WBV exercise, p ≤ 0.05; r effect size (ES).

Table 2
Between-group comparisons of Δ% (post–pre) sway path values (mean ± SD) in medio-lateral and anteroposterior directions during static and dynamic balance conditions.

Static body sway				
Variables	**ACL-R**	**HC**	**p**	**ES**
Double-leg OE M-L (mm)	5.7 ± 126.7	−2.2 ± 43.4	0.797	0.05
Double-leg OE A-P (mm)	−2.8 ± 117.8	−26.1 ± 112.5	0.644	0.09
Double-leg CE M-L (mm)	28.1 ± 86.7	46.9 ± 81.7	0.959	0.01
Double-leg CE A-P (mm)	−46.6 ± 197.0	47.7 ± 122.5	0.305	0.20
Single-leg operated leg/dominant leg M-L (mm)	38.1 ± 254.1	−74.63 ± 173.0	0.572	0.12
Single-leg operated leg/dominant leg A-P (mm)	−0.6 ± 457.6	−115.9 ± 196.1	0.383	0.18
Single-leg non-operated leg/ non-dominant leg M-L (mm)	10.1 ± 186.6	−117.5 ± 121.0	0.057	0.38
Single-leg non-operated leg/ non-dominant leg A-P (mm)	−14.9 ± 166.5	−132.1 ± 193.2	0.151	0.29
Dynamic body sway				
Variables	**ACL-R**	**HC**	**p**	**ES**
Double-leg OE M-L (mm)	13.9 ± 31.8	2.6 ± 27.6	0.572	0.12
Double-leg OE A-P (mm)	−28.1 ± 108.2	0.1 ± 203.7	0.111	0.32
Double-leg CE M-L (mm)	30.2 ± 39.6	3.4 ± 32.2	0.123	0.30
Double-leg CE A-P (mm)	29.5 ± 102.2	0.8 ± 72.4	0.329	0.20
Single-leg operated-leg/ dominant-leg M-L (mm)	16.3 ± 40.7	9.7 ± 26.9	0.719	0.07
Single-leg operated-leg/ dominant-leg A-P (mm)	33.9 ± 58.0	−33.7 ± 135.1	0.091	0.34
Single-leg non-operated leg/ non-dominant leg M-L (mm)	5.9 ± 33.5	−6.9 ± 43.5	0.441	0.16
Single-leg non-operated leg/ non-dominant leg A-P (mm)	29.1 ± 241.9	2.8 ± 72.5	0.608	0.11

Abbreviations: anterior cruciate ligament reconstruction (ACL-R) group; healthy control (HC) group; open eyes (OE); closed eyes (CE); medio-lateral (M-L); anterior-posterior (A-P); r effect size (ES).

reduced during the dynamic double-leg condition with OE ($p = 0.032$, ES = 0.57) (Fig. 3). No other significant changes were observed ($p > 0.05$) (Supplementary Table S4). The healthy athletes, vastus lateralis activity decreased in the dominant leg during dynamic the double-leg OE condition ($p = 0.023$, ES = 0.61). During the dynamic single-leg condition, tibialis anterior and lateral gastrocnemius sEMG activity decreased significantly in both dominant ($p = 0.048$, ES = 0.52; $p = 0.041$, ES = 0.55) and non-dominant legs ($p = 0.046$, ES = 0.53; $p = 0.013$, ES = 0.66) (Supplementary Table S5).

Between-group comparisons of pre-post change scores (Δ%) the sEMG activity for dynamic conditions revealed no significant differences ($p > 0.05$). However, the largest moderate effect size was observed for the biceps femoris during the double-leg OE condition (ES = 0.38) indicating a greater reduction in the ACL-R group. A moderate effect size was also found for the lateral gastrocnemius during the double-leg CE condition on the non-operated leg/non-dominant leg (ES = 0.38) (Table 3).

4. Discussion

The present study investigated the acute effects of WBV exercise on postural control and neuromuscular activation in athletes following ACL-R and healthy controls. The results supported our initial hypothesis, showing group-specific responses in both balance condition and muscle activity.

