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Correlation Analysis Between Ankle Proprioception and Biomechanical Characteristics in Patients with Chronic Ankle Instability

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Abstract

Purpose

To compare ankle proprioception and biomechanical features between individuals with chronic ankle instability (CAI) and healthy controls, and to investigate the interplay between proprioceptive deficits and biomechanical alterations in CAI.

Methods

Thirty-six male participants (18 CAI, 18 healthy controls) were recruited. Proprioception was evaluated using a joint position reproduction test, quantifying absolute errors. For biomechanical assessment, participants performed six single-leg hopping tests. An infrared motion-capture system (Vicon T40, 200 Hz) and a force platform (Kistler, 1000 Hz) simultaneously captured ankle kinematics/kinetics. Ankle muscle activation was recorded via surface electromyography (Noraxon, 2000 Hz).

Results

Participants with CAI demonstrated significantly greater joint position sense errors in plantarflexion ($P = 0.002$), dorsiflexion ($P = 0.001$), inversion ($P = 0.011$), and eversion ($P = 0.022$) compared with controls. Compared with healthy controls, individuals with CAI exhibited greater peak ankle inversion angles (P=0.039), reduced peak ankle dorsiflexion angles (P=0.029), and lower activation of the tibialis anterior (P=0.019) and peroneus longus (P=0.033) during single-leg landing. Correlation analyses indicated significant associations between inversion position sense errors and both peak ankle dorsiflexion angle (r = -0.584, $P = 0.011$) and peak ankle inversion angle (r = -0.622, $P = 0.006$) in the CAI group.

Conclusion

Individuals with CAI exhibit impaired ankle proprioception and altered biomechanical characteristics compared with healthy controls. Decreased proprioception in the ankle was correlated with biomechanical defects. These findings suggest that proprioceptive impairments may contribute to persistent biomechanical abnormalities in CAI. Comprehensive interventions targeting proprioceptive enhancement may improve ankle biomechanics in this population.

Keywords: chronic ankle instability; biomechanics; proprioception; correlation analysis

Introduction

Ankle sprain is one of the most common injuries in sports, accounting for approximately 14% of all sport-related injuries[1]. Unfortunately, only a small proportion of individuals fully recover after a lateral ankle sprain without residual impairment[2], whereas nearly 40% experience recurrent sprains and progress to chronic ankle instability (CAI)[3,4]. CAI encompasses a complex interplay of sensory-perceptual, path mechanical, and motor-behavioral impairments[4], leading to considerable discomfort and functional limitations. Moreover, long-term joint instability may predispose individuals to post-traumatic osteoarthritis and substantially reduce quality of life[5,6]. The high cost of CAI management also imposes a substantial economic burden on both patients and the healthcare system[7]. Therefore, identifying the underlying deficits in individuals with CAI and developing effective therapeutic strategies are crucial for improving patient quality of life and alleviating the overall healthcare burden.

Ankle biomechanical deficits of the ankle joint are considered one of the most critical risk factors contributing to recurrent ankle sprains in individuals with CAI[4]. Specifically, during high-demand motor tasks such as single-leg landings, greater ankle inversion and internal rotation angles, reduced dorsiflexion angles, and decreased activation of the tibialis anterior and peroneus longus muscles increase the risk of ankle sprain[8,9]. Biomechanics relying on integrated sensory input, central nervous system processing, and motor output[10-12]. Among these components, proprioceptive information plays a crucial role in detecting and correcting movement deviations[13]. Proprioception provides information about joint position and velocity through mechanoreceptors (e.g., Ruffini endings), which is the basis for feedforward control of dynamic postural adjustments[13]. To prevent potential injury, the nervous system must acquire proprioceptive input and appropriately generate feedforward or reflexive motor commands to stabilize the joint[14]. Insufficient neuromuscular responses to sensory feedback may lead to ankle sprain[15]. Furthermore, interventions aimed at improving proprioception have been shown to enhance lower-extremity biomechanics, suggesting a potential interaction between sensory input and biomechanical function[16,17]. An ankle sprain may damage peripheral mechanoreceptors, disrupting afferent sensory transmission on the injured side and suppressing γ-motoneuron activation, thereby resulting in abnormal biomechanical patterns[12].

