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RESEARCH

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Comparative analysis of sensory-motor function and its correlation with gait biomechanics in patients with unilateral chronic ankle instability

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Abstract

Objective This study was to evaluate the correlation between postural stability, proprioception, tactile sensation, and gait biomechanics in young patients with unilateral chronic ankle instability (CAI).

Methods A total of 85 patients with CAI (80% females) and 51 healthy individuals (78% females) aged 18–35 years were recruited for this study. Standardized tests were used to assess bilateral sensory-motor function and gait biomechanics, to compare differences in sensory-motor function and gait biomechanics between groups, and to analyze the correlation between sensory-motor function and gait on the affected side of CAI patients. Postural stability was quantified by jump-landing test for stabilization time in the anterior-posterior direction; proprioception was quantified by bilateral thresholds for ankle plantarflexion, dorsiflexion, inversion, and eversion; and plantar sensation was determined by measuring the minimum thresholds of sensation in the five plantar regions. Gait biomechanics were analyzed by collecting ankle dorsiflexion-plantarflexion/inversion-exversion range of motion and ankle-toe kinetic parameters during barefoot walking.

Results Compared with Non-CAI, CAI patients had longer stabilization time in both anterior-posterior directions bilaterally ($P=0.015$, $P=0.024$); longer stabilization time was observed only in the medial-lateral direction on the affected side ($P=0.012$). Thresholds for plantarflexion, dorsiflexion, inversion, and eversion of the ankle joint were higher bilaterally in CAI than in Non-CAI (all $P<0.05$); tactile sensation was reduced bilaterally in CAI for the big toe, the 1st metatarsal head, the 5th metatarsal head, the lateral arch, and the heel (all $P<0.05$); and gait biomechanics were reduced bilaterally in CAI patients than in Non-CAI individuals (all $P<0.05$). Thresholds for plantarflexion, dorsiflexion, inversion, and eversion had significant negative correlations with gait biomechanics ($r>0.5$, $P<0.05$). There was a weak to moderate correlation between the lowest tactile sensation thresholds at the big toe and heel and gait biomechanics ($r>0.3$, $P<0.05$). No significant correlation was observed between stabilization time and gait biomechanics ($P<0.05$).

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Conclusion Young patients with unilateral CAI have poor bilateral postural stability, proprioception and tactile deficits, and altered gait biomechanics. These changes not only affect the affected side but also involve the non-affected side.

Keywords Ankle joint, Chronic ankle instability, Gait biomechanics, Proprioception

Introduction

Ankle sprains represent the most frequent musculoskeletal injuries in sports, making up about 40% of all injuries [1, 2]. Some patients with a first acute sprain develop recurrent sprains and dysfunction, eventually progressing to chronic ankle instability (CAI) [3, 4]. CAI is treated with either conservative methods or surgery, mainly targeting ankle instability [5]. Surgery is often considered when conservative treatment fails to effectively restore stability [6]. The development of CAI is strongly associated with sensory-motor deficits, including decreased postural stability, impaired proprioception, and reduced tactile sensation [7, 8]. The selection of these three variables as core assessment indicators stems from their synergistic roles in maintaining dynamic ankle stability: (1) postural stability reflects the ability of the central nervous system to integrate multimodal sensory inputs (vision, vestibular sensation, proprioception) and to coordinate motor outputs, and deficits in this directly contribute to the increased risk of falls in patients with CAI; (2) 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; (3) tactile sensation, as an afferent signal to cutaneous mechanoreceptors (e.g., Merkel discs), is responsible for sensing the distribution of ground reaction forces, which influences the feedback to regulate gait support [9, 10]. Therefore, it is believed that the three components may together form a "sensory-motor loop", and that damage to any one of them may lead to decreased stability of the ankle joint. For example, patients with CAI demonstrate increased center of foot pressure displacement during balance activities like one-legged stance, compared to healthy individuals, indicating a substantial impact on their balance control [11]. This reduced balance ability may be related to proprioception deficits [12]. Decreased tactile sensation has also been recognized as a major problem in patients with CAI, which can affect their balance and stability [13]. For example, CAI patients show reduced plantar tactile sensation during walking, resulting in decreased ability to perceive ground reaction forces, which in turn affects gait stability [14]. At the same time, the proprioceptive deficits show significant impairments in joint positional and kinesthetic senses, exacerbating the decline in balance control [15]. In CAI patients, abnormalities in ankle joint function can disrupt sensory-motor abilities and elevate the risk of sprains, with recurring sprains exacerbating CAI and complicating recovery. These abnormalities in sensory-motor function are closely related to the onset and progression of CAI, but existing studies have mostly focused on the localized effects of the affected ankle joint and lacked a systematic exploration of the functional interactions of the bilateral limbs.