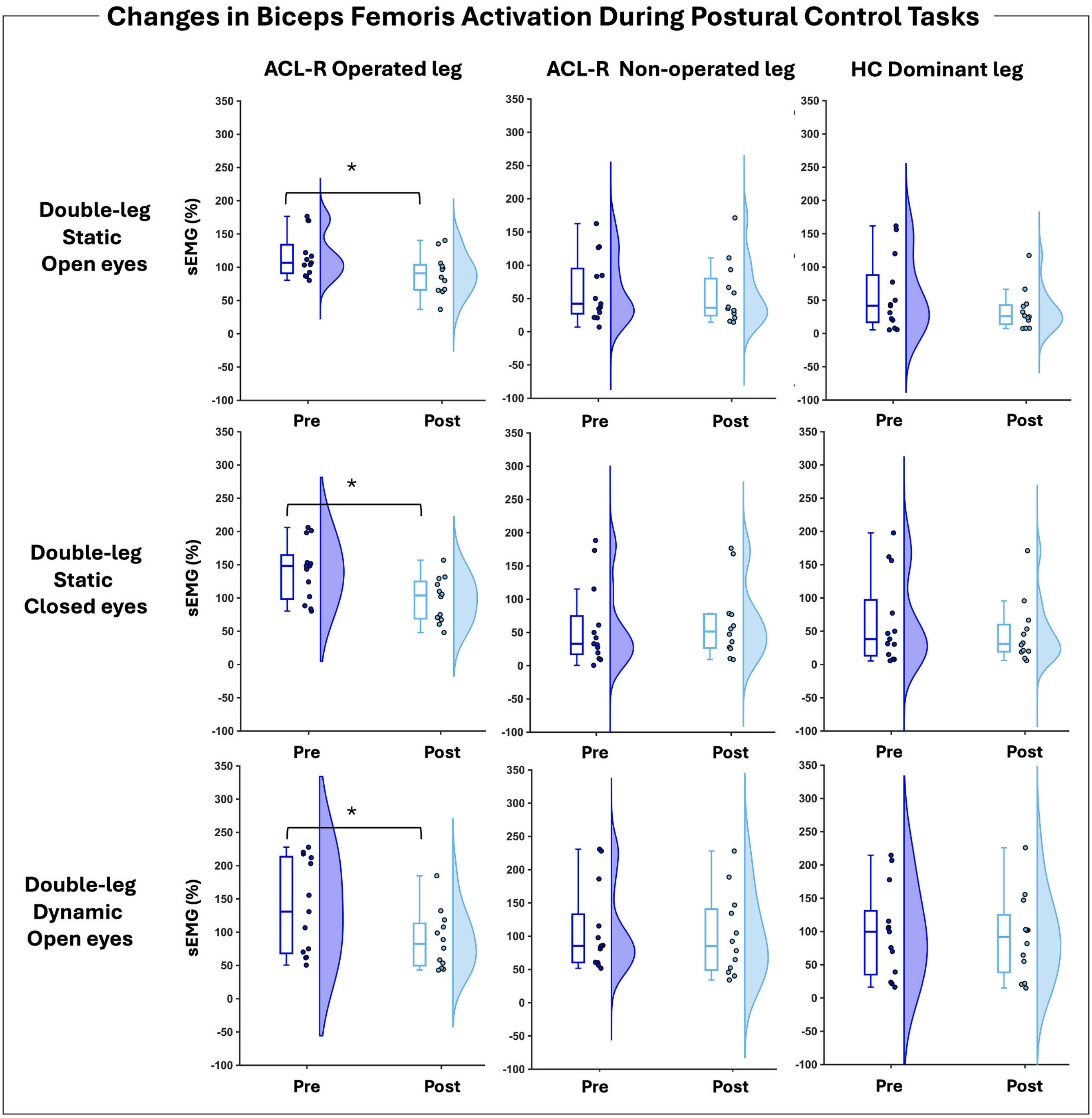

Fig. 3. Changes in Biceps Femoris sEMG activity during postural control under different conditions, pre- and post-WBV exercise, in the ACL-R group and health control (HC) group.

