TITEL: Do individuals with ankle instability show altered lower extremity kinematics and kinetics during walking? A systematic review and meta-analysis

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Abstract

Objective To determine if individuals with chronic ankle instability (CAI) demonstrate altered lower extremity kinematics and kinetics during walking.
Data sources Relevant studies were sourced from PubMed, Embase, Cochrane Library, Web of Science, EBSCO and PEDro.
Study selection Kinematic and kinetic studies involving joint angle and/or joint moment measured in individuals with CAI were included.
Study appraisal and synthesis methods The Risk of Bias in Non-randomised Studies - of Interventions (ROBINS-I) tool was used to assess literature quality. Weighted mean differences (WMDs) in joint angles and moments between CAI and controls were analyzed as continuous variables.
Results 1261 articles were screened, with a final selection of 13 studies involving 729 participants. Compared to non-CAI controls, CAI participants showed significantly greater ankle inversion angle (degree) (WMD: 3.71, 95% CI: 3.15 to 4.27, $p < 0.001$), hip adduction angle (degree) (WMD: 1.60, 95% CI: 0.09 to 3.11, $p = 0.04$), and knee valgus moment (N m/kg) (WMD: 0.07, 95% CI: 0.01 to 0.13, $p = 0.02$) during walking. Additionally, there were no consistent findings or specific altered patterns in other lower extremity joint angles, or moment changes, regardless of the motion plane (sagittal, coronal, horizontal), for CAI compared with controls.
Conclusions This review provides further evidence of altered lower limb kinematics and kinetics in the frontal plane in CAI participants during certain walking phases, which may partially explain the high level of recurrent ankle sprains observed in the CAI population, and support hip abduction and ankle eversion motor control exercises for CAI rehabilitation.

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Contribution of the Paper

- Individuals with CAI exhibit greater ankle inversion and hip adduction angles during certain phases of walking compared to non-CAI controls.

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- There may be an increase in the knee valgus moment of individuals with CAI.
- Altered lower extremity kinematics and kinetics may be associated with the occurrence of recurrent ankle sprains in CAI.

Keywords: Chronic ankle instability; Walking; Kinematic; Kinetic; Systematic review

Introduction

After an ankle sprain, there is a high risk of developing chronic ankle instability (CAI) [1,2], characterized by recurring episodes of giving way, pain, and instability, with a negative impact on the daily activities of those affected [3].

Understanding the features and effects of CAI is critical for effective diagnosis and treatment [4]. Gait pattern analysis of individuals with CAI is of particular importance [5]. By studying the way individuals walk, researchers can identify abnormalities, compensatory mechanisms, and the impact of instability on gait patterns [6,7]. For instance, individuals with CAI often exhibit reduced step length, increased stance time, and reduced joint range of motion, compared to self or age-matched non-CAI [8–10].

Several biomechanical methods are employed to investigate gait patterns, including electromyographic (EMG), kinematics, and kinetics [11,12]. While EMG has been widely used in gait studies, there have been concerns about its practicality in observing local muscles during walking as regards postural control, and EMG cannot provide a global view of gait characteristics and stability [13–15], whereas kinematics and kinetics have the ad- vantage of providing objective and comprehensive in- formation about gait characteristics and movement strategies [12,16]. Quantifying joint angles, forces, and moments during walking can provide more detailed un- derstanding of the mechanics underlying CAI [11,16].

However, current studies employing kinematics and kinetics in individuals with CAI have yielded conflicting results [17], with some reporting significant differences between CAI and control groups in walking [18,19] not obtained in others [6,20]. Therefore, the aim here was to conduct a systematic review and meta-analysis of current research findings on lower extremity kinematics and kinetics during walking with CAI and non-CAI controls, to provide better understanding of the gait characteristics, and potentially the adaptive strategies, associated with CAI.

Methods

This study was conducted according to the PRISMA guidelines, and registered on the international prospective register of systematic reviews (PROSPERO, registration number: CRD42023420418).

Search strategy

Six databases (PubMed, Embase, Cochrane Library, Web of Science, EBSCO and PEDro) were searched to 30th June 2023, without language restriction. The search string is provided as online supplementary material (Supplementary File 1). An updated search was conducted on 3rd May 2024, and no new studies met the inclusion criteria.

Study selection

Search results were assessed by two reviewers independently (LL, JH), with panel adjudication if necessary. After removal of duplicates, the titles and abstracts were screened, and the full texts were further evaluated. The references in the obtained studies were examined to ensure that all relevant studies were included.

Different studies have varying definitions for CAI and copers. To facilitate comparative analysis, reference is made to the CAI selection criteria outlined by the International Ankle Consortium in 2014 [21], and the minimum reporting standards for copers with CAI proposed by Wikstrom and Brown in 2014 [22]; both are currently the most widely used. This approach aims to relatively standardize and clarify the definition of study subjects. Accordingly, the established inclusion criteria were: (1) participant: individuals with mechanical/functional/chronic ankle instability (The criteria for CAI were based on the recommendations proposed by the International Ankle Consortium: ① a history of at least 1 significant ankle sprain, ② previous feelings of instability or “giving way” or recurrent sprains, ③ self-reported decline in foot-ankle functional performance [21]); (2) intervention: walking; (3) comparator: healthy controls (individuals who have never experienced ankle sprains and sensations of ankle instability) or copers (individuals who reported a history of ankle sprain but without ongoing ankle instability [22–24]); by current consensus and clinical practice [25–27], copers are considered to be able to maintain a stable gait and resume normal daily life following ankle sprain [28,29], through self-recovery or adaptive strategies [30,31], without ankle instability sensations [32], even during sports or other high-intensity activities [33,34]; (4) outcome: lower extremity kinematic and/or kinetic data; (5) study design: controlled study. By adhering to such criteria, the included studies can be targeted and relevant for this study.

