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Research article

Exploring the interplay between ankle muscle strength, postural control, and pain intensity in chronic ankle instability: A comprehensive analysis

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A R T I C L E I N F O

Keywords:
Chronic ankle instability
Ankle muscle strength
Postural control
Pain mediation

A B S T R A C T

Background: Chronic Ankle Instability (CAI) is a common musculoskeletal condition characterized by recurring ankle sprains and impaired postural control (PC). Understanding the relationship between ankle muscle strength, PC, and the role of pain is essential for effective management.
Objectives: This prospective cross sectional study aimed to 1. Compare ankle isometric muscle strength (IMS) and PC between CAI and asymptomatic sides. 2. Assess the correlations between ankle IMS and PC and explore the potential mediating effect of pain in individuals with CAI.
Methods: A total of 44 individuals with CAI, were enrolled in the study. Ankle IMS (dorsiflexors, plantar flexors, invertors, and evertors) was measured using a dynamometer, while PC was evaluated using sway parameters (anterior-posterior and medial-lateral sway, ellipse area). Pain levels were reported using a Visual Analog Scale.
Results: The CAI ankles exhibited significantly lower ankle IMS in all muscle groups compared to the asymptomatic ankles ($p < 0.001$). Additionally, the CAI side showed increased postural sway and a larger ellipse area ($p < 0.001$), indicating reduced PC. Negative correlations were observed between ankle IMS and PC parameters on the CAI side, with dorsiflexor strength showing correlations ranging from −0.423 to −0.387, plantar flexor strength ranging from −0.423 to −0.371, invertor strength ranging from −0.412 to −0.238, and evertor strength ranging from −0.451 to −0.365 ($p < 0.001$). Mediation analysis revealed that pain played a significant mediating role in connecting ankle IMS and PC parameters among individuals with CAI, with statistical significance ($p < 0.05$).
Conclusions: Individuals with CAI exhibit weaker ankle IMS and diminished PC in comparison to their healthy side. Moreover, pain was identified as a mediator in the relationship between ankle IMS and PC in CAI. These findings underscore the importance of addressing both ankle IMS and pain in the rehabilitation and management of CAI.

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1. Introduction

Chronic Ankle Instability (CAI) is a prevalent and debilitating condition that afflicts a considerable portion of the population [1]. It is marked by recurrent ankle sprains, persistent pain, and a perceived sensation of joint instability [2]. These recurring injuries can have lasting consequences, including reduced physical activity, impaired quality of life, and an elevated risk of subsequent musculoskeletal problems [3]. Understanding the intricate factors contributing to CAI and its consequences is crucial for devising effective interventions and improving the well-being of those affected [4].

Ankle isometric muscle strength (IMS) plays a central role in the pathophysiology of CAI. This condition often arises from ligamentous and neuromuscular deficits, with a key focus on the muscles surrounding the ankle joint [5]. In individuals with CAI, there is a common observation of reduced ankle muscle strength, especially in the muscles responsible for dorsiflexion and plantarflexion movements [6]. This decrease in strength compromises the muscles' ability to provide sufficient joint stability during weight-bearing activities, increasing susceptibility to ankle sprains and recurrent instability episodes [7]. Additionally, diminished ankle IMS can negatively affect proprioception, which is the body's awareness of its position in space, further impairing balance and stability [8]. Investigating ankle IMS nuances in CAI is crucial for comprehending the condition's underlying mechanisms and for developing targeted rehabilitation strategies to restore strength and enhance postural control (PC) in affected individuals [9].

PC is a fundamental component of everyday activities, and it is particularly impaired in individuals dealing with CAI [10]. CAI is typically distinguished by recurring ankle sprains and a perceived feeling of joint instability, greatly affecting an individual's capacity to sustain equilibrium and steadiness across diverse tasks [11]. Those with CAI frequently exhibit deficits in PC, particularly during single-leg stance tasks [12]. These deficits manifest as increased sway and a reduced ability to make rapid adjustments in response to changes in surface or body position [12]. Such compromised PC not only elevates the risk of further ankle injuries but also hinders everyday activities and athletic performance [13]. Comprehending the complexities of PC in CAI holds significance in formulating precise rehabilitation strategies to enhance balance and stability [14]. Ultimately, these interventions can lead to an improved quality of life for individuals grappling with this condition [15]. Thus, objective one aims to compare ankle IMS and PC between the CAI and asymptomatic sides.

The relationship between ankle IMS and PC is a fundamental aspect of CAI research [12]. While it is intuitive that stronger ankle muscles should contribute to better PC, the extent and nature of this relationship remain an area of active investigation [16]. Objective two aims to shed light on this relationship by quantifying the correlation between ankle IMS and PC in individuals with CAI. By understanding this association, we can elucidate the key factors influencing PC and contribute to the management of CAI.