In healthy athletes, WBV improved postural control during static condition, particularly in single-leg tasks, as indicated by reduced CoP path length and decreased ankle muscle activation (tibialis anterior and lateral gastrocnemius) in the non-dominant leg. During dynamic conditions, WBV did not significantly reduce CoP displacement; however, decreased ankle muscles activations was observed in both limbs. These findings are consistent with previous studies showing that WBV can induce the maintenance or enhancement of balance performance by optimising neuromuscular strategies. Krause et al. (2019b) reported reduced H-reflex excitability and shank co-contraction after WBV during dynamic single-leg condition, while Maslova et al. (2024) reported that WBV induced a modulation of proprioceptive integration and improve balance in young healthy adults. Similarly, Rigoni et al. (2023) showed that acute WBV induces sensorimotor recalibration during static balance, leading to changes in neuromuscular activation, postural control, and corticomuscular coupling. Together, these findings indicate that healthy athletes respond to WBV through optimisation of neuromuscular activation strategies.

In contrast, ACL-R athletes showed no significant changes in CoP displacement during static balance. However, during double-leg static condition, WBV induced a reduction in proximal muscles activity, particularly the biceps femoris of the operated leg, observed in both static and dynamic condition. Despite this neuromuscular modulation, ACL-R athletes exhibited an increase in medio-lateral CoP sway during

Table 3

Between-group comparisons (mean ± SD) of Δ% (post–pre) normalized sEMG activity values (mean ± SD) during dynamic balance conditions.

Variables	Operated/Dominant leg				Non-Operated/Non-Dominant leg			
Double-leg dynamic CE	**ACL-R**	**HC**	**p**	**ES**	**ACL-R**	**HC**	**p**	**ES**
VL (%)	5.2 ± 14.3	−8.3 ± 15.9	0.151	0.29	5.3 ± 18.5	−1.5 ± 8.2	0.757	0.06
BF (%)	−43.1 ± 132.5	−20.1 ± 60.4	0.792	0.06	−6.2 ± 82.89	34.7 ± 54.7	0.212	0.27
TA (%)	77.8 ± 196.5	−28.7 ± 105.7	0.259	0.32	−28.5 ± 182.5	−5.9 ± 28.2	0.804	0.08
LG (%)	−17.6 ± 66.9	1.6 ± 31.2	0.472	0.15	−25.6 ± 77.7	14.0 ± 39.1	0.057	0.38
Double-leg dynamic OE	**ACL-R**	**HC**	**p**	**ES**	**ACL-R**	**HC**	**p**	**ES**
VL (%)	−0.4 ± 16.1	−9.3 ± 12.8	0.342	0.19	−0.8 ± 19.8	−3.2 ± 10.2	0.837	0.04
BF (%)	−61.7 ± 116.7	−4.8 ± 7.9	0.087	0.37	−19.9 ± 97.2	−8.5 ± 78.7	0.733	0.08
TA (%)	111.8 ± 318.7	−37.5 ± 97.7	0.383	0.26	13.8 ± 255.1	−14.4 ± 30.7	0.804	0.09
LG (%)	−22.7 ± 94.3	3.3 ± 27.6	0.472	0.15	−30.2 ± 73.7	−4.9 ± 49.9	0.719	0.07

Single-leg dynamic OL/DL	**ACL-R**	**HC**	**p**	**ES**
VL (%)	6.1 ± 22.1	−0.3 ± 8.7	0.441	0.15
BF (%)	−5.3 ± 43.7	−30.2 ± 52.3	0.324	0.22
TA (%)	−24.9 ± 191.9	−287.7 ± 492.3	0.259	0.32
LG (%)	−28.2 ± 79.3	−34.8 ± 72.6	0.382	0.18
Single-leg dynamic N-OL/N-DL	**ACL-R**	**HC**	**p**	**ES**
VL (%)	−4.2 ± 16.4	−6.2 ± 27.6	0.538	0.13
BF (%)	−27.3 ± 93.0	−5.9 ± 19.9	0189	0.29
TA (%)	−237.2 ± 314.3	−287.8 ± 329.6	0.901	0.05
LG (%)	−18.6 ± 86.7	−27.5 ± 53.1	0.199	0.26