The focus of research has been on the detrimental effects of CAI on the affected ankle, yet there are suggestions that the unaffected side might also be involved. Neuroplasticity theory states that unilateral ankle injuries can alter sensory-motor control strategies of the contralateral limb through cross-education effects and bilateral cortical reorganization. Sprains may damage peripheral mechanoreceptors, which may result in damage to afferent nerves in the affected ankle joint [16]. Reduced sensory afferent signals may inhibit the activation of gamma motor neurons, resulting in erroneous motor outputs [17]. These erroneous motor outputs in turn feed back into the central nervous system, affecting the integration of neural signals. In response, the brain undergoes remodeling or adaptive changes to optimize the connectivity and function of neural networks [18]. Due to the complex interactions between the two cerebral hemispheres, dysfunction in one hemisphere may affect the function of the other hemisphere [19]. As a result, injury on one side could affect both limbs adversely. Studies have shown that joint motion patterns on the non-affected side of CAI patients differ significantly from those of healthy individuals, particularly with regard to mechanical interaction at the knee and ankle joints [20, 21]. This altered biomechanics may increase the risk of injury on the non-affected side, further exacerbating the patient's dysfunction.

This study hypothesized that the non-affected side of unilateral CAI patients is affected by the affected side. The aim was to analyze the differences in motor function, including postural stability, proprioception, and tactile sensation of the ankle joint bilaterally in patients with unilateral CAI compared to healthy controls, as well as to assess the correlation between these motor functions and gait biomechanics. The study design focused on assessing the degree of deficit in proprioceptive function by measuring proprioceptive function of the ankle joint bilaterally in patients with CAI and unilaterally in healthy controls, including joint active or passive repositioning, and passive motion perception threshold measurements. At the same time, the gait of the affected side and the healthy side were biomechanically analyzed using a three-dimensional gait analysis system to compare the differences between them in the gait cycle.

Materials and methods

Patients

Eighty-five patients with unilateral CAI were recruited for this study. The patients' contralateral ankle joints were evaluated and examined according to previously reported criteria to exclude any signs and symptoms of instability and injury.

Inclusion criteria: (1) 18–35 years old; (2) at least one or more acute lateral ankle sprains, resulting in pain, swelling, and/or temporary loss of function more than 6 months prior to the diagnosis of CAI, according to the International Ankle Consortium Guideline [22]; (3) at least two "giving-way" sprains in the past 6 months; (4) Cumberland Ankle Instability Tool (CAIT) score < 24 [23].

Exclusion criteria: (1) musculoskeletal disorders other than injury of the lateral ligament complex of the ankle joint, such as joint laxity, hinge-ligament injuries, or deltoid ligament injuries; (2) neurologic disorders, such as neuropathies and paralysis of the lower limbs; (3) signs of lower limb pain or swelling due to lower limb injuries not solely related to CAI that occurred in the 3 months prior to the study; (4) a history of severe bilateral ankle sprains and injuries; (5) No informed consent.

The control group consisted of individuals who had never suffered an acute lateral ankle sprain, never experienced ankle instability, and had a CAIT score of 28 or higher. The test limb of the control group was randomly selected. Table 1 shows that there was no statistical difference in age, gender, height, weight, and BMI between the two groups ($P > 0.05$).

The study was approved by the Kunming Municipal Hospital of Traditional Chinese Medicine ethics committee [No. 2023KM002]. The trial procedure was fully explained to the patients before testing, and patients were included after signing an informed consent form.

Assessment of foot dominance

CAI patients were screened for foot dominance (i.e., dominant vs. Non-dominant foot) at recruitment. Foot dominance was defined by the following two questions: (1) Which foot do you habitually use to kick a soccer ball? (2) Which foot do you first step on stairs? The foot that is the answer to both questions is identified as the dominant foot.

Postural stability tests

The tests were carried out by physicians specializing in orthopedics and sports medicine, focusing on postural stability using the Jumping-Landing Test. The subjects were positioned in a standing position 70 cm from the center of the force platform (AMTI, Watertown, MA, USA) while standing. Upon command, the subjects performed a half-squat, swung their arms fully, and jumped forward with both legs in unison to reach the test strip of the feeler gauge. The subjects then landed on the test leg, placed both hands on the waist as soon as possible after landing, and looked straight ahead, staying stable for 5 s. The target height of the test strip to be touched is equal to 50% of the maximum vertical height of the 3 jumps plus the standing touch height. The test protocol has been validated to have high reliability (ICC values = 0.76–0.84) [24]. Data on ground reaction forces in the anterior-posterior and medial-lateral directions were collected at 1000 Hz. Under the tester's guidance, the subjects practiced at least three times after the main points of the tests were explained. The subjects took a 5-minute rest before conducting three valid tests, each separated by a 1-minute interval to prevent fatigue. Ground reaction force data were analyzed by fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz. Landing was defined as the moment when the ground reaction force in the Z-axis direction reached or exceeded 10 N. The ground reaction force data were intercepted in Matlab software (The Mathworks, Natick, RI, USA) from the beginning of the landing moment to 5 s after the landing, and stabilization time in the anterior-posterior

Table 1 Demographic characteristics of patients with CAI and healthy controls (Non-CAI)

	CAI (n = 85)	Non-CAI (n = 51)	P value
Gender			
Male	17 (20.00%)	11 (21.57%)	0.827
Female	68 (80.00%)	40 (78.43%)	
Age, years	26.6 ± 3.3	25.6 ± 4.2	0.257
Height, cm	174.5 ± 12.2	173.5 ± 11.3	0.954
Weight, kg	70.2 ± 15.9	69.2 ± 13.9	0.857
BMI, kg/m^2	22.2 ± 2.4	22.0 ± 2.6	0.752
CAIT score	15.9 ± 0.5	29.0 ± 0.6	< 0.001
Number of ankle sprains	3 (2, 3.8)		

Data were expressed as n (%), X ± S, or median (IQR) and compared by person chi-square or Student's t test. $P < 0.05$ was statistically different and medial-lateral directions were calculated using the Sequential Average method [25].

