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Original Investigation

An Evaluation of Postural Balance in Single-leg and Double-leg Conditions in Patients with Reconstruction of the Anterior Cruciate Ligament and Healthy Controls

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Purpose: Following anterior cruciate ligament reconstruction (ACL-R) and rehabilitation, individuals undergo a series of evaluations to ensure a safe return to sports participation. The high re-injury rates that have persisted following ACL-R indicate that the current assessments may not be able to accurately identify persistent deficits. This investigation was designed to evaluate the balance control of ACL-R individuals and healthy controls in different task conditions (single and double legs).
Methods: The study involved twenty-seven participants: 13 ACL-R (age: 24.46 ± 2.73 years; height: 1.78 ± .09 m; body mass: 77.00 ± 10.35 kg; BMI: 24.10 ± 2.19 kg/m^2) and 14 healthy controls (age: 25.36 ± 3.37 years; height: 1.77 ± .06 m; body mass: 77.93 ± 14.65 kg and BMI: 24.84 ± 4.07 kg/m^2). The postural balance was assessed by measuring the center of pressure (CoP) displacement in the medio-lateral and anterior-posterior directions under various conditions, including static and dynamic, open and closed eyes, and single-leg and double-leg support. To quantify the activity of the lower limb muscles (vastus lateralis, biceps femoris, tibialis anterior, and lateral gastrocnemius), the sEMG activity was recorded synchronously with the CoP in the various tasks.
Results: There were no differences observed between the limbs of either group ($P > .05$). In comparison to the control group, the ACL-R exhibited a significantly higher CoP displacement (medio-lateral) in the double-leg dynamic condition ($P < .05$). In contrast, the two groups did not show any significant differences in CoP in the single-leg condition ($P > .05$). sEMG analysis revealed significantly higher tibialis anterior activity in the ACL-R group than the control group during dynamic double-leg balance ($P < .05$).
Conclusions: In contrast to healthy controls, individuals who underwent ACL-R appeared to exhibit a persistent postural balance deficit, particularly in dynamic double-leg conditions. The tibialis anterior of both legs exhibited abnormal neuromuscular activation patterns, which characterized these alterations. Therefore, the comparison of operated and non-operated limbs in the assessment of postural balance may not be a reliable criterion for determining the alterations and, ultimately, the safe return to sports play of individuals with ACL-R.
Keywords: surface electromyography activity, neuromuscular alteration, dynamic evaluation, postural control, ACL safe return to sport

Introduction

ACL rupture is a prevalent injury among athletes, with an annual incidence exceeding 120,000 cases[1,2]. Kinematic and kinetic changes are observed following ACL rupture[3–5]. In certain instances, these deficits persist for an extended period[3]. It is widely recognized that the ACL rupture should be regarded as a neurophysiological dysfunction rather than a local injury[3–5], as the damage affects mechanoreceptors present within the ligamentous tissue[4,5].
This injury results in the deafferentation of nerve endings, which leads to altered somatosensory afferent input[4,5], impaired integration into the central nervous system[3], and altered motor unit recruitment strategies[6–8]. The alteration of afferent input results in reflexive adaptations that decrease the capacity of muscles to activate and increase the demand for the central nervous system to produce enough force to protect the joints[4]. These adaptations are hypothesized to initiate neuroplastic mechanisms in the central nervous system, such as structural, functional, and connectivity reorganization[4,5,7]. Criss et al.[7] investigated the potential for diffuse reorganization in primary and secondary sensorimotor areas, the cerebellum, and the lingual gyrus through the analysis of altered cortical activation patterns during isokinetic maximal voluntary contractions. Needle et al.[4] have observed that these cortical reorganizations result in impaired balance control and altered proprioception, as well as a reduced capacity of the nervous system to respond to unexpected events.
Postural balance is the capacity to regulate the body's position in space to maintain stability[9]. This process entails the intricate integration of somatosensory, vestibular, and visual functions[10]. The ACL is crucial for the preservation of postural stability, as it provides critical information regarding the position and movement of the knee joint[9,11], as a result of the presence of various mechanoreceptors in cruciate ligaments, including Pacinian, Ruffini, Golgi, and free nerve endings[12]. Thus, the activation of other mechanoreceptors can result in compensatory muscle activations and altered postural balance, as the disruption

of somatosensory feedback following ACL rupture can impair postural balance[13,14].

The timing of the athlete's return to sports is essential for reducing the risk of re-injury in athletes who have undergone ACL reconstruction (ACL-R). This necessitates a functional assessment that is appropriate for the individual following rehabilitation[15]. This assessment should include neuromuscular and biomechanical measurements to identify any persistent motor control deficits[16].

Currently, the battery of tests that has been proposed to evaluate the readiness of individuals with ACL-R involves motor tasks that are performed on a single leg, comparing the operated leg to the non-operated leg[17]. Although the majority of studies evaluate balance during single-leg standing[18–22], it is still uncertain whether single-leg or double-leg conditions are more reliable for detecting neuromuscular alterations in postural balance after ACL-R than in healthy subjects[13]. The heterogeneous metrics employed in the various studies to evaluate the postural balance of individuals following ACL-R may be the cause of these discrepancies.

Recent research indicates that a bilateral motor task may be a dependable approach to detecting these changes[23–25]. In this regard, Bodkin et al.[26] noted that the balance assessment in a single-leg stance may not be sufficiently sensitive to identify persistent impairments in ACL-R individuals upon their return to sports. Balance in a double-leg condition has been evaluated in a limited number of studies[13,27,28].

Although certain studies have reported substantial disparities in balance control between ACL-R individuals and healthy controls[13], no definitive or widely accepted conclusions have been identified. Additionally, balance is regularly evaluated in static environments[13,29]. While it is considered a valid measure of somatosensory integration, statically postural balance does not require active muscle control, as the body's center of mass remains directly above the foot support[10,30]. Conversely, the balance control system is further challenged by dynamic postural control[13], as it necessitates active adjustments to restore the balance in response to perturbations[10]. This method more accurately imitates the conditions that athletes experience on the field, where they are subjected to unforeseen disruptions. Dynamic assessments are therefore more pertinent than static assessments in sports contexts, as they provide essential insights into athletic performance.