Abbreviations: anterior cruciate ligament reconstruction (ACL-R) group; healthy control (HC) group; open eyes (OE); closed eyes (CE); operated leg (OL); non-operated leg (N-OL); dominant leg (DL); non-dominant leg (N-DL); vastus lateralis (VL); biceps femoris (BF); tibialis anterior (TA); lateralis gastrocnemius (LG); r effect size (ES).

double-leg dynamic condition with eyes closed, suggesting altered postural response to WBV exercise. This behaviour suggests a dissociation between neuromuscular modulation and postural control outcomes. This indicate that acute neuromuscular changes alone may be insufficient to compensate for persistent sensorimotor deficits after ACL-R (Criss et al., 2021; Needle et al., 2017). The increase in medio-lateral sway observed in ACL-R athletes during dynamic tasks, particularly with closed eyes, reflects deficits when visual input is removed. This observation aligns with the concept of “sensory reweighting” described by Kim et al. (2017), whereby ACL-R athletes rely more on visuospatial information to compensate the reduced knee proprioception. This finding may be interpreted within the framework of postural control models in which sensory integration is less effective when a sensory channel is unavailable (Kuo et al., 1998). In addition, medio-lateral stability requires greater cortical involvement than anterior-posterior stability (Slobounov et al., 2008), and proprioceptive deficits may limit the use of somatosensory pathways (Kapreli et al., 2009). Previous studies in this population have reported heterogeneous responses to WBV; some of them showing improvements in proprioception and balance (Fu et al., 2013; Moezy et al., 2008) and others reporting partial benefits (Qiu et al., 2022; Rowe et al., 2022). The present findings seem to align with the latter, supporting the notion that altered afferent integration may limit the translation of acute neuromuscular responses into improved postural stability.

Within this context, muscle modulation provides insight into these neuromuscular adjustments. The biceps femoris appear particularly responsive to WBV stimulation. In uninjured individuals, WBV has been shown to acutely reduce hamstring activation (Chaltron et al., 2023), suggesting a high sensitivity of this muscle to WBV stimuli. In ACL-R athletes, hamstring over-recruitment of the operated leg is commonly reported as a compensatory strategy to enhance knee joint stability (Fu et al., 2013; Johnson et al., 2018; Moezy et al., 2008) and may persist despite rehabilitation (Di Giminiani et al., 2023). Consistently, La Greca et al. (2025a) observed greater biceps femoris activity during balance in fully rehabilitated ACL-R athletes compared with healthy controls. The reduction in biceps femoris activation observed following WBV may reflect a beneficial attenuation of this over-activation, potentially indicating a favourable neuromuscular recalibration (Rigoni et al., 2023), although its translation into functional stability remains unclear.

Between-group comparisons of delta scores revealed no statistically significant differences in CoP sway or EMG activity. Nevertheless, several outcomes showed moderate effect sizes, suggesting physiologically relevant trends that may not be reflected by null hypothesis testing. These included medio-lateral sway during dynamic single-leg condition (ES = 0.38), biceps femoris activity of the operated leg during double-leg dynamic condition (ES = 0.37), and lateral gastrocnemius activity of the non-operated leg during double-leg dynamic with eyes closed condition (ES = 0.39). As these muscles play a key role in postural stabilisation, the observed pattern may reflect persistent neuromuscular asymmetries or compensatory strategies in ACL-R individuals (Criss et al., 2021; Needle et al., 2017). Although not statistically conclusive, these findings indicate a modest intergroup differences that may become more evident under challenging postural conditions, such as dynamic tasks requiring greater sensorimotor integration to maintain balance. This pattern appears consistent with sensorimotor deficits previously reported in ACL-R individuals (Criss et al., 2021). The lack of statistical significance is likely related to the limited sample size of this preliminary study, which may reduce statistical power and increase the risk of type II error. In this context, effect sizes provide complementary insight into neuromechanically meaningful differences that may not reach conventional significance thresholds (Cohen, 2013).