Sequential Average x(n)=Σ $\frac{1000}{n=1}F_X$/n (1).

Sequential Average x(n)=Σ $\frac{1000}{n=1}F_y$/n (1).

Fx and Fy represent the ground reaction forces in the anterior-posterior and medial-lateral directions, respectively.

Ankle proprioception

The proprioception test was performed using an ankle proprioception tester (AP-11–800 W-3 A, AnklePro Inc., USA). The subjects were seated in a height-adjustable seat with the legs placed on movable pedals. The seat height was then adjusted to ensure that both the knee and hip joints were at 90° flexion, with the ankle in a neutral position and the lower leg perpendicular to the pedal. Subjects were required to wear test socks to avoid the effects of tactile sensation, and eye masks and noise-canceling headphones to eliminate external distractions. By randomly pressing a button in one direction (plantarflexion/dorsiflexion/inversion/eversion), the pedal began to rotate in that direction at a constant angular velocity of 0.4°/s. After recognizing the pedal's rotation direction, the participant was required to swiftly press the stop button and specify the direction [26]. When a correct judgment was made, the angular displacement of the rotary pedal was documented. An incorrect judgment resulted in a failed test, prompting the next test, with three valid tests needed for each direction. The rotary direction and angle were recorded. The time interval of each test was 2–10 s.

Tactile sensation test

Tactile sensation was measured using Semmes-Weinstein monofilaments (NorthCoast Medical, Inc., Morgan Hi, CA, USA) [27]. Subjects were arranged face down on the treatment bed, with their feet supported at the end, donning noise-canceling headphones and a black eye mask to minimize disturbances. The testing process was shown by aligning a nylon monofilament at a 90° angle to the test site, pressing until it curved into a C-shape and keeping it there for one second. The subject confirmed with a 'yes' upon feeling the stimulus. Tactile sensation was tested sequentially in the big toe, 1st metatarsal head, 5th metatarsal head, lateral arch, and heel using a 4-2-1 progression. At first, a 4.74-size SWM monofilament was used, and if the participant responded, the test continued by decreasing the size by 4. If there was no response, the size was increased by 4. In cases of three consecutive reversals, where there was no response to the smaller size but a response to the larger size, the SWM monofilament was decreased by two sizes for the following test. Each time this reversal happened for the third time in a row, the SWM monofilament size was decreased by two sizes, followed by a reduction of one size for the subsequent test. The minimum tactile threshold was determined following three consecutive reversals. The timing of SWM monofilament application was altered randomly to prevent subjects from predicting the stimuli. The 5 plantar subdivisions were tested sequentially and the minimum SWM monofilament size was recorded.

Gait test

Anthropometric measures such as height, weight and body mass index (BMI) were measured. Eighteen body markers (bilateral: posterior inferior iliac spine, anterior superior iliac spine, thigh, knee, leg, ankle, heel, toes, metatarsals) were placed according to the Vicon™ Plug-in Gait model [28]. Participants were instructed to walk barefoot along the path, wearing minimal clothing and maintaining their usual walking pace. All gait test data were processed by professionally trained technicians. Measurements were taken and recorded using a camera and Nexus software (version 2.5; Sonatype™, Fül ton, USA). The setup of the motion analyzer and force plates was organized in such a way that the anterior-posterior direction was aligned with the "Y" axis, the medial-lateral direction was aligned with the "X" axis, and the vertical direction followed the "Z" axis. Dorsiflexion, plantarflexion, inversion, and eversion angles were measured.

Gait parameters included ankle-toe velocity (m/s), ankle-toe acceleration (m/s^2), ankle-toe angular velocity (m/s), ankle-toe angular acceleration (m/s^2), dorsal-plantarflexion range of motion (RoM), and eversion-inversion RoM.

Kinematic data analysis

All data were calculated on the X, Y, and Z axes. The data were analyzed using MatLab 7.04 (Mathworks Inc, Natick, MA). The raw data were pre-processed by Nexus software and exported to MatLab 7.04 (Mathworks Inc., Natick, MA) for further analysis. Kinematic signals (e.g., joint angles, angular velocities) were smoothed using a fourth-order Butterworth low-pass filter with the cutoff frequency set to 6 Hz. Abnormal data points (e.g., abrupt change values due to marker loss) were identified and processed by the following criteria: outlier definition, the marker's positional change rate in any frame surpassed three times the standard deviation of the average change rate of the neighboring 10 frames; interpolation method, the interval where the outlier was located was filled by cubic spline interpolation, and the single interpolation interval was no more than 5 consecutive frames (corresponding to 0.05 s at a sampling rate of 100 Hz).