The results of a review indicate that there are few studies that have examined dynamic postural stability following ACL-R, with small to moderate effect sizes and conflicting findings[13]. Some studies employ tilting or shifting surfaces[21,31–33], while others involve dynamic single-legged plyometric tasks on force plates[34] or relocate their centre of pressure (CoP) to specific coordinates with real-time visual feedback (HUMAC balance system)[28]. The lack of standardized dynamic assessment protocols may be the cause of these discrepancies.

Winter[9] has employed various perturbations, including segment-specific imbalances (e.g. arm, leg, trunk) and tilting platforms, to ascertain dynamic balance regulation without the subject's awareness. There is a general agreement that the central nervous system aims to simplify the complex process of dynamic postural control. The system determines an appropriate control strategy depending on the perturbed body segment in response to imbalance[9,10]. According to Winter[9], a critical inquiry in the definition of the experimental setup is whether the selected paradigm accurately represents real-world perturbations.

The moving platform, which has the ability to rapidly shift or tilt, is a frequently employed system for evaluating dynamic balance in ACL-R individuals. Nevertheless, the extent to which ground perturbation replicates "on-field" conditions is still uncertain, as ACL injuries are not a result of surface movement but rather of external forces such as pushing or jostling during competition. Moreover, double-leg balance assessments may offer a more sensitive approach to identifying persistent changes in neuromuscular and postural control in individuals with ACL-R than single-leg assessments[26,29]. Noble et al.[35] have demonstrated that bilateral motor tasks necessitate greater neural network connectivity than unilateral tasks, which is consistent with the bilateral nature of lower limb motor control[36].

Individuals frequently demonstrate diminished motor output and elevated bilateral corticospinal excitability after ACL-R, which implies a reorganization of the central motor pathway[37]. The central adaptations appear to indicate that the uninjured limb may not be a valid control for functional comparisons[38], as the alteration would appear to involve both limbs[22]. The literature has reported persistent changes in the double-leg condition, which are consistent with the aforementioned findings[13].

Additionally, no research has looked at the sEMG activity in the leg muscles during postural balance tests with people who have ACL-R in different conditions (such as single-leg, double-leg, static, and dynamic). Thus, the objective of the current study was to examine any disparities in neuromuscular function and postural balance between young athletes with ACL-R and a matched control group. The body sway was measured in various conditions, including static and dynamic conditions, as well as with eyes open and closed, to evaluate postural balance. Body sway measurements were synchronised with the sEMG activity of the lower limb muscles. We hypothesized that individuals with ACL-R would exhibit impaired postural balance and altered neuromuscular activation in comparison to healthy controls when subjected to dynamic trunk perturbations in double-leg conditions.

Materials and Methods

Experimental procedure and participants

Twenty-seven athletes of regional level (skier, soccer, rugby, volleyball, and basketball players) voluntarily took part in this study. Thirteen of them, were individuals with ACL-R and fourteen were healthy control (HC). In Table 1, the participants' anthropometric characteristics are summarized. The sample size estimation was computed a priori using G*Power 3.1.9.4 statistical software for power analysis (Heinrich Heine-Dusseldorf University, Düsseldorf, Germany). The computation was based on previous study[39] and performed in relation to the study design (t-test family for parametric and nonparametric distribution), setting the effect size (ES) and using the protocol for a power analysis: test attributes, large ES (1.00), $\alpha = .05$, power $(1-\beta) = .80$, sample size n°=24 participants. In the ACL-R group, participants who had undergone a comprehensive rehabilitation protocol (6-9 months) following a single-leg operation were included. The following were the requirements for inclusion in this group: full functional recovery with a minimum 6-month lag and full return to athletic competition. The rehabilitation program was managed in accordance with the recommendations of Beynnon et al.[40] and was conducted at a national health system (NHS) center that is affiliated with our university.

For the control group, the inclusion criteria were as follows: no history of musculoskeletal, ligament, or meniscus injuries to the lower extremities. The exclusion criteria for the two groups were as follows: actual or a history of skeletal muscular or nervous injuries, neuromuscular system pathologies, herniated disks, arrhythmias, epilepsies, and comorbidities with other disturbances. The Internal Review Board approved the study, which was conducted at the Biomechanics Laboratory of the University (Prot. n°33/2022). Participants visited the biomechanics laboratory on the testing day to complete a postural balance task in various conditions (primary outcome), which was synchronized with sEMG activity recorded in both leg muscles (secondary outcome). An informed consent form was signed by each participant before the study started.

Table 1. Participants characteristics.

Variables	Group			
	ACL-R Group (n = 13)	Health Control Group (n = 14)	*P*	ES
Age (years)	24.5±2.7	25.4±3.4	.497	.029
Stature (cm)	178.5±.09	177.4±.06	.884	.019
Body Mass (Kg)	77.0±10.4	77.9±14.7	.990	.070
BMI (Kg/m^2)	24.1±2,2	24.8±4.1	.607	.210
Sex (M/F)	10/3	11/3	.928	.040
Sport level	Competitive	Competitive	.933	.134
Leg Dominance	Right (n=11) / Left (n=2)	Right (n=12) / Left (n=2)	.888	.030
Operated Leg	Right (n=7) / Left (n=6)	N/A	N/A	N/A
Graft type	SGT (n=13)	N/A	N/A	N/A
Event Distribution	No-Contact Mechanism	N/A	N/A	N/A
Post-Operative Period	6 Months-2 Years	N/A	N/A	N/A

Abbreviations: body mass index (BMI), semitendinosus/gracilis tendon (SGT).