These group-specific responses may explain the different effects observed across conditions. In healthy athletes, greater improvements during single-leg tasks suggest that WBV-induced sensorimotor recalibration (Rigoni et al., 2023) becomes more evident as postural demands increase, whereas in less challenging double-leg conditions the effect is mainly reflected in optimised muscle activity. In contrast, in ACL-R athletes, even double-leg conditions, particularly with eyes closed, appear to represent a meaningful sensorimotor challenge, as suggested by reduced biceps femoris activity without corresponding improvements in postural control, consistent with persistent somatosensory deficits (Criss et al., 2021). Single-leg tasks showed a similar but attenuated pattern, with smaller, non-significant changes, suggesting a limited responsiveness to a single WBV session under higher task demands.

Taken together, these findings highlight group specific acute responses in postural control and neuromuscular activation following a WBV session, with potential clinical implications. Clinically, WBV may serve as a useful adjunct tool in rehabilitation, potentially reducing hamstring over-activity in ACL-R athletes. However, these results should be considered within the context of the study's limitations, including that only acute responses were assessed. As a preliminary investigation, the sample size may have limited statistical power, although the inclusion of competitive athletes with similar characteristics strengthens internal validity. These results cannot be generalised to all ACL-R athletes, as only those with a semitendinosus/gracilis graft were included. Neuromuscular activity was assessed via EMG amplitude, which, while clinically interpretable, may not fully capture temporal and spectral complexity, referring to the frequency content and variability of muscle activation patterns. Complementary biomechanical measures, such as kinematics, were not included. Nevertheless, the rigorous experimental design and simultaneous assessment of balance and sEMG provide novel insights into the acute neuromechanical effects of WBV in ACL-R athletes. Future research should involve larger samples, integrated kinematic analysis, and longitudinal designs to confirm these preliminary findings and determine whether WBV induces long-term neuromuscular and postural adaptations. Finally, individualised vibration loading, as suggested by Di Giminiani et al. (2015), may enhance intervention protocols and optimize neuromuscular responses during postural control after ACL-R.

5. Conclusion

This preliminary study suggests that WBV acutely determines different neuromechanical responses on postural control in ACL-R and healthy athletes. In healthy athletes, WBV promoted a reduction in distal muscle activation with improvements in single-leg balance performance, suggesting optimisation of muscle activation patterns. In ACL-R athletes it induced neuromuscular changes, characterised by a reduction in biceps femoris activity in the operated leg without improvements in postural stability, suggesting sensorimotor recalibration. These findings highlight the potential of WBV exercise as a complementary rehabilitation tool, while emphasising the need for larger, longitudinal studies to determine its long-term clinical relevance.

CRediT authorship contribution statement

Stefano La Greca: Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Stefano Marinelli:** Software, Methodology, Formal analysis, Data curation. **Francesco Farina:** Software, Methodology, Formal analysis. **Riccardo Di Giminiani:** Writing – review & editing, Validation, Supervision, Project administration, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used the Language Tool (LT) Premium in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

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References

Beynnon, B.D., Uh, B.S., Johnson, R.J., Abate, J.A., Nichols, C.E., Fleming, B.C., Poole, A. R., Roos, H., 2005. Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, Double-Blind comparison of programs administered over 2 different time intervals. Am. J. Sports Med. 33, 347–359. https://doi.org/10.1177/0363546504268406.

Bogaerts, A., Verschueren, S., Delecluse, C., Claessens, A.L., Boonen, S., 2007. Effects of whole body vibration training on postural control in older individuals: A 1 year randomized controlled trial. Gait Posture 26, 309–316. https://doi.org/10.1016/j.gaitpost.2006.09.078.

Cardinale, M., Bosco, C., 2003. The use of vibration as an exercise intervention. Exerc. Sport Sci. Rev. 31, 3–7. https://doi.org/10.1097/00003677-200301000-00002.

