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Research Article

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Dynamic Stability Impairment in Adults With Complete Anterior Cruciate Ligament Rupture

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Abstract

This study investigated the impact of complete anterior cruciate ligament (ACL) rupture on the dynamic stability of adults during the initiation phase of gait. The sample consisted of 32 adults, divided into two groups: G1, with 16 adults who presented a complete ACL rupture, and G2, with 16 physically active adults without injuries. Displacements of the Center of Pressure (CoP) in the anteroposterior (CoP_AP) and mediolateral (CoP_ML) directions were evaluated across the anticipatory, first step execution, and second step execution phases. The results revealed that the ACL-injured group showed significantly greater CoP_AP and CoP_ML displacements during the anticipatory and first step execution phases, indicating compensatory strategies to maintain dynamic balance. In the second step execution phase, no significant differences were observed between the groups, suggesting a progressive stabilization of the gait pattern. It was concluded that adults with ACL injuries rely on anticipatory postural adjustments and muscular compensations to control balance during gait initiation. These findings underscore the importance of incorporating dynamic balance training, strengthening, and proprioception into rehabilitation programs to minimize compensatory overload and promote a more efficient and safer gait.

Keywords: Anterior cruciate ligament, Center of pressure, Dynamic stability, Anticipatory postural adjustments, Rehabilitation

1. Introduction

Gait initiation is a complex motor task essential for dynamic stability, involving anticipatory postural adjustments (APAs) that enable the transition from a stable posture to dynamic movement, ensuring both safety and continuity of motion [1-3]. In adults with a complete anterior cruciate ligament (ACL) injury, one of the primary stabilizing structures of the knee, this process may be compromised, resulting in reduced dynamic postural control and a need for compensatory adaptations that may be insufficient to prevent falls and additional injuries [4-6].

The ACL plays a critical role in stabilizing the knee during activities that require rapid changes in direction or deceleration. When injured, proprioceptive feedback is altered, impairing the control of both the center of pressure (CoP) and the center of mass (CoM), which are essential for maintaining stability during gait [7,8]. In adults with ACL injuries, a significant reduction in the ability to generate effective APAs is observed, increasing the risk of falls during the initial phase of gait [9-11].

Under normal conditions, APAs prepare the body for gait initiation by shifting the CoP toward the supporting foot, allowing controlled movement of the CoM toward the new base of support [12,13]. However, in individuals with ACL injuries, CoP displacement is often limited, resulting in less efficient CoM control during the initial movement [14,15]. This inadequate CoP displacement may lead to increased CoM oscillation, especially in the mediolateral plane, where stability is more challenged [16-18].

To compensate for the lack of stability, adults with ACL injuries often rely on increased activation of stabilizing muscles, such as those in the ankle, particularly the soleus and tibialis anterior [19,20]. However, this reliance leads to a stiffer and less efficient movement pattern, impacting propulsion and increasing rigidity during the transition phase to dynamic movement [21,22]. Such biomechanical adaptations may temporarily protect the injured knee but create gait patterns that increase joint load and muscular effort, compromising movement safety and efficiency [23,34].

Studies reveal that adults with ACL injuries exhibit a reduced base of support and shorter initial step length, reflecting an attempt to minimize CoM oscillation and reduce fall risk [25-27]. Force platform analysis and kinematic methods confirm that CoP displacement amplitude is lower in these patients, indicating significant difficulty in stabilizing the CoM during the initial steps [28,29].

Age also has a notable impact on dynamic stability during gait initiation, as older adults face greater challenges in controlling balance due to declines in muscle strength and reaction speed [30,31]. The combination of advanced age and ACL injury further exacerbates the challenges for postural control, increasing the risk of falls and secondary injuries [32,33].

Longitudinal studies indicate that individuals with an ACL injury are more likely to experience falls due to limitations in rapid postural response, particularly during directional changes or on uneven surfaces [34,35]. Over time, these short-term biomechanical adaptations result in rigid movement patterns that increase joint wear and place added stress on muscles, which may further compromise the ability to perform safe and effective movements [36,37].

This study aims to investigate the impact of complete ACL rupture on the dynamic stability of adults during the gait initiation phase, focusing on anticipatory postural adjustments and CoP behavior, providing a detailed analysis of response patterns and postural adaptations in individuals with this condition.

2. Methodology

2.1. Participants

The sample in this study consisted of 32 adults of both sexes, divided into two groups. Group 1 (G1) included 16 adults with a complete anterior cruciate ligament (ACL) injury, with an average age of 25.41 years (±6.71), average height of 1.73 m (±1.9), and average body mass of 74.71 kg (±5.16). Group 2 (G2), composed of 16 physically active adults without injury, had an average age of 23.21 years (±0.89), average height of 1.69 m (±0.05), and average body mass of 77.51 kg (±11.59), as shown in Table 1.