Elucidating the association between biomechanical characteristics of the ankle joint and proprioception in patients with CAI may facilitate the development of more targeted interventions, such as the combination of balance and proprioceptive training. However, the precise relationship between ankle biomechanical characteristics and proprioception in CAI patients remains to be fully elucidated. Therefore, this study aimed to investigate the differences in ankle joint biomechanics and proprioception between patients with CAI and healthy controls. A further objective was to determine the correlation between ankle joint biomechanics and proprioception in CAI patients. The study hypothesized that (1) compared with healthy controls, patients with CAI would exhibit greater ankle inversion and internal rotation angles, reduced dorsiflexion angles, lower activation of the tibialis anterior and peroneus longus muscles, and impaired proprioception; and (2) ankle proprioception would be associated with eversion angle and peroneus longus activation.

Methods

Participants

Sample size was determined as a priori using G*Power 3.1.2. Based on the calculation, a total of 36 participants were required to achieve a statistical power of 0.80 (effect size $d = 0.85$, $\alpha = 0.05$) for an independent-samples *t*-test. Consequently, 18 male participants with CAI and 18 male healthy controls were enrolled.

The inclusion criteria for the CAI group were as follows: (1) male, aged 18–30 years, with right limb dominance; (2) Tegner activity level ≥ 7; (3) diagnosis of functional ankle instability; (4) at least one episode of significant right lateral ankle sprain within the past 12 months, associated with pain and swelling and resulting in ≥3 weeks of inability to participate in sports; (5) ≥2 episodes of giving-way and/or recurrent sprain on the injured side within the preceding 6 months, accompanied by subjective perception of ankle instability; (6) a Cumberland Ankle Instability Tool (CAIT) score ≤ 24, indicating impaired ankle function[18]; and (7) a Functional Ankle Instability Identification score ≥ 11. The inclusion criteria for healthy controls were as follows: (1) male, aged 18–30 years, with right limb dominance; (2) Tegner activity level ≥ 7; (3) no history of ankle sprain; (4) CAIT score = 30, indicating normal ankle function and absence of instability[18]; and (5) Functional Ankle Instability Identification score = 0[19].

Exclusion criteria for all participants included: (1) history of lower-limb fracture or surgery; (2) presence of neuromusculoskeletal disorders; (3) history of significant cognitive impairment; and (4) incomplete data during testing or inability to complete assessments as required. All participants were informed of the testing procedures and provided written informed consent prior to participation. The study protocol was approved by the Medical Ethics Committee of Wuhan Sports University (No. 2024113).

Proprioception Data Acquisition

Proprioceptive data were collected using a goniometer to assess the sense of joint position of the dominant and injured ankle. Participants wore blindfolds and earplugs to eliminate visual and auditory cues. Starting from the neutral ankle position, they were asked to memorize and replicate joint angles at 15° plantarflexion, 15° dorsiflexion, 15° varus, and 15° valgus, performing six trials in each direction[20]. Absolute errors in joint position sense were calculated, and the mean value of the six trials was used for analysis.

Biomechanical Data Acquisition

Participants first completed a standardized warm-up routine, including bodyweight squats, lunges, high kicks, marching drills, and repeated vertical jumps. Subsequently, thirty-eight reflective markers were affixed at anatomical landmarks, including the bilateral anterior superior iliac spines, iliac crests, posterior superior iliac spines, greater trochanters, lateral and medial femoral condyles, lateral and medial malleoli, calcanei, toe tips, and the heads of the first and fifth metatarsals, with three additional markers placed on the lateral aspects of each thigh and shank[21,22]. Before electrode placement, the skin was abraded and cleaned with alcohol swabs to remove surface oils and keratin. Electrodes were then secured using 3M adhesive tape. According to SENIAM guidelines[23], surface EMG electrodes were placed on five ankle muscles: tibialis anterior, peroneus longus, lateral and medial gastrocnemius, and soleus.