Sample size calculation

Referring to the differences in postural stability, proprioception and gait parameters between CAI patients and healthy controls (e.g., longer stabilization time, higher proprioception thresholds), a medium effect size (e.g., Cohen's d = 0.5–0.7) was assumed and the significance level was set to be $\alpha = 0.05$, and the efficacy was set to $1\text{-}\beta = 0.8$. Calculated by statistical software such as G*Power 3.1, the sample size required for a one-sided test is approximately 40–60 cases per group, and the actual sample size included in this study (85 cases in the CAI group and 51 cases in the control group) exceeded this estimate, ensuring sufficient statistical power to detect between-group differences.

Statistical analysis

Statistical analyses were performed using SPSS 20.0 software. Data normality was determined using the Shapiro-Wilk test. Continuous values that followed a normal distribution were expressed as mean ± standard deviation ($\bar{X} \pm S$) and compared using Student's t-test for two groups or one-way ANOVA and Tukey's post hoc test for multiple groups. Skewed distributions were expressed as median [interquartile range, IQR], with Mann-Whitney U test for between-group comparisons and Kruskal-Wallis H test with Dunnett's multiple comparisons test for multiple-group comparisons. $P < 0.05$ was considered statistically significant for all group comparisons. For correlations between continuous variables, Spearman's correlation test was used. To control the False Discovery Rate (FDR) due to multiple comparisons, statistical significance for correlation analyses was set at FDR-corrected $P < 0.1$. Pearson's correlation analysis and Spearman's correlation were used to analyze the correlation between CAIT scores and postural stability, proprioception, tactile sensation, and gait biomechanics in patients with CAI.

Results

General information about the subjects

A total of 85 patients with CAI and 51 healthy individuals were included, and all of these patients completed all tests. Among the CAI patients, 45 had the left limb affected (16 cases of dominant foot, 29 cases of non-dominant foot), while 40 had the right limb affected (29 cases of dominant foot, 11 cases of non-dominant foot). In the Non-CAI cohort, a randomized sequence was utilized to choose 26 left (6 cases of dominant foot, 20 cases of non-dominant foot), and 25 right ankles (18 cases of dominant foot, 7 cases of non-dominant foot) for testing. There was no significant difference in the proportion of dominant feet between CAI and Non-CAI patients (52.94% vs. 47.06%, $P = 0.507$). Age, gender, height, weight, and BMI in both groups were not statistically different (Table 1, $P > 0.05$). Patients in the CAI group had significantly lower CAIT scores than the non-CAI group ($P < 0.001$) (Table 1).

Postural stability, proprioception, and tactile sensation

Postural stability, proprioception, and tactile sensation were measured in the dominant (45 cases) and nondominant (40 cases) feet in the affected side of CAI patients (Supplementary Table 1). No significant differences in postural stability, proprioception, and tactile sensation were observed between the dominant and nondominant feet ($P > 0.05$). In terms of postural stability, compared with Non-CAI patients, CAI patients had longer stabilization time in both anterior and posterior directions bilaterally (affected and contralateral sides) ($P = 0.015$, $P = 0.024$); and stabilization time was longer in medial-lateral directions on the affected side ($P = 0.012$). In terms of proprioception, the thresholds for ankle plantarflexion, dorsiflexion, inversion, and eversion were higher in CAI patients than in Non-CAI patients bilaterally (all $P < 0.05$); it is worth noting that the non-affected side of CAI patients was affected by the affected side, with ankle plantarflexion, dorsiflexion, inversion, and eversion thresholds on the non-affected side of CAI patients being lower than those of non-CAI patients but slightly higher than those on the affected side of CAI (with the exception of ankle dorsiflexion, all $P < 0.05$). Tactile sensation was lower in the big toe, 1st metatarsal head, 5th metatarsal head, lateral arch, and heel bilaterally in CAI patients (all $P < 0.05$). Tactile sensation thresholds for the 1st metatarsal head and 5th metatarsal head were not statistically different between the affected and non-affected sides in CAI patients ($P = 0.134$, $P = 0.540$), but both were lower than in Non-CAI patients. Although tactile sensation thresholds for the big toe, lateral arch, and heel were higher on the non-affected side of CAI than on the affected side of Non-CAI, they were lower than on the affected side of CAI (Table 2).

Gait biomechanics and correlations with postural stability, proprioception, and tactile sensation

Comparisons between the CAI and Non-CAI groups revealed significant differences in biomechanical responses (Table 3). Ankle-toe velocity, ankle-toe acceleration, ankle-toe angular velocity, and inversion-eversion RoM were lower in CAI patients than in Non-CAI patients bilaterally (all $P < 0.05$). It was found that among the above kinematic characteristics, the differences between the affected and non-affected sides of CAI patients were of particular interest. The affected side of CAI patients severely affected the acceleration and angular velocity of the non-affected side, which showed no statistical difference between the affected and non-affected sides and were lower than those of Non-CAI.