Chaltron, C., Sherman, D.A., Pamukoff, D.N., Bazett-Jones, D.M., Glaviano, N.R., Norte, G.E., 2023. Whole-body vibration reduces hamstrings neuromuscular function in uninjured individuals. Phys. Ther. Sport 60, 17–25. https://doi.org/10.1016/j.ptsp.2023.01.004.

Cohen, J., 2013. Statistical Power Analysis for the Behavioral Sciences, 0 ed. Routledge. https://doi.org/10.4324/9780203771587.

Colebatch, J.G., Govender, S., Dennis, D.L., 2016. Postural responses to anterior and posterior perturbations applied to the upper trunk of standing human subjects. Exp. Brain Res. 234, 367–376. https://doi.org/10.1007/s00221-015-4442-2.

Criss, C.R., Melton, M.S., Ulloa, S.A., Simon, J.E., Clark, B.C., France, C.R., Grooms, D.R., 2021. Rupture, reconstruction, and rehabilitation: a multi-disciplinary review of mechanisms for central nervous system adaptations following anterior cruciate ligament injury. Knee 30, 78–89. https://doi.org/10.1016/j.knee.2021.03.009.

Da Costa, K.S.A., Borges, D.T., De Brito Macedo, L., De Almeida Lins, C.A., Brasileiro, J. S., 2019. Whole-body vibration on performance of quadriceps after ACL reconstruction: a blinded randomized controlled trial. J. Sport Rehabil. 28, 52–58. https://doi.org/10.1123/jsr.2017-0063.

Di Giminiani, R., Masedu, F., Tihanyi, J., Scrimaglio, R., Valenti, M., 2013. The interaction between body position and vibration frequency on acute response to whole body vibration. J. Electromyogr. Kinesiol. 23, 245–251. https://doi.org/10.1016/j.jelekin.2012.08.018.

Di Giminiani, R., Masedu, F., Padulo, J., Tihanyi, J., Valenti, M., 2015. The EMG activity–acceleration relationship to quantify the optimal vibration load when applying synchronous whole-body vibration. J. Electromyogr. Kinesiol. 25, 853–859. https://doi.org/10.1016/j.jelekin.2015.09.004.

Di Giminiani, R., Rucci, N., Capuano, L., Ponzetti, M., Aielli, F., Tihanyi, J., 2020. Individualized whole-body vibration: neuromuscular, biochemical, muscle damage and inflammatory acute responses. Dose-Response 18, 155932582093126. https://doi.org/10.1177/1559325820931262.

Di Giminiani, R., Marinelli, S., La Greca, S., Di Blasio, A., Angelozzi, M., Cacchio, A., 2023. Neuromuscular characteristics of unilateral and bilateral maximal voluntary isometric contractions following ACL reconstruction. Biology 12, 1173. https://doi.org/10.3390/biology12091173.

Di Giminiani, R., La Greca, S., Marinelli, S., Attanasio, M., Masedu, F., Mazza, M., Valenti, M., 2024. Locomotion and postural control in young adults with autism spectrum disorders: a novel kinesiological assessment. JFMK 9, 185. https://doi.org/10.3390/jfmk9040185.

Fu, C.L.A., Yung, S.H.P., Law, K.Y.B., Leung, K.H.H., Lui, P.Y.P., Siu, H.K., Chan, K.M., 2013. The effect of early whole-body vibration therapy on neuromuscular control after anterior cruciate ligament reconstruction: a randomized controlled trial. Am. J. Sports Med. 41, 804–814. https://doi.org/10.1177/0363546513476473.

Gyulai, G., Rácz, L., Di Giminiani, R., Tihanyi, J., 2013. Effect of whole body vibration applied on upper extremity muscles. Acta Physiol. Hung. 100, 37–47. https://doi.org/10.1556/APhysiol.99.2012.005.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10, 361–374. https://doi.org/10.1016/S1050-6411(00)00027-4.