CHARACTERISTICS	G1	G2
Number of Subjects	16	16
Age (years)	25.41 (±6.71)	23.21 (±0.89)
Height (m)	1.73 (±1.9)	1.69 (±0.05)
Body Mass (kg)	74.71 (±5.16)	77.51 (±11.59)
Legend: G1 – adults with a complete ACL injury; G2 – physically active adults without injury. Data for age, height, and body mass are presented as mean ± standard deviation.		

Table 1: Sample Characterization

2.2. Inclusion and Exclusion Criteria

For the inclusion criteria, Group 1 (G1) included adults with a clinical diagnosis and/or imaging-confirmed complete anterior cruciate ligament (ACL) injury. For Group 2 (G2), only physically active adults without a history of ACL injury or any other significant injury that could compromise knee stability were included. In both groups, participants were between 18 and 35 years of age and had the physical condition required to participate in stability and gait evaluation activities. Additionally, all participants provided informed consent prior to the start of the study.

The exclusion criteria covered factors that could compromise data integrity and participant safety. Individuals with a history of injuries or previous surgeries in the lower limbs, aside from the ACL injury in G1, were excluded, including other ligament injuries, fractures, or significant muscular injuries that could affect knee stability or gait. Participants with neurological, vestibular, or other medical conditions affecting balance, proprioception, or gait were also excluded. Furthermore, individuals taking medications that could interfere with motor coordination, balance, or the ability to participate in study activities were excluded. Lastly, individuals with a body mass index (BMI) above 30 kg/m² were excluded to avoid the inclusion of participants with overweight or obesity, which could impact the stability and gait patterns analyzed.

2.3. Ethical Aspects

This study obtained approval from the Research Ethics Committee, as per the opinion number 24845019.2.0000.5083, and adhered to current ethical resolutions, including Resolution 466/12 of the National Health Council. Participation of adults in the research was conditional upon completing and signing the Informed Consent Form (ICF), in which they authorized their participation and were informed of their right to withdraw consent at any stage of the study. Data collection and processing followed the principles of the General Data Protection Law (LGPD), ensuring the privacy and confidentiality of participants' personal information and upholding ethical standards, respect for autonomy, and data protection principles.

2.4. Experimental Protocol

During the gait initiation phase, participants stood on the plantar pressure platform with their feet comfortably positioned, one on each side of the platform. After an auditory signal indicating the start of the activity, participants took a step off the platform, alternating between the limb affected by the ACL injury and the healthy limb, repeating the process in each trial.

Plantar pressure data were recorded using a Baroscan plantar pressure platform by Podotech (Brazil), with dimensions of 50x50 cm. The platform contains 4,096 capacitive sensors, allowing for precise measurements of the pressure exerted on participants' feet. A sampling rate of 100 Hz was used, ensuring detailed data capture at each phase of movement.

2.5. Analyzed Variables

The displacement amplitude of the center of pressure (CoP) in the anteroposterior (CoP_AP) and mediolateral (CoP_ML) directions was expressed in centimeters, representing the distance between the maximum and minimum CoP positions in each direction [1-3]. The CoP trajectory during the gait initiation phase was divided into three distinct phases, in accordance with established protocols in the literature on postural control and dynamic stability [4-10]:

- **Phase 1 - Anticipatory:** This phase began with the start of the movement and extended until the CoP reached its most lateral position toward the swing foot. This phase is crucial for anticipatory postural planning and the initial shift of the CoP.
- **Phase 2 - First Step Execution:** This phase began at the end of the anticipatory phase and extended until the CoP reached its most lateral position toward the support foot. It is characterized by the body weight shift and the transfer of stability to the new support base.
- **Phase 3 - Second Step Execution:** This phase began at the end of the first step and extended until the end of the movement, when the CoP shifted forward. In this phase, the CoP advances to sustain propulsion and stabilize the body in the new support position.

These phases allowed for a detailed analysis of CoP behavior and postural adaptation of participants during gait initiation, as described in previous studies on dynamic stability and balance control in adults with ACL injury and individuals without injuries [13-16].

2.6. Statistical Analysis

Statistical analysis was conducted using Minitab 21 software (Minitab). Initially, the normality of distributions and data homogeneity were assessed using the Kolmogorov-Smirnov test. Subsequently, the non-parametric Tukey test was applied to investigate possible intragroup differences in the analyzed variables. A significance level of $p \leq 0.05$ was adopted, establishing a statistical threshold for considering results as statistically significant. Variables were described as mean ± standard deviation.

3. Results

Table 2 presents data on the Center of Pressure (CoP) behavior in the anteroposterior (CoP_AP) and mediolateral (CoP_ML) directions during the gait initiation phases for Group 1 (G1 - adults with complete ACL injury) and Group 2 (G2 - physically active adults without injury).

