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RESEARCH

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Association between lower extremity movement patterns and ACL loading in CAI patients across varied ankle sprain frequencies within a year

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Abstract

Purpose To investigate the relationship between the biomechanical characteristics of lower extremity and anterior cruciate ligament (ACL) loading during single-leg landing in patients with chronic ankle instability (CAI) who have different ankle sprain frequencies within a year.

Study Design Cross-sectional study; Level of evidence, 3.

Methods The incidence of ankle sprains among 74 male participants was meticulously documented over a one-year period. The participants had an average age of 21.78 years, a height of 176.37 cm, and a weight of 72.61 kg. Subsequently, a one-year monitoring period was implemented to assess the incidence of ankle sprains among the participants. The participants were classified into five groups according to their documented frequency of ankle sprains. The categories were as follows: The 2, 3, 4, 5, and 6 or more ankle sprain groups. Kinematic, kinetic, and electromyographic data were collected while participants performed a single-leg landing task. Lower extremity muscle force and ACL loading were modeled using OpenSim software.

Results CAI patients with more than four ankle sprains had higher peak ACL loading during single-leg landing than those with only two or three ankle sprains ($P < 0.05$). Additionally, CAI patients with more than four ankle sprains exhibited a limited range of ankle dorsiflexion and biceps femoris muscle force, which was significantly correlated with ACL loading ($P < 0.05$). CAI patients with more than 5 ankle sprains had greater ankle inversion angle, inversion angular velocity, vertical ground reaction force (GRF), rectus femoris muscle strength, and lower gastrocnemius, soleus muscle force during single-leg landing, and these biomechanical indices were significantly correlated with ACL strain ($P < 0.05$).

Conclusion Based on these findings, it appears that experiencing four ankle sprains within a year might be a threshold for the development of knee compensation in CAI patients. This compensation could result in a significant increase in ACL loading. The study also found that CAI patients with more than four ankle sprains commonly exhibited altered motor characteristics such as limited ankle dorsiflexion angle, increased ankle inversion angle, excessive

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vertical GRF, and insufficient gastrocnemius and soleus muscle force during the landing phase. These characteristics might be responsible for the observed increase in ACL loading. In the future, clinical practice and scientific research may benefit from targeted interventions to prevent ACL injuries in CAI patients with different sprain histories, in accordance with the findings of this study.

Key points

Findings Patients with CAI who have experienced more than four ankle sprains within a year exhibited severe knee compensation and increased ACL load during single-leg landing. Limited ankle dorsiflexion, increased ankle inversion angle, excessive vertical GRF, and insufficient gastrocnemius and soleus muscle strength might increase ACL load in patients with CAI who have experienced more than four ankle sprains within a year.

Implications Individuals with a history of more than four ankle sprains should undergo a thorough examination of knee health and receive regular monitoring to prevent the development of ACL injuries. Patients with more than four ankle sprains within a year should focus on increasing ankle dorsiflexion, performing rehabilitation of the ankle evertor, plantar flexor, and hamstring, and consider adjusting the energy absorption patterns of the lower extremity joints to more effectively cushion GRF.

Caution This study only explored participants who had experienced 2, 3, 4, 5 or 6 or more ankle sprains, and future studies could further subdivide the "6 or more" category so that the results of the study can be more targeted.

Keywords Ankle sprain frequencies, CAI patients, ACL loading, Biomechanics, OpenSim modelling

Introduction

Ankle sprains are a prevalent type of lower extremity injury, with 11.88% of cases occurring during sports activities [1]. Regrettably, without proper rehabilitation, around 73% of patients developed chronic ankle instability (CAI) [1]. CAI is characterized by lateral ankle ligament laxity, pain, swelling, and ankle dysfunction [2]. It is important to note that CAI increases the risk of recurrent ankle sprains [3]. A systematic review found that 68 ~ 78% of CAI patients experience recurring ankle sprains due to impaired balance and neuromuscular control of the affected lower extremity during exercise, which significantly reduces the quality of life and participation in sports [4].

Prolonged repetitive ankle sprains can damage mechanical receptors in the joint capsule [5]. This can disrupt electrical conduction between the mechanoreceptors and the central nervous system, leading to a significant reduction in ankle position and motion perception, which impairs control of the joint and the ability to cushion foot landings [5]. Moreover, it might trigger proximal adaptive responses that increase the risk of knee injuries, particularly anterior cruciate ligament (ACL) injuries [5]. Research has shown that the prevalence of ACL injuries in patients with CAI and a history of ankle sprains is as high as 59.6%, which is 15.8% higher than in healthy individuals [6–8].

Therefore, several studies have attempted to investigate the biomechanical mechanisms that make patients with CAI more susceptible to ACL injury [9, 10]. These studies, both domestically and internationally, have typically used OpenSim modeling software to calculate dynamic ACL loads, which is a widely utilized and accurate method [11]. Delahunt et al. [9] found that patients with CAI experienced significantly limited ankle dorsiflexion during the landing phase compared to healthy subjects. Furthermore, the knee flexion angle was significantly reduced during initial contact [10]. These biomechanical changes might increase the angle between the patellar tendon and the tibial shaft, leading to greater anterior tibial shear forces, which increase susceptibility to ACL injuries [10]. However, other research investigated the movement strategies of lower extremities during single-leg landing in patients with CAI and found that they often exhibit larger ankle dorsiflexion angle, knee flexion angle, and hip flexion angle than healthy individuals [12]. Simpson et al. [13]. conducted a systematic study and found that patients with CAI exhibited prolonged activation latency of the peroneus longus and soleus muscles during the landing phase. This reduced the cushioning effect of the ankle against the medial-lateral ground reaction force (GRF), which in turn led to an increase in knee loading and thus higher ACL loads [14]. However, a study analyzed the forces and energy dissipation in the lower extremity of CAI patients during vertical jump landing. The findings elucidated a noteworthy revelation: the knee joint experienced lower loads compared to other joints in individuals with CAI [15]. As indicated by these varied reports, the biomechanical mechanism that made CAI patients more susceptible to ACL injuries is not well understood. This might be due, in part, to the fact that none of the above studies carefully differentiated the incidence of ankle sprains in patients with CAI [9, 10, 12, 13, 15]. Previous research has shown that the number of self-reported previous sprains was associated with physical dysfunction, lower extremity instability and ACL injury severity, particularly in individuals with two or more prior ankle sprains [16]. As demonstrated by KO et al. [17], an increased number of ankle sprains is associated with a reduction in dynamic stability of the lower extremity, with correlation coefficients ranging from 0.21 to 0.66. Similarly, Bruce et al. [18] observed that individuals with multiple ankle sprains exhibited significant physical dysfunction. Additionally, the number of previous ankle sprains in CAI patients was positively correlated with the severity of ACL injuries, with a χ^2 value of up to 5.27 [7]. It is therefore evident that a more detailed classification of ankle sprain incidences in patients with CAI is required, given that varying frequencies of ankle sprains can result in distinct kinematic characteristics of the ankle and knee joints, as well as differences in physical function. This approach will facilitate an exploration of the relationship between ankle kinematics and ACL loading in CAI patients with different sprain histories, ultimately leading to more accurate research conclusions.

The objective of this study was to compare lower extremity biomechanics in CAI patients across different ankle sprain frequencies within a year. Additionally, the relationship between these biomechanical characteristics and ACL strain was analyzed. The present study hypothesizes that patients with CAI who have experienced more frequent ankle sprains might experience increased ACL loading. Additionally, this population exhibited insufficient ankle dorsiflexion angle, gastrocnemius muscle force, soleus muscle force, greater ankle inversion angle, and inversion angle velocities during single-leg landing, which might result in an increase in ACL loading. The results of this study may help to identify the threshold at which CAI patients begin to experience knee compensation, and provide a scientific reference for future studies to evaluate potential associations between ankle sprain and ACL injury.