Conference abstracts, descriptive studies, trial registry records, clinical trial protocols, case reports, or reviews were excluded, as were studies conducted with in vitro models, cadavers, animals, simulators, and prostheses, and studies investigating foot orthoses, kinesiology taping/braces, and auxiliary devices/materials for ankle stability.

Risk of bias assessment

The quality and risk of bias of the included studies was assessed independently by two reviewers using the Risk of Bias in Non-randomised Studies - of Interventions (ROBINS-I) tool [35], and disagreements resolved by panel discussion. This scale contains seven domain items and an overall risk rating, and each item and overall bias were scored as low, moderate, serious, critical, or no information [36]. The overall rating assessment was low risk of bias only if all domain items are scored as low risk. To ensure the quality of the review, studies given an overall risk rating of "serious/critical" were excluded.

Data extraction and outcome measures

Data about the measurement instrumentation, experimental procedures, inclusion criteria for ankle instability and coper/healthy control, characteristics of participants, and walking speed were extracted. The kinematics and kinetics of the ankle, knee, and hip on the sagittal plane, coronal plane, and horizontal plane were summarized to extract two primary outcomes for analysis – joint angle and joint moment, to indicate how individuals control posture and stability during walking [16]. The former was commonly obtained using a 3-dimensional motion capture system with a force platform used in combination. Stability was evaluated by calculating synchronous data from both measurements [11]. Kinematic and kinetic data were divided into two subgroups: (1) CAI and healthy controls; (2) CAI and copers.

Data synthesis and statistical analysis

Due to differences in the equipment parameters, sampled frequency, software algorithm, measuring time, and setting standards (such as stance phase (%), initial contact, and toe off), the results of various studies could not be combined for direct comparison at the same phase, so the difference in joint angles and moments between individuals with CAI and control groups in each included study became the focus, with $p < 0.05$ considered a statistically significant difference. If a significant difference between CAI and non-CAI controls was reported, the results were extracted and labeled. For each joint, the focus was the motion with the most significant difference labels, and studies investigating this joint motion were given specialized analysis, conducted to identify the most prominent outcomes.

Although copers have intact functional performance without symptoms of ankle instability, and some previous studies have considered them to be comparable to healthy controls [9,37], they still have potential variability and may exhibit differences from healthy individuals [24,26,29,32,34], so to explore the characteristics of copers, two subgroups were delineated, healthy controls and copers.

If the results of the same joint motion were reported with means and standard deviations (SD), or could be converted into continuous data, they were pooled and included in meta-analysis. Where the results of studies investigating a joint motion did not report statistical differences, or if the results reported statistical differences but there was a tendency towards both CAI and controls at different phases of an experiment, then the result with the greatest difference was taken.

Meta-analysis was performed using RevMan (Version 5.3). The directions of joint motion (positive and negative values) were normalized, and the most significant differences during the phase of measurements were recorded. When there was a significant difference, it was deemed to 'favor' the group with higher values. Weighted mean differences (WMDs) were calculated for joint angles and moments. For continuous data, a randomized effects model was applied, and the inverse variance method used. Statistical heterogeneity was evaluated with I^2 tests, with $< 50\%$ indicating low heterogeneity.

Although joint angle and moment data were often reported with numerical values, there were also graphically presented results, so numerical values were obtained by estimation. These estimations were performed independently by LL and JH, and their average value taken. Where differences exceeded 10%, a third reviewer was involved for consensus.

Results

Literature search and screening

The PRISMA flow diagram is shown in Fig. 1. The initial search yielded 1261 results. Following removal of duplicates, 671 studies underwent title and abstract screening, and full texts of 346 studies were reviewed. 13 studies (729 participants) were included in this review [6–9,18–20,37–42], of which 12 studies were included for meta-analysis [6–9,18–20,37,38,40–42].

Quality evaluation and risk of bias assessment

The risk of bias for each study is given in Table 1. Eight studies assessed with the ROBINS-I tool were considered as low overall risk of bias [7–9,18,20,39,41,42], five studies as moderate overall risk of bias [6,19,37,38,40], and none with serious or critical risk of bias. Based on the