In addition to exploring the direct relationship between ankle IMS and PC, it is crucial to consider the role of pain in this context [17]. Pain is a common symptom experienced by individuals with CAI and can significantly impact their ability to engage in physical activities and maintain PC [18]. Objective three seeks to explore the potential mediation effect of pain, shedding light on its role in the intricate relationship between ankle IMS and PC. Unraveling how pain may act as a mediator can offer valuable insights into the underlying mechanisms of CAI, paving the way for tailored interventions. Furthermore, it underscores the significance of effective pain management in enhancing PC and overall functional outcomes for individuals grappling with CAI [19].

In summary, chronic ankle instability represents a complex condition with wide-ranging implications for individuals' daily functioning. The goals of this study were to comprehensively assess and compare ankle IMS and PC in CAI-afflicted side compared to their asymptomatic side. Additionally, the study aimed to establish correlations between ankle IMS and PC while exploring the mediating role of pain in this context. Through the pursuit of these objectives, we aim to enhance our comprehension of CAI and set the stage for more targeted interventions, ultimately leading to improved outcomes for those grappling with this condition.

2. Materials and methods

2.1. Study design, settings, and ethics

This prospective comparative cross-sectional study was carried out at physical therapy clinics from May 2022 to June 2023, in the biomechanics laboratory for outcome assessments. Ethical clearance was secured from the IRB at King Khalid University with Approval Number [REC/2021-234-567].

2.2. Participants

Purposive sampling was employed in selecting forty-four participants from outpatient clinics affiliated with King Khalid University and community sports centers. The diagnosis of CAI was established based on predefined criteria, including self-reported recurrent ankle sprains, clinical evaluations, and confirmation by a sports medicine specialist. The inclusion criteria for individuals with CAI encompassed participants who met the following conditions [20]: a documented history of one or more lateral ankle sprains within the preceding six months, a reported history of "giving way" episodes or sensations of ankle instability, and a score equal to or greater than "11″ on the Identification of functional ankle instability questionnaire [20]. Individuals were excluded from the study if they met any of the following criteria: the presence of lower extremity neuro-musculoskeletal abnormalities, excluding ankle sprains, which could impede the testing process, a documented history of prior lower extremity fractures, dislocations, or surgeries, and the existence of cardiorespiratory or neurological disorders.

2.3. Ankle muscle strength measurement

The evaluation of strength was performed using an isometric handheld dynamometer (MicroFET- Hoggan Scientific. LLC), with meticulous calibration before each participant's assessment. Four specific directions were examined, including dorsiflexion (Fig. 1A), plantar flexion (Fig. 1B), inversion (Fig. 1C), and eversion (Fig. 1D). To ensure consistent testing conditions, all participants were positioned in a subtalar neutral alignment. Stabilization of the lower leg was achieved by securing it to prevent any inadvertent movements. The determination of the subtalar neutral position followed the congruency method, which identifies the position where the foot is neither supinated nor pronated, with the examiner palpating the equally prominent positions of the medial and lateral aspects of the talus. It is important to note that the participant's positioning varied for each tested direction, as depicted in Fig. 1 (A to D).

The handheld dynamometer was strategically placed at the superior aspect of the metatarsal heads, depending on the specific foot positioning required. Detailed instructions were given to the participants, instructing them to exert maximum force either by pulling or pushing against the device in each direction. The investigator, utilizing both hands, countered this force for a standardized duration of 3 s per trial. All manual muscle-testing movements and positions adhered to the established protocols outlined by Brown et al. [21]. Each participant underwent three consecutive trials for each direction, with a brief 10-s rest interval between trials. The peak force exerted by the participant, measured in newtons, was selected for subsequent analysis. This approach ensured consistency and accuracy in the assessment of muscular strength.

2.4. Postural control assessment

PC assessment was conducted using computerized posturography, a sophisticated and objective method for quantifying an individual's ability to maintain balance [22]. To ensure the reliability and consistency of the PC assessment, meticulous standardization measures were implemented. Firstly, the computerized posturography equipment was diligently calibrated before each assessment session to ensure precise and accurate data collection, eliminating potential sources of measurement error. Secondly, the assessment was carried out in a controlled and quiet environment to minimize distractions or external influences that could affect participants' PC. Thirdly, participants were instructed to be barefooted to maintain uniformity and eliminate the potential impact of footwear variations on the measurements. Before commencing the PC assessment, participants received clear instructions on the testing procedure to ensure their understanding and cooperation. They were informed about the assessment's objectives and were familiarized with the computerized posturography equipment. During the assessment, a range of PC variables was quantified to provide a comprehensive assessment of participants' balance control. These variables included Anterior-Posterior (A-P) sway in millimeters, Medial-Lateral (M-L) sway in millimeters, and the calculation of the Ellipse area in square millimeters (mm^2). The sway area quantified the overall range of postural sway, while the sway path length reflected the cumulative distance traveled during postural adjustments. These