Methods

Participants

The study participants were chosen according to the International Ankle Consortium's criteria for identifying patients with CAI [19]. Participants were included in the study if they satisfied the following criteria: (1) Participants were required to have experienced at least one ankle sprain that resulted in ≥ 1-day interruption of physical activity and was associated with inflammatory symptoms (e.g., pain, swelling). Furthermore, participants must have suffered an initial ankle sprain at least 12 months previously, the most recent of which have occurred at least 3 months before the experiment; (2) On at least two occasions, participants must have experienced their ankle "giving way" due to repeated (two or more) ankle sprains of the affected ankle within the six months prior to the experiment, and each individual's Cumberland Ankle Instability Scale (CAIT) score must have been less than 24; and (3) their Foot and Ankle Ability Measure (FAAM)-Activities of Daily Living (ADL) scale score had to be less than 90%, and their FAAM-Sport scale score had to be less than 80%. Additionally, their Foot and Ankle Outcome Score (FAOS) score had to be less than 75% in three or more categories. Exclusion criteria for participation in the experiment included the following: (1) Participants had a history of previous surgeries to the musculoskeletal structures (i.e., bones, joint structures and nerves) in either lower extremity; (2) Participants had a history of lower extremity fracture; and (3) Within 3 months prior to the experiment, participants had an acute injury to the joint structures of the lower extremity that compromised the integrity and function of the joints and resulted in cessation of physical activity for at least 1 day.

The sample size was determined using Gpower software (3.1.9.2), with a statistical power of 0.8, an alpha value of 0.05, and a number of groups set to 5. This yielded a sample size of 70 individuals, with 14 in each group. In this investigation, 80 CAI patients were enlisted into the study one year antecedent to the formal biomechanical assessments. During this period, the testers recorded the incidence of ankle sprains experienced by each participant over the one-year interval with great care and attention to detail. In this study, ankle sprains were diagnosed by a professional clinician in conjunction with the magnetic resonance imaging (MRI) results. The diagnostic criteria employed in this study are in accordance with the internationally recognised diagnostic criteria for the diagnosis of lateral ankle sprains [20–23]. The criteria categorise ankle sprains into three distinct categories, as follows: A Grade I (mild) sprain is characterised by a stretching of the ligament without macroscopic tearing, minimal swelling or tenderness, and a slight or absent functional loss, as well as no mechanical instability of the joint. A Grade II (moderate) injury is characterised by a partial macroscopic tear of the ligament, accompanied by moderate pain, swelling and tenderness over the affected structures. Some degree of loss of motion and mild or moderate instability of the joint are observed. A Grade III sprain is characterised by a complete rupture of the ligament, accompanied by severe swelling, haemorrhage and tenderness. Furthermore, there is a reduction in the ability to bear weight on the affected foot, accompanied by a limitation in functional capacity and a notable degree of abnormal motion and instability of the joint. The ankle sprains that occurred in the subjects of this study should be classified as either grade I or grade II ankle sprains.

Subsequently, participants were stratified into groups based on the frequency of ankle sprains occurring within the specified time frame, categorized as 2, 3, 4, 5, or greater than 6 instances of injury history. However, one participant was excluded due to a history of lower extremity fractures, while five others were unable

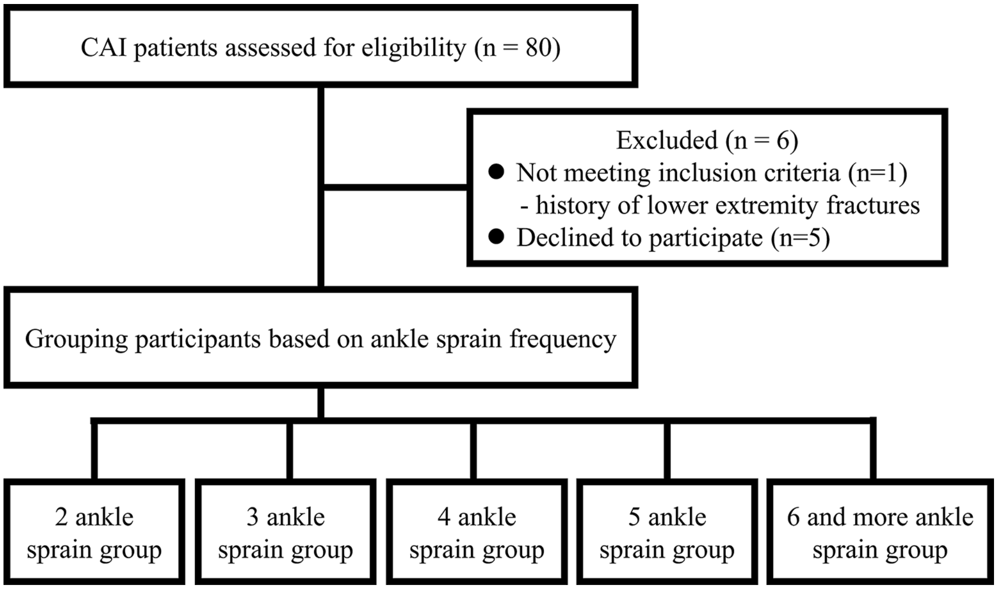

Fig. 1 Study flow diagram

Table 1 Demographics of participants (mean ± SD)

Number of ankle sprains/(times)	2	3	4	5	6 or more	*P*
Sample size/(n)	15	15	15	15	14	—
gender	male	male	male	male	male	—
Age/(year)	22.1 ± 1.3	21.6 ± 0.9	23.0 ± 2.0	20.8 ± 2.2	21.4 ± 1.4	0.125
Height/(cm)	175.1 ± 7.1	176.9 ± 7.1	177.3 ± 4.8	176.7 ± 6.7	175.9 ± 7.0	0.141
Weight/(kg)	71.2 ± 6.2	71.4 ± 8.6	70.9 ± 6.4	73.8 ± 8.6	75.8 ± 9.7	0.181
CAIT score	21.8 ± 1.9	20.8 ± 1.6	20.4 ± 2.3	17.5 ± 1.9$^{*\#\$}$	17.1 ± 2.2$^{*\#\$}$	<0.001
FAAM-ADL score/(%)	81.5 ± 5.9	82.0 ± 6.1	77.9 ± 6.4	78.5 ± 6.8	79.9 ± 5.2	0.064
FAAM-Sport score/(%)	69.0 ± 4.9	70.1 ± 6.3	68.2 ± 6.3	68.9 ± 5.9	67.5 ± 5.2	0.360
FAOS score/(%)						
Symptom/(%)	69.8 ± 4.2	68.1 ± 5.7	66.9 ± 7.3	67.6 ± 7.1	66.2 ± 5.9	0.709
Pain/(%)	72.6 ± 9.7	72.9 ± 8.8	71.2 ± 11.3	68.7 ± 10.3	69.3 ± 9.5	0.174
Activities of Daily Living/(%)	81.9 ± 3.6	78.4 ± 5.6	79.7 ± 5.1	80.2 ± 4.2	78.9 ± 6.6	0.855
Sport/(%)	70.4 ± 3.5	70.7 ± 3.8	68.4 ± 5.7	66.9 ± 4.9	68.7 ± 4.2	0.127
Quality of Life/(%)	70.9 ± 4.7	73.2 ± 6.3	66.4 ± 5.2$^{\#}$	68.7 ± 7.8$^{\#}$	65.8 ± 3.5$^{\#}$	0.004

Note The symbol * indicates a statistically significant difference between the current group and patients with two ankle sprains. Similarly, the symbol # indicates a statistically significant difference between the current group and patients with three ankle sprains, while the symbol $ indicates a statistically significant difference between the current group and patients with four ankle sprains

to participate in the formal experiment for personal reasons, resulting in a final participation count of 74 individuals (Fig. 1). All participants carefully read the protocol of this experiment, understood the experimental procedure and signed the informed consent form. Basic anthropometric tests, including gender, age, height, weight, CAIT score, FAAM-ADL score, FAAM-Sport score and FAOS score were performed on the subjects prior to the formal experiment, and the results are shown in Table 1. The CAIT scores were found to be significantly higher in patients with CAI who had experienced five or more ankle sprains. Furthermore, a significant decrease in quality of life scores was observed in patients who had experienced four or more ankle sprains.