Postural balance assessment

The postural balance was evaluated by measuring the body sway during upright standing using the force platform (Muscle-Lab 4000e, Ergotest Technology, Langesund, Norway)[41–45]. White walls were positioned 1.50 meters away from the platform, and a 1-cm red square was positioned at eye level in front of the participant. To ensure that the participant had normal binocular vision and could comfortably focus on the red dot on the wall, they were permitted to wear spectacles if needed. The body sway was evaluated in different conditions, including double-leg static and double-leg dynamic, both with closed eyes (CE) and with open eyes (OE), as well as single-leg static and single-leg dynamic, with OE. The participants maintained a fixed gaze on the red square during the OE condition. To guarantee that each participant maintained a consistent position throughout the trials, the force plate was marked with the appropriate toe and heel positions[46]. Under double-leg conditions, the forefeet were slightly extra-rotated (about 30°), and the intermalleolar distance (distance between the medial malleoli) was approximately 1.50 cm. In the single-leg condition, the participant placed the support foot in the middle part of the platform, and the other leg was flexed at 90° (femur-tibia axis), keeping the thigh aligned with the supporting leg (Figure 1B). For each trial, the body sway was recorded for 30 s while the participants stood as still as possible with their hands held relaxed laterally along their hips. The dynamic conditions are represented by an external stimulus generated by a pendulum system, individualized on the height of the subjects (Figure 1A, B). The pendulum, placed behind the subject, impacted on the dorsal part corresponding to the area between the inferior angles of the two scapulae, generating a slight trunk perturbation. The stimulus was produced three times every 7 s (at 7, 14, and 21 s) during the 30 s of the dynamic trials[41,42,45]. The mass of the pendulum was about 3.5% of the average mass of the participant. Data from the force plate was collected with a sampling frequency of 100 Hz. Body sway was measured by quantifying the displacement of the CoP (Figure 1C). Previous study suggested that the total CoP pathway has good reliability (ICC ranged from .79 to .91), recommending its use as an assessment tool in individuals with ACL-R[47]. The medio-lateral CoP and anterior-posterior CoP displacements were considered in the offline analysis. A nominal resolution of .10 – .20 mm was evaluated in the medio-lateral (M-L) and anterior-posterior (A-P) CoP directions[46]. The path displacements of the CoP (in millimeters) were analysed throughout the entire 30-second trial in static conditions. Three 1.50-second windows were analysed in dynamic conditions (Figure 2A, B, C). Each window was opened when the ground reaction force changed in response to the external stimulus (Figure 2A). The body sway was synchronized with the surface electromyography (sEMG) of leg muscles.

Synchronised sEMG activity with the Body Sway

The sEMG activity was detected in the following muscles of both the legs: vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA) and lateralis gastrocnemius (LG). sEMG activity was measured using triode electrodes (T3402M, nickel-plated brass, electrode diameter = 1 cm, inter-electrode-distance = 2 cm, Thought Technology Ltd., Montreal, QC, Canada)[48]. The electrodes were placed side by side according to the recommendations of sEMG for the non-invasive assessment of muscles (SENIAM)[49]. Before placing the electrodes, the skin was shaved, slightly abraded with sandpaper (P320) and cleaned with alcohol to minimize impedance (<5 kΩ). The electrodes and cables were fixed with an elastic band (Flexa Elast, Pic Solution, Pikdare S.p.A.) to prevent motion artefacts. The raw sEMG signal (Muscle Lab 4000e, Ergotest-Innovation, Porsgrunn, Norway) was amplified and filtered using a preamplifier located near the electrodes to reduce noise from external sources through the signal cables. The sEMG preamplifier characteristics were as follows: voltage supply ±5 VDC; input impedance 2 GΩ; common mode rejection rate: 100 dB; input noise level (1 kHz band with): 3u Vcc; output impedance (max.) 10 Ω; output voltage level: ±4 V; gain at 100 Hz: 1000; 3 dB low-cut frequency: 8 Hz; and 3 dB high-cut frequency: 1.20 kHz. The hardware circuit network, which computed the true RMS level in accordance with

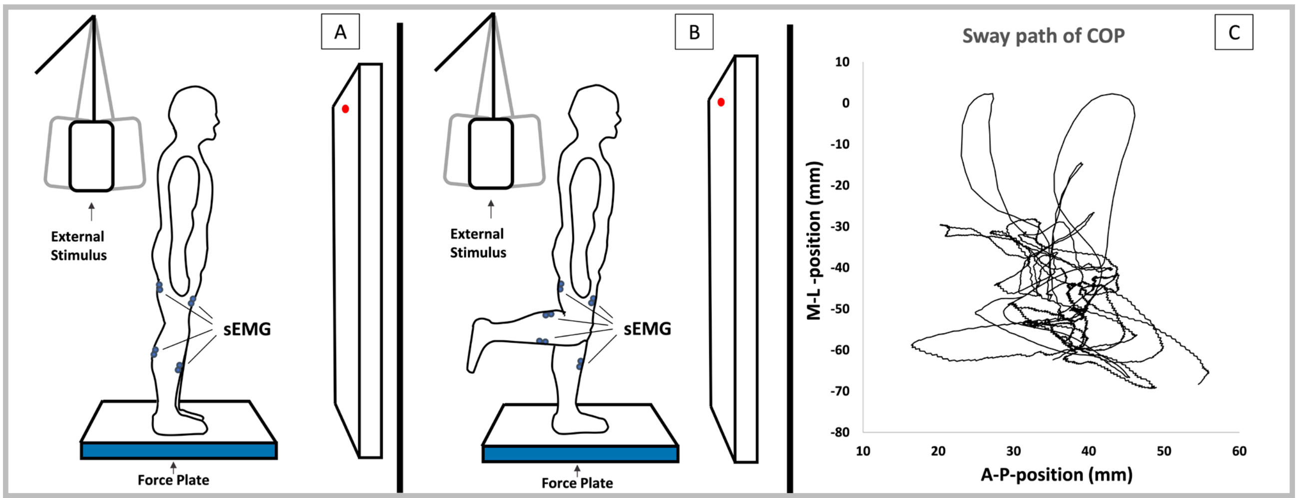

Figure 1. Experimental set up for assessment of body sway in dynamic upright standing conditions. **A:** double-leg; **B:** single-leg; **C:** representative body sway path of CoP.