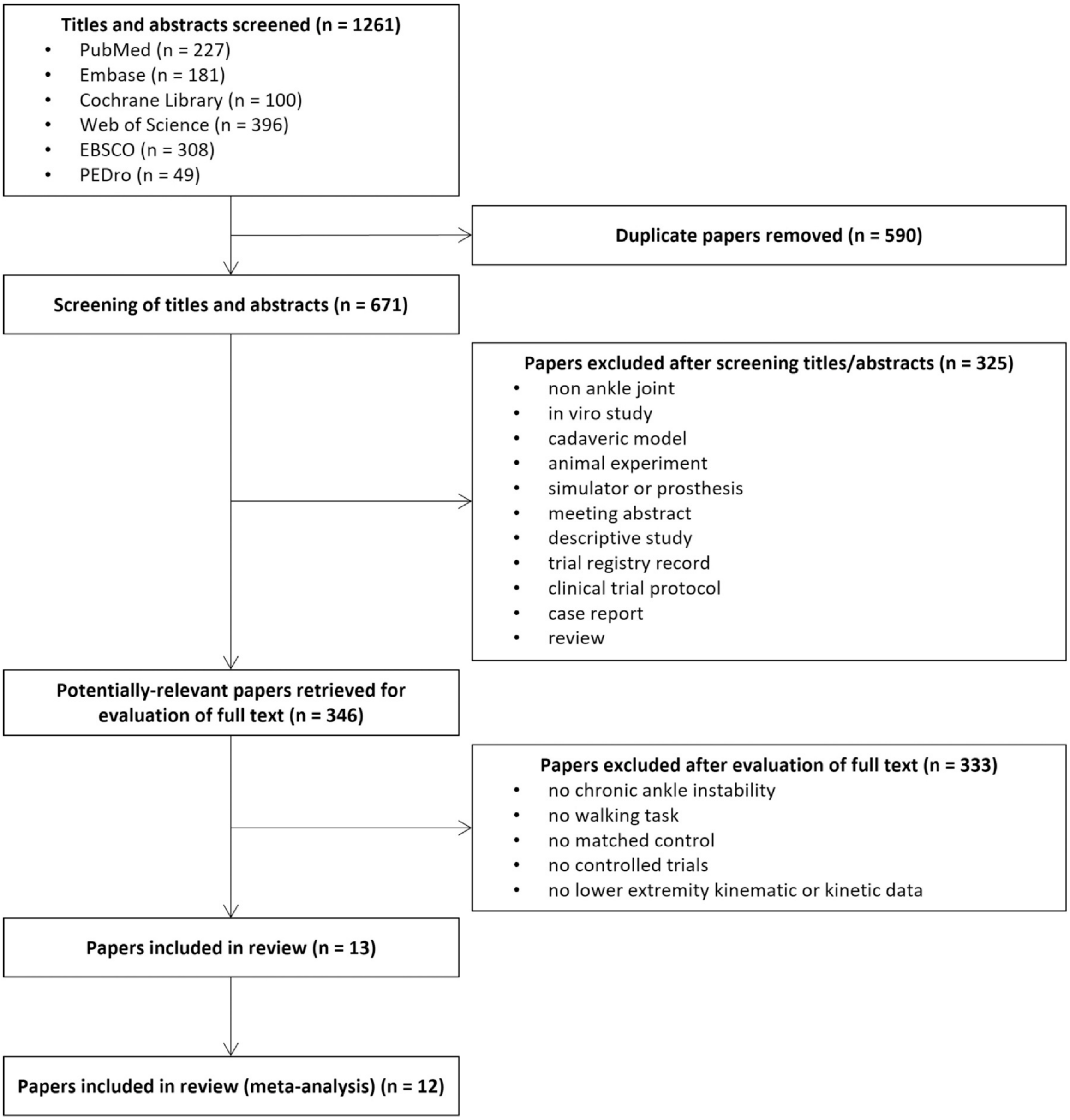

Fig. 1. PRISMA flow diagram.

explanation in the ROBINS-I tool [35,36], such variations in the quality are unlikely to substantially affect the review outcomes.

Characteristics of the eligible studies

Study and participant characteristics are summarized in Table 2. Eight studies reported both joint angles and joint moments [6,7,9,18,19,39–41], and five only reported joint angles [8,20,37,38,42]. The CAI inclusion criteria accorded with the International Ankle Consortium guidelines in nine studies [6–9,18,20,39,41,42], and nine studies explicitly stated that participants walked at a self-selected or normal speed [7–9,18–20,39,40,42].

Kinematic data

Differences in joint angles at the three lower extremity joints at three planes are described in Table 3. Twelve trials compared CAI with healthy controls and six trials compared CAI with copers. Of these, 11 reported that the ankle inversion angle in CAI was significantly greater than non-CAI controls at certain phases (CAI vs. healthy controls: 7 trials, CAI vs. copers: 4 trials) [6,7,9,18,19,38,40,42]. Two trials reported that knee external rotation angle in CAI was significantly higher than in healthy controls at certain phases [41], but significantly lower than in the healthy controls in some phases, and 3 trials reported that hip adduction angle in CAI was significantly greater than copers

Table 1
Risk of bias assessment with ROBINS-I tool.

Study	Pre-intervention		At intervention	Post-intervention				Overall
	1	2	3	4	5	6	7	8
Brown 2011	M	M	L	L	L	L	L	M
Delahunt 2006	M	M	L	L	L	L	L	M
Jang 2021	L	L	L	L	L	L	L	L
Kakihana 2005	M	M	L	L	L	L	L	M
Koldenhoven 2019	L	L	L	L	L	L	L	L
Koshino 2015	L	L	L	L	L	L	L	L
Lee 2021	M	L	L	L	L	L	L	M
Moisan 2020	L	L	L	L	L	L	L	L
Moisan 2021	L	L	L	L	L	L	L	L
Monaghan 2006	L	M	L	L	L	L	L	M
Northeast 2018	L	L	L	L	L	L	L	L
Son 2019	L	L	L	L	L	L	L	L
Yen 2016	L	L	L	L	L	L	L	L

1: Confounding; 2: Selection of participants; 3: Classification of interventions; 4: Deviations from intended intervention; 5: Missing Data; 6: Measurements of outcomes; 7: Selection of Reported Results; 8: Overall ROB Judgement.
L: low; M: moderate; H: high; C: critical; NI: no information.

at certain phases [9]. Compared to controls, ankle inversion, knee external rotation, and hip adduction were the motions with the most reports of significant differences.