Test apparatus

In this study, 12 Vero v2.2 infrared cameras (Vicon, UK) and a motion capture system with a 14 mm infrared marker ball were used to record single-leg landing maneuvers. The cameras were positioned at a height of 2.5 m and used a sampling frequency of 100 Hz. Furthermore, two AMTI 3D force plates (AMTI, USA) were used to record the GRF of the subjects during single-leg landing with a sampling frequency of 1 kHz. The surface electromyography (EMG) device used in this paper was the Ultium wireless telemetry system (Noraxon, USA) that contained a 32-channel signal collector, a USB data transfer interface and a wireless receiver card that either could be connected wirelessly or via a cable to a computer. For surface EMG testing, it was often used in conjunction with electrodes and pre-amplifiers.

Experimental design and testing procedures

The experiment was conducted at the conclusion of the one-year monitoring period, at which point the subjects had already experienced multiple sprains. All subjects exhibited a complete recovery from the symptoms commonly associated with ankle sprains, including pain, swelling, limited mobility and joint instability, at the time of experimental testing. The present study primarily analyzes the biomechanical data from the injured side, which is the limb exhibiting symptoms of CAI. To ensure an objective evaluation of results, it is essential to eliminate the potential confounding effects of the dominant and non-dominant sides. The injured side of the participants included in this study was the dominant side. Additionally, nine subjects in this study exhibited bilateral CAI, with only their dominant side undergoing monitoring and biomechanical analysis.

Before the formal experiment, to ensure optimal adhesion of electromyography electrodes, the designated areas underwent meticulous hair removal. Additionally, participants were provided with uniform shorts, vests and sports shoes, and performed uniform warm-up movements, including jogging, deep squatting, lunging, longitudinal jumping, direction-change running, etc. The warm-up time was 10 min. Afterward, testers provided a detailed explanation of the essentials of the test movements to the subjects, and sufficient time was allowed for practice. After the preparatory work was completed, the reflective marker ball and the electrodes were uniformly attached to the participants, and static calibration data were collected. The static calibration movements are shown in Fig. 2. Markers were attached to 39 bony marker points, including the left anterior head, right anterior head, 7th cervical vertebra, 10th lumbar vertebra, left anterior superior iliac spine, right anterior superior iliac spine, left posterior superior iliac spine, right posterior superior iliac spine, knees, thighs, calves, ankle joints, toes, heels, etc. The electrodes were attached to 8 lower limb muscles including the biceps femoris, rectus femoris, vastus lateralis, vastus medialis, gastrocnemius, soleus, peroneus longus and tibialis anterior in accordance with Surface Electromyography for the Non-Invasive Assessment of Muscle (SENIAM) guidelines [24]. At the start of the formal test, CAI patients were asked to stand on a 40 cm high test platform with the injured (dominant) leg [25]. Once the infrared camera had commenced recording, the participants proceeded to place a single leg (injured side) onto the force platform. Subsequently, the participants were required to maintain body equilibrium for a minimum of three seconds following landing. A time period of less than three seconds would

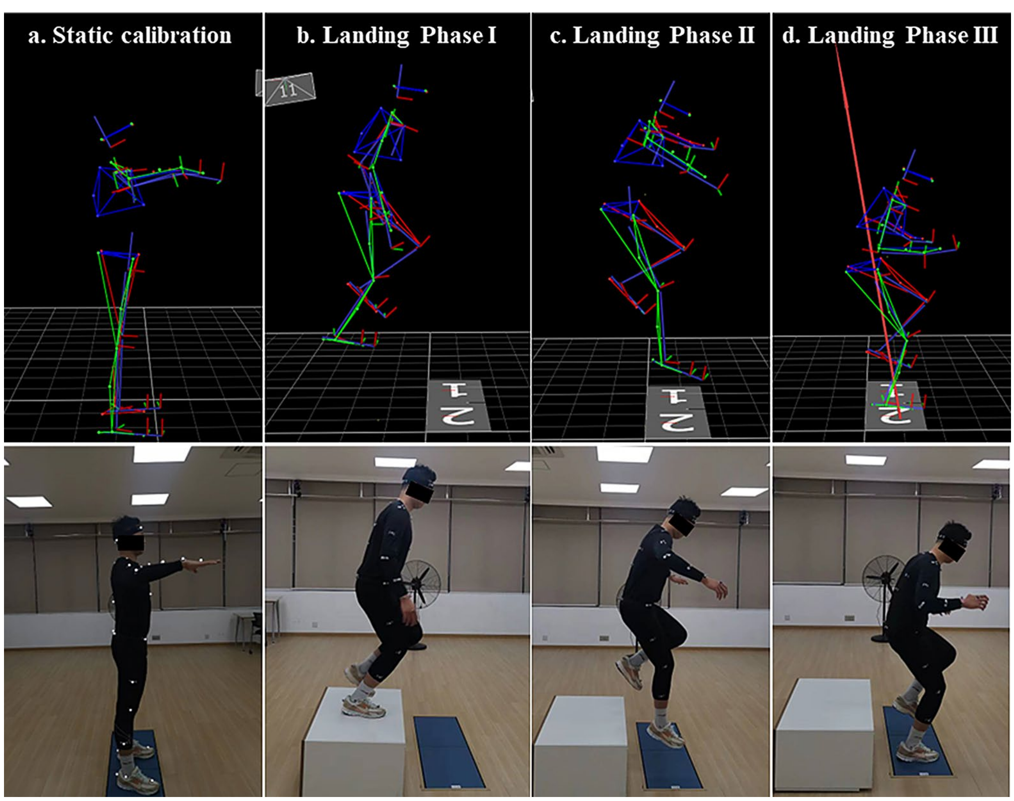

Fig. 2 Static calibration and single-leg landing movement

be considered an unsuccessful experiment [26]. Instances of secondary movement post-grounding resulting in an inability to sustain balance were excluded from data analysis. (Fig. 2). They rested for one minute and repeated the same maneuver four times, resulting in a total of five valid data sets.

Data extraction and preparation

This section describes analyses of the biomechanical data from the moment of landing, when the force value on the platform exceeded 10 N, to the moment of maximum knee flexion. Data from the marked points and the GRF data were collected and processed using Vicon software (Vicon Industries, Inc., UK). The original data were smoothed using a fourth-order Butterworth filter with cut-off frequencies of 10 Hz and 100 Hz for the marker and GRF data, respectively. The midpoint of the line connecting the medial and lateral femoral condyle markers was defined as the center of the knee joint, and the midpoint of the line connecting the medial and lateral ankle markers was defined as the center of the ankle joint [27]. EMG signal data were processed using Matlab 2016b software, including applying a Butterworth band-pass filter with frequencies ranging from 10 Hz to 400 Hz, full-wave rectification, and low-pass filtering with a cut-off frequency of 6 Hz [27]. All EMG signals were normalized to maximum voluntary contraction (MVC) in order to facilitate inter-subject comparisons and to ensure the consistency of the dataset.