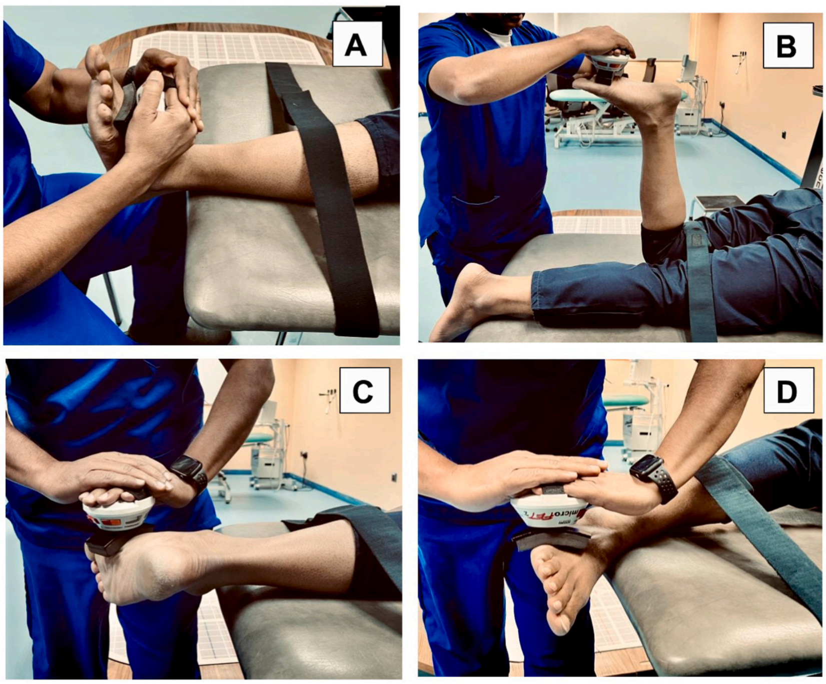

Fig. 1. Different positions for isometric testing using the handheld dynamometer (MicroFet, Hoggan Scientific, LLC, Salt Lake City, UT, USA) are depicted, encompassing dorsiflexion (A), plantar flexion (B), inversion (C), and eversion (D).

standardized procedures ensured the reliability and accuracy of the PC measurements, facilitating a thorough evaluation of participants' balance control abilities. The PC assessment was specifically tailored to concentrate on static balance tasks. During these tasks, participants were required to stand on a single leg, with the testing side being selected. Their other leg was flexed away from the force platform (Fig. 2).

The primary objective for participants was to maintain a stable standing position for a duration of 30 s while keeping their gaze firmly fixed on the computer screen, which featured a prominent "X." The assessment of PC was conducted using computerized posturography, with both the affected ankle afflicted with CAI and the asymptomatic leg being tested. The order of testing between the two legs was randomized to minimize any potential order-related biases. This carefully designed condition allowed for an investigation into the influence of visual input and focused attention on postural control. By assessing both the affected ankle and the asymptomatic leg in a randomized order, the study aimed to obtain comprehensive insights into the participants' postural control abilities in relation to CAI. To ensure the robustness and reliability of the data, each participant completed this task three times. From these three trials, the best performance was selected for subsequent analysis. This rigorous approach to data collection and trial selection was implemented to guarantee the accuracy of the PC measurements, allowing for a more comprehensive and precise evaluation of participants' balance control abilities. Recognizing the potential for fatigue or learning effects during the assessment, a 1-min rest period was thoughtfully incorporated between each trial. This strategic interval between trials aimed to minimize any potential carryover effects, allowing participants to approach each trial with a refreshed focus and minimizing the risk of confounding variables affecting the results.

