

Title: Inter-Joint Coordination and Coordination Variability in Lower Limb Function during Single-Leg Stance Postural Control Following Anterior Cruciate Ligament Reconstruction

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Abstract

Background: ACL reconstruction is known as the standard treatment for restoring knee joint function, but undergo this surgery shows deficits in sensorimotor control that often impair movement coordination of the lower limb.

Objectives: The study aimed to investigate the coordination and coordination variability of lower limb joints during single-leg stance in individuals with ACL reconstruction.

Methods: The study analyzed 24 participants: 12 with right ACL reconstructions using hamstring auto-grafts (12-16 months' post-surgery) and 12 healthy controls, all of the same gender and aged 20–37. Kinematic variables of lower limb joints were recorded using eight motion analysis cameras (250 Hz). Inter-joint coordination and coordination variability were examined using the Continuous Relative Phase (CRP) method across different phase planes involving angular velocity, acceleration, and jerk for the ankle, knee, and hip joints in the anterior-posterior direction.

Results: ACL-reconstructed individuals showed higher hip-ankle joint coordination in angular velocity ($p=0.004$) indicating a reduction in coordination between these joints. and reduced coordination variability in hip-knee (all phase planes) and knee-ankle joints (velocity-acceleration and jerk-acceleration phase planes) compared to the healthy group ($p<0.05$).

Conclusions: Altered movement patterns in individuals with ACL reconstruction could increase re-injury risk. Thus, it is necessary to design optimal rehabilitation protocols for these individuals.

Keyword: ACL reconstruction, Single Leg Stance, Coordination, Coordination Variability

Highlights

- Single leg stance (SLS) postural control is a significant task in clinical investigations of ACLR individuals
- Impaired motor functions, such as joint coordination and coordination variability in individuals with ACLR, elevate the risk of re-injury during various sports activities
- Designing optimal rehabilitation protocols to restore natural movement patterns and reduce the risk of injury in ACLR individuals is essential.

Plain Language Summary

ACL reconstruction (ACLR) is recognized as the standard treatment for restoring joint stability and function. But reduced coordination and coordination variability between joints can lead to abnormal movement patterns, compensatory movement patterns, and injury, all of which are at risk of re-injury. Consideration of lower extremity coordination and coordination variability after ACLR can be valuable for improving rehabilitation strategies. Therefore, it is necessary to pay attention to these points in designing optimal rehabilitation protocols to restore normal movement patterns and reduce the risk of injury in ACLR individuals

1. Background

The stability of the knee joint is maintained through both passive mechanisms, such as bone structure and ligamentous arrangements, and dynamic components, including muscular contractions and neuromuscular control (1). Anterior cruciate ligament (ACL) rupture is common and can disrupt this stability (1). It leads to the loss of mechanoreceptors, reduced afferent input to the sensorimotor system, compromised neuromuscular function, and subsequent deficits in knee functionality (2, 3). ACL reconstruction (ACL-R) is widely regarded as the standard treatment for restoring joint stability and function (4). However, only about 65% of patients fully recover in terms of daily activities, and just 50% of them are able to return to their previous level of sports participation (5) (6), and they still face a high risk of re-injury (5).

Altered inter-joint coordination in the lower limbs is a common impairment following ACL-R due to structural changes in the knee joint (6). Movement coordination is defined as the selection and generation of movement, as well as the degrees of freedom available for a given task (7). Coordination results from dynamic interactions among the musculoskeletal system, nervous system, and environment, with self-organized relationships among these components enabling flexibility in movement patterns (4). Consequently, as a movement becomes more complex, the coordination between joints or the rhythm of the movement also grows more intricate, increasing its significance (8, 9). Research suggests that injuries to the ACL or other passive components of the knee joint are unlikely to result solely from dysfunction in a single joint (10). When evaluating the effects of therapeutic interventions, it is essential to assess the function of the injured joint in relation to other joints within the kinetic chain (11). Reduced coordination can lead to abnormal movement patterns, compensatory mechanisms, and an increased risk of injury (7). These findings highlight the importance of understanding and improving inter-joint coordination in the lower limbs for effective rehabilitation after ACL reconstruction and injury prevention.