the standards for reporting sEMG data (International Society of Electrophysiology and Kinesiology, https://isek.org/resources/), was used to convert the sEMG signal sampled at 1 kHz to a root-mean-square (RMS) signal. The RMS conversion circuit's technical data is as follows: a standard frequency response of ±3 dB, a bandwidth of 450 kHz, an average of 100 ms, and a conversion accuracy of ± .50% of the reading. The averaged RMS signal was sampled at 100 Hz using a 16-bit A/D converter. Technical specifications of the RMS conversion circuit include a frequency response (usually) of ±3 dB, a bandwidth of 450 kHz, an average of 100 ms, and a conversion accuracy (total error) of ± .50% of the reading. The signal was analysed using the same windows that were used for body sway in the static condition (entire 30 s duration) and the dynamic condition (three windows commenced the perturbation) (Figure 2 C).

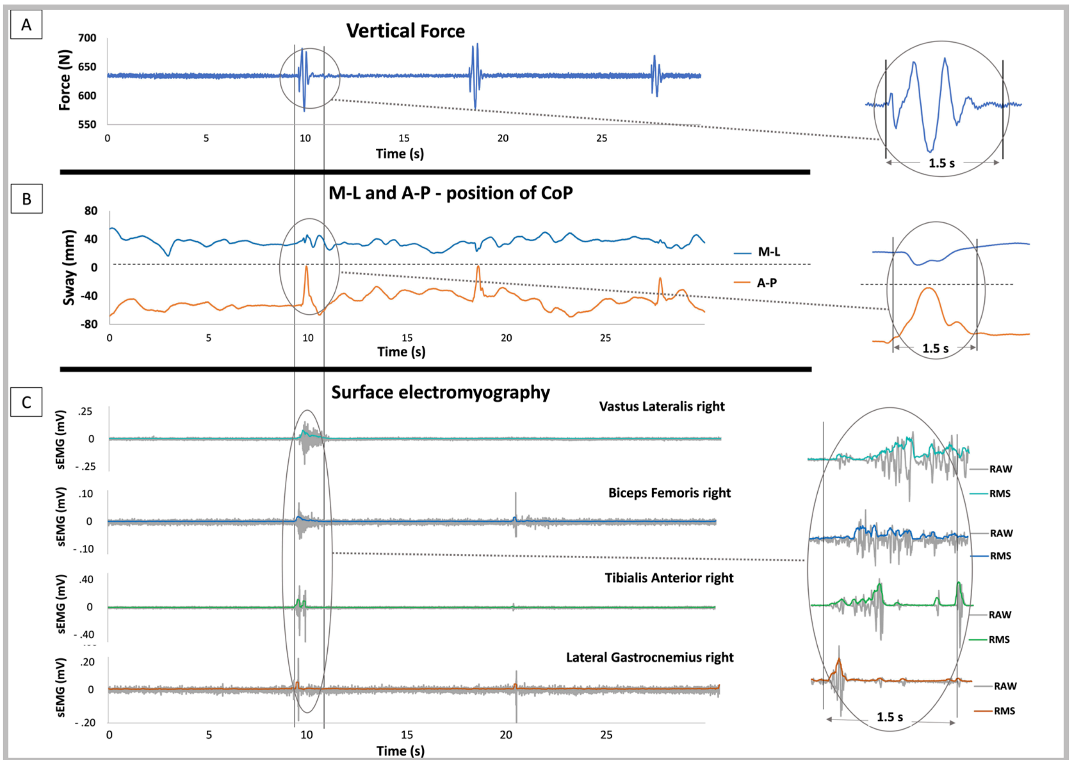

Figure 2. Representative examples of the window to analyze the synchronized signals during dynamic conditions. **A:** vertical ground reaction force recording during body sway in dynamic conditions; **B:** CoP displacement in anterior–posterior (A-P) and medio–lateral (M-L) direction, during the dynamic postural assessment; **C:** sEMG activity recorded during postural assessment.

Statistical analysis

Shapiro-Wilks's W test was implemented to assess the normality of the variables, and non-parametric tests were implemented due to the absence of a standard Gaussian distribution. The Wilcoxon test was employed for within-group comparisons and the Mann–Whitney test for between-group comparisons to investigate the statistical differences between the anthropometric measured and the dependent variables (body sway and sEMG activity of legs muscles). The intraclass correlation coefficient (ICC) was employed to quantify the intrasession reliability of the pendulum perturbation. ICC values ranging from .50 to.69 are classified as "moderate," those between .70 and .89 as "high," and those exceeding.90 as "excellent." The Holm-Bonferroni sequence[50] was employed to adjust the P value in the within-group comparison, as it enables more effective control of Type I error and reduces the risk of false negatives. Using the Bonferroni correction, we adjusted P between the comparisons. Both modifications were implemented in accordance with the number of contrasts carried out (4 → in each sway condition: static, dynamic, double-leg, and single-leg; and 4 → in sEMG of the leg muscles during each condition). We used α = .05 to set the level of significance and Hedges' g to find the size of the effect. An effect was small if g < .50, moderate if .50 < g < .80, and large if g > .80.[41] The XLSTAT 2023 25.3.0.0 software (Addinsoft; New York, NY, USA) was used for statistical analysis.