2.5. Pain assessment

Pain assessment using the Visual Analogue Scale (VAS) was a widely employed method for quantifying and evaluating pain intensity. This scale provided a simple yet effective way for individuals to express their pain experiences visually. It typically consisted of a horizontal line, usually 100 mm in length, with endpoints representing "no pain" at one extreme and "worst pain imaginable" at the other. CAI Patients were asked to mark a point on this line that best corresponded to the intensity of their pain, with the distance from

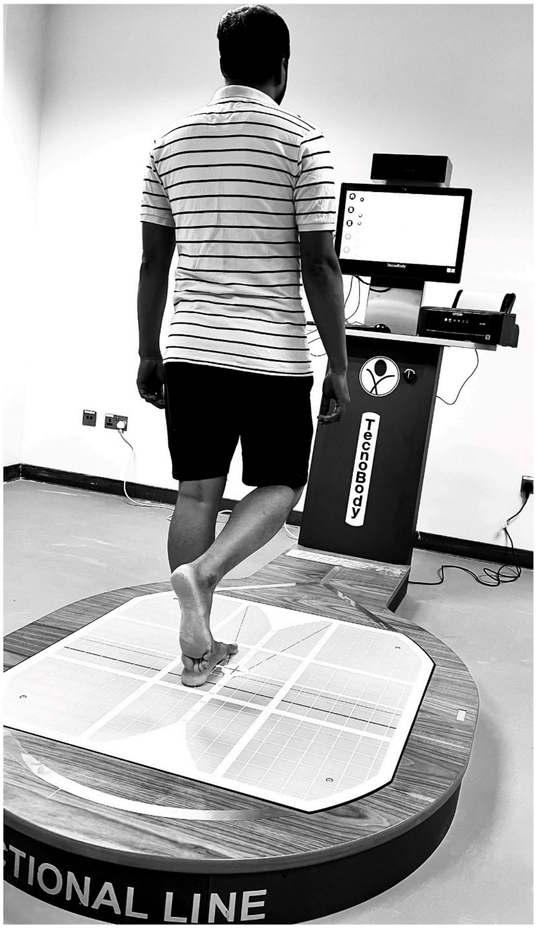

Fig. 2. Postural control assessment conducted through computerized posturography, focusing on the subject's performance in the single-leg standing position.

the "no pain" end serving as a numerical representation of pain intensity.

The data collection process was conducted by experienced physical therapists with a minimum of 5 years of post-doctoral experience in sports medicine, ensuring standardized procedures and accurate assessments. All authors involved in the study actively participated in the data collection process. Each author contributed their expertise and experience to ensure comprehensive and accurate data gathering.

2.6. Sample size calculation

In the sample size calculation for this study, the effect size was determined by referencing the findings from a relevant prior study, specifically the research conducted by Alfaya et al. [10] With a moderate effect size (Cohen's $d = 0.5$), an alpha level of 0.05, indicating a 5% risk of Type I error, and a desired statistical power level of 0.80, equivalent to a 20% risk of Type II error, the calculation yielded a requirement for 44 participants, accounting for potential attrition. This method enhanced the research's scientific validity and ensured that it was adequately powered to meet its objectives.

2.7. Data analysis

The normality of the data was analyzed using the Shapiro-Wilk tests. Descriptive analyses were presented as mean ± standard error in all measured variables. Independent sample *t*-test was used to detect significant differences between the two sides. To assess the correlation between ankle IMS and PC in the CAI side, Pearson's correlation coefficient was applied. Furthermore, a multiple linear regression analysis was carried out to explore the mediating role of pain. The thresholds for the correlations coefficient (r) were as follows: weak: >0.1–0.30; moderate: >0.31–0.60; strong: >0.61. All analyses were conducted in SPSS 27.0 (IBM Corp.; Chicago, IL, USA) or SAS 9.4 (SAS; Cary, NC, USA). The significant level was set at $\alpha = 0.05$.

3. Results

Table 1 provides an overview of the demographic characteristics of the study population, including 44 individuals with CAI. The average age of the CAI individuals was 23.5 years, with a standard deviation (SD) of 5.2, and the gender distribution was 23 males and 21 females. The mean height of CAI individuals was 173.2 cm (SD = 7.1), and their average weight was 68.7 kg (SD = 9.3). The mean Body Mass Index (BMI) for CAI individuals was 22.9 (SD = 2.6). The distribution of injured sides showed that 33 individuals had the injury on their right side, while 11 had it on their left side. Furthermore, in terms of sports and activity levels, 16 individuals reported low activity, while 28 reported high activity levels. These demographic characteristics provide important context for the subsequent analyses and findings related to ankle muscle strength, postural control, and the mediating influence of pain in individuals with CAI.