Coordination variability represents the dynamic balance between stability and adaptability in response to environmental demands (11, 12). Diminished variability, which implies reduced flexibility, indicates a lowered ability to adapt to external perturbations (11). Interestingly, lower coordination variability might be linked to an increased occurrence of ACL injuries (11). Several studies have analyzed inter-joint coordination and coordination variability in lower limb movements among ACL-R individuals during various activities like walking (4, 5, 7, 13), running,

and cutting maneuvers (5). For instance, a study demonstrated a lower in-phase hip-knee coordination pattern in ACL-R individuals during running and cutting (5). In other cases, individuals with ACL-R exhibited greater variability in hip-knee coordination during walking compared to healthy controls (4, 7). Additionally, investigations into unipedal postural coordination and single-leg jumping have further shown altered coordination patterns in ACL-R individuals, with reduced ankle-knee coordination but increased ankle-hip coordination variability compared to their non-injured counterparts [10, 11].

Clinically, it is crucial to assess the knee joint's performance. Single-Leg Stance (SLS) postural control is a critical task in clinical assessments of ACLR individuals (13-16). This task provides insight into the performance of the injured limb independently of the healthy limb. Researchers have specifically studied the center of pressure (COP) in ACL-R patients during SLS (17), as reduced somatosensory feedback and proprioceptive functionality following ACL-R can lead to increased COP changes (18). Investigating inter-joint coordination and its variability can discover abnormal movement patterns that elevate the risk of re-injury and help design suitable rehabilitation exercise programs (7, 19).

Previous studies indicate that joint angular acceleration is a suitable kinematic variable for analyzing inter-joint coordination during a double quiet stance (20, 21). Therefore, incorporating joint acceleration into continuous relative phase (CRP) calculations may help identify changes in inter-joint coordination in ACL-R individuals during SLS. Currently, there are no existing reports on the inter-joint coordination patterns during SLS, prompting this study to analyze it using the CRP method. The analysis will utilize various phase planes, including angular velocity versus angle, angular acceleration versus angular velocity, and angular jerk versus angular acceleration. The aim of this study was to investigate the inter-joint coordination and coordination variability of the lower limb joints during SLS in individuals with ACL-R. In this research, an effort is made to analyze the coordination in different phase planes to assess all potential changes and differences between the two evaluated groups.

2. Methods

This study involved two groups of subjects: 12 individuals who had undergone anterior cruciate ligament (ACL) reconstruction and 12 healthy controls matched for age, weight, and height. The

sample size is consistent with that used in previous ACL research (22, 23) Participants were referred by the Bone, Joint, and Related Tissues Research Center at Shahid Beheshti University of Medical Sciences. An orthopedic physician evaluated the patients before their referral to the laboratory. Inclusion Criteria: Ages between 20 and 37 years, Right ACL-R performed using a hamstring autograft, Timeframe of 12 to 16 months post-reconstruction, No pain or medication at the time of evaluation, Completion of the same rehabilitation program, Normal musculoskeletal system (except the right knee) and Active lifestyle involving regular physical activity. Exclusion Criteria: Visual or vestibular disturbances and Pain or deformities in the lower limbs. The control group consisted of active healthy individuals with no history of lower limb injuries, surgeries, or musculoskeletal abnormalities; they were also neurologically sound. Ethical approval was obtained from the Institute of Physical Education and Sports Sciences, and all participants provided informed consent prior to data collection.

Balance was evaluated during a SLS, with each test lasting 35 seconds. Participants completed three trials of standing on their right leg, with a 2-minute rest interval between each attempt. For the duration of the tests, participants remained barefoot and kept their hands on their hips. They were instructed to bend the knee of the non-supporting leg to a 90-degree angle.