The kinematic and kinetic data were exported to a c3d format file, converted to mot (Multiple Object Tracking) and trc (Track Row Column) formats using the c3dExport.m package in Matlab 2016b, and then imported into OpenSim 4.1. In this study, the Gait_2354 model in OpenSim was used and the ACL was added to this model. The ACL model extended from the anterior fossa of the tibial condyle to the lateral condyle of the femur, and represented a passive nonlinear elastic soft tissue along the direction of the ligament starting and ending points. The ACL was set up as a passive tissue, with activation of contractile elements being inhibited (Fig. 3).

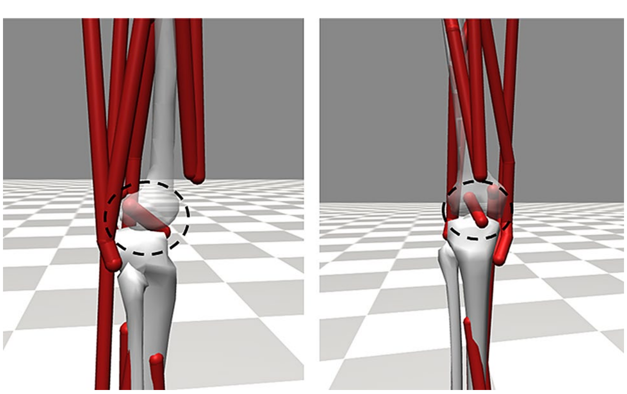

Fig. 3 Location of ACL insertion in the OpenSim model, indicated by a dashed circle

In OpenSim, we first constructed a generic model based on the subject's height, weight and muscle data, and then scaled the length and mass of the segments using the marker point data obtained from the experiment (Scaling Model, SM). Furthermore, we verified the optimality of the model by finding the best-fit model for the data through inverse kinematics. The process primarily utilized the weighted least squares method to compute the disparities between the experimentally measured 3D coordinates of the marker points, the coordinate system, and the model coordinates, and to minimize these disparities. Force residuals (*Fresidual*) represented discrepancies between the experimental mechanical data and the simulation results. The Reduce Residuals Algorithm in OpenSim could reduce the residuals by optimizing the trajectory and making adjustments to the coupling quality and other variables. The maximum permissible force error was generally between 0 and 10 N, and the maximum permissible torque error was between 0 and 50 N. In addition, Calculate Muscle Control was used to simulate lower extremity muscle force and ACL load. Finally, the kinematic, kinetic and muscle activation data from OpenSim simulations were compared with experimental data in this study using the validation method proposed by Błażkiewicz et al. [28]. OpenSim simulations were considered accurate if differences between residual pelvic forces and peak residual moments derived from OpenSim simulations and experimental measurements did not exceed 20 N and 75 N·m, respectively, and EMG curves were similar.

Experimental indicators

(1) ACL load was defined as the force on the ACL during human movement. It was derived from OpenSim modeling and normalized to a multiple of body weight (BW). (2) Joint angle was defined as the angle between adjacent hinges. The knee angle was defined as the angle between the thigh hinge and the calf hinge, and the ankle angle was defined as the angle between the calf hinge and the foot hinge. (3) Joint angular velocity is the angular displacement of the hinge around the joint's center per unit of time and was usually derived from the differentiation of angular displacement and time. (4) GRF is the force generated when the human body strikes the ground and was directly measured by the three-dimensional force plates. As GRF is strongly influenced by body weight, it was normalized by body weight. (5) Muscle force was defined as the force generated by muscle contraction during lower extremity movement and was derived from OpenSim modeling. The following muscles were included in the analysis: the long head of biceps femoris, the short

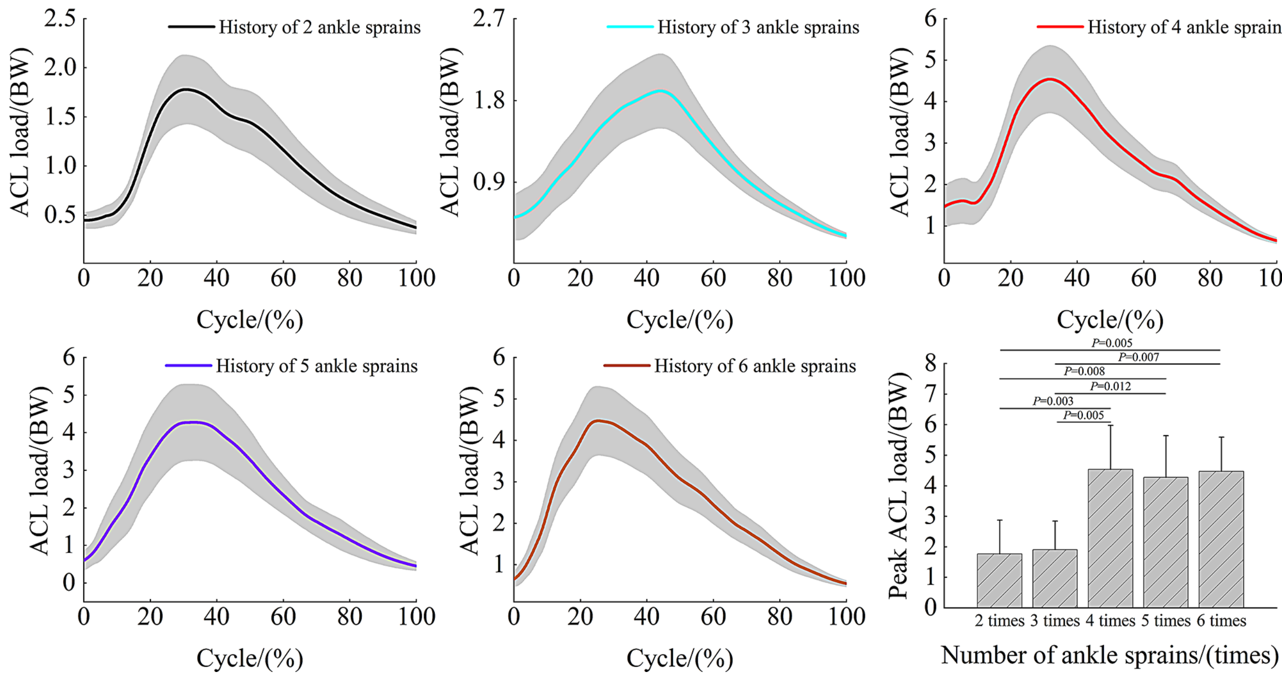

Fig. 4 ACL load curve and peak characteristics of CAI patients during single-leg landing. Note: within the figure, the solid line delineates the mean curve of the indicator, whereas the shaded portion depicts the standard deviation

Table 2 F and η^2 values for one-way ANOVA (indicators with significant differences)

Index	F	η^2
ACL Loading	4.812	0.218
Ankle dorsiflexion angle	6.394	0.270
Ankle inversion angle	3.741	0.178
Knee varus angle	5.230	0.233
Ankle inversion angular velocity	1.624	0.086
Vertical GRF	6.309	0.268
Long head of biceps femoris strength	2.455	0.125
Rectus femoris muscle strength	6.199	0.264
Gastrocnemius muscle strength	3.644	0.174
Soleus muscle strength	8.146	0.321

head of biceps femoris, the sartorius muscle, the gracilis muscle, the rectus femoris muscle, the gastrocnemius muscle, the soleus muscle, the tibialis posterior muscle, and the tibialis anterior muscle. As lower extremity muscle force during single-leg landing might be affected by body weight, muscle force was also normalized by body weight.