When comparing individuals with a CAI-afflicted ankle to those with a healthy ankle, Table 2 highlights notable differences in both ankle IMS and PC parameters. In individuals with CAI, there were significant differences observed in all ankle IMS parameters (Dorsiflexors, Plantar Flexors, Invertors, and Evertors), with the CAI side showing lower strength values compared to the asymptomatic side, resulting in mean differences ranging from 51.19 to 57.76 N and Cohen's d effect sizes ranging from 1.47 to 1.91 (all $p < 0.001$). Moreover, for PC parameters, including anterior-posterior (A-P) sway, medial-lateral (M-L) sway, and ellipse area, the CAI side exhibited substantial differences compared to the asymptomatic side, with mean differences of −5.06 mm, −2.93 mm, and −423.64 mm^2, respectively, and Cohen's d effect sizes of −1.63, −1.03, and −1.91 (all $p < 0.001$). These results indicate significant disparities in both ankle IMS and PC between the CAI and healthy sides, emphasizing the impact of CAI on these parameters. Fig. 3 presents the comprehensive stabilometric (Fig. 3A) and trunk sway (Fig. 3B) analyses comparing the CAI side with the healthy side. The results indicate significantly greater stabilometric and trunk sway on the CAI side in comparison to the asymptomatic side.

Table 3 presents the correlation coefficients between ankle IMS and PC parameters in individuals with CAI. The data reveals statistically significant negative correlations ($p < 0.001$) between ankle IMS and PC. Specifically, dorsiflexors strength exhibited a negative correlation with anterior-posterior sway (A-P Sway) at −0.387, medial-lateral sway (M-L Sway) at −0.412, and ellipse area at −0.423. Similarly, plantar flexors strength showed negative correlations with A-P Sway (−0.423), M-L Sway (−0.388), and ellipse area (−0.371). Invertors strength displayed negative correlations with A-P Sway (−0.238), M-L Sway (−0.345), and ellipse area (−0.412). Evertor strength also exhibited negative correlations with A-P Sway (−0.365), M-L Sway (−0.378), and ellipse area (−0.451). These

Table 1
Demographic characteristics of study population.

Characteristic	Chronic Ankle Instability individuals (n = 44) (mean ± SD)
Age (years), Mean ± SD	23.5 ± 5.2
Gender (Male/Female)	23/21
Height (cm), Mean ± SD	173.2 ± 7.1
Weight (kg), Mean ± SD	68.7 ± 9.3
Body Mass Index (BMI), Mean ± SD	22.9 ± 2.6
Injured side (right/left)	33/11
Sports and activity, n (low: high)	16/28
Pain Intensity (Visual analogue scale 0–100 mm)	55.63

Table 2
Quantitative Comparison of Ankle Muscle Strength and Postural Control between CAI and asymptomatic side.

Characteristic	Chronic Ankle Instability side (n = 44) (mean ± SD)	Asymptomatic side (n = 44) (mean ± SD)	Mean Diff	Cohen's d	p-value
Dorsiflexors Strength (N)	112.62 ± 22.32	165.8 ± 33.67	53.18	1.63	<0.001
Plantar Flexors Strength (N)	186.61 ± 33.34	237.8 ± 44.36	51.19	1.47	<0.001
Invertors Strength (N)	103.8 ± 18.45	159.76 ± 31.64	55.96	1.81	<0.001
Evertors Strength (N)	102.8 ± 20.98	160.56 ± 34.36	57.76	1.91	<0.001
A-P Sway (mm)	9.62 ± 2.17	4.56 ± 1.39	−5.06	−1.63	<0.001
M-L Sway (mm)	7.56 ± 2.45	4.63 ± 1.21	−2.93	−1.03	<0.001
Ellipse Area (mm^2)	996.75 ± 233.23	573.11 ± 123.46	−423.64	−1.91	<0.001

A-P Sway, Anterior to posterior sway; M-L Sway, Medial to lateral sway; N, newtons; mm, millimeters.

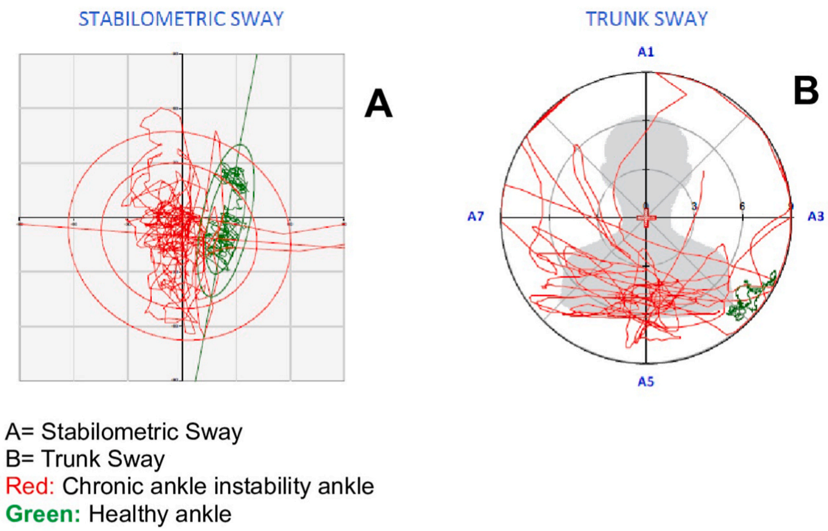

Fig. 3. Illustrates the stabilometric (A) and trunk sway (B) differences between the chronic ankle instability side (in red) and the healthy side (in green).