Howells, B.E., Ardern, C.L., Webster, K.E., 2011. Is postural control restored following anterior cruciate ligament reconstruction? A systematic review. Knee Surg. Sports Traumatol. Arthrosc. 19, 1168–1177. https://doi.org/10.1007/s00167-011-1444-x.

Jenkins, S.M., Guzman, A., Gardner, B.B., Bryant, S.A., Del Sol, S.R., McGahan, P., Chen, J., 2022. Rehabilitation after anterior cruciate ligament injury: review of current literature and recommendations. Curr. Rev. Musculoskelet. Med. 15, 170–179. https://doi.org/10.1007/s12178-022-09752-9.

Johnson, A.K., Palmieri-Smith, R.M., Lepley, L.K., 2018. Contribution of neuromuscular factors to quadriceps asymmetry after anterior cruciate ligament reconstruction. J. Athl. Train. 53, 347–354. https://doi.org/10.4085/1062-6050-463-16.

Kapreli, E., Athanasopoulos, S., Gliatis, J., Papathanasiou, M., Peeters, R., Strimpakos, N., Van Hecke, P., Gouliamos, A., Sunaert, S., 2009. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. Am. J. Sports Med. 37, 2419–2426. https://doi.org/10.1177/0363546509343201.

Kim, K.-M., Kim, J.-S., Grooms, D.R., 2017. Stroboscopic vision to induce sensory reweighting during postural control. J. Sport Rehabil. 26. https://doi.org/10.1123/jsr.2017-0035.

Krause, A., Ritzmann, R., Lee, K., Freyler, K., Gollhofer, A., 2019a. Acute neuromuscular modulation enhances postural control after whole-body vibration. Dtsch. Z. Sportmed. 5–13. https://doi.org/10.5960/dzsm.2018.357.

Krause, Anne, Lee, K., Freyler, K., Bührer, T., Gollhofer, A., Ritzmann, R., 2019b. Whole-body vibration impedes the deterioration of postural control in patients with multiple sclerosis. Mult. Scler. Relat. Disord. 31, 134–140. https://doi.org/10.1016/j.msard.2019.03.026.

Kuo, A.D., Speers, R.A., Peterka, R.J., Horak, F.B., 1998. Effect of altered sensory conditions on multivariate descriptors of human postural sway. Exp. Brain Res. 122, 185–195. https://doi.org/10.1007/s002210050506.

La Greca, S., Marinelli, S., Farina, F., Di Giminiani, R., 2025a. An evaluation of postural balance in single-leg and double-leg conditions in patients with reconstruction of the anterior cruciate ligament and healthy controls. Acta kinesiol. 67–79. https://doi.org/10.51371/issn.1840-2976.2025.19.3.8.

La Greca, S., Marinelli, S., Totaro, R., Pistoia, F., Di Giminiani, R., 2025b. Effect of individualized whole-body vibration exercise on locomotion and postural control in a person with multiple sclerosis: a 5-year case report. Appl. Sci. 15, 8351. https://doi.org/10.3390/app15158351.

Luo, J., McNamara, B., Moran, K., 2005. The use of vibration training to enhance muscle strength and power. Sports Med. 35, 23–41. https://doi.org/10.2165/00007256-200535010-00003.

Maslova, O., Shusharina, N., Videnin, A., Pyatin, V., 2024. Integrative function of proprioceptive system in the acute effects of whole body vibration on the movement performance in young adults. Front. Sports Act. Living 6, 1357199. https://doi.org/10.3389/fspor.2024.1357199.

Moezy, A., Olyaei, G., Hadian, M., Razi, M., Faghihzadeh, S., 2008. A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. Br. J. Sports Med. 42, 373–385. https://doi.org/10.1136/bjsm.2007.038554.

Needle, A.R., Lepley, A.S., Grooms, D.R., 2017. Central nervous system adaptation after ligamentous injury: a summary of theories, evidence, and clinical interpretation. Sports Med. 47, 1271–1288. https://doi.org/10.1007/s40279-016-0666-y.