Lower limb joint kinematics were captured using eight motion analysis cameras (Oqus 5+, Qualisys, Sweden) at a frequency of 250 Hz. The data were filtered using a Butterworth low-pass filter with a 6 Hz cutoff frequency. The first 5 seconds of each trial were removed to minimize transient effects at the start of the movement. Twenty 14-mm reflective markers were affixed to anatomical landmarks according to the V3D ¹model. Visual 3D software (V6 x64) was used to construct a biomechanical model comprising the pelvis, thigh, shank, and foot segments. This model was then used to calculate angular displacement, velocity, and acceleration of the ankle, knee, and hip joints within the sagittal plane. Angular jerk was computed using the three-point derivation method. To analyze non-sinusoidal signals, normalizing both the input signals' displacement and their first derivative was necessary (7). The objective was to transform the phase portraits in a manner that confines both displacement and its first derivative within the range of -1 to 1 (24). This normalization allows for the comparability of data across different individuals with

¹ Visualize Three Dimensional

varying ranges. The signal's displacement was normalized using Equation 1. Its first derivative was normalized using Equation 2 (25). In the phase planes angular velocity versus angle, angular acceleration versus angular velocity, and angular jerk versus angular acceleration were considered as the input signals, respectively.

$$\theta_{\text{normal}} = \frac{2(\theta - \min(\theta))}{\max(\theta) - \min(\theta)} - 1 \quad (1)$$

$$\dot{\theta}_{\text{normal}} = \frac{\dot{\theta}}{\max(\max(\dot{\theta}), \max(-\dot{\theta}))} \quad (2)$$

Following normalization, the phase angle of the signal at time t_i is computed as the angle of the line between point i and the origin (0, 0) (equation 3). The phase angle is calculated in all three phase planes.

$$\varphi_i = \tan^{-1} \frac{\dot{\theta}_i}{\theta_i} \quad (3)$$

Following the calculation of phase angles, continuous relative phase (CRP) is computed between the hip-knee, hip-ankle, and knee-ankle in sagittal plane (Equation 4). The average CRP curve across participant trials is then used as the ensemble CRP curve to simplify further analysis (26). Synchronized joint movements are defined by in-phase (CRP = 0°) and anti-phase (CRP = 180°) patterns, representing movements in the same and opposite directions, respectively. Other CRP values indicate the phase deviation between the movements of the two joints. Finally, three variables are calculated from the CRP values for statistical analysis.

$$\text{CRP} = \varphi_{\text{Proximal}} - \varphi_{\text{Distal}} \quad (4)$$

For statistical analysis of the CRP data, three variables were calculated. Firstly, the Mean Absolute Relative Phase (MARP), calculated as the mean of ($|\text{CRP}|$), was used to indicate the degree of coordination between two joints, representing the temporal relationship of their movements (27). Secondly, the Deviation Phase (DP), determined as the standard deviation of the CRP, was calculated for both intra-individual (within each participant's repetitions) and inter-individual

(between the mean patterns of individuals within a group) cases (28, 29). DP reflects the coordinative variability, indicating the extent of variability in a coordination pattern (30). All calculations were performed using Circular Statistics (31). Independent t-tests, with a significance level of $\alpha = 0.05$, were used for statistical analysis. Effect sizes (Cohen's d) were calculated and interpreted using conventional thresholds: small (≈ 0.2), medium (≈ 0.5), and large (≈ 0.8) (32). MATLAB R2019b and SPSS 26 were used for calculations and statistical analysis, respectively.

3. Results

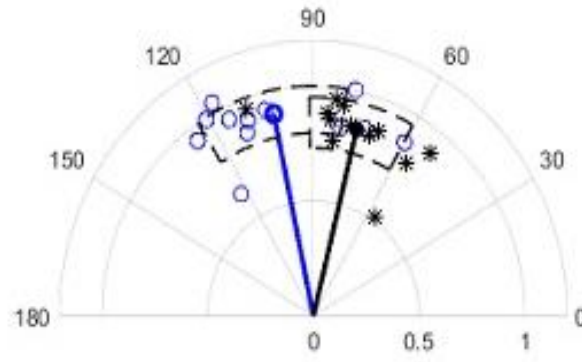
The coordination and coordination variability for both the control and experimental groups are illustrated in Figures 1 to 3. In these figures, the coordination with respect to the horizontal axis (zero origin) for the experimental group is represented by blue circles, while the control group is indicated by black stars. The radial distance from these points to the origin (0, 0) illustrates the variability for each participant's repetitions. The angle formed between the blue line and the horizontal axis indicates the average coordination angle of the experimental group, whereas the angle between the black line and the horizontal axis represents that of the control group. The length of these lines indicates the average variability among participants in both groups. Specifically, in the graphical representation, the arc length corresponds to participants variability, while the chord length represents the standard deviation (SD) of the Mean Absolute Relative Phase (MARP). These lines are plotted for both groups.