Results

For the single-leg condition, the ICC for the pendulum perturbation was "high" (ranging from .70 to .84), while in the double-leg condition it was "excellent" (ranging from .86 to .95). The anthropometric variables (age, height, body mass, and BMI) measured did not exhibit any statistically significant differences between the ACL-R group and the HC group (*P* > .05) (Table 1). No significant differences in within-group comparisons between the dominant leg (DL) and non-dominant leg (N-DL) HC were observed in all tests conducted (Tables S1 and S2) (*P* > .05). Furthermore, there was no significant difference between the operated leg (OL) and the non-operated leg (N-OL) in individuals with ACL-R (Tables S3 and S4) (*P* > .05). As one-half of the ACL-R participants had the operated limb coincident with the dominant leg (9 DL / 4 N-DL), comparisons were made between the DL of the HC group and the OL of the ACL-R group, as well as between the N-OL and the N-DL. The ACL-R group showed a significant higher CoP displacement during double-leg static condition in A-P sway path with OE (*P* = .032; ES = 1.20) (Figure 3A) and CE (*P* = .032; ES = 1.17) (Figure 3B) compared to HC. The double-leg dynamic condition exhibited a significantly higher CoP displacement in the M-L sway path with OE (*P* = .012; ES = 1.39) (Figure 3C) in the ACL-R group. In the single-leg dynamic and single-leg static conditions, there were no significant differences between the groups (*P* > .05) (Table 2).

Table 2. ACL-R group and health control group, sway path values (M-L and A-P) of static and dynamic body sway.

Variables	ACL-R	HC	*P*
Static Postural Balance			
Double-leg OE M-L (mm)	308.8 ± 104.4	242.6 ± 56.1	.204
Double-leg CE M-L (mm)	338.7 ± 114.7	271.7 ± 81.2	.204
Double-leg OE A-P (mm)	550.3 ± 186.3	350.6 ± 145.9	.032*
Double-leg CE A-P (mm)	658.5 ± 226.3	422.4 ± 176.2	.032*
Single-leg operated-leg/dominant-leg M-L (mm)	850.1 ± 165.1	940.4 ± 214.4	.660
Single-leg non operated-leg/ non dominant-leg M-L (mm)	867.8 ± 133.2	930.2 ± 245.4	1.000
Single-leg operated-leg/dominant-leg A-P (mm)	1145.5 ± 409.2	1082.7 ± 318.9	1.000
Single-leg non operated-leg/ non dominant-leg A-P (mm)	1194.7 ± 314.0	1005.6 ± 335.4	.500
Dynamic Postural Balance			
Double-leg OE M-L (mm)	161.5 ± 48.6	86.6 ± 58.9	.012*
Double-leg CE M-L (mm)	162.8 ± 54.7	107.9 ±70.0	.117
Double-leg OE A-P (mm)	362.5 ± 74.9	271.1 ± 198.2	.740
Double-leg CE A-P (mm)	385.6 ± 88.1	269.0 ± 178.4	.170
Single-leg operated-leg/dominant-leg M-L (mm)	130.7 ± 36.5	108.8 ± 42.4	1.000
Single-leg non operated-leg/ non dominant-leg M-L (mm)	124.2 ± 27.9	117.6 ± 55.5	1.000
Single-leg operated-leg/dominant-leg A-P (mm)	316.6 ± 59.9	302.8 ± 244.3	1.000
Single-leg non operated-leg/ non dominant-leg A-P (mm)	308.4 ± 87.9	261.4 ± 139.1	1.000

Abbreviation: anterior cruciate ligament reconstruction group (ACL-R) health control group (HC); open eyes (OE); closed eyes (CE); medio-lateral (M-L); anterior-posterior (A-P); *= *P* < .05.

In the double-leg dynamic condition, the sEMG activity of the TA was significantly higher in the ACL-R group than in the HC group with OE (*P* = .040; ES = 1.62, and *P* = .028; ES = 1.82, respectively OL/DL and N-OL/N-DL) (Figure 4, Fable 3). In the single-leg dynamic assessment, there was no significant difference in sEMG TA between the groups (*P* > .05) (Figure 4, Table 3).

No significant differences (Table 4) were observed between the groups in the sEMG of muscles under the static condition (*P* > .05).

In double-leg dynamic condition with OE, ACL-R showed a significant greater activation of BF muscles for OL (*P* = .040; ES = 1.05) and N-OL (*P* = .028; ES = .83) in comparison to HC group. During the single-leg dynamic condition, the ACL-R exhibits a greater activation of the BF in the OL (*P* > .024; ES = 1.15) and in the N-OL (*P* = .012; ES = 1.03) compared to the HC group (Figure 4).