Table 2 Comparison of postural stability, proprioception and tactile sensation between affected and healthy side and Non-CAI patients with CAI

	CAI-A ($n=85$)	CAI-H ($n=85$)	Non-CAI ($n=51$)	*P* value
Postural Stability, (s)				
Anterior direction	2.40 ± 0.10*	2.40 ± 0.09*	2.35 ± 0.12	0.011
Posterior direction	2.07 ± 0.46*	1.85 ± 0.49	1.82 ± 0.49	0.003
proprioception (°)				
Plantarflexion	1.09 (0.86, 1.49)*	0.90 (0.69, 1.43)*#	0.74 (0.64, 1.14)	< 0.001
Dorsiflexion	1.15 (0.89, 1.63)*	1.06 (0.72, 1.53)*	0.69 (0.59, 1.08)	< 0.001
Inversion	2.63 (1.93, 3.5) *	2.22 (1.61, 2.64) *#	1.49 (1.33, 1.94)	< 0.001
Eversion	2.67 (1.67, 3.72) *	1.99 (1.66, 2.85) *#	1.61 (1.29, 1.98)	< 0.001
Plantar tactile sensation				
Big toe	3.65 (3.39, 3.86) *	3.43 (3.17, 3.79) *#	2.90 (2.69, 3.12)	< 0.001
First metatarsal head	3.70 (3.39, 4.10) *	3.55 (3.19, 4.00) *	3.16 (2.98, 3.29)	< 0.001
Fifth metatarsal head	3.47 (3.28, 4.11) *	3.48 (3.26, 3.74) *	3.28 (3.18, 3.54)	< 0.001
Lateral arch	3.31 (3.15, 3.74) *	3.22 (3.00, 3.50) *#	2.90 (2.67, 3.23)	< 0.001
Heel	4.04 (3.79, 4.17) *	3.71 (3.39, 4.12) *#	3.30 (3.20, 3.57)	< 0.001

Data are shown as X ± S or median (IQR), using one-way ANOVA test or Kruskal-Wallis H test with post hoc Tukey test or Dunnett's multiple comparisons test for comparisons. $P < 0.05$ is considered statistically significant. * Indicates a statistically significant difference compared to the Non-CAI group ($P < 0.05$); # denotes a statistically significant difference between the CAI-H and CAI-A groups ($P < 0.05$)

Table 3 Comparison of gait biomechanics between affected and healthy sides of CAI patients and Non-CAI patients

	CAI-A ($n=85$)	CAI-H ($n=85$)	Non-CAI ($n=51$)	*P* value
Ankle-toe velocity (m/s)	6.13 ± 0.09*	0.71 ± 0.09*#	1.08 ± 0.18	< 0.001
Linear acceleration (m/s^2)	6.15 (5.09, 7.08) *	6.39 ± 1.42*	9.14 ± 1.40	< 0.001
Angular velocity (radiant/s)	0.35 ± 0.17*	0.38 ± 0.18*	0.50 ± 0.09	< 0.001
Angular acceleration (radiant/s^2)	1.58 ± 0.52	1.67 ± 0.79	1.69 ± 0.37	0.461
Dorsal-plantarflexion range of motion (°)	92.80 ± 3.34	93.71 ± 3.49	94.04 ± 3.52	0.133
Inversion/eversion RoM (°)	21.13 ± 6.15*	17.33 ± 5.89*#	26.05 ± 4.67	< 0.001

Data are shown as X ± S or median (IQR), using one-way ANOVA test or Kruskal-Wallis H test with post hoc Tukey test or Dunnett's multiple comparisons test for comparisons. $P < 0.05$ is considered statistically significant. * indicates a statistically significant difference compared to the Non-CAI group ($P < 0.05$); # denotes a statistically significant difference between the CAI-H and CAI-A groups ($P < 0.05$)