Participants performed two to three familiarization trials before each testing session. For the single-leg jump-landing task, participants stood outside the force plate with arms crossed over the chest to eliminate arm-swing effects on marker tracking, following a standardized procedure. They squatted to a self-selected depth on the dominant (Healthy controls) or injured leg (CAI patients) and immediately jumped forward to land on the force plate[24]. A trial was considered successful if landing occurred within the motion capture volume and the participant-maintained balance for at least two seconds post-landing. Unsuccessful trials were repeated until six successful landings were obtained, and the mean values were used for analysis. Kinematic data were collected using a nine-camera infrared motion capture system (Vicon T40, 200 Hz), and kinetic data were acquired using a three-dimensional force plate (Kistler, 1000 Hz). Surface EMG signals were recorded using a 16-channel wireless system (Noraxon, MR3 3.6.20, USA) at a sampling rate of 1000 Hz.

Biomechanical Data Processing

Biomechanical data processing was performed using Visual 3D software (C-Motion, Inc) for kinematic and inverse dynamics analyses. A previously described method was employed to construct a 3D lower limb model[21,22], which was used to calculate three-dimensional ankle joint angles, moments, and power. Marker trajectories and force plate data were filtered using a low-pass Butterworth digital filter with a cutoff frequency of 12 Hz, which effectively minimizes artifacts during inverse dynamics analyses of high-impact activities [17,25]. Initial contact was defined as the first instant when the vertical ground reaction force exceeded 50 N[26]. The landing phase was defined as the period from initial contact to 100 ms post-contact, considered the phase when ankle sprains are most likely to occur [26]. The kinematic variables of interest include peak ankle dorsiflexion, inversion, and internal rotation angles during the landing phase. The kinetic variables of interest include peak ankle dorsiflexion, inversion, and internal rotation moments and power during the landing phase. Three-dimensional ankle joint angles were computed using Euler angles, determined by the relative angles between distal and proximal segments. Joint moments were calculated via inverse dynamics and normalized to body weight. Negative values for kinematic and kinetic variables corresponded to plantarflexion, eversion, and external rotation of the joint. EMG signals were band-pass filtered between 10 and 500 Hz. Muscle activation was assessed using the root mean square (RMS) values during the landing phase. RMS values were computed from the EMG envelopes for each muscle and normalized to the peak EMG values recorded during testing.

Statistical Analysis

Statistical analyses were conducted using SPSS version 25.0. A *p*-value of less than

0.05 was considered statistically significant. Continuous variables are presented as mean ± standard deviation (Mean ± SD). Normality of data distribution was assessed using the Shapiro-Wilk test, and homogeneity of variance was evaluated with Levene's test. Independent samples t-tests were employed for between-group comparisons of demographic characteristics, ankle proprioception, and biomechanical variables. Pearson correlation analysis was conducted for ankle biomechanical variables that showed significant differences between groups to examine the relationships between proprioception and biomechanical characteristics in patients with CAI. Correlation coefficients were interpreted as small (|r|=0.1–0.29), moderate (|r|=0.3–0.49), large (|r|=0.5–0.69), and very large (|r|≥0.7)[27].

Results

A total of 18 male patients with CAI and 18 male healthy controls were included. No significant differences were found between the two groups in terms of age, height, weight, body mass index (BMI), and Tegner scores ($P > 0.05$) (**Table 1**).

Table 1 Participant characteristics

	CAI patients (n=18)	Healthy controls (n=18)	*P*-value
Age (year)	21.4±1.6	21.1±1.7	0.552
Height (cm)	177.6±3.4	178.8±4.2	0.337
Weight (kg)	73.5±5.9	73.5±6.0	0.962
BMI (kg/m^2)	23.3±1.3	22.9±1.3	0.388
Tegner score	7.8±0.51	7.8±0.55	0.756

Notes: CAI: chronic ankle instability; BMI: body mass index.