Statistical analysis
The study expressed all index data as mean ± standard deviation (SD) and used an independently designed one-way ANOVA to compare differences in lower extremity joint kinematics, kinetics, muscle strength, and ACL loading between CAI patients who experienced 2, 3, 4, 5, and 6 or more ankle sprains, with the significance level set at $P < 0.05$. The effect size of the one-way ANOVA, η^2, was calculated. A low effect size was indicated by $0.01 \leqq \eta^2 < 0.06$, a medium effect size by $0.06 \leqq \eta^2 < 0.14$, and a high effect size by $\eta^2 \geqq 0.14$ [29]. Pearson's correlation analysis was used to further investigate the relationship between lower extremity kinematics, kinetics, muscle strength and ACL loading in CAI patients. The correlation coefficient $|r| \geq 0.50$ was considered high, $0.50 > |r| \geq 0.30$ was moderate, and $0.30 > |r| \geq 0.10$ was low.

Results
ACL loading
As illustrated in Fig. 4; Table 2, patients with CAI who had sustained four or more ankle sprains exhibited a markedly elevated peak ACL load during single-leg landing in comparison to patients with 2 or 3 ankle sprains.

Kinematics, kinetics and muscle force of the lower extremity
Kinematics
As shown in Fig. 5; Table 2, patients with CAI who suffered 4, 5, or 6 or more sprains exhibited a significantly lower ankle dorsiflexion angle during single-leg landings than those who suffered only 2 or 3 ankle sprains. Furthermore, CAI patients with 5 ankle sprains exhibited a significantly greater ankle inversion angle during single-leg landing than those with only 3 or 4. The ankle inversion angle during single-leg landing was significantly greater in patients with CAI who had experienced 6 or more ankle sprains than those who had only experienced

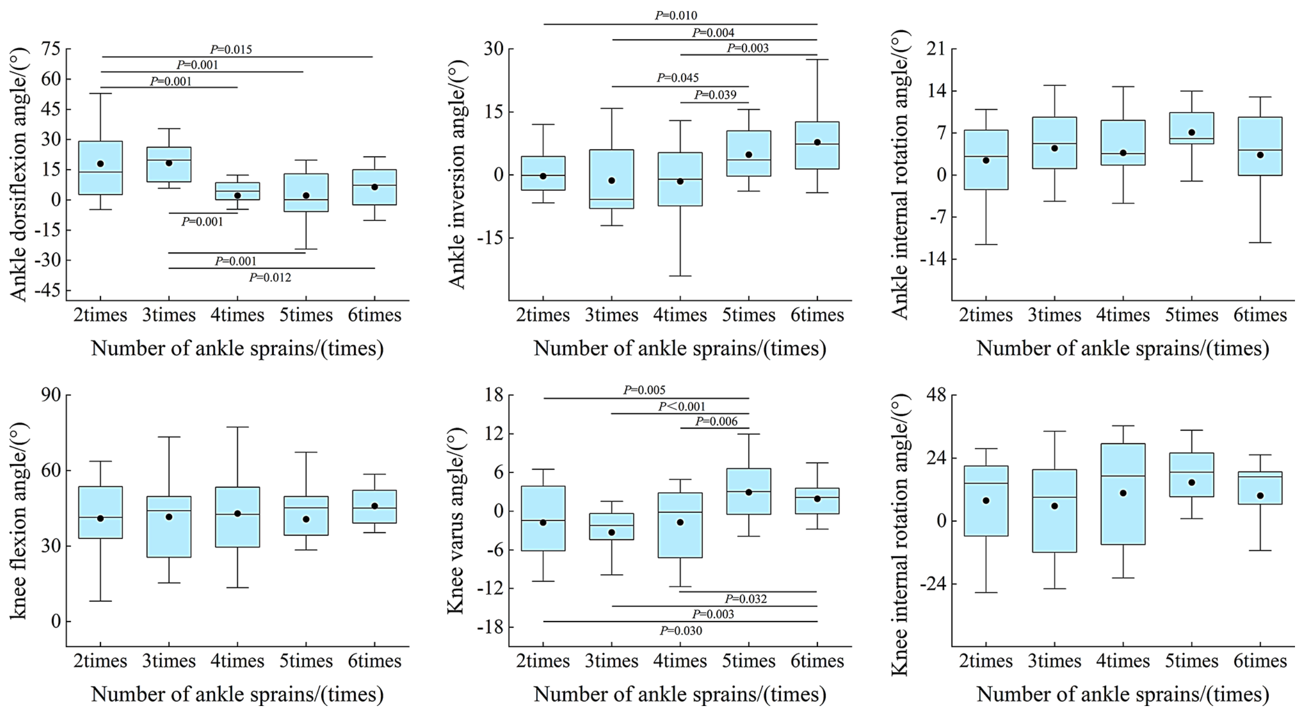

Fig. 5 Joint angle of CAI patients during single-leg landing

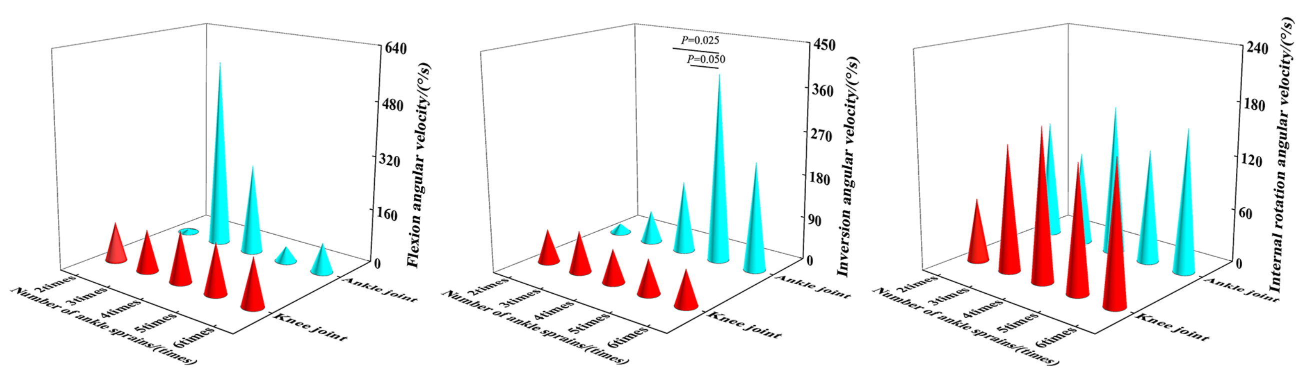

Fig. 6 Joint angular velocity of CAI patients during single-leg landing

2, 3, or 4 sprains. Furthermore, the study found that CAI patients who had experienced 5 or more than 6 ankle sprains exhibited a markedly increased knee varus angle during single-leg landing in comparison to those who had experienced only 2, 3, or 4 ankle sprains.

Figure 6; Table 2 shows that CAI patients with 5 ankle sprains had a significantly greater ankle inversion angular velocity during single-leg landing than those with only 3 or 4 sprains.

Kinetics

Vertical GRF was greater in CAI patients with 5 or more than 6 sprains than CAI patients with only 2, 3, or 4 sprains (Fig. 7; Table 2).

Muscle force

Figure 8 shows that CAI patients with 4 ankle sprains had greater strength in the long head of the biceps femoris muscle than those with 2, 3, 5, or 6 or more sprains. Additionally, CAI patients with 5 or more than 6 ankle sprains had significantly greater rectus femoris muscle strength during single-leg landing than those with only 2 or 3 sprains. Furthermore, CAI patients who experienced 5 or more than 6 sprains exhibited reduced gastrocnemius muscle strength during single-leg landings than those who had only 2 to 4 ankle sprains. Additionally, CAI patients with 5 or 6 sprains exhibited significantly lower soleus muscle force during single-leg landing than those with only 2–4 ankle sprains (Table 2).