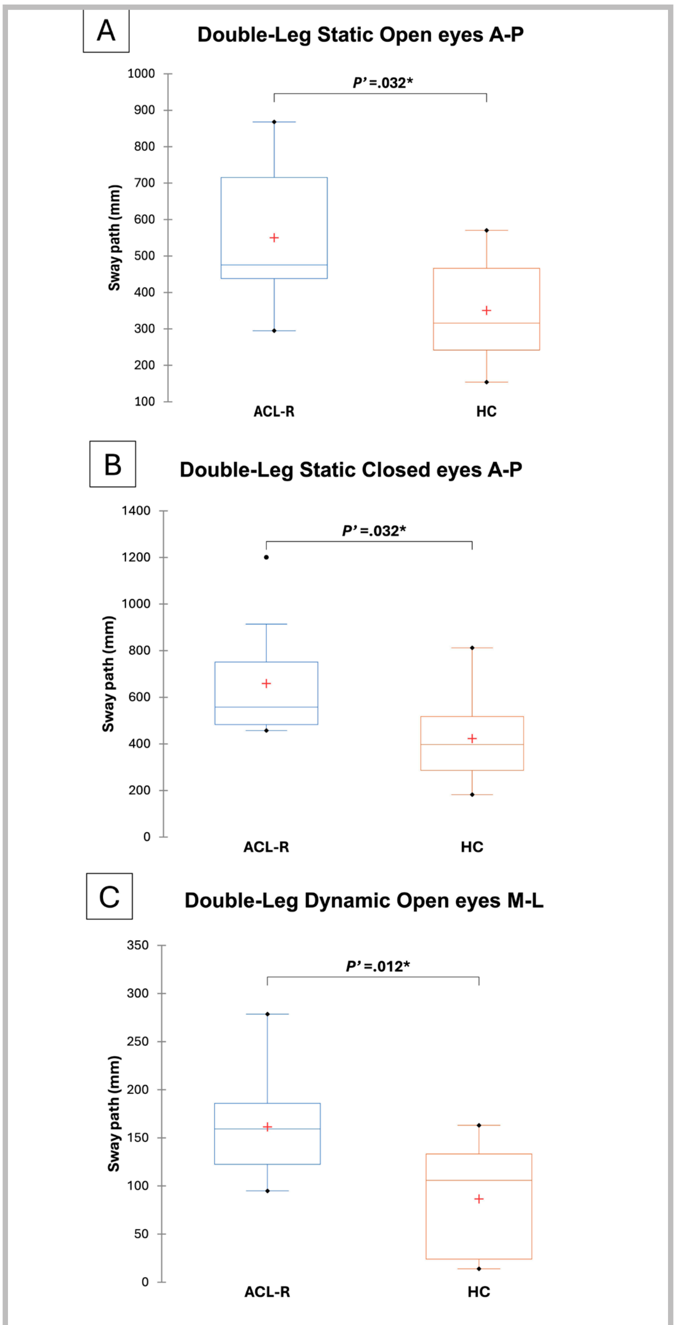

Figure 3. Displacement of medio-lateral (M-L) and anterior-posterior (A-P) directions of the centre of pressure (CoP) during double-leg condition. Differences between anterior cruciate ligament reconstruction group (ACL-R) and healthy control group (HC). *= $P < .05$.

Table 3. sEMG$_{RMG}$ activity values of ACL-R group and healthy control group during dynamic body sway assessment.

Variables	Operated leg/dominant leg			Non operated leg/Non dominant leg		
Double-leg dynamic CE	**ACL-R**	**HC**	***P***	**ACL-R**	**HC**	***P***
VL (mV)	.075 ± .033	.059 ± .032	.696	.078 ± .026	.047 ± .042	.339
BF (mV)	.039 ± .025	.030 ± .035	.696	.037 ± .026	.026 ± .026	.528
TA (mV)	.097 ± .044	.032 ± .042	.088	.122 ± .072	.027 ± .043	.104
LG (mV)	.029 ± .017	.021 ± .010	.696	.034 ± .021	.024 ± .017	.528
Double-leg dynamic OE	**ACL-R**	**HC**	***P***	**ACL-R**	**HC**	***P***
VL (mV)	.084 ± .039	.055 ± .035	.132	.086 ± .041	.044 ± .040	.052
BF (mV)	.042 ± .024	.021 ± .022	.040*	.035 ± .025	.017 ± .013	.028*

TA (mV)	.108 ± .058	.026 ± .036	.040*	.129 ± .074	.025 ± .043	.028*
LG (mV)	.028 ± .021	.030 ± .008	.132	.030 ± .021	.017 ± .009	.054

Single-leg dynamic OL/DL	**ACL-R**	**HC**	***P***
VL (mV)	.116 ± .063	.074 ± .048	.315
BF (mV)	.053 ± .025	.030 ± .024	.024*
TA (mV)	.138 ± .072	.127 ± .065	.816
LG (mV)	.053 ± .030	.068 ± .026	.315
Single-leg dynamic N-OL/N-DL	**ACL-R**	**HC**	***P***
VL (mV)	.114 ± .034	.081 ± .048	.198
BF (mV)	.050 ± .028	.024 ± .017	.012*
TA (mV)	.166 ± .088	.120 ± .067	.766
LG (mV)	.062 ± .023	.068 ± .031	.768

Abbreviation: anterior cruciate ligament reconstruction group (ACL-R) health control group (HC); 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); vastus medialis (VM); tibialis anterior (TA); lateralis gastrocnemius (LG); *= *P* < .05.

Table 4 sEMG$_{RMG}$ activity values of ACL-R group and healthy control group during static body sway assessment.

Variables	**Operated leg/dominant leg**			**Non Operated leg/Non dominant leg**		
Double-leg static CE	**ACL-R**	**HC**	***P***	**ACL-R**	**HC**	***P***
VL (mV)	.019 ± .018	.015 ± .016	.766	.018 ± .010	.011 ± .012	.249
BF (mV)	.023 ± .020	.013 ± .015	.680	.026 ± .027	.009 ± .008	.240
TA (mV)	.016 ± .016	.009 ± .008	.766	.020 ± .022	.005 ± .002	.249
LG (mV)	.014 ±.006	.012 ± .008	.699	.021 ± .016	.017 ± .016	.342
Double-leg static OE	**ACL-R**	**HC**	***P***	**ACL-R**	**HC**	***P***
VL (mV)	.018 ± .019	.016 ± .016	1.000	.017 ± .012	.008 ± .008	.246
BF (mV)	.022 ± .020	.017 ± .019	1.000	.017 ± .013	.011 ± .008	.470
TA (mV)	.025 ± .028	.010 ± .010	1.000	.028 ± .028	.006 ± .003	.232
LG (mV)	.014 ± .007	.012 ± .008	1.000	.021 ± .016	.012 ± .009	.246

Single-leg static OL/DL	**ACL-R**	**HC**	***P***
VL (mV)	.029 ± .026	.030 ± .028	1.000
BF (mV)	.030 ± .020	.012 ± .006	.060
TA (mV)	.066 ± .062	.070 ± .045	1.000
LG (mV)	.030 ± .015	.043 ± .024	.450
Single-leg static N-OL/N-DL	**ACL-R**	**HC**	***P***
VL (mV)	.024 ± .013	.025 ± .019	1.000
BF (mV)	.026 ± .032	.014 ± .009	.772
TA (mV)	.064 ± .040	.081 ± .045	1.000
LG (mV)	.038 ± .027	.048 ± .031	1.000

Abbreviation: anterior cruciate ligament reconstruction group (ACL-R) health control group (HC); 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); vastus medialis (VM); tibialis anterior (TA); lateralis gastrocnemius (LG); *= *P* < .05.