Table 3
Correlation between Ankle Muscle Strength and Postural control in chronic ankle instability.

Parameter	APS in mm	MLS in mm	COP - EA in mm^2
	R	r	R
Dorsi flexors Strength (N)	−0.387**	−0.412**	−0.423**
Plantar Flexors Strength (N)	−0.423**	−0.388**	−0.371**
Invertors Strength (N)	−0.238**	−0.345**	−0.412**
Evertors Strength (N)	−0.365**	−0.378**	−0.451**

N, newton; r, correlation coefficient, Anterior to Posterior Sway; MLS, Medial to lateral sway, COP-EA, Centre of pressure Ellipse Area **, p-value significant at <0.001.

findings suggest that individuals with weaker ankle IMS tend to have greater postural instability, as indicated by increased sway and larger ellipse area. The negative correlation coefficients emphasize the inverse relationship between ankle IMS and PC in the CAI side.

Table 4 explored the mediating role of pain on the relationship between ankle IMS and PC in individuals with CAI, and several significant findings emerged. Across various test variables involving different ankle muscle strengths, pain, and postural sway measurements, significant total effects (B) were observed, ranging from 0.53 to 0.69. These total effects indicated a substantial impact of ankle IMS and pain on PC parameters. Furthermore, significant direct effects (c-Path) were present for all the strength variables, with values ranging from 0.14 to 0.35, highlighting their direct influence on PC irrespective of pain. Most notably, significant indirect effects (b-Path) mediated by pain were evident in multiple cases, with values ranging from 0.05 to 0.12, emphasizing pain's role as a mediator in the relationship between ankle IMS and PC.

Table 4
Mediating role of pain on the relationship between ankle muscle strength and postural control in chronic ankle instability.

Test Parameters	Total effect	Direct effect	Indirect effect
	B	B	B
Dorsiflexors Strength (N) x Pain x APS	0.53**	0.14**	0.06*
Plantar Flexors Strength (N) x pain x APS	0.53**	0.21**	0.05*
Invertors Strength (N) x Pain x APS	0.69**	0.17**	0.08*
Evertors Strength (N) x Pain x APS	0.57**	0.15**	0.12*
Dorsiflexors Strength (N) x Pain x MLS	0.44**	0.32**	0.06*
Plantar Flexors Strength (N) x pain x MLS	0.64**	0.31**	0.05*
Invertors Strength (N) x Pain x MLS	0.59**	0.27**	0.10*
Evertors Strength (N) x Pain x MLS	0.57**	0.25**	0.12*
Dorsiflexors Strength (N) x Pain x COP-EA	0.59**	0.17**	0.10*
Plantar Flexors Strength (N) x Pain x COP-EA	0.57**	0.15**	0.12*
Invertors Strength (N) x Pain x COP-EA	0.53**	0.35**	0.06*
Evertors Strength (N) x Pain x COP-EA	0.64**	0.31**	0.05*

N, newtons; APS, Anterior to Posterior Sway; MLS, Medial to lateral sway, COP-EA, Centre of pressure Ellipse Area; ** = indicates statistical significance ($p < 0.001$).

4. Discussion

This study aimed to assess ankle IMS and PC on the CAI side to the asymptomatic side and explore the potential mediating role of pain. The results revealed significant differences between the CAI side and the asymptomatic side, with the CAI side exhibiting weaker ankle IMS and increased postural sway. Furthermore, negative correlations were observed between ankle IMS and PC parameters within the CAI ankle, suggesting that stronger ankle muscles were associated with improved PC. Mediation analysis indicated that pain significantly mediated the relationship between ankle IMS and PC parameters in the CAI leg, highlighting its role as an intermediary factor influencing PC.