Accordingly, meta-analyses on ankle inversion, knee external rotation, and hip adduction were performed (Fig. 2). During certain walking phases, CAI participants demonstrated significantly more ankle inversion (unit: degree) compared to non-CAI controls, healthy controls, and copers, with WMD: 3.71 (95% CI: 3.15 to 4.27, I^2: 18%, $p < 0.00001$), WMD: 3.80 (95% CI: 2.66 to 4.95, I^2: 48%, $p < 0.00001$), and WMD: 3.64 (95% CI: 3.04 to 4.25, I^2: 0%, $p < 0.00001$), respectively (Fig. 2A).

No significant differences in knee external rotation (unit: degree) were found for CAI participants compared to non-CAI controls, healthy controls, and copers, with WMD: −0.55 (95% CI: −3.93 to 2.83, I^2: 80%, $p = 0.75$), WMD: −1.07 (95% CI: −6.32 to 4.19, I^2: 85%, $p = 0.69$), and WMD: 0.07 (95% CI: −1.68 to 1.82, $p = 0.94$), respectively (Fig. 2B).

For hip adduction (unit: degree) there was a significant difference between CAI and non-CAI controls and copers, with WMD: 1.60 (95% CI: 0.09 to 3.11, I^2: 93%, $p = 0.04$) and WMD: 2.60 (95% CI: 0.58 to 4.62, I^2: 93%, $p = 0.01$), while CAI participants had insignificantly greater hip adduction angle compared to healthy controls, with WMD: 0.29 (95% CI: −0.83 to 1.41, I^2: 66%, $p = 0.61$) (Fig. 2C).

Kinetic data

Joint moment differences in the three lower extremity joints at three planes for CAI compared with a control group are described in Table 4. Eight trials compared CAI with healthy controls and four trials compared CAI with copers during walking [6,7,9,18,19,39–41]. Irrespective of which planes the three joints (ankle, knee, and hip) were on, the results of the included studies were not consistent, and no regular patterning was apparent.

Three trials reported the statistical differences for ankle eversion moment between CAI and healthy controls (2 trials: favor CAI, 1 trial: favor CAI at certain phases and favor healthy controls in some phases) [18,19,40], and 4 trials reported the statistical differences of knee valgus moment between CAI and healthy controls (3 trials: favor CAI, 1 trial: favor CAI at certain phases and favor healthy controls in some phases) [7,18,41]; while only 1 study reported statistical differences in hip joint moment [7]. Therefore, only meta-analyses on ankle eversion and knee valgus were conducted (Fig. 3).

In terms of ankle eversion moment (unit: Nm/kg), there was no significant difference for CAI compared to non-CAI controls, healthy controls, and copers, with WMD: 0.02 (95% CI: −0.07 to 0.12, I^2: 96%, $p = 0.63$), WMD: 0.02

Table 2
Characteristics of included studies.

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Brown 2011	A 3-dimensional electromagnetic motion tracking system and a piezoelectric nonconductive force plate (Joint moments were not reported)	Participants walked on a raised walkway. (barefoot)	(a) FAI A history of mild to moderate ankle sprain at least 12 months before the study that required immobilization or non-weightbearing status for 3 days, and participants reported repeated episodes of spraining, rolling, or ‘giving way’ after the initial ankle sprain, with a minimum of 2 episodes of ‘giving way’ or spraining in the past 12 months. (b) MAI The characteristics of the participant were similar with that of FAI, but they demonstrated positive clinical laxity to the anterior drawer and/or talar tilt test.	(a) *n* = 11 F/M: 0/11 Age: 23 (4) Height: 178 (7) Weight: 78 (12) (b) *n* = 11 F/M: 0/11 Age: 23 (5) Height: 180 (10) Weight: 77 (14)	1.2 to 1.4 (m/s)	Coper A history of mild to moderate ankle sprain at least 12 months before the study that required immobilization or non-weightbearing status for 3 days, and participants demonstrated clinically negative anterior drawer and talar tilt tests.	*n* = 11 F/M: 0/11 Age: 22 (5) Height: 182 (4) Weight: 75 (8)	1.2 to 1.4 (m/s)
Delahunt 2006	A general-purpose 3D motion analysis tracking system (Joint moments were not reported)	Participants walked on an electrically driven treadmill. (barefoot)	FAI Participants reported a history of a minimum of 2 inversion injuries to 1 ankle that required a period of protected weightbearing and/or immobilization; the involved ankle was subjectively reported to be chronically weaker, more painful, and less functional than was the other ankle at the time of testing; they reported a tendency for the ankle to ‘give way’ during sporting activities; and current subjective complaints were reported to be secondary to history of inversion sprains.	*n* = 24 F/M: 10/14 Age: 26 (6) Height: 170 (8) Weight: 72 (11)	4 (km/h)	Healthy control Participants had no history of ankle sprain or fracture of the lower extremity.	*n* = 22 F/M: 8/14 Age: 23 (4) Height: 180 (8) Weight: 71 (8)	4 (km/h)

Table 2 (*Continued*)