Needle, A.R., Howard, J.S., Downing, M.B., Skinner, J.W., 2024. Neural-targeted rehabilitation strategies to address neuroplasticity after joint injury. J. Athl. Train. 59, 1187–1196. https://doi.org/10.4085/1062-6050-0215.23.

Palmieri, R.M., Weltman, A., Edwards, J.E., Tom, J.A., Saliba, E.N., Mistry, D.J., Ingersoll, C.D., 2005. Pre-synaptic modulation of quadriceps arthrogenic muscle inhibition. Knee Surg. Sports Traumatol. Arthrosc. 13, 370–376. https://doi.org/10.1007/s00167-004-0547-z.

Pistone, E., Laudani, L., Camillieri, G., Cagno, A., Tomassi, G., Macaluso, A., Giombini, A., 2016. Effects of early whole-body vibration treatment on knee neuromuscular function and postural control after anterior cruciate ligament reconstruction: a randomized controlled trial. J. Rehabil. Med. 48, 880–886. https://doi.org/10.2340/16501977-2150.

Pollock, R.D., Provan, S., Martin, F.C., Newham, D.J., 2011. The effects of whole body vibration on balance, joint position sense and cutaneous sensation. Eur. J. Appl. Physiol. 111, 3069–3077. https://doi.org/10.1007/s00421-011-1943-y.

Qiu, J., Ong, M.T.-Y., Leong, H.T., He, X., Fu, S.-C., Yung, P.S.-H., 2022. Effects of whole-body vibration therapy on quadriceps function in patients with anterior cruciate ligament reconstruction: a systematic review. Sports Health. 14, 216–226. https://doi.org/10.1177/19417381211004937.

Ribot-Ciscar, E., Rossi-Durand, C., Roll, J.-P., 1998. Muscle spindle activity following muscle tendon vibration in man. Neurosci. Lett. 258, 147–150. https://doi.org/10.1016/S0304-3940(98)00732-0.

Rigoni, I., Degano, G., Hassan, M., Fratini, A., 2023. Sensorimotor recalibration of postural control strategies occurs after whole body vibration. Sci. Rep. 13, 522. https://doi.org/10.1038/s41598-022-27117-7.

Ritzmann, R., Kramer, A., Bernhardt, S., Gollhofer, A., 2014. Whole body vibration training - improving balance control and muscle endurance. PLoS One 9, e89905. https://doi.org/10.1371/journal.pone.0089905.

Roll, J.P., Vedel, J.P., Ribot, E., 1989. Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp. Brain Res. 76. https://doi.org/10.1007/BF00253639.

Rowe, P.L., Taflan, S., Hahne, A.J., 2022. Does the addition of whole-body vibration training improve postural stability and lower limb strength during rehabilitation following anterior cruciate ligament reconstruction: a systematic review with meta-analysis. Clin. J. Sport Med. 32, 627–634. https://doi.org/10.1097/JSM.0000000000001001.

Slobounov, S., Hallett, M., Cao, C., Newell, K., 2008. Modulation of cortical activity as a result of voluntary postural sway direction: an EEG study. Neurosci. Lett. 442, 309–313. https://doi.org/10.1016/j.neulet.2008.07.021.

Stensdotter, A.-K., Tengman, E., Häger, C., 2016. Altered postural control strategies in quiet standing more than 20 years after rupture of the anterior cruciate ligament. Gait Posture 46, 98–103. https://doi.org/10.1016/j.gaitpost.2016.02.020.

Suvorov, G.A., Schajpak, E.J., Kurerov, N.N., Seidel, H., Blüthner, R., Schuster, U., Erdmann, U., 1989. The effect of low-frequency whole-body vibration on the vestibular apparatus. Z. Gesamte Hyg. 35, 496–498.

Tankisheva, E., Bogaerts, A., Boonen, S., Feys, H., Verschueren, S., 2014. Effects of intensive whole-body vibration training on muscle strength and balance in adults with chronic stroke: a randomized controlled pilot study. Arch. Phys. Med. Rehabil. 95, 439–446. https://doi.org/10.1016/j.apmr.2013.09.009.