PHASE	G1	G2	P-VALUE
Anticipatory Phase			
CoP_AP_1 (cm)	5.76 (±2.36)	1.22 (±0.51)	0.001*
CoP_ML_1 (cm)	8.53 (±2.36)	1.18 (±0.44)	0.001*
First Step Execution			
CoP_AP_2 (cm)	9.92 (±1.60)	6.12 (±1.84)	0.003*
CoP_ML_2 (cm)	10.72 (±2.28)	8.17 (±1.84)	0.062
Second Step Execution			
CoP_AP_3 (cm)	1.17 (±0.75)	0.86 (±0.66)	0.330
CoP_ML_3 (cm)	1.92 (±0.89)	1.90 (±0.65)	0.120
Legend: G1 – adults with complete ACL injury; G2 – physically active adults without injury. Tukey test significant at p < 0.05. Data are presented as mean ± standard error.			

Table 2: Center of Pressure Behavior During Gait Initiation Phases

In the anticipatory phase, Group 1 showed significantly higher displacements for both parameters. CoP_AP presented a mean value of 5.76 ± 2.36 cm in Group 1, compared to 1.22 ± 0.51 cm in Group 2, with a statistically significant difference (p=0.001). Similarly, CoP_ML showed a mean of 8.53 ± 2.36 cm in Group 1 compared to 1.18 ± 0.44 cm in Group 2, also with statistical significance (p=0.001). These results indicate a considerable increase in CoP displacement for the ACL-injured group during the initial phase of movement.

In the first step execution phase, Group 1 maintained a higher CoP_AP displacement, with a mean of 9.92 ± 1.60 cm, compared to 6.12 ± 1.84 cm in Group 2, with a statistically significant difference (p=0.003). However, for CoP_ML, although Group 1 showed a higher mean value (10.72 ± 2.28 cm) compared to Group 2 (8.17 ± 1.84 cm), this difference was not statistically significant (p=0.062), suggesting variability in postural response in the mediolateral direction during this phase.

In the second step execution phase, no statistically significant differences were observed between the groups. Group 1 showed mean values of 1.17 ± 0.75 cm for CoP_AP and 1.92 ± 0.89 cm for CoP_ML, while Group 2 displayed means of 0.86 ± 0.66 cm and 1.90 ± 0.65 cm, respectively, with p-values above the significance threshold (CoP_AP: p=0.330; CoP_ML: p=0.120).

These results suggest that individuals with an ACL injury demonstrate greater CoP displacement, particularly in the early phases of gait initiation, reflecting potential compensatory adaptations for stability during dynamic movement.

4. Discussion

The analysis of Center of Pressure (CoP) behavior during gait initiation phases among adults with complete anterior cruciate ligament (ACL) injuries and adults without injuries provided important insights into postural adaptation and dynamic balance control in these individuals. Studies show that the ACL plays a crucial role in knee stability, especially during movements that involve rapid changes in direction and deceleration, such as gait initiation [1-3]. In individuals with a complete ACL injury, the loss of functional stability requires compensatory strategies that may alter gait patterns, a phenomenon corroborated by literature on dynamic postural control [4-6].

In the anticipatory phase, the significantly greater CoP displacement in the anteroposterior (CoP_AP) and mediolateral (CoP_ML) directions for the ACL-injured group (G1) highlights the additional effort needed to stabilize the body before movement. These findings align with studies emphasizing the importance of anticipatory postural adjustments (APAs) in preparing the body for weight displacement, facilitating control of the CoM and CoP during gait initiation [7,8]. The increased CoP_AP and CoP_ML displacements suggest adaptation in response to instability, consistent with findings indicating that ACL injury impacts proprioceptive feedback and APA coordination [9].

This heightened reliance on APAs in the injured group suggests an attempt to compensate for proprioceptive deficiencies associated with an injured ACL. Previous studies suggest that loss of proprioceptive feedback causes the neuromuscular system to adopt alternative patterns to promote dynamic stability, particularly during movement phases where the CoP needs to shift rapidly [10,11]. These findings are especially relevant for understanding how ACL injuries not only compromise knee stability but also force a reconfiguration of balance strategies that affect the entire body.

The literature also indicates that to compensate for knee instability, individuals with ACL injuries often rely on ankle stabilizer muscles, particularly the soleus and tibialis anterior, which play a fundamental role in modulating the CoP [12,13]. Activation of these muscles is an attempt to increase stability during the initial phase of gait, reflected in the greater CoP displacements observed in the injured group. Biomechanical studies suggest that these adjustments aim to create a wider support base, enabling better CoM control during the anticipatory phase [14,15].