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Jang 2021	A 10-camera motion capture system and three embedded force plates	Participants was instructed to walk across the walkway as if they were normally walking down a sidewalk. (barefoot)	CAI Participants had at least one ankle sprain and at least 2 'giving way' episodes in the past six months, and scoring ≥11 on the IdFAI. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n = 42$ F/M: 30/12 Age: 21 (2) Height: 169 (7) Weight: 72 (15)	1.214 (0.132) (m/s) (self-selected)	Healthy control Participants had no history of ankle sprains or 'giving way' episodes as well as scoring < 11 on the IdFAI.	$n = 42$ F/M: 30/12 Age: 20 (4) Height: 169 (8) Weight: 67 (13)	1.262 (0.153) (m/s) (self-selected)
Kakihana 2005	A 3D gait motion analysis system and 8 force platforms that were situated at the midpoint of a 7 m walkway	The laterally wedged (0°) insoles were attached to the participant's feet, and they were asked to walk at a self-selected walking cadence indicated by a metronome. (certain shoes)	Unstable ankle Participants were a history of at least two lateral ankle sprains to the same ankle during the past 2 years, a history of ankle pain or swelling during injury, apprehension toward the clinically performed manual stress tests, and instabilities great enough that athletes were unable to perform their activities without taping or bracing.	$n = 25$ F/M: 0/25 Age: 21 (1) Height: 172 (5) Weight: 63 (7)	95.8 (4.0) steps/min (self-selected)	Healthy control Participants had no history of lateral ankle sprain.	$n = 25$ F/M: 0/25 Age: 21 (1) Height: 175 (5) Weight: 77 (13)	102.1 (7.4) steps/min (self-selected)
Koldenhoven 2019	A 12- camera Vicon motion capture system and a fully instrumented treadmill	Participants completed 5 minutes of walking on a split-belt treadmill. (laboratory shoes)	CAI Participants had a history of at least 1 significant lateral ankle sprain at least 12 months prior to study participation, self-reported dysfunction (FAAM-Sport ≤ 85%), and feelings of instability or 'giving way' (IdFAI ≥ 11). (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n = 18$ F/M: 16/2 Age: 22 (3) Height: 168 (9) Weight: 67 (14)	(a) 1.0 (0.2) (m/s) (Preferred) (b) 1.2 (0.2) (m/s) (120% Preferred) (c) 1.34 (m/s) (Standardized)	Coper Participants had a history of at least 1 significant lateral ankle sprain at least 12 months and did not have self-reported dysfunction (FAAM-Sport ≥ 97%) or feelings of instability (IdFAI < 10 or they answered "no" to the question about 'giving way' and "never" or "once a year" to the question about 'ankle feel unstable').	$n = 18$ F/M: 16/2 Age: 21 (2) Height: 168 (6) Weight: 66 (11)	(a) 0.9 (0.1) (m/s) (Preferred) (b) 1.1 (0.2) (m/s) (120% Preferred) (c) 1.34 (m/s) (Standardized)

Table 2 (*Continued*)

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Koshino 2015	Motion analysis software with six digital cameras and a force plate (Joint moments were not reported)	Participants walked straight on a walkway while looking straight ahead. (certain shoes)	CAI Participants had a history of at least one significant lateral ankle sprain that resulted in protected weight bearing and/or immobilization, a history of two or more lateral sprains to the same ankle, multiple episodes of the ankle 'giving way', and a score of CAIT ≤ 25. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	*n* = 10 F/M: 1/9 Age: 21 (1) Height: 174 (8) Weight: 66 (7)	natural speed	Healthy control Participants were no history of lower limb injuries, ankle joint instability, and/or an episode of 'giving way'.	*n* = 10 F/M: 1/9 Age: 21 (2) Height: 174 (7) Weight: 67 (8)	natural speed
Lee 2021	An 8-camera motion analysis system and a force plate	Participants walked along the 8 m walkway, and the gait speed was controlled by a metronome. (running shoes)	CAI Participants had a history of more than one lateral ankle sprain and remaining symptoms, including recurrent feelings of 'giving way', and/or recurrent sprains, and/or feelings of instability; initial lateral ankle sprain occurring at least 12 months prior to study enrollment; the last sprain occurring at least 3 months prior to participation in this study; at least five "yes" responses for the AII, including the "yes" response for question 1; scoring below 90% and 80% for the FAAM-ADL and FAAM-Sport, respectively. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	*n* = 18 F/M: 8/10 Age: 25 (3) Height: 173 (8) Weight: 68 (15)	≈1.34 (m/s)	(a) Healthy control Participants had no history of lateral ankle sprain; "no" responses to all questions of AII; scoring a 100% on both of FAAM-ADL and FAAM-Sport. (b) Coper Participants had a history of one lateral ankle sprain resulting in at least one day of interrupted physical activity, without residual symptoms caused by initial lateral ankle sprain; initial lateral ankle sprain occurring at least 12 months prior to study enrollment; a "yes" response for question 1 of the AII; scoring over a 99% and 97% on the FAAM-ADL and FAAM-Sport, respectively.	(a) *n* = 18 F/M: 8/10 Age: 26 (2) Height: 172 (8) Weight: 63 (11) (b) *n* = 18 F/M: 7/11 Age: 26 (5) Height: 173 (8) Weight: 67 (10)	≈1.34 (m/s)

Table 2 (*Continued*)