Discussion

This study aimed to determine the postural balance of individuals with ACL-R and matched HC in both single-leg and double-leg conditions. The ACL-R group did not demonstrate any significant differences between the operated and non-operated leg, which was consistent with their status as "ready for a safe return to sport participation". Nevertheless, the ACL-R group

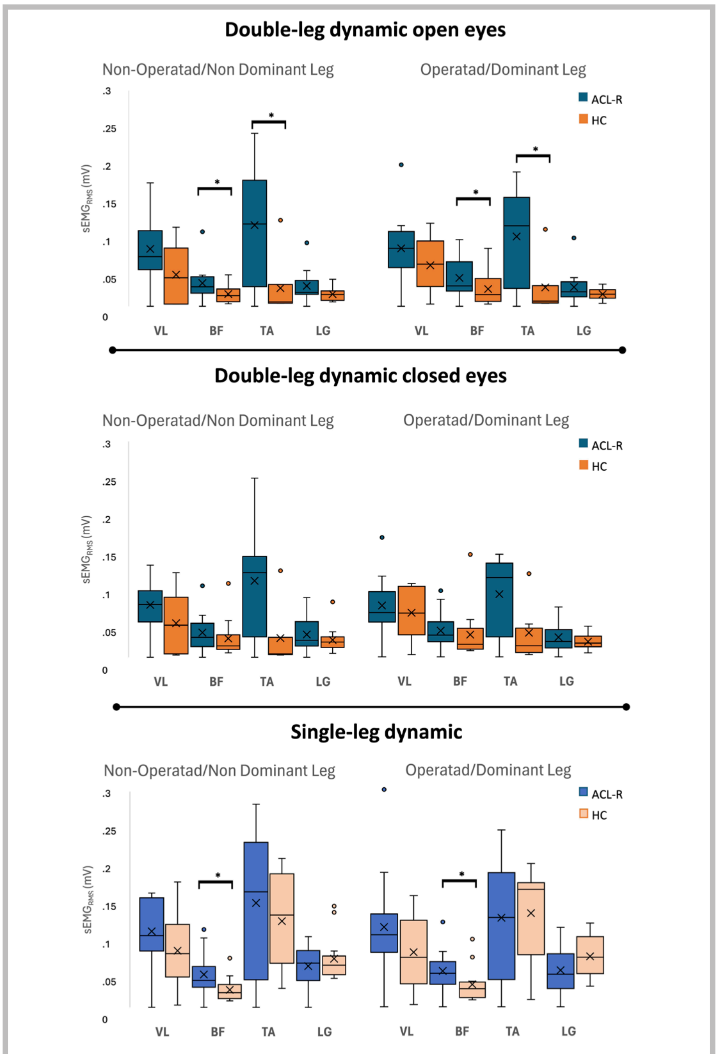

Figure 4. Surface electromyography root-mean square ($sEMG_{RMS}$) activity of leg muscles synchronized whit dynamic body sway assessment. Differences between anterior cruciate ligaments reconstruction group (ACL-R) and healthy control group (HC). VL= vastus lateralis, BF= biceps femoris, TA= tibialis anterior, LG= lateral gastrocnemius. *= *P* < .05.

demonstrated a compromised CoP displacement in double-leg conditions (static and dynamic; OE and CE) in contrast to the healthy control group. A decrease in the capacity to effectively regulate balance control is frequently linked to an increase in CoP length from a clinical perspective[9,13,51].

Other research[26,29] has indicated that single-leg assessment may not be an adequate method for detecting substantial changes in balance control between individuals with ACL-R and healthy controls. However, none of the latter studies evaluated the postural balance in the double-leg condition.

In our investigation, the CoP demonstrated significant variations in the A-P direction under double-leg static conditions, with both closed and open eyes. In line with the current findings, Wang et al.[52] found that ACL-R individuals had a significant increase in CoP in the A-P direction but not in the M-L direction. This implies that the only area where changes in proprioception after an ACL injury are seen to impact the static condition is the A-P direction.

Kouvelioti et al. [47] indicated that there were no clinically relevant differences in CoP parameters (including amplitude, velocity, and path length) between individuals with ACL-R and healthy controls in both single- and double-leg conditions. On the other hand, Paterno et al. [21] observed a considerable increase in CoP displacement in individuals with ACL-R compared to controls, even after their return to play. This seems to suggest that postural stability may not be fully restored. Despite the apparent overall stability, it would seem that altered postural control strategies involving CoP regulation can persist for over 20 years following ACL-R in this regard [33].

Our findings during double-leg dynamic conditions indicated substantial contrasts in the M-L direction of CoP, with OE conditions. The highest M-L direction is characteristic of neurological diseases, including Parkinson's disease[53], cerebellar deficits[54], and young adults with autism spectrum disorder[41]. It has also been linked to fall risk in the elderly population[55]. Furthermore, Slobounow et al.[54] indicate that the M-L direction of the CoP necessitates more neural resources than the A-P direction. This could emphasize persistent impairment in balance control among individuals with ACL-R, particularly during challenging balance tasks that necessitate greater sensory integration.

In reality, the neuromuscular system and cortical areas regulate balance control more in dynamic conditions than in static conditions[56]. The differences in the A-P and M-L displacements are consistent with the literature, which demonstrates that the neuromuscular control of the two directions is independent in a double-leg with "side-by-side" foot standing position[9,57,58]. Specifically, the M-L control is primarily ruled out by a hip loadunload mechanism, while the A-P control is primarily controlled by the ankle[9].

In addition, our findings indicate that the sEMG activity of the tibialis anterior muscles in both OL and N-OL was significantly increased by the ACL-R group during dynamic double-leg exercise compared to healthy controls. Conversely, the activations of the tibialis anterior are unaltered between the two groups during the single-leg dynamic condition. It has been observed that the tibialis anterior, which is involved in balance control[59], contributes more during a loss of balance in the M-L direction to regulate the CoP[60].

Our findings appear to indicate that the trunk perturbation implemented during the dynamic double-leg condition induces a modified regulation of the body's sway in the M-L direction in the ACL-R group, which leads to an elevated activation of the tibialis anterior muscles. Nevertheless, it has been reported that the trunk perturbation in the double-leg condition induces muscular activation to rectify the imbalance in a proximal-distal sequence (thigh muscles were activated before the shank muscles), resulting in a diminished activation of the ankle muscles[30,51].