Figure.1 Displays coordination and variability values from the phase plane of angular velocity versus angle for hip-ankle, hip-knee and knee-ankle joints. The experimental group's hip-ankle average coordination (101.7 ± 22.2 degrees) was significantly greater than control group (75.9 ± 16.1 degrees) with a p-value of 0.004 ($d = 0.41$). However, there was no significant difference in coordination variability between groups (experimental: 51.5 ± 6.2 ; control: 48.2 ± 6.7 ; $p > 0.05$). Result shows that hip-knee coordination was not significantly different between groups (control: 103.8 ± 32.5 ; experimental: 105.5 ± 31.5 ; $p > 0.05$), but the average variability was significantly lower in the experimental group (49.2 ± 11.2) compared to the control group (66.7 ± 13.9 ; $p = 0.003$, $d = 0.66$). Findings show no significant differences in knee-ankle coordination between groups (experimental: 89.1 ± 37.00 ; control: 66.00 ± 40.3 ; $p > 0.05$), nor in variability (experimental: 49.1 ± 9.00 ; control: 60.4 ± 18.7 ; $p > 0.05$).

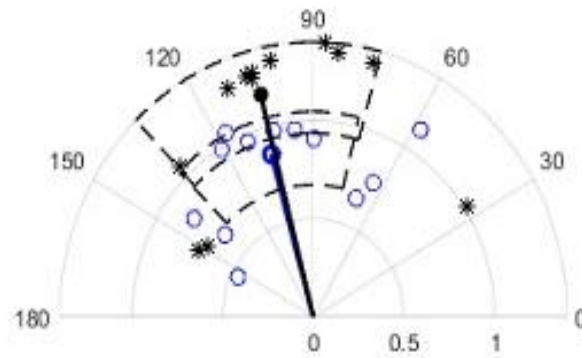
Figure 2: Presents values from the phase plane of angular acceleration versus angular velocity for hip-ankle, hip-knee, and knee-ankle joints, revealing no significant differences in coordination values across all joint pairs ($p > 0.05$). Coordination values for the experimental group were hip-ankle: 88.6 ± 18.2 , hip-knee: 88.7 ± 6.00 , knee-ankle: 90.3 ± 18.1 , compared to control values of hip-ankle: 86.5 ± 3.3 , hip-knee: 89.3 ± 4.4 , knee-ankle: 85.4 ± 5.00 . Variability Findings: The variability for hip-ankle (a-2) in the experimental and control groups was 51.9 ± 6.2 and 49.8 ± 5.7 , respectively. There was no significant difference ($p > 0.05$). Significant differences were found for hip-knee ($p = 0.027$, $d = 0.50$) and knee-ankle ($p = 0.001$, $d = 0.95$) between groups.

Figure 3: Displays coordination and variability values from the phase plane of angular jerk versus angular acceleration for hip-ankle, hip-knee, and knee-ankle joints, with no significant differences in coordination values between groups for any joint pairs ($p > 0.05$). Coordination values for the experimental group were hip-ankle: 103.5 ± 31.4 , hip-knee: 75.1 ± 36.7 , knee-ankle: 122.3 ± 29.2 ; control group values were hip-ankle: 109.8 ± 28.8 , hip-knee: 91.0 ± 35.3 , Knee-ankle: 110.5 ± 27.2 . Variability results showed no significant differences for hip-ankle joint movements between groups (experimental: 51.2 ± 7.7 , control: 51.3 ± 5.6 , $p > 0.05$). The variability in the hip-knee joints was 49.7 ± 7.7 for the experimental group and 62.8 ± 15.2 for the control group. The knee-ankle joint values were 48.7 ± 9.1 for the experimental group and 63.5 ± 9.9 for the control group. The between-group differences in the variability of the hip-knee ($p = 0.015$, $d = 0.54$) and knee-ankle ($p = 0.001$, $d = 0.99$) joints were significant.