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Moisan 2020	A three-dimensional active motion analysis system and a force platform embedded in the floor on the participants' path	Participants walked on a 5-m walkway. (shoe model)	CAI Participants had at least one significant ankle sprain that occurred more than one year prior to study onset and self-reported functional deficits due to ankle symptoms that were quantified by a score of respectively $<90\%$ and $<80\%$ on the FAAM-ADL and FAAM-Sport, and they reported at least two episodes of ankle 'giving way' in the last six months and/or have a feeling of instability. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n=21$ F/M: 17/4 Age: 26 (9) Height: 165 (8) Weight: 65 (13)	(a) 1.38 (0.19) (m/s) (b) 2.00 (0.23) (m/s)	Healthy control Participants never sustained an ankle sprain.	$n=21$ F/M: 17/4 Age: 25 (5) Height: 167 (9) Weight: 62 (13)	(a) 1.49 (0.21) (m/s) (b) 2.12 (0.21) (m/s)
Moisan 2021	A three-dimensional active motion analysis system and a force plate embedded in the floor	Participants walked on a 7.5-m walkway with the force plate located in the center. (certain shoes)	CAI Participants had a history of one or more lateral ankle sprain, ankle 'giving way' and/or recurrent sprains and/or feeling of ankle instability, and they had to score less than 90% and 80% at the FAAM-ADL and FAAM-Sport subscales, respectively. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n=28$ F/M: 18/10 Age: 26 (6) Height: 169 (9) Weight: 71 (12)	1.42 (0.15) (m/s) (self-selected)	Healthy control Participants had never sustained a lateral ankle sprain.	$n=26$ F/M: 17/9 Age: 24 (4) Height: 170 (9) Weight: 67 (12)	1.46 (0.14) (m/s) (self-selected)

Table 2 (*Continued*)

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Monaghan 2006	A single motion analysis system that was fully integrated with a force plate embedded in the walkway	Participants walked across the 10 m walkway. (barefoot)	CAI Participants reported a history of at least 2 ankle inversion injuries which had required a period of protected weight bearing and/or immobilization; they perceived that the ankle was chronically weaker, more painful, and/or less functional than the other ankle or than before first injury; they reported a tendency for the ankle to 'give way' or repeatedly 'turn over' during functional activity.	*n* = 25 F/M: 11/14 Age: 26 (8) Height: 176 (8) BMI: 25 (2)	1.39 (0.20) (m/s) (normal)	Healthy control Participants had no history of ankle sprain.	*n* = 25 F/M: 10/15 Age: 24 (5) Height: 173 (8) BMI: 22 (2)	1.46 (0.13) (m/s) (normal)
Northeast 2018	An Owl Digital Real Time 10 camera system (Joint moments were not reported)	Participants were instructed to walk 3.5 m before data were collected and proceeded for 7 m across the walkway. (barefoot)	CAI Participants were allocated into the CAI group based on results of the IdFAI questionnaire, where a score of ≥11 indicated ankle instability. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	*n* = 18 F/M: 5/13 Age: 22 (3) Height: 177 (8) Weight: 74 (10)	1.18 (0.09) (m/s) (normal)	Healthy control Participants were allocated into the control group based on results of the IdFAI questionnaire.	*n* = 18 F/M: 4/14 Age: 22 (4) Height: 178 (8) Weight: 70 (12)	1.20 (0.15) (m/s) (normal)

Table 2 (*Continued*)

Study	Instrumentation	Procedures	Chronic ankle instability group			Control group		
			Inclusion criteria	Participants[a]	Walking speed	Inclusion criteria	Participants[a]	Walking speed
Son 2019	The twelve high-speed video cameras and 2 force plates embedded in the laboratory floor	Participants walked at their normal stride and in their normal gait pattern in a consistent way. (athletic shoes)	CAI Participants had a history of at least 2 recurrent unilateral ankle sprains, the most recent sprain having occurred 3 months before study enrollment and the previous ankle sprain(s) having caused acute inflammatory symptoms (e.g. pain, swelling) and at least 1 interrupted day of desired physical activity; they had a history of at least 2 episodes of 'giving way' in the injured ankle in the 6 months before study enrollment; they had at least 2 responses of "yes" on questions 4 to 8 (i.e. a feeling of an unstable ankle during functional activity) of the modified AII; they had a score of less than 90% on the FAAM-ADL and a score of less than 80% on the FAAM-Sport. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n = 100$ F/M: 51/49 Age: 22 (2) Height: 174 (10) Weight: 71 (14)	1.55 (0.13) (m/s) (self-selected)	Healthy control Participants had no history of ankle sprain, no responses of "yes" on questions 4 to 8 of the modified AII, a score of 100% on the FAAM-ADL and a score of 100% on the FAAM-Sport.	$n = 100$ F/M: 45/55 Age: 23 (3) Height: 173 (13) Weight: 73 (19)	1.56 (0.14) (m/s) (self-selected)
Yen 2016	A motion-capture system with 6 cameras recorded the ankle motion during treadmill walking (Joint moments were not reported)	Participants were instructed to walk on the treadmill. (unreported)	CAI Participants scored 24 or lower on the CAIT, and had recurrent ankle sprain that was defined as at least 2 ankle sprains in the past 6 months prior to the study. (Inclusion criteria for individuals with CAI were in accordance with the International Ankle Consortium guidelines)	$n = 12$ F/M: 5/7 Age: 22 (1) Height: 170 (11) Weight: 68 (17)	1.99 (0.1) (mph) (self-selected)	Healthy control Participants scored 28 or higher on the CAIT and had no ankle sprain in the past year.	$n = 12$ F/M: 5/7 Age: 23 (2) Height: 175 (10) Weight: 74 (14)	2.01 (0.1) (mph) (self-selected)

FAI: Functional Ankle Instability; MAI: Mechanical Ankle Instability; IdFAI: Identification of Functional Ankle Instability; FAAM: Foot and Ankle Ability Measure; CAIT: Cumberland Ankle Instability Tool; AII: Ankle Instability Instrument; ADL: Activities of Daily Living.

[a] Participant information includes the sample size (n), gender ratio (F for female, M for male), age (in years), height (uniformly converted to centimeters), weight (uniformly converted to kilograms) or BMI (body mass index), with the latter three presented as mean (standard deviation), rounded to the nearest integer.