Proprioceptive Characteristics

Patients with CAI exhibited significantly greater absolute errors in position sense for plantarflexion ($P = 0.002$), dorsiflexion ($P = 0.001$), varus ($P = 0.011$), and valgus ($P = 0.022$) compared to controls (**Figure 1**).

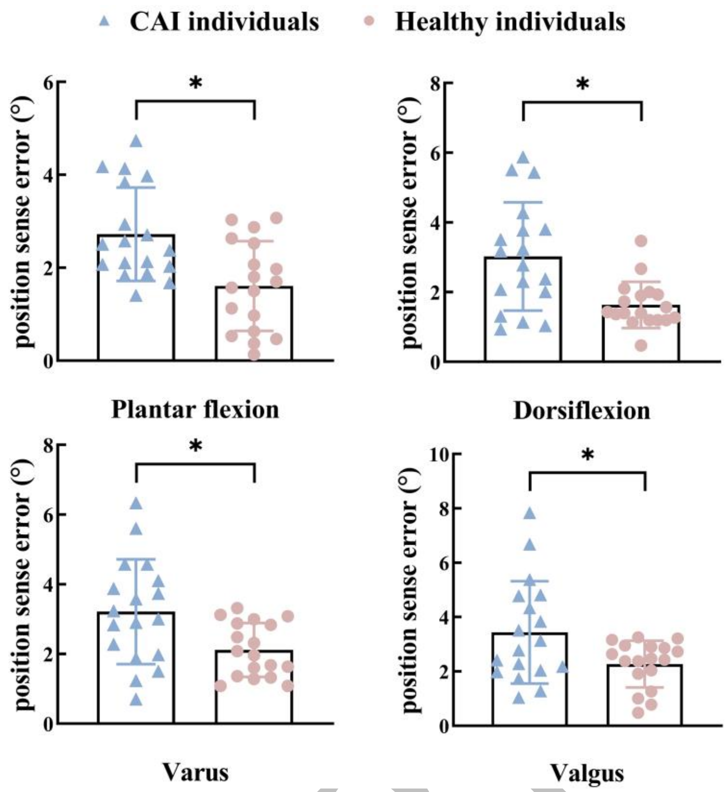

Figure 1 Proprioceptive characteristics of the ankle

Kinematic and Kinetic Characteristics

Compared to healthy controls, patients with CAI demonstrated significantly lower peak dorsiflexion angle (*P* = 0.029) and higher peak inversion angle (*P* = 0.039), peak internal rotation angle (*P* = 0.031), peak plantarflexion moment (*P* = 0.035), and peak plantarflexion power (*p* = 0.038) during the landing phase (**Table 2**).

Table 2. Kinematic and kinematic characteristics of the ankle

	CAI patients (n=18)	Healthy controls (n=18)	*P*-value
Peak ankle angle (°)			
Dorsiflexion	15.50±3.81	18.19±3.23	**0.029**
Inversion	11.00±3.72	8.35±3.68	**0.039**
Internal rotation	5.27±2.57	3.46±2.23	**0.031**
Peak ankle moment (Nm/kg)			
Dorsiflexion	-1.80±0.38	-1.56±0.26	**0.035**
Inversion	0.21±0.18	0.30±0.21	0.213
Internal rotation	0.13±0.11	0.16±0.10	0.372
Peak ankle power (J/kg)			
Dorsiflexion	-13.33±4.20	-10.63±3.20	**0.038**
Inversion	0.17±0.19	0.32±0.25	0.060
Internal rotation	0.26±0.17	0.26±0.13	0.875

Notes: CAI: chronic ankle instability.

Ankle Muscle Activation

Compared to healthy controls, patients with CAI exhibited significantly lower activation of the peroneus longus (P = 0.019) and tibialis anterior (P = 0.033), but higher activation of the lateral gastrocnemius (P = 0.019, **Figure 2**).