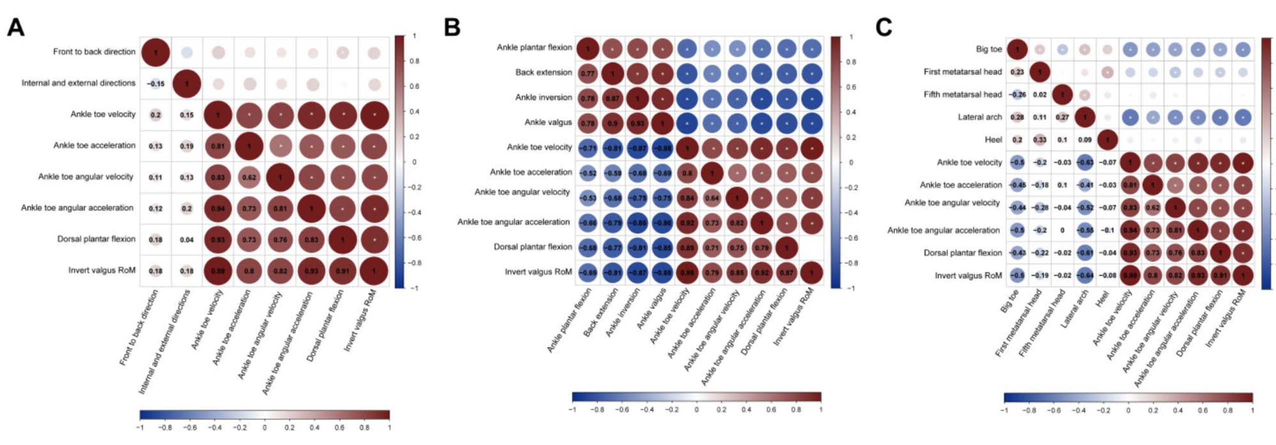

Fig. 1 Correlation coefficients of postural stability, proprioception and tactile sensation with gait biomechanics on the side of the affected limb in patients with CAI. (**A**) Postural stability and gait biomechanics; (**B**) Proprioception and gait biomechanics; (**C**) Tactile sensation and gait biomechanics. The results were expressed as Spearman correlation coefficients rs, with coefficients interpreted as, 0.3–0.5 weak, 0.5–0.7 moderate, and 0.7-1.0 strong. *P*-values were corrected for FDR, and * denoted statistical significance at $P < 0.05$

Correlation analysis was utilized to assess the relationship between postural stability, proprioception, and tactile sensation on the affected side of CAI patients and gait biomechanics. As shown in Fig. 1, proprioception, including thresholds for ankle plantarflexion, dorsiflexion, and inversion and eversion angles, had significant negative correlations with gait biomechanics ($r > 0.5$, $P < 0.05$, Fig. 1B). Tactile thresholds were lowest in the big toe and heel and were significantly negatively correlated with gait biomechanics ($r > 0.3$, $P < 0.05$, Fig. 1C). No significant

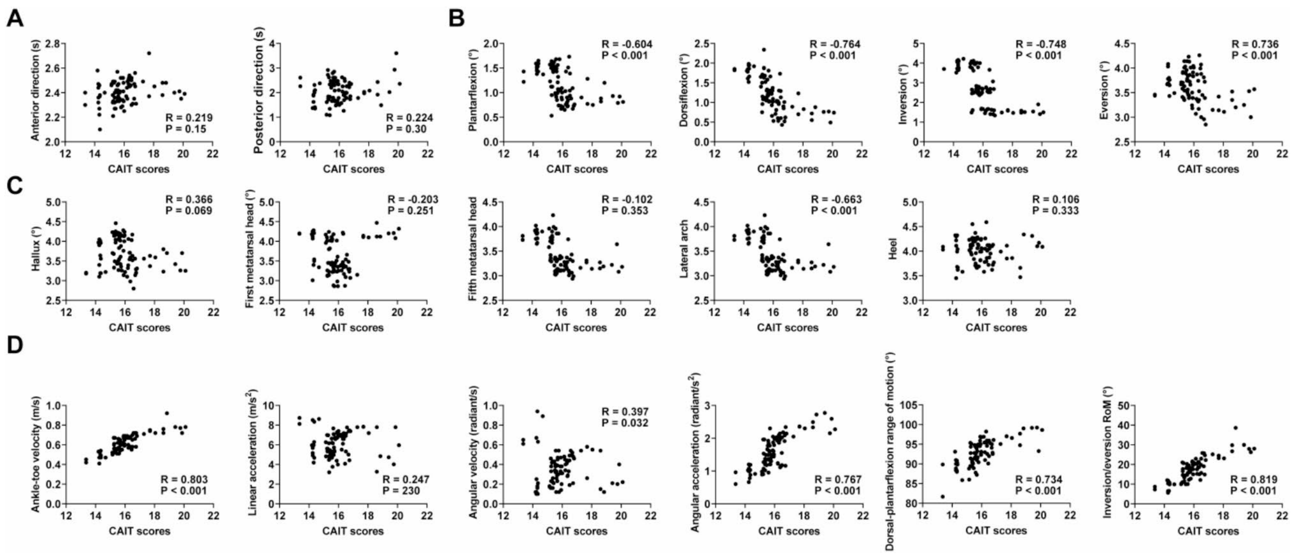

Fig. 2 Correlation between CAIT scores and each parameter of postural stability, proprioception, tactile sensation, and gait biomechanics in CAI patients. Correlation plots between CAIT scores and (**A**) postural stability, (**B**) proprioception, (**C**) tactile sensation, and (**D**) gait biomechanics, respectively. r was the coefficient of correlation, and $P < 0.05$ was statistically significant. Coefficients were interpreted as, 0.3–0.5 weak, 0.5–0.7 moderate, and 0.7-1.0 strong

correlation was observed between stabilization time and gait biomechanical parameters, including ankle-toe velocity, ankle-toe acceleration, ankle-toe angular velocity, ankle-toe angular acceleration, dorsal-plantarflexion RoM, and inversion RoM ($P > 0.05$, Fig. 1A).