Table 3
Significant kinematic differences between the CAI and controls.

Study	Ankle joint angle						Knee joint angle						Hip joint angle					
	sagittal		frontal		transverse		sagittal		frontal		transverse		sagittal		frontal		transverse	
	PF	DF	IV	EV	IR	ER	FX	EX	VR	VG	IR	ER	FX	EX	AD	AB	IR	ER
Individuals with CAI vs. Healthy controls																		
Delahunt 2006	-	-	*	ɵ	-	-	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ
Jang 2021	-	-	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Kakihana 2005	○	○	*	-	○	○	○	○	-	-	○	○	○	○	○	○	○	○
Koshino 2015	ɵ	-	-	ɵ	ɵ	ɵ	-	ɵ	ɵ	ɵ	ɵ	ɵ	-	ɵ	-	ɵ	-	ɵ
Lee 2021 (a)	-	§	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Moisan 2020 (a)	-	-	ɵ	ɵ	ɵ	ɵ	-	-	-	-	ɵ	§	○	○	○	○	○	○
Moisan 2020 (b)	-	-	ɵ	ɵ	ɵ	ɵ	-	-	-	-	ɵ	§	○	○	○	○	○	○
Moisan 2021	-	-	*	ɵ	-	-	-	-	-	-	-	-	○	○	○	○	○	○
Monaghan 2006	-	-	*	ɵ	-	-	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ
Northeast 2018	-	-	*	-	-	-	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ
Son 2019	*	§	*	§	○	○	§	ɵ	ɵ	§	○	○	*	ɵ	-	-	○	○
Yen 2016	-	-	-	-	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Individuals with CAI vs. Copers																		
Brown 2011 (a)	-	ɵ	-	-	-	*	ɵ	ɵ	ɵ	ɵ	*	ɵ	○	○	○	○	○	○
Brown 2011 (b)	§	ɵ	-	*	§	*	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	○	○	○	○	○	○
Koldenhoven 2019 (a)	ɵ	ɵ	*	ɵ	○	○	ɵ	ɵ	ɵ	ɵ	○	○	ɵ	ɵ	*	ɵ	○	○
Koldenhoven 2019 (b)	ɵ	ɵ	*	ɵ	○	○	ɵ	ɵ	ɵ	ɵ	○	○	ɵ	ɵ	*	ɵ	○	○
Koldenhoven 2019 (c)	ɵ	ɵ	*	ɵ	○	○	ɵ	ɵ	ɵ	ɵ	○	○	ɵ	ɵ	*	ɵ	○	○
Lee 2021 (b)	-	§	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

PF: plantar flexion; DF: dorsiflexion; IV: inversion; EV: eversion; FX: flexion; EX: extension; VR: varus; VG: valgus; AD: adduction; AB: abduction; IR: internal rotation; ER: external rotation; CAI: chronic ankle instability. Cells shaded with a grid pattern represent the action that have the most findings with statistical differences among the six movements within a joint.
Cells shaded with a dark gray background indicate statistical differences observed during walking, while cells shaded with a light gray background signify participation in the meta-analysis despite the absence of statistical differences. Specifically, *: The value of CAI was higher. §: The value of CAI was lower. ‡: Both higher and lower values of CAI were reported. -: The statistical differences were not observed. ɵ: This term was not explicitly reported in the original text. ◌: This term was not conducted in the original text.