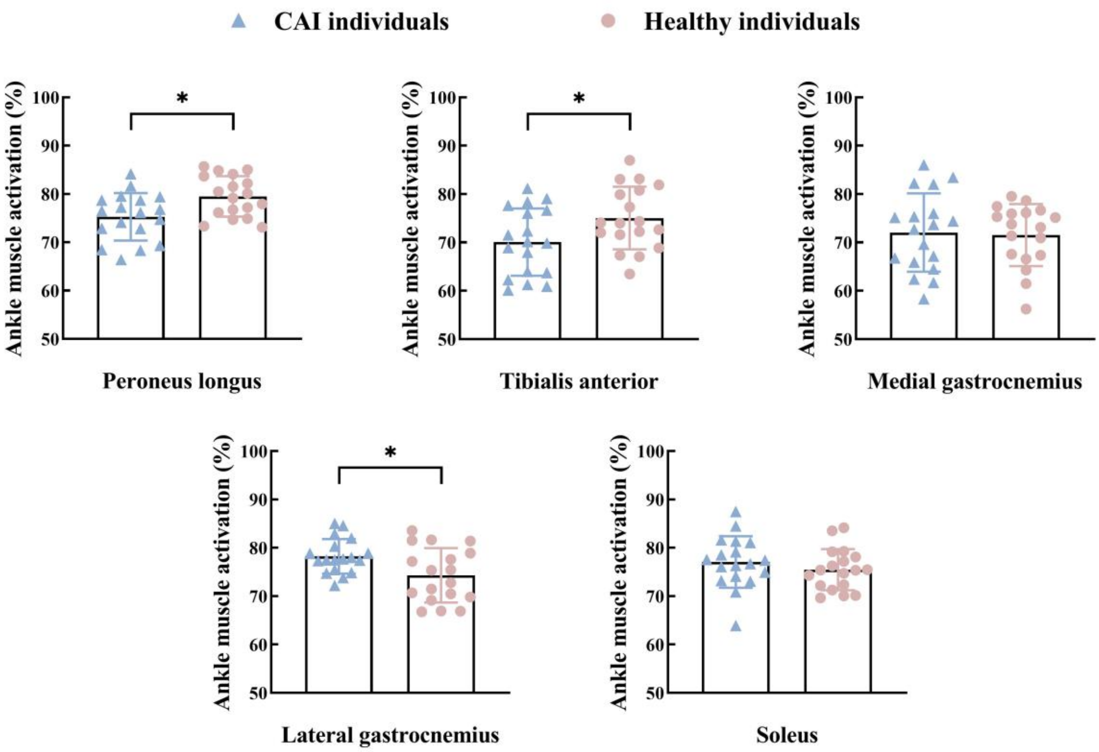

Figure 2 Characteristics of ankle muscle activation

Correlations Between Proprioception and Lower Limb Biomechanical Characteristics

Significant correlations were observed between ankle dorsiflexion position sense error and peak ankle dorsiflexion angle (r = -0.589, P = 0.010). Ankle inversion position sense error was significantly correlated with peak ankle dorsiflexion angle (r = -0.584, P = 0.011) and peak ankle inversion angle (r = -0.622, P = 0.006). Additionally, ankle eversion position sense error showed a significant correlation with peak ankle dorsiflexion angle (r = -0.541, P = 0.020). No significant correlations were found between other ankle proprioception measures and biomechanical variables (P > 0.05, **Table 3**).

Table 3. Correlation analysis between proprioception and lower limb biomechanical characteristics

Variable	Peak ankle dorsiflexion angle	Peak ankle inversion angle	Peak ankle internal rotation angle	Peak ankle plantar flexion moment
Plantar flexion position perception error (°)	-0.072 (0.777)	-0.076 (0.764)	-0.233 (0.353)	0.208 (0.408)

Dorsiflexion position perception error (°)	**-0.589 (0.010)**	0.023 (0.927)	-0.261 (0.295)	-0.296 (0.232)
Inversion positional perception error (°)	**-0.584 (0.011)**	**-0.622 (0.006)**	0.047 (0.852)	-0.195 (0.437)
Eversion position perception error (°)	**-0.541 (0.020)**	-0.282 (0.257)	-0.200 (0.425)	0.287 (0.249)