To further understand the relationship between functional ankle instability and these biomechanical factors, attention was paid to the correlations between CAIT scores and various parameters of postural stability, proprioception, tactile sensation, and gait biomechanics in patients with CAI (Fig. 2). Correlation analysis between CAIT scores and several biomechanical parameters in patients with CAI revealed differences. Specifically, in terms of postural stability (Fig. 2A), the correlation between CAIT scores and anterior and posterior stability was weak and statistically insignificant. In terms of proprioception (Fig. 2B), plantarflexion and dorsiflexion showed a significant moderate to strong negative correlation with CAIT scores (R = -0.604, -0.764, $P < 0.001$), while inversion and eversion showed a significant strong positive correlation ($R = 0.748$, 0.736, $P < 0.001$). In terms of tactile sensation (Fig. 2C), tactile sensation of the lateral arch showed a significant moderate-negative correlation with CAIT scores (R = -0.663, $P < 0.001$), and tactile sensation of the first and fifth metatarsal heads did not significantly correlate with CAIT scores ($P = 0.251$, 0.353). In gait biomechanics (Fig. 2D), ankle-toe velocity and angular acceleration showed significant strong positive correlations with CAIT scores ($R = 0.803$, 0.767, $P < 0.001$). Dorsal-plantarflexion RoM and inversion/eversion RoM also showed significant strong positive correlations ($R = 0.734$, 0.819, $P < 0.001$), while linear-acceleration showed a weak and statistically insignificant correlation.

In summary, the correlations between CAIT scores and various parameters of postural stability, proprioception, tactile sensation, and gait biomechanics in patients with CAI were complex and diverse, with significant correlations between some parameters and weak or non-significant correlations between others. These results provide valuable reference information for a deeper understanding of gait characteristics and potential therapeutic targets in CAI patients.

Discussion

The present study revealed significant correlations between bilateral proprioception, plantar sensation, and gait biomechanics in patients with unilateral CAI, a finding that contrasts with a previous study that focused only on localized functioning of the affected side [29], suggesting that the overall effect of CAI on the bilateral sensory-motor system may be an important mechanism for gait abnormalities. In this study, the affected side of CAI had decreased postural stability, impaired proprioception (i.e., increased proprioception thresholds and decreased tactile sensation), and substantial gait kinematics, and that proprioception on the affected side of CAI had a strong correlation with altered gait biomechanics. In addition, we were concerned that instability on the affected side of CAI involved the healthy side.

Patients with CAI have significant deficits in postural stability, proprioception and tactile sensation. These deficits not only affect the patient's daily activities, but may also lead to further motor injuries [30]. The current research found that unilateral CAI patients experienced decreased postural stability in the anterior-posterior direction on both sides and only on the affected side in the medial-lateral direction. The mechanisms by which the body maintains postural stability in the anterior-posterior and medial-lateral directions are different. Postural stability in medial-lateral directions is more dependent on the coordination and responsiveness of the lateral muscles. Lateral movement demands that the body's center of gravity be shifted more on a reduced base, which requires superior muscle coordination and faster response times [31]. It has been found that maintaining dynamic stability in medial-lateral directions relies heavily on active foot positioning and the integration of sensory feedback (e.g., proprioception) [32]. To compensate for reduced postural stability in medial-lateral directions, the body can maintain balance on the non-affected side through a range of compensatory mechanisms. These mechanisms include, but are not limited to, adjusting movement strategies such as altering gait, stride length, or stride frequency, as well as utilizing sensory integration capabilities and neural adaptations to optimize postural control [33]. Postural stability relies more on the central integration capacity of the vestibular-visual-somatosensory system [34], whose temporal metrics (e.g., stabilization time in the present study) reflect the efficiency of processing multimodal sensory information. This higher-order neural integration may be compensated by altering muscle synergy patterns (rather than local joint dynamics), which explains why postural stability is not directly related to gait parameters. From the perspective of neural reorganization, when sensory and motor dysfunction occurs on the affected side of CAI, the nervous system will initiate self-repair mechanisms. On the one hand, the motor and sensory regions of the cerebral cortex may undergo functional reorganization to enhance the control and perception of the healthy limb to compensate for the deficiencies on the affected side. After a limb injury, neurons in the motor cortex of the brain that originally innervated the affected limb may gradually transfer some of their functions to the contralateral limb, compensating for the function by increasing the strength and number of neural connections [35]. On the other hand, spinal cord neural networks may also experience changes, with synaptic connections of intermediate neurons modifying in response to new sensory inputs and motor demands, thus optimizing postural control and movement patterns [36].

The core pathology of CAI is characterized by damage to the posterolateral ligament complex, which may exacerbate biomechanical abnormalities through two pathways: loss of mechanical stability and disruption of nerve afferents [37]. This is due to the fact that damage to the lateral ligament complex may result in disruption of nerve afferents. Disruption of nerve afferents affects muscle activation patterns, thereby altering the kinematic characteristics of the joint [38]. Patients with CAI showed significant deficits in ankle sensation [12]. In addition, reduced tactile sensation has been suggested to be an important factor affecting balance control in patients with CAI. Compared to healthy individuals, CAI patients have poorer performance on tactile sensation tests, which might influence their stability during standing and walking [7, 39]. This study demonstrated that individuals with unilateral CAI had elevated proprioception thresholds and decreased tactile sensation when compared to Non-CAI individuals. Unilateral CAI in joint and muscle afferent nerves, along with sensory inputs from skin receptors and descending supraspinal motor commands, work together to activate gamma motor neurons [40]. There is a group of interneurons that receive afferent signals not only from the affected ankle but also from the contralateral ankle [41]. Specifically, these interneurons receive supraspinal inputs not only from the vestibulospinal cord, the reticulospinal pathway, and the pyramidal tracts, but also bilateral inputs from type Ia and type II neurons as well as joint afferent nerve fibers [41]. Based on these findings, it can be inferred that when afferent signals to the affected ankle are reduced, the signals from the contralateral ankle received by these interneurons may also be affected, resulting in decreased sensitivity of the contralateral periprosthetic mechanoreceptors and plantar tactile receptors, which in turn affects contralateral ankle proprioception and tactile sensation. In the nervous system, interneurons have a complex network of synaptic connections that enable them to integrate and modulate sensory inputs from both limbs [42]. Therefore, when afferent neural signals to the affected ankle joint are diminished due to injury, the activity pattern of interneurons is altered, and this alteration may affect the excitability of the neural pathways associated with the contralateral ankle joint through the mechanism of synaptic plasticity, leading to changes in contralateral sensory function. This suggests that traditional unilateral rehabilitation programs (e.g., balance training on the affected side) may not be sufficient to reverse bilateral functional deficits. Bilateral symmetry training is recommended to promote neural plasticity remodeling on the affected side by enhancing sensory inputs from the healthy side to activate the cross-pathway.