a



b



c

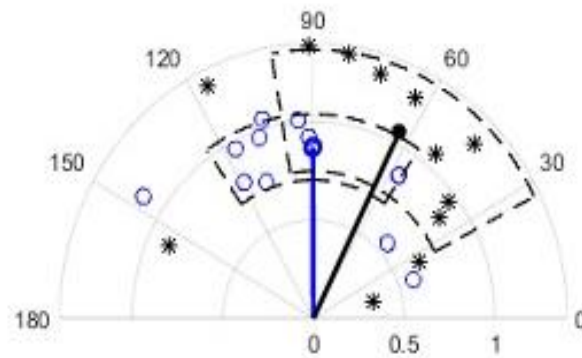
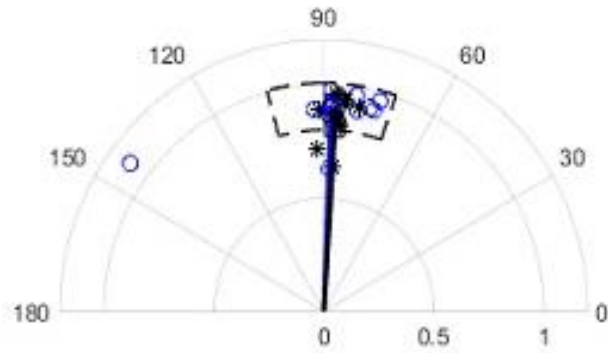
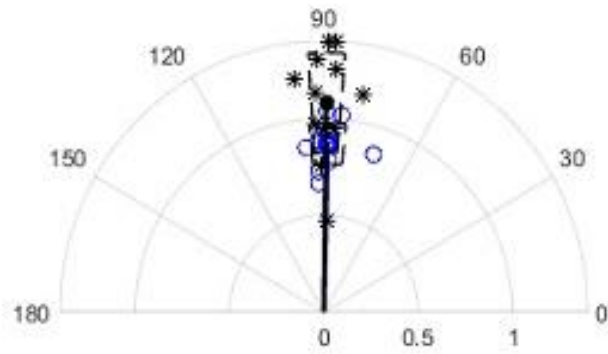


Figure 1. Calculated coordination and variability values from the phase plane of velocity versus angle for the hip-ankle (a-1), hip-knee (b-1), and knee-ankle (c-1) joints.

a



b



c

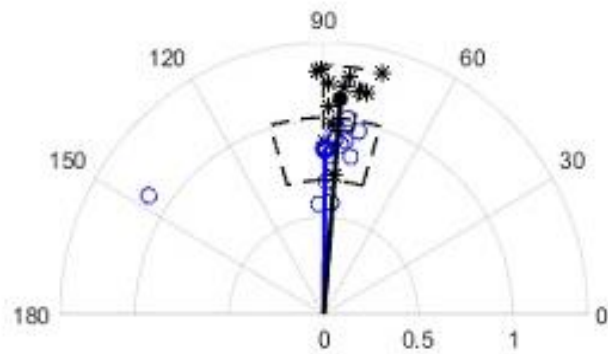
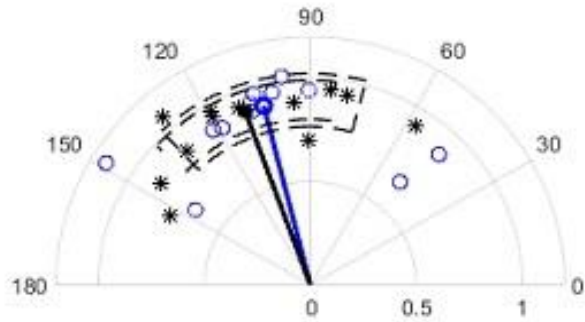
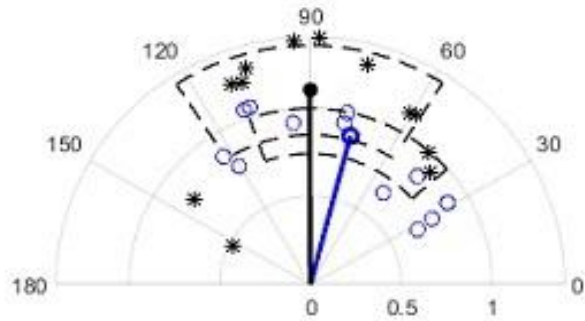