Furthermore, the slight delay in the angular changes observed in a previous study[9] implies that neural responses are not induced by stretch reflexes in the lower limb muscles (platform perturbation), but rather by higher-level responses that are triggered by receptors in or near the site of the perturbation[9]. The ankle muscles should be minimally involved in this context[51], as demonstrated by the health control group, and the slight dynamic trunk perturbation that was induced in our study. Consequently, the increased activation of the tibialis anterior muscle in individuals with ACL-R may be a compensatory mechanism that has arisen due to ACL rupture[14,61].

Conversely, both groups exhibit comparable neuromuscular activations in single-leg conditions. The reduction of the supporting surface during the single-leg condition may be the cause of this phenomenon. This results in a greater neuromuscular activation by multiple joints (hip, ankle) to stabilize the CoP within the foot support[10]. It is imperative to acknowledge that the physical constraint imposed by the support base has a greater impact on the selection of a control strategy than the underlying neural organization[10].

The paradigm for the return to sport suggests a series of tests that include unilateral assessment[19] and comparison of the non-operated limb with the operated limb[22,62]. However, recent studies have shown that persistent alterations of the neuromuscular system in individuals with ACL-R can only be observed during bilateral conditions[23,24]. This may be because bilateral tasks that involve the lower limb necessitate heightened activation of various brain regions (e.g., cortical, subcortical, and cerebellar areas) and distinct motor regions in comparison to unilateral tasks[35]. Therefore, bilateral assessments may be more suitable and sensitive for detecting motor control impairments due to the bipedal nature of humans.

The dynamic double-leg condition in our study revealed discrepancies in biceps femoris activation between the groups. It has been hypothesized that the heightened biceps femoris activity in the operated limb is a protective mechanism that stabilizes the reconstructed knee[63,64]. However, we observed the same activation of the biceps femoris in the operated and non-operated leg. This is consistent with the findings of Zult et al.[22], who hypothesize that the motor control of the non-operated leg is impacted by alterations caused by ACL rupture when the body experiences a dynamic perturbation. Indeed, it has been proposed that an ACL injury impairs the function of both the injured and uninjured leg, even though the injury is unilateral[22]. In this context, Konishi et al.[65,66] propose that the gamma loop dysfunction in the operated leg in ACL-R also affects the non-operated leg.

It is intriguing to observe that postural balance was evaluated in dynamic double-leg conditions with open eyes, and ACL-R individuals exhibited a greater activation of the biceps femoris muscles in the operated and non-operated leg than the HC group. Conversely, the two groups did not exhibit any distinctions when the identical task was executed with closed eyes. One potential explanation for the disparities between the two conditions (open and closed eyes) is the visual system's involvement in the multisensory process of body stabilization[67].

In the absence of a visual system, the postural control network becomes more unstable, relying more on other afferent information, such as the proprioceptive and vestibular systems[10]. In fact, healthy control exhibits a higher level of biceps femoris activity when the eyes are closed compared to when the eyes are open (see Table 3, Figure 3).

These results appear to indicate that individuals with ACL-R may have a persistent deficit of the proprioceptive system, as they require the biceps femoris to be activated to maintain balance, even when the visual system is employed (open-eye condition). However, when performing dynamic double-leg exercises with open eyes, the ACL-R group's members exhibit noticeably greater tibialis anterior sEMG activity and M-L direction path of CoP than healthy controls. This again indicates that dynamic double-legs can be sensitive enough to detect persistent changes in postural balance. Compared to conventional strategies[68], the risk of ACL injury or re-injury may be reduced through the implementation of new assessment paradigms and contemporary preventive training approaches.

Limitations

The absence of sEMG signal normalization is a limitation of this study, as it may impact the results of between-group comparisons in muscle activation. Although EMG_{RMS} values provided valuable insights into general activation patterns, the lack of normalization restricts the ability to draw definitive conclusions about the relative magnitude of muscle activity. Nevertheless, the main findings are not significantly affected by this limitation, as sEMG was a secondary outcome. Additionally, kinematic analyses should be incorporated into future research to substantiate the mechanistic interpretation of tibialis anterior compensatory behavior in individuals with ACL-R during dynamic perturbations.

Practical Applications

The current paradigm, which is based on a similar neuromuscular pattern between the operated and non-operated legs during the single-leg exercise, to determine an athlete's readiness to return to play following ACL-R, may be misleading if the neuromuscular alterations appear to affect both limbs equally. Consequently, it may be imperative that Kinesiologists and Physiotherapists consider the postural balance when individuals are in double-leg support, and the external stimulus is implemented through unexpected trunk perturbations. It may be capable of identifying balance changes and neuromuscular compensatory mechanisms in individuals with ACL-R, which the single-leg assessment condition is unable to highlight.

Conclusions

Postural balance appears to be generally impaired in individuals with ACL-R when contrasted with healthy controls who are matched. To mitigate the unexpected dynamic trunk perturbation, individuals with ACL-R demonstrated compromised postural balance and increased sEMG activation of the tibial anterior muscles in both the operated and non-operated legs during double-leg dynamic conditions (trunk perturbation). These differences were not revealed in the single-leg evaluation.

According to these findings, it appears that even individuals with ACL-R who are considered "ready for a safe return to sport competition" may continue to exhibit persistent changes in their postural balance compared to healthy individuals.

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Informed Consent Statement

Informed consent was obtained from the participants involved in the study.

Ethical Committee approval

University of L'Aquila Internal Review Board (IRB) approved this study (Prot. n° 33/2022).

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Topic

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Conflicts of interest

The authors have no conflicts of interest to declare.

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Author-s contribution

Conceptualization, SLG; methodology, SM and FF; software, SM and FF; validation, RDG; formal analysis, SLG; investigation, SM and FF; writing—original draft preparation, SLG; writing—review and editing, RDG; supervision, RDG; project administration, RDG. All authors have read and agreed to the published version of the manuscript.

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