In terms of gait biomechanics, the inversion-eversion RoM of the non-affected ankle in CAI patients was lower than that of the Non-CAI group; however, in terms of dorsiflexion ROM, there was no statistically significant difference between the Non-CAI and CAI groups. Increased inversion of the unstable ankle and increased activity of the rectus femoris and peroneus longus muscles are protective mechanisms to counteract increased ankle inversion [43]. In studying gait biomechanics in patients with CAI, it was found that the biomechanical characteristics of the affected side had a significant effect on the movement patterns of the healthy side. This effect was not only seen in the symmetry of the gait, but also in the RoM of the joints and the pattern of muscle activation. Dysfunction on the affected side of CAI patients may lead to compensatory adjustments on the healthy side when performing exercise, thus affecting overall gait performance [44]. In addition, neuromuscular control may be affected in patients with CAI. Research suggests that functional instability on the affected side may lead to altered muscle activation patterns on the healthy side during movement, especially when performing rapid response and dynamic balance tasks. Specifically, muscles on the healthy side may exhibit higher levels of activation to compensate for deficits on the affected side, thereby maintaining overall motor stability [16]. Unfortunately, we did not focus on muscle measures. Deficits in proprioception in patients with CAI may affect their gait and dynamic balance. Patients with CAI exhibit significant biomechanical alterations during gait, such as abnormal ankle angles and movement patterns, which may be related to their deficits in proprioception and tactile sensation [4]. The overall decrease in inversion-eversion ROM in patients with CAI is the result of a combination of increased inversion and limited eversion. Changes in inversion-eversion RoM may result in uneven ankle stress distribution, greater ankle inversion angles, and higher ground reaction forces [45]. Therefore, improving proprioception and tactile sensation in CAI patients may be an important intervention to improve their gait biomechanics and overall function. Vibration therapy (localized vibration frequency of 30–50 Hz) can be used to selectively activate slow-adaptive mechanoreceptors (Ruffini endings) in conjunction with virtual reality scenarios to simulate dynamic tasks and enhance sensory-motor closed-loop integration [46]. Walking training using texture-variable insoles (e.g., bump density gradient design) improves gait support through enhanced plantar tactile feedback [47].

This study has some limitations. Participants were limited to those between 18 and 35 years old, as gait biomechanics are more affected by aging factors like improper walking techniques or muscle weakness. Future studies could include CAI of different age groups for in-depth studies. Second, muscle strength was not included in this study for in-depth analysis, and the potential impact of muscle strength deficits with altered gait biomechanics could be explored in depth. Finally, participants' habitual physical activity levels (e.g., sedentary behavior, recreational sports, or competitive training) were not included in the measurements. Despite circumventing the specific interference of professional athletes, differences in activity intensity in the general population may still influence ankle stability through neuromuscular adaptations (e.g., stronger compensatory postural control strategies may be present in those with high activity levels) [48], which may lead to biased interpretation of the results of the between-group comparisons and correlation analyses.

Conclusion

Patients with unilateral CAI have poor bilateral postural stability, proprioception and tactile sensation, and altered gait biomechanics. Unilateral CAI can affect the kinematics of the contralateral healthy ankle. Therefore, the rehabilitation needs of the bilateral limbs should be fully considered in the treatment of CAI.

Supplementary Information

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Supplementary Material 1

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Not applicable.

Author contributions

QiLong Gao and Jiao Li designed the research study. QiLong Gao and Jiao Li performed the research. Qi Wang, Dan Liu and Lei Guo provided help and advice. Qi Wang and Dan Liu analyzed the data. QiLong Gao and Jiao Li wrote the manuscript. Lei Guo reviewed and edited the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets used and/or analyzed during the present study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The present study was approved by the Ethics Committee of Kunming Municipal Hospital of Traditional Chinese Medicine [No. 2023KM002] and written informed consent was provided by all patients prior to the study start. All procedures were performed in accordance with the ethical standards of the Institutional Review Board and The Declaration of Helsinki, and its later amendments or comparable ethical standards.

Competing interests

The authors declare no competing interests.

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