Variable	Peak ankle plantar flexion power	Peroneus longus activation	Tibialis anterior activation	Lateral gastrocnemius activation
Plantar flexion position perception error (°)	0.332 (0.178)	-0.025 (0.922)	0.246 (0.325)	0.162 (0.520)
Dorsiflexion position perception error (°)	-0.314 (0.204)	0.184 (0.466)	-0.184 (0.465)	0.268 (0.283)
Inversion positional perception error (°)	-0.055 (0.829)	0.001 (0.999)	0.026 (0.919)	-0.257 (0.304)
Eversion position perception error (°)	0.272 (0.274)	-0.195 (0.439)	-0.350 (0.154)	-0.300 (0.226)

Notes: CAI: chronic ankle instability; RMS: root mean square.

Discussion

This study examined differences in ankle proprioception and biomechanical characteristics between patients with CAI and healthy controls. Furthermore, it investigated the relationship between proprioception and biomechanical features in CAI patients. The results indicated that CAI patients exhibited impaired proprioception compared to healthy controls. Importantly, significant correlations between proprioceptive deficits and biomechanical abnormalities were observed in the CAI group.

Main findings

This study demonstrated that patients with CAI exhibited significantly greater peak ankle inversion angles compared to healthy controls. Excessive ankle inversion can cause medial displacement of the talus and increase stress on the lateral malleolar groove, distal fibula, and talar dome, thereby elevating the risk of ankle sprain[28]. Recent investigations have reported group differences in ankle inversion angles during jump-landing tasks between CAI patients and healthy controls[29-31]. This study further supports this notion and reveals the underlying mechanism through the observed alterations in ankle muscle activation. Specifically, reduced peroneus longus activation was observed in CAI patients. The primary function of the peroneus longus is ankle eversion, serving as a key stabilizer that limits excessive ankle inversion[32,33]. Decreased activation of this muscle may impair CAI patients' ability to stabilize the forefoot and resist excessive inversion. Moreover, damage to mechanoreceptors within the lateral ankle ligaments in CAI patients diminishes γ-motor neuron regulation of muscle fiber sensitivity[34], prolonging the peroneus longus response time to abnormal ankle positions. This delay hinders timely generation of eversion torque, resulting in greater ankle inversion angles[32].

Compared to healthy controls, patients with CAI exhibited significantly greater peak ankle internal rotation angles. A recent study reported that isolated ankle inversion primarily strains the calcaneofibular ligament, whereas sudden ankle inversion combined with internal rotation imposes strain on both the anterior talofibular and calcaneofibular ligaments[35]. These ligaments mainly provide static stability to the talus and subtalar joints. As the inversion and internal rotation angles of the ankle complex increase, the ligaments become more susceptible to failure beyond their maximal load capacity, contributing to subsequent lateral ankle sprains[36-38]. In the present study, the greater peak ankle inversion and internal rotation angles observed on the affected side of CAI underscore a plausible mechanism for recurrent lateral ankle sprains. This finding may offer valuable insights for clinicians and practitioners in designing rehabilitation protocols aimed at correcting aberrant ankle kinematics, particularly in individuals with CAI, to reduce the risk of recurrent injury during landing tasks.

Our findings demonstrate that patients with chronic ankle instability (CAI) exhibit significantly greater errors in ankle plantarflexion, dorsiflexion, inversion, and eversion joint position sense compared to healthy controls, indicating impaired proprioceptive accuracy. According to motor control theory, proprioceptive feedback from the central nervous system generates electrochemical signals that modulate motor neuron recruitment thresholds. This process determines the spatial activation patterns aligned with the body's geometry, ultimately contributing to movement stability [13,39]. One potential explanation for the proprioceptive deficits observed in CAI is damage to mechanoreceptors within the ankle complex caused by ankle sprains. These receptors include muscle spindles, Golgi tendon organs, Ruffini endings, and Pacinian corpuscles[40], whose injury reduces or distorts afferent sensory input on the injured side. Motor neuron activation is modulated by afferent signals from joints, muscles, skin, and descending spinal pathways[12]. Enhanced γ-motor neuron activation of muscle spindles improves both feedback and feedforward control, thereby regulating motor patterns[41]. Consequently, a reduction in complex afferent input from the ankle inhibits motor neuron activation[12]. While sensory integration from multiple body regions predominantly occurs at the spinal level, some afferent signals bypass synapses and project directly to the cortex[12]. Reduced sensory input disrupts integration at spinal and supraspinal levels, leading to neural reorganization or adaptive changes and diminished motor output[42]. In summary, decreased sensory input may induce central nervous system adaptations, reorganization, or inhibition, which potentially contribute to altered ankle biomechanics in individuals with CAI.