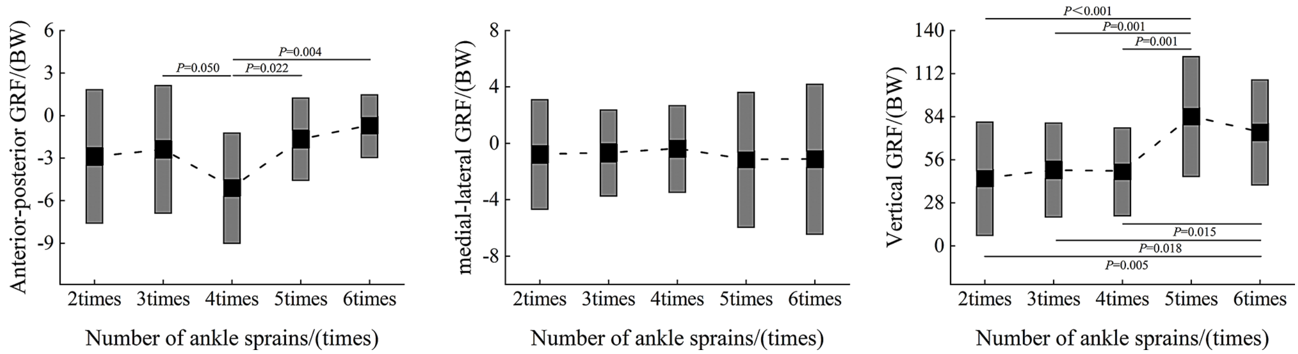

Fig. 7 GRF characteristics of CAI patients during single-leg landing

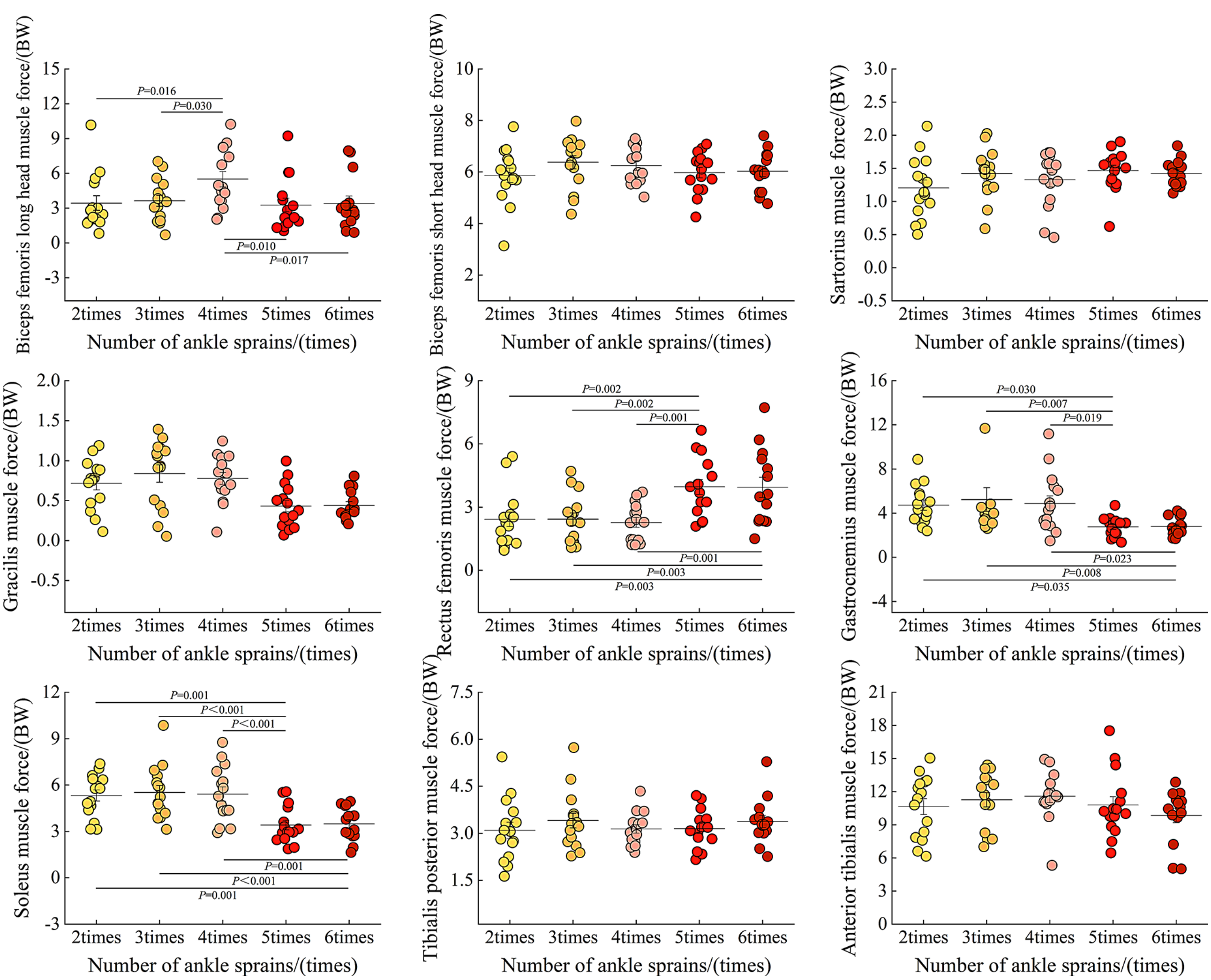

Fig. 8 Muscle strength of CAI patients during single-leg landing

Correlation of biomechanical indices with ACL loading

The study found significant positive correlations between force produced by the long head of the biceps femoris muscle ($r = 0.532$, $P = 0.041$) during single-leg landing and ACL load in patients with CAI who had experienced 4 ankle sprains. Additionally, the dorsiflexion angle of the ankle was significantly negatively correlated with ACL load ($r = -0.707$, $P = 0.003$). In CAI patients with five ankle sprains, ankle inversion angle ($r = 0.750$, $P = 0.001$), ankle inversion velocity ($r = 0.538$, $P = 0.039$), and vertical GRF ($r = 0.761$, $P = 0.001$) during single-leg landing were significantly positively correlated with ACL load. Conversely, ankle dorsiflexion angle ($r = -0.765$, $P = 0.001$), gastrocnemius muscle force ($r = -0.565$, $P = 0.028$), and soleus muscle force ($r = -0.762$, $P = 0.001$) were negatively correlated with ACL loading. In patients with CAI who experienced more than 6 ankle sprains, ankle inversion angle ($r = 0.808$, $P < 0.001$), knee varus angle ($r = 0.720$, $P = 0.004$), vertical GRF ($r = 0.550$, $P = 0.041$), and rectus femoris muscle strength ($r = -0.863$, $P < 0.001$) were positively correlated with ACL load, whereas ankle dorsiflexion angle ($r = -0.640$, $P = 0.014$) and soleus muscle force ($r = -0.763$, $P = 0.002$) was negatively correlated with ACL load (Table 3).

Discussion

The objective of this study was to compare lower extremity biomechanics in CAI patients across different ankle sprain frequencies within a year. Furthermore, the relationship between these biomechanical characteristics and ACL strain was analyzed. The findings demonstrate that CAI patients who have experienced more than four ankle sprains exhibited increased ACL loading during single-leg landing. This finding supported the study's hypothesis, which suggested that knee joint compensation in CAI patients primarily occurred after four ankle sprains.