Figure 2. Calculated coordination and variability values from the phase plane of acceleration versus velocity for the hip-ankle (a-2), hip-knee (b-2), and knee-ankle (c-2) joints.

a



b



c

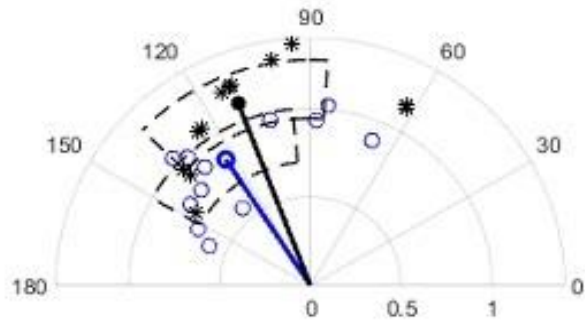


Figure 3. Calculated coordination and variability values from the phase plane of jerk versus acceleration for the hip-ankle (a-3), hip-knee (b-3), and knee-ankle (c-3) joints.

4. Discussion:

This study aimed to investigate the impact of ACL-R on the coordination and variability of lower limb joints using continuous relative phase (CRP) analysis in the AP direction during balance control in the SLS position. The findings indicated that the average coordination (movement phase difference) for the hip-ankle joints in the velocity-angle phase plane was significantly higher in individuals with ACL-R compared to healthy controls, indicating a reduction in coordination between these joints. Additionally, the variability of coordination was lower in ACL-R participants for hip-knee joints in all three phase planes, and knee-ankle joints in the acceleration -velocity and jerk-acceleration phase planes when compared to healthy individuals. Previous research has primarily focused on lower limb joint coordination during tasks such as single-leg jumps and rhythmic coordination, while studies specifically examining SLS remain limited. Most findings indicate reduced coordination of hip-ankle joints in the velocity-angle phase plane during these tasks (33, 34).

The lower extremity acts as a linked chain (11). The unique biomechanical composition of the lower limbs and the sequential interactions among the ankle, knee, and hip joints suggest a coordinated system (11). Consequently, This interconnectedness suggests that an injury, like one impacting the knee joint or ACL, seldom leads to dysfunction limited to just one joint (11). According to Kiefer et al (2013) indicates that in individuals who have undergone ACL reconstruction (ACLR), the absence of functional mechanoreceptors in the grafted tissue can disturb the coordination of the ankle-hip joints (14). Alterations in coordination and movement patterns elevate the risk of recurrent injuries and osteoarthritis in individuals with ACLR (35).

The current study's findings on hip-knee joint coordination variability align with Park et al (2021) (5). but contradict the results of Shi et al (2021) (11), Blache et al. (2017) (23), and Srinivasan et al. (2018) (36). These studies examined coordination variability of hip-knee joint across tasks like 60-degree cutting, mid-stance gait, maximal vertical single-leg jumps, and one-leg hopping. Coordination variability is essential for adapting to environmental changes and accommodating shifting movement patterns (11).