Our findings demonstrate significant correlations between joint position sense errors and peak ankle dorsiflexion and inversion angles in patients with CAI, suggesting that impaired proprioception is associated with biomechanical deficits. One possible explanation for the biomechanical deficits observed in CAI is impaired perception of joint position signals, which partially disrupts the calibration of descending motor commands and consequently alters biomechanical patterns[39,43]. Previous limited studies have reported associations between joint position sense and static postural control in CAI[44,45]; however, static postural control does not fully represent high-risk movement patterns. The present study extends current knowledge by revealing correlations between ankle proprioception and biomechanics during a single-leg landing task. The present study extends current knowledge by revealing correlations between ankle proprioception and biomechanics during a single-leg landing task. These findings underscore the importance of assessing and rehabilitating proprioceptive function. Enhancing proprioception may improve biomechanical function in CAI and reduce the risk of sprain. Future research should incorporate additional factors to elucidate the primary contributors to biomechanical deficits. Moreover, given that increased ankle inversion angle during landing is a major risk factor for recurrent sprains in CAI[46], our findings imply that proprioceptive impairments may elevate the risk of ankle sprain in this population.

Clinical Implications

The findings of this study may help establish the concept that CAI treatment should address not only ankle function and balance deficits but also impaired proprioception. A more comprehensive assessment of proprioceptive characteristics in patients with CAI may contribute to optimizing rehabilitation strategies following such injuries. Traditional rehabilitation programs have primarily focused on improving ankle function and balance ability. Developing interventions that specifically target proprioceptive deficits to enhance rehabilitation outcomes and reduce the risk of recurrent ankle sprains represents a promising direction. Future research should further investigate whether interventions aimed at central and/or peripheral sensory pathways can improve proprioception and subsequently enhance biomechanical characteristics in individuals with CAI.

Limitations

Certainly, this study has several limitations. First, due to its cross-sectional design, it remains unclear whether proprioceptive deficits in CAI are a consequence of injury or preexisting conditions. Prospective studies are needed to investigate the relationship between proprioception and ankle sprain risk. Second, to minimize confounding variability associated with sex-specific differences in biomechanics and neuromuscular control, this study recruited exclusively male participants. Consequently, the findings may not be entirely generalizable to female individuals with chronic ankle instability. Future research encompassing both sexes is warranted to determine whether the observed associations are sex-specific. Third, as all participants were young and physically active, the results may not be applicable to older or less active populations. Finally, the potential impact of limb dominance on individual biomechanics was not fully addressed. Finally, given the exploratory nature of this study and the modest sample size, formal corrections for multiple comparisons were not applied.

Conclusions

The primary findings of this study indicate that during single-leg hop landing, patients with CAI exhibit significantly greater peak ankle inversion and internal rotation angles in the affected ankle. These results highlight potential mechanisms underlying "giving way" episodes and recurrent ankle sprains during landing in CAI patients. Furthermore, impaired ankle proprioception was observed in CAI individuals, which showed associations with biomechanical abnormalities. These findings suggest that proprioceptive deficits may contribute to the impaired restoration of normal biomechanics in CAI. Comprehensive interventions aimed at enhancing ankle proprioception may improve lower limb biomechanics and reduce injury risk in this population.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Human and Animal Rights/Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study protocol was approved by the [Medical Ethics Committee of Wuhan Sports University] (Approval No [2024113]).

Informed consent

Informed consent was obtained from all individual participants included in the study.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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