This paper reported that ankle dorsiflexion was limited during the landing phase in patients with CAI who had more than four ankle sprains. This might be due to excessive tension in the non-contractile tissues or degenerative lesions of the ankle joint caused by multiple sprains, which might reduce the flexibility of the anterior-posterior sliding of the talus and affect the brain's ability to perceive the distance between the talus and the malleolus [30]. These alterations ultimately result in reduced ankle dorsiflexion [30]. Furthermore, the study revealed that individuals who had experienced more than four ankle sprains within a one-year period demonstrated a reduction in CAIT scores. Prior research has indicated a correlation between lower CAIT scores and more severe CAI [31]. Severe CAI have been linked to a range of ankle dysfunctions, including limited ankle dorsiflexion [31]. The study results revealed that decreased ankle dorsiflexion angle leads to a substantial increase in ACL load in CAI patients. The performance of landing tasks places a significant demand on the function of ankle dorsiflexion, given its pivotal role in absorbing and dissipating GRF [32]. Restrictions on ankle dorsiflexion in CAI patients result in a considerable reduction in the cushioning capacity of the ankle joint [32, 33]. This hypothesis is further supported by the results of the present study, which revealed that the strength of the major cushioning muscles of the ankle joint (gastrocnemius and soleus) was significantly reduced in CAI patients after multiple sprains. An inability of the ankle to provide an adequate degree of cushioning for the GRF will result in its continued transmission upwards to the knee joint, leading to an increase in the overall load on the knee and an increase in the ACL load [32, 33]. Therefore, it is recommended that dorsiflexion stretching exercises and plantarflexor strength training should be used to increase ankle dorsiflexion and reduce knee compensation during landing in CAI patients with more than four ankle sprains [30].

In addition, the study revealed that CAI patients with more than 5 ankle injuries had a greater ankle inversion angle during single-leg landing, which might be due to joint kinematics and positioning deficits that made it difficult for them to accurately return the ankle to a neutral orientation, resulting in landing with an inverted posture [34]. The meta-analysis showed that CAI patients had moderate or mild eversion muscle weakness at centripetal contraction velocities between 30°/s and 120°/s. This weakness might be a significant contributing factor to the increased ankle inversion angle, which in turn further contributed to the increased knee varus angle due to the presence of kinematic chains in the joints of the lower extremity. The above kinematic characteristics were significantly correlated with ACL loading. The reason for this was that the ACL was pre-strained in the inverted orientation due to its anatomical position, originating from the anterior fossa of the tibial condyle and terminating at the lateral condyle of the femur, making knee varus highly susceptible to ACL injuries than the neutral and valgus positions [35]. The study by Orsi et al. [36] confirmed the above assumption and found that ACL tearing due to knee varus was 46.6% higher than that due to valgus. Therefore, the present results suggest that patients with CAI who have experienced more than five ankle sprains should perform both ankle evertor strength training and proprioceptive exercises simultaneously to maintain a neutral ankle orientation during the landing phase and reduce knee compensatory responses. Simultaneously, it is important to strengthen muscles around the knee joint and core muscle groups to enhance the stability of the knee joint and minimize ACL load during exercise.

This study found that CAI with five ankle sprains had a significantly greater ankle inversion angular velocity during single-leg landing than CAI with only three or four ankle sprains. The reason for this was that the activation time of the ankle eversion muscles, such as the peroneus longus and peroneus brevis, was 126 ms later in CAI patients than the healthy population at the moment of initial contact. The underlying mechanism is that each ankle sprain is accompanied by oedema and pain [37]. These physiological responses subsequently trigger enhanced H-reflexes and neuromuscular inhibition, including arthrogenic muscle inhibition and muscle weakness, in the periprosthetic muscles of the ankle,

Table 3 Correlation of lower extremity kinematics, kinetics, and muscle strength with ACL load in patients with CAI

Index	ACL loading									
	2 sprains		3 sprains		4 sprains		5 sprains		6 or more sprains	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Ankle dorsiflexion angle	−0.024	0.934	0.077	0.786	−0.707	0.003*	−0.765	0.001*	−0.640	0.014*
Ankle inversion angle	0.262	0.346	0.072	0.798	−0.009	0.974	0.750	0.001*	0.808	< 0.001*
Ankle internal rotation angle	0.010	0.972	0.174	0.536	0.197	0.482	0.006	0.982	0.715	0.004*
Knee flexion angle	0.005	0.987	−0.196	0.484	0.378	0.165	0.265	0.340	−0.184	0.530
Knee varus angle	−0.591	0.020*	0.341	0.214	−0.279	0.313	0.418	0.121	0.720	0.004*
Knee internal rotation angle	0.363	0.184	−0.268	0.334	0.026	0.928	0.343	0.211	−0.007	0.981
Ankle plantarflexion angular velocity	0.026	0.927	−0.094	0.739	0.124	0.659	0.446	0.095	0.441	0.114
Ankle inversion angular velocity	0.593	0.020*	0.472	0.076	0.534	0.040*	0.538	0.039*	−0.144	0.623
Ankle internal rotation angular velocity	−0.057	0.840	−0.149	0.596	0.338	0.217	0.022	0.937	0.335	0.241
Knee flexion angular velocity	0.375	0.168	0.316	0.251	0.109	0.698	−0.019	0.947	0.025	0.931
Knee inversion angular velocity	0.379	0.164	0.652	0.008*	0.260	0.349	0.655	0.008*	0.311	0.279
Knee internal rotation angular velocity	0.059	0.835	0.442	0.099	0.311	0.260	0.495	0.061	0.560	0.037*
Anterior-posterior GRF	0.423	0.116	0.732	0.002*	0.665	0.007*	−0.060	0.832	0.411	0.144
Medial-lateral GRF	−0.544	0.036*	−0.582	0.023*	−0.380	0.163	−0.816	< 0.001*	−0.725	0.003*
Vertical GRF	0.605	0.017*	0.251	0.367	0.205	0.464	0.761	0.001*	0.550	0.041*
Long head of biceps femoris strength	−0.406	0.133	0.305	0.270	0.532	0.041*	−0.416	0.123	−0.163	0.578
Short head of biceps femoris strength	0.498	0.059	0.178	0.526	0.018	0.950	0.123	0.663	−0.432	0.123
Sartorius muscle strength	0.867	< 0.001*	0.313	0.255	0.622	0.013*	0.337	0.219	−0.173	0.555
Gracilis muscle strength	0.417	0.122	0.234	0.400	−0.094	0.740	−0.119	0.672	−0.059	0.841
Rectus femoris muscle strength	0.715	0.003*	0.423	0.116	0.189	0.501	−0.042	0.882	0.863	< 0.001*
Gastrocnemius muscle strength	−0.041	0.883	0.007	0.979	0.042	0.881	−0.565	0.028*	−0.763	0.002*
Soleus muscle strength	0.505	0.055	−0.056	0.842	0.273	0.325	−0.762	0.001*	−0.377	0.184
Tibialis posterior muscle strength	0.206	0.464	−0.165	0.556	−0.070	0.804	−0.092	0.746	−0.003	0.992
Tibialis anterior muscle strength	−0.017	0.952	−0.316	0.251	−0.346	0.207	−0.478	0.072	−0.032	0.914

Note The presence of an asterisk (*) indicates that the corresponding indicator is significantly correlated with ACL loading particularly the eversion muscle [37]. It is important to note that in cases where an individual has sustained multiple sprains of the ankle joint, particularly more than five sprains, the expected relief from oedema and pain may not be achieved in a timely or effective manner. This can lead to notable alterations in neural drive [37]. This alteration further impairs the homeostasis of the central nervous system (encompassing the spinal cord and/or supraspinal levels), resulting in a considerable reduction in the number of motor unit action potentials (MUAPs) received by the ankle eversion muscle [37]. This ultimately restricts the capacity of these muscles to activate [37]. As a consequence, patients who had sustained more than five ankle sprains were unable to promptly generate eversion moment, thereby inhibiting the immediate reduction of ankle inversion angular velocity [38]. The study found a positive correlation between the ankle inversion angular velocity and ACL loading. Previous studies have demonstrated that increased ankle inversion angular velocity leads to a reduction in postural stability in patients with CAI [39]. A lack of postural control has been demonstrated to precipitate an instability of the center of mass. This instability gives rise to excessive body sway, which in turn elevates the lateral shear forces exerted at the lower extremity joints, particularly the knee [40]. Consequently, the repeated tensile forces exerted on the ACL result in an increased loading of the ligament, which has been demonstrated to lead to an elevated risk of injury [40]. Having said all of the above, during the rehabilitation process of CAI patients, it is important to not only improve the strength of the ankle eversion muscles, but also to focus on exercises that enhance body posture control. Implementing this approach could effectively mitigate knee joint compensation in patients with CAI, thus providing a preventive measure against the occurrence of ACL injuries [40].