In the first step execution phase, the significantly greater CoP_AP displacement in Group 1 suggests a need for additional dynamic adjustment during movement. This finding aligns with studies observing adaptive gait patterns in individuals with ACL injuries, who require greater weight displacement to maintain balance while transferring the CoM toward the new support foot [16]. This behavior is frequently described in the literature as a "launching strategy" of the CoM, a necessary adaptation to overcome knee joint instability [17,18].

Interestingly, for mediolateral displacement (CoP_ML) in the first step execution phase, the difference between the groups was not statistically significant, although the injured group showed higher average values. Literature suggests that this variation may be a complex postural response, in which the body utilizes multiple mechanisms to minimize lateral sway while compensating for knee instability [19]. These mechanisms may include reduced lateral CoM displacement to avoid loss of balance, as observed in studies on compensatory gait patterns in ACL injuries [20,21].

The data from the second step execution phase showed stabilization of the CoP in both directions, suggesting that the neuromuscular system was able to adapt to initial instability and reduce the need for major adjustments. This finding is consistent with studies indicating progressive stabilization of the CoM and CoP as gait movement progresses [22,23]. According to the literature, this adaptive capacity allows the body to regain postural control in a continuous movement, reducing the demand for compensatory responses as the gait pattern stabilizes [24].

The lack of significant difference in the second step phase between groups may be explained by the gradual stabilization that occurs during movement, as the neuromuscular system tends to regulate the CoP to promote a more stable CoM displacement [25]. Studies on postural control in adults with ACL injuries demonstrate that after the initial phase of gait, the system can optimize CoM displacement, reducing the need for abrupt corrections [26,27]. This adaptive behavior reinforces the importance of APAs for successful gait in unstable conditions.

The increased CoP amplitude in Group 1 throughout the initiation phases highlights the additional compensation required to maintain balance. Literature suggests that these strategies are crucial for individuals with ACL injuries to safely transition to gait [28,29]. However, the constant demand for compensatory adjustments may pose an overload risk to the musculoskeletal system, increasing the likelihood of secondary injuries and accelerating joint wear [30].

These findings have important implications for ACL injury rehabilitation. The increased CoP displacement amplitude, especially in the initial gait phases, suggests that rehabilitation programs should focus on strengthening and proprioceptive training of ankle and knee stabilizer muscles to improve CoM control and reduce reliance on compensatory adjustments [31,32]. Recent studies indicate that specific training to promote dynamic stability can help reduce CoP displacement amplitude and improve balance in individuals with ACL instability [33,34].

Moreover, the findings suggest that rehabilitation should emphasize APA efficiency to reduce the time and amplitude of necessary adjustments during gait initiation. Literature shows that APA training can lead to improved postural performance and a more efficient response to dynamic balance demands, which would be particularly beneficial for patients with ACL injuries [35,36]. This focus may decrease reliance on distal muscles, such as those of the ankle, reducing compensatory effort and potentially preventing the development of gait patterns that overload other joints [37].

Additionally, considering that progressive stabilization was observed in the second step phase, gait training may be beneficial in encouraging adaptation to continuous movement. Studies suggest that repetitive practice of gait patterns with a focus on stability can promote neuromuscular reprogramming that minimizes demands for excessive corrective adjustments in individuals with ACL injuries [38,39]. Thus, exercises aimed at fluidity and control of continuous movement could complement APA training.

In conclusion, the findings underscore the relevance of rehabilitation approaches that focus on both proximal and distal control, recognizing the impact of ACL injury on overall body stability. As suggested in the literature, a comprehensive rehabilitation approach including balance, strength, and proprioceptive training can provide significant improvements in functionality and postural safety for patients with ACL injuries [40].

5. Conclusion

Based on the objective of this study, which aimed to investigate the impact of complete anterior cruciate ligament (ACL) rupture on the dynamic stability of adults during the gait initiation phase, it was concluded that individuals with ACL injuries demonstrated significantly greater Center of Pressure (CoP) displacements in the anteroposterior and mediolateral directions during the initial phases of gait. These findings indicate that the injured group adopted compensatory strategies to address joint instability, especially during the anticipatory and first-step execution phases.

The greater CoP displacement amplitudes observed suggest that individuals with ACL injuries rely on postural adaptations to maintain dynamic balance, associated with compensatory activation of stabilizing muscles, particularly in the ankle. While these strategies may be effective in the short term, they can overload the musculoskeletal system and increase the risk of secondary injuries over time.

These results underscore the importance of incorporating anticipatory postural adjustment (APA) training and CoM control into rehabilitation programs to reduce dependency on excessive compensations and promote a safer, more efficient gait pattern. Rehabilitation focused on strengthening, proprioception, and dynamic stabilization may be essential for improving functionality and minimizing the risk of new injuries in individuals with ACL impairment.

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