Although ACLR surgery is generally effective in restoring mechanical stability at the knee, there is conflicting evidence regarding the restoration of sensory function post-ACL-R (1, 37). The absence of proper neural feedback mechanisms may result in alterations in coordination variability (36). This study indicates reduced joint coordination variability in ACL-R individuals, suggesting possible neuromuscular sensorimotor deficits related to neuromuscular control (4). Diminished joint variability suggests a more rigid system, potentially leading to decreased adaptability to external perturbations (11, 38). This lowered coordination variability could be interpreted pathologically as adopting a cautious action strategy due to fear or movement discomfort (5), potentially increasing the risk of non-contact injuries in a less flexible system.

The current study emphasizes the importance of the knee in coordination and coordination variability during single-leg balance control. The central nervous system likely employs various performance criteria to plan movements, such as minimum jerk, minimum torque change, or minimum angle jerk, which are models proposed to describe the smoothness of human movement (39). Therefore, in this study, the level of coordination and coordination variability was calculated in the phase planes of angular velocity vs. angle, acceleration vs. velocity, and jerk vs. acceleration in three joint pairs. Considering acceleration and jerk variables in the current study can be viewed as a comprehensive assessment of joint performance in individuals with ACL-R.

While ACL reconstruction restores the mechanical stability of the joint, the restoration of sensory and motor function remains a subject of controversy (1). Impaired motor functions, such as joint coordination and coordination variability in individuals with ACL-R, elevate the risk of re-injury during various sports activities (4). The findings indicate that mechanosensitive nerve endings of the ACL play a role in providing information to the central nervous system (CNS) about the position and movement of the knee joint. This is indirectly supported by the impairment in the ability to recognize the position of the knee in space, known as joint position sense, in individuals ACL-R.(40, 41) Individuals with ACLR may exhibit lower mean amplitude compensatory responses in muscles compared to healthy individuals due to altered regulation of joint and muscle stiffness as a result of abnormalities in the gamma muscle spindle system of patients with ACLR compared to healthy individuals.Indeed, abnormal gamma loop sensitivity has been reported after ACLR (42). and may alter muscle spindle signals, which are known to play a major role in signaling information about limb position in terms of muscle length (43). The capacity of a joint to remain stable in the

face of disturbances appears to rely on its stiffness, which, in addition to other factors, is also affected by the stiffness of the surrounding muscles (44). The stiffness of joints and muscles can be adjusted dynamically through changes in the intensity of muscle activation (45). Therefore, increased activation of the muscles surrounding a joint leads to increased joint stiffness, enhancing the joint's ability to withstand external forces (resulting in greater dynamic stability). Conversely, lower levels of muscle contraction may reduce an individual's capacity to resist perturbation (46) (47).

Therefore, designing optimal rehabilitation protocols to restore natural movement patterns and reduce the risk of injury in ACL-R individuals is essential. The goals of a rehabilitation program after anterior cruciate ligament reconstruction (ACLR) in athletes can be to restore the strength and function needed for daily activities, increase neuromuscular control of the lower extremities through basic movement patterns, and adapt prescribed weight training to facilitate a gradual return to team sports.(48).Paying attention to lower limb coordination after ACL-R can be valuable for improving rehabilitation strategies (4). Blache et al. (2016) suggested that to enhance motor control, rehabilitation protocols should incorporate multi-joint and multiplanar movements (23).

It is suggested that researchers in future studies investigate how treatments may modify the adaptability and motor coordination of the affected lower limb. They should focus on designing and implementing rehabilitation programs with optimal timing to restore natural movement patterns and reduce the risk of re-injury in individuals after ACL-R.

Research Limitation:

The results of this study are limited to male ACLR participants, and the relatively small sample size may reduce the ability to detect smaller effects. To enhance the generalizability of the findings, it is recommended that future research be conducted with larger and mixed-gender samples. Additionally, the current study's focus solely on sagittal plane kinematics limits the understanding of multiplanar movement patterns. It is suggested that research be conducted alongside electromyography (EMG) data to examine muscle activation patterns and their effects on joint coordination changes.

Ethical Considerations

Ethical approval was obtained from the ethics committee at the Institute of Physical Education and Sports Sciences (Code IR.SSRC.REC.1404.091).

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Conflict of interest

The authors declared no conflict of interest.

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