This study found that CAI patients who had experienced more than five ankle sprains exhibited a larger vertical GRF during single-leg landing. This was because CAI patients developed a strategy to protect the ankle after multiple sprains, often completing the landing with a lower ankle dorsiflexion angle, which reduced the proportion of energy absorbed at the ankle. While this strategy might enhance ankle stability to some extent, it did not promote landing cushioning and tended to result in a higher vertical GRF [41]. Weinhandl et al. [42] discovered a positive correlation between vertical GRF and ACL loading through forward kinetic modeling, which was consistent with the findings of this study. This was due to the fact that a higher vertical GRF increased the overall loading rate of the lower extremity and the load on the ACL [41]. The above results highlight the importance of enhancing ankle sagittal plane mobility in the prevention of ACL injuries. In addition, because the hip extensors were stronger than the knee and ankle extensors, increasing the hip's contribution to energy absorption might be beneficial in reducing knee compensation in CAI patients [43].

Serpell et al. [44] demonstrated that the biceps femoris frequently contracts in conjunction with the vastus lateralis muscles, resulting in increased anterior-posterior tibial displacement and passive stretching of the ACL by approximately 0.52 mm. In addition, sustained contraction of the biceps femoris during exercise could cause muscle strain and contractile inhibition, leading to an imbalance of forces around the knee that may further aggravate ACL load [44]. The present study found that CAI patients with four ankle sprains demonstrated greater biceps femoris muscle strength during exercise, which positively correlated with ACL loading, consistent with previous research [44]. The underlying reason for this may be that experiencing multiple ankle ligament injuries within a year can lead to continuous ankle instability, resulting in increased abnormal displacement of the tibia during landing [45]. This results in elevated compression and friction within the knee joint, which may subsequently stimulate the receptors of the biceps femoris in an anomalous manner, thereby triggering aberrant activation of the biceps femoris [45]. It is interesting to note that only patients who have sustained four ankle sprains will exhibit excessive biceps femoris muscle strength. In comparison, CAI patients who had experienced five or six ankle sprains exhibited similar biceps femoris muscle strength to those who had experienced two or three sprains. This is attributable to the fact that following five, six, or more ankle sprains, the aberrant lower limb cushioned pattern precipitates a notable elevation in GRF [46]. In response to this intensified loading, the lower extremity joints exhibit a protective mechanism that manifests itself by increasing the muscle strength of the knee extensors (rectus femoris) and decreasing the strength of the knee flexors (biceps femoris). This increases the stiffness of the knee joint, thus enhancing the capacity to absorb GRF and safeguarding the soft tissues within the knee joint [47]. The identification of this protective mechanism may provide insight into the clinical management of patients with CAI.

This study found that CAI patients with more than 5 ankle sprains exhibited greater rectus femoris muscle force during the landing phase. This was attributed to the limited ankle dorsiflexion in CAI patients, which reduced the energy absorption capacity of the ankle joint [48]. As a result, patients had to maintain higher knee extensor muscle force to absorb the residual GRF [49]. In accordance with the findings of Li et al. [50], the application of a force measuring 200 N to the rectus femoris muscle during knee extension yielded a pronounced increase in the anteroposterior displacement of the tibia, concomitant with an approximate 70 N augmentation in the load exerted on the ACL. Furthermore, co-contraction of the quadriceps and hamstrings further increased the ACL force, and if it exceeded 2020 N, a serious ACL injury might occur [50]. It was suggested that patients with CAI should first focus on improving the flexibility of the ankle joint in the sagittal plane, increasing the energy absorption capacity of the ankle joint during landing, and reducing the energy absorption ratio on the rectus femoris muscle.

The gastrocnemius and soleus muscles together form the triceps surae muscles, which are responsible for keeping the body upright and play a crucial role in maintaining the stability of the ankle and knee joints. A study utilizing a 2D geometric model discovered that activation of the gastrocnemius and soleus muscles resulted in a reduction of ACL strain at all knee flexion angles [51]. In a subsequent study, Ali et al. [52] simulated a single-leg landing maneuver and found that full activation of the gastrocnemius muscle had a protective effect on the ACL. The present results indicate that CAI patients with more than five ankle sprains exhibited lower gastrocnemius and soleus muscle strength during single-leg landing, which increased the load on the ACL. The primary reason of these phenomena is that ankle sprains occurring five or more times in a year can result in varying degrees of ligament tears, inflammation, and swelling [53]. Such symptoms may subsequently precipitate aberrant stimulation of peri-ankle neurons and receptors [53]. Consequently, the precise recruitment capability of the gastrocnemius and soleus muscles during landing is compromised, which ultimately results in the inhibition of these muscles [53].

In summary, although the results of this study can help to understand the relationship between lower extremity movement patterns and ACL load in CAI patients with different numbers of ankle sprains, there are some limitations. For example, this study only explored participants who had experienced 2, 3, 4, 5 or 6 or more ankle sprains, and future studies could further subdivide the "6 or more" category so that the results of the study can be more targeted. Furthermore, it should be noted that the occurrence of ankle sprains was self-reported by the participants and subsequently evaluated at a designated hospital. This approach may have introduced a degree of potential for omission. Finally, the present study exclusively examined male participants. It is thus recommended that future research should endeavor to incorporate female participants in order to facilitate the derivation of more comprehensive conclusions.

Conclusion

Patients with CAI who have experienced more than four ankle sprains within a year exhibited knee compensation and increased ACL load during single-leg landing. Limited ankle dorsiflexion, increased ankle inversion angle, excessive vertical GRF, and insufficient gastrocnemius and soleus muscle strength might increase ACL load. Therefore, patients with more than four ankle sprains should focus on increasing ankle dorsiflexion, performing rehabilitation of the ankle evertor, plantar flexor, and knee extensor muscle groups, and consider adjusting the energy absorption patterns of the lower extremity joints to more effectively cushion GRF, and reduce ACL load.

Supplementary Information

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Supplementary Material 1

Author contributions

Zeyi Zhang and Youping Sun was responsible for the conception and design of the study and data collection; Zeyi Zhang, Shengmeng Wei and Hanlin Shi were involved in the processing and statistical analysis of data; Zeyi Zhang were involved in the drafting of the manuscript; and all authors contributed to the interpretation of the data for the work and revising it critically for important intellectual content. All the authors finally approved the manuscript. Youping Sun was responsible for obtaining project funding and takes responsibility for the integrity of the work as a whole. All authors have read and agreed to the published version of the manuscript.

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Data availability

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

Declarations

Ethics approval and consent to participate

The study was performed in accordance with the ethical standards of the Declaration of Helsinki given ethics approval was obtained from the Ethics Committee of East China Normal University, under the number 2024-22. Furthermore, all subjects consented to participate in this experiment by signing the informed consent form approved by the Ethics Committee.

Consent for publication

The authors of this study have consented to the publication of the paper in the Journal of NeuroEngineering and Rehabilitation.

Competing interests

The authors declare no competing interests.

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