The significant differences observed between the CAI side and the asymptomatic side concerning ankle IMS and postural sway can be attributed to several factors. CAI individuals often endure recurrent ankle sprains, which can result in structural damage and mechanical impairments within the ankle joint [23]. These impairments, including ligament laxity and altered joint mechanics, can compromise their ability to generate adequate muscle strength and control [24,25]. Consequently, ankle muscle weakness is a common consequence of chronic ankle instability [25]. The recurring injuries and disuse of the affected ankle can lead to muscle atrophy and weakness, especially in the dorsiflexors, plantar flexors, invertors, and evertors [26]. This muscle weakness directly affects their capacity to maintain stability during weight-bearing activities [27]. Moreover, CAI individuals frequently exhibit altered neuromuscular control strategies [15]. These alterations encompass reduced proprioception and disrupted muscle recruitment patterns, which can disrupt the coordination necessary for maintaining PC [28]. These neuromuscular alterations often manifest as increased postural sway, particularly evident in challenging conditions such as single-leg stance. Additionally, pain, a prevalent symptom of CAI, significantly impacts motor control and PC [29]. It can induce protective muscle guarding and alter movement patterns, ultimately contributing to heightened postural sway [29]. Furthermore, the fear of ankle instability further exacerbates motor control and stability issues [30]. To cope with their ankle instability, individuals with CAI may develop adaptive movement strategies [31]. While these strategies can help prevent giving way or experiencing pain, they can also lead to an increase in postural sway as the body attempts to find alternative means to maintain balance [31]. These various factors collectively contribute to the observed differences in ankle IMS and postural sway between CAI ankles and their asymptomatic sides [20].

To justify these results, previous studies have shown similar findings [32,33]. For instance, research has consistently demonstrated that CAI individuals exhibit weaker ankle IMS and increased postural sway compared to healthy controls (Hoch et al., [32] Khalaj et al., [33]. Additionally, investigations into the neuromuscular deficits in CAI individuals have revealed altered muscle activation patterns and proprioceptive impairments (Sugimoto et al., [34] Jeon et al., [35]). Moreover, studies have highlighted the role of pain and fear of instability in influencing motor control and PC in CAI [36]; Wikstrom et al., [37].

The negative correlations observed between ankle IMS and PC parameters in the CAI ankles can be attributed to a combination of compensatory mechanisms, neuromuscular adaptations, muscle co-contraction, feedback mechanisms, and adaptive strategies [38–40]. Weaker ankle muscles may prompt individuals with CAI to employ these mechanisms to enhance stability [39,41]. This includes recruiting other muscle groups, increasing muscle activation, and using co-contraction to counteract instability [41]. The feedback of sensory information indicating instability may also lead to heightened muscle activation [42]. Moreover, individuals with stronger ankle muscles may have greater confidence in their ability to maintain balance, allowing them to employ more stable postural strategies [43,44]. Collectively, these factors contribute to the observed negative association between ankle IMS and PC within the CAI side.

The negative correlations between ankle IMS and PC parameters in individuals with CAI are supported by previous research. A study by Suttmiller et al. [45] found that reduced ankle IMS was associated with increased postural sway in individuals with CAI. This suggests that weaker muscles may necessitate compensatory mechanisms to maintain stability [45]. Additionally, a study by Rosen et al. [46] demonstrated that CAI individuals exhibited altered neuromuscular control strategies, further highlighting the link between muscle weakness and postural instability [46]. Furthermore, a study by Helly et al. [47] indicated that improved ankle IMS through rehabilitation interventions led to enhanced PC in CAI patients [47]. These findings collectively support the notion that stronger ankle muscles are associated with improved PC in individuals with CAI, as observed in the present study.

The mediation effect observed in this study, where pain significantly mediated the relationship between ankle IMS and PC parameters in individuals with CAI, can be attributed to several interconnected factors [10]. First, pain is known to disrupt proprioception and sensorimotor control in the ankle joint [10,34]. This disruption can lead to altered muscle recruitment patterns, creating a less efficient neuromuscular control system [48]. As a result, CAI individuals may exhibit impaired PC due to their pain-induced neuromuscular adaptations [31]. Second, the fear of experiencing pain or recurrent ankle instability can prompt CAI individuals to adopt protective strategies during weight-bearing activities, such as avoiding certain movements or shifting their body weight in a way that minimizes pain [2,49]. These protective strategies can negatively impact PC and stability by introducing compensatory movements that deviate from the optimal motor control patterns [49]. Lastly, persistent pain can contribute to a cycle of disuse and muscle weakness, further impairing the ankle's ability to generate the necessary strength for maintaining stability [19]. Consequently, the mediation effect of pain in this study highlights the multifaceted role of pain in influencing both the neuromuscular control and PC of CAI individuals, ultimately emphasizing the importance of addressing pain in rehabilitation strategies for this population [19].

The mediation of pain in the relationship between ankle IMS and PC in CAI individuals is substantiated by several studies. Oh et al. [50] demonstrated how pain alters ankle proprioception, affecting neuromuscular control. Cai et al. [51] highlighted pain's disruptive impact on motor control and PC. Schmid et al. [52] explored pain-related adaptations and fear of re-injury, linking psychosocial factors to PC. Adal et al. [1] established the connection between pain, muscle weakness, and instability. Additionally, Ye [53] and Rosen [46] delved into the complex interplay of pain and PC. Together, these studies underscore pain as a pivotal mediator, elucidating its role in shaping the intricate relationship between ankle IMS and PC in CAI individuals.

4.1. Clinical significance

The findings of this study hold clinical significance in the context of managing CAI. The observed weaknesses in ankle IMS and impaired PC in CAI individuals underscore the importance of targeted rehabilitation interventions. Addressing muscle weakness, especially in the dorsiflexors, plantar flexors, invertors, and evertors, should be a priority in rehabilitation program. Clinicians can incorporate exercises that aim to enhance muscle strength and control into their treatment plans, potentially mitigating the increased risk of recurrent ankle sprains and associated functional limitations. Moreover, understanding the mediating role of pain provides insights into the multifaceted nature of CAI and highlights the need for comprehensive assessment and pain management as an integral component of rehabilitation strategies. Clinicians should consider addressing pain not only as a symptom but as a mediator influencing PC. This study underscores the importance of a holistic approach to CAI management, encompassing muscle strength, neuromuscular control, and pain management to optimize outcomes and restore functional stability.

4.2. Limitations and areas of future research

In addressing the study limitations, it's important to acknowledge certain flaws inherent in the selected research design and potential biases. Our study adopted a cross-sectional design, inherently limiting our ability to establish causality or infer temporal relationships between variables. While cross-sectional studies provide valuable insights into associations, longitudinal or interventional designs would offer a more robust understanding of the dynamic interplay between ankle muscle strength, postural control, and pain intensity in chronic ankle instability (CAI) over time. Additionally, our study sample may have been biased towards individuals with right-sided CAI, potentially leading to an overrepresentation of right-side participants, which could limit the generalizability of our findings. Future studies should aim for more balanced participant recruitment to mitigate this bias. Despite these limitations, our study contributes valuable insights into the multifaceted nature of CAI and provides a foundation for further research to explore these relationships in more depth.

This study opens avenues for future research to expand our understanding of CAI and its management. Longitudinal studies can investigate the temporal relationships between ankle muscle strength, postural control, and pain, shedding light on causal pathways. Exploring the impact of various rehabilitation interventions on these relationships is essential for refining treatment strategies. Additionally, investigating psychosocial factors such as fear of re-injury and their interplay with pain and postural control could enhance our comprehension of CAI. The use of advanced imaging techniques, like electromyography and functional MRI, may provide insights into the neuromuscular mechanisms underlying these relationships. Moreover, studies examining the effectiveness of tailored, multidisciplinary rehabilitation approaches that consider both musculoskeletal and pain-related factors are warranted. Lastly, expanding research to encompass diverse populations and injury severities will contribute to the generalizability and clinical applicability of findings, ultimately improving the management of CAI.

5. Conclusions

In summary, CAI ankles exhibited significant weaknesses in ankle IMS, particularly in the dorsiflexion, plantar flexors, invertors, and evertors, compared to the asymptomatic side. This underscores the importance of targeted strength training interventions to address these deficits and enhance functional stability. Furthermore, our study reveals that the CAI side experiences increased postural sway, indicative of impaired PC. The negative correlations observed between ankle IMS and PC parameters within the CAI ankle emphasize the pivotal role of muscle strength in maintaining stability during weight-bearing activities. These findings emphasize the need for comprehensive rehabilitation strategies that encompass both muscle strength and neuromuscular control to optimize outcomes in CAI management. Perhaps one of the most intriguing findings is the mediating role of pain. Pain significantly influences the relationship between ankle IMS and PC in CAI individuals. This underscores the importance of assessing and managing pain comprehensively in CAI rehabilitation protocols. Clinicians should consider pain not merely as a symptom but as an intermediary factor that can substantially impact PC.

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Institutional Review Board statement

The study was conducted following the Declaration of Helsinki and approved by the Institutional Review Board at King Khalid University (protocol code: REC# 67/65/654 and date of approval: 30-05-2022)." for studies involving humans.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Data availability statement

The data associated with this study have been deposited into the publicly available Zenodo repository and can be accessed at https://doi.org/10.5281/zenodo.10639140.

CRediT authorship contribution statement

Mastour Saeed Alshahrani: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ravi Shankar Reddy:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adel Alshahrani:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Ajay Prashad Gautam:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Saud F. Alsubaie:** Writing – review & editing, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Ajay Prashad Gautam reports financial support was provided by King Khalid University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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