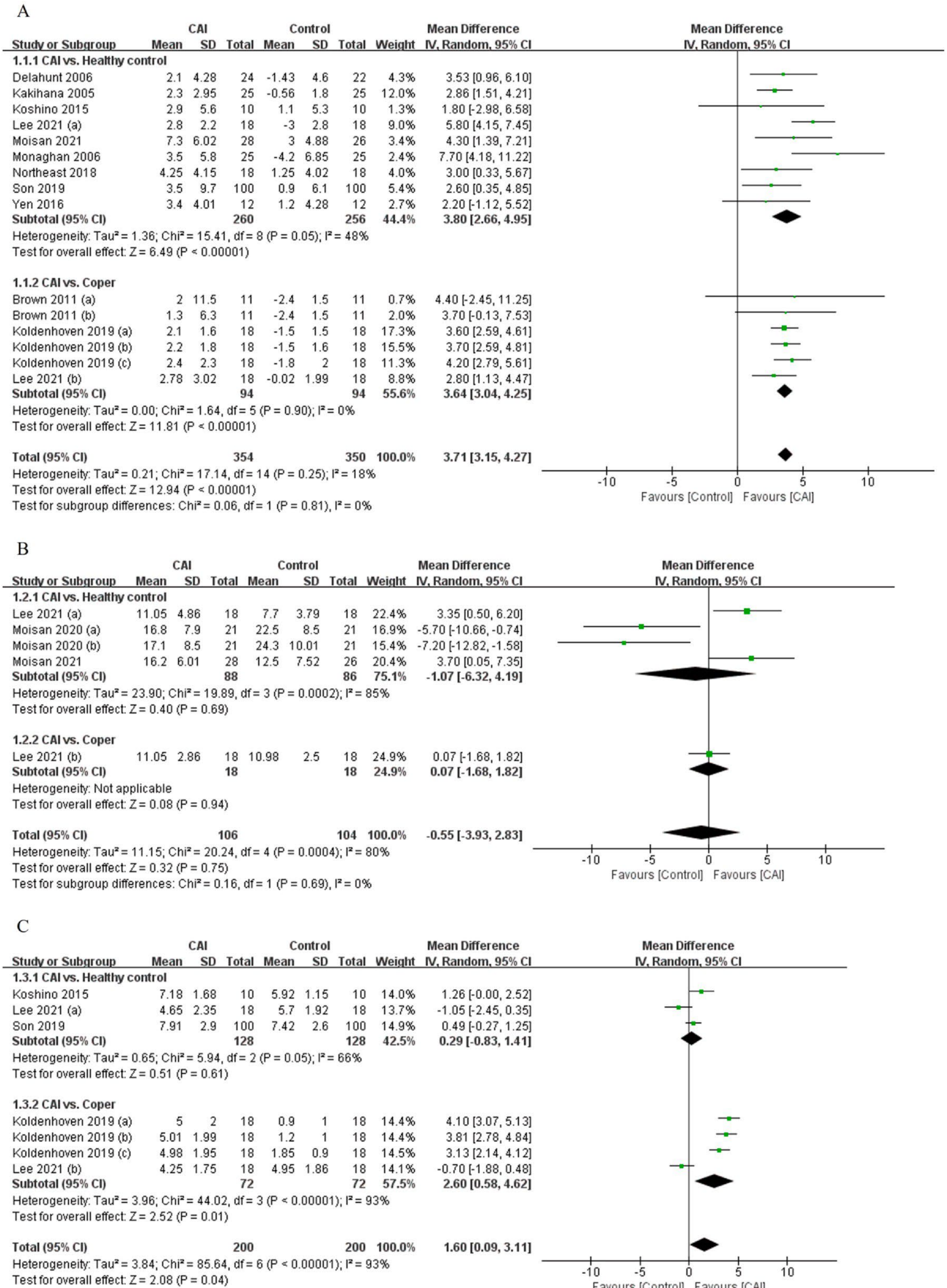

Fig. 2. Ankle inversion angle (A), knee external rotation angle (B), and hip adduction angle (C) during walking between CAI and controls. "Favours": Indicates that the value of this group is higher when there is a significant difference between the two compared groups. CAI: people with chronic ankle instability.

Table 4
Significant kinetic differences between the CAI and controls.

Study	Ankle joint moment						Knee joint moment						Hip joint moment					
	sagittal		frontal		transverse		sagittal		frontal		transverse		sagittal		frontal		transverse	
	PF	DF	IV	EV	IR	ER	FX	EX	VR	VG	IR	ER	FX	EX	AD	AB	IR	ER
Individuals with CAI vs. Healthy controls																		
Jang 2021	-	§	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Kakihana 2005	○	○	ɵ	§	○	○	○	○	*	ɵ	○	○	○	○	○	○	○	○
Lee 2021 (a)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Moisan 2020 (a)	-	-	-	-	-	-	-	-	-	*	-	-	○	○	○	○	○	○
Moisan 2020 (b)	-	-	-	-	-	-	-	-	-	*	-	-	○	○	○	○	○	○
Moisan 2021	-	-	-	*	-	-	-	-	-	*	-	-	○	○	○	○	○	○
Monaghan 2006	-	-	-	*	-	-	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ	ɵ
Son 2019	‡	ɵ	‡	ɵ	○	○	*	‡	ɵ	§	○	○	*	*	*	§	○	○
Individuals with CAI vs. Copers																		
Koldenhoven 2019 (a)	-	-	○	○	○	○	-	-	○	○	○	○	-	-	○	○	○	○
Koldenhoven 2019 (b)	*	ɵ	○	○	○	○	-	-	○	○	○	○	-	-	○	○	○	○
Koldenhoven 2019 (c)	*	ɵ	○	○	○	○	-	-	○	○	○	○	-	-	○	○	○	○
Lee 2021 (b)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

PF: plantar flexion; DF: dorsiflexion; IV: inversion; EV: eversion; FX: flexion; EX: extension; VR: varus; VG: valgus; AD: adduction; AB: abduction; IR: internal rotation; ER: external rotation; CAI: chronic ankle instability. Cells shaded with a grid pattern represent the action that have the most findings with statistical differences among the six movements within a joint.
Cells shaded with a dark gray background indicate statistical differences observed during walking, while cells shaded with a light gray background signify participation in the meta-analysis despite the absence of statistical differences. Specifically, *: The value of CAI was higher. §: The value of CAI was lower. ‡: Both higher and lower values of CAI were reported. -: The statistical differences were not observed. ɵ: This term was not explicitly reported in the original text. ◌: This term was not conducted in the original text.

(95% CI: −0.09 to 0.13, I^2: 97%, $p = 0.73$), and WMD: 0.05 (95% CI: −0.01 to 0.11, $p = 0.08$), respectively (Fig. 3A).

For knee valgus moment (unit: Nm/kg), there was a statistical significance for CAI compared with non-CAI controls and healthy controls, with WMD: 0.07 (95% CI: 0.01 to 0.13, I^2: 93%, $p = 0.02$) and WMD: 0.10 (95% CI: 0.02 to 0.17, I^2: 94%, $p = 0.01$), while CAI participants did not demonstrate significantly more knee valgus moment compared to copers as WMD: −0.03 (95% CI: −0.07 to 0.01, $p = 0.13$) (Fig. 3B).

Discussion

Meta-analyses conducted here revealed differences in ankle inversion and hip adduction angles between CAI and non-CAI controls during walking, and CAI participants demonstrated significantly more knee valgus moment.

Reported differences between CAI and the control groups (non-CAI, healthy individuals, copers) were not consistent, as also seen in previous research [29–31]. Considering that copers have a history of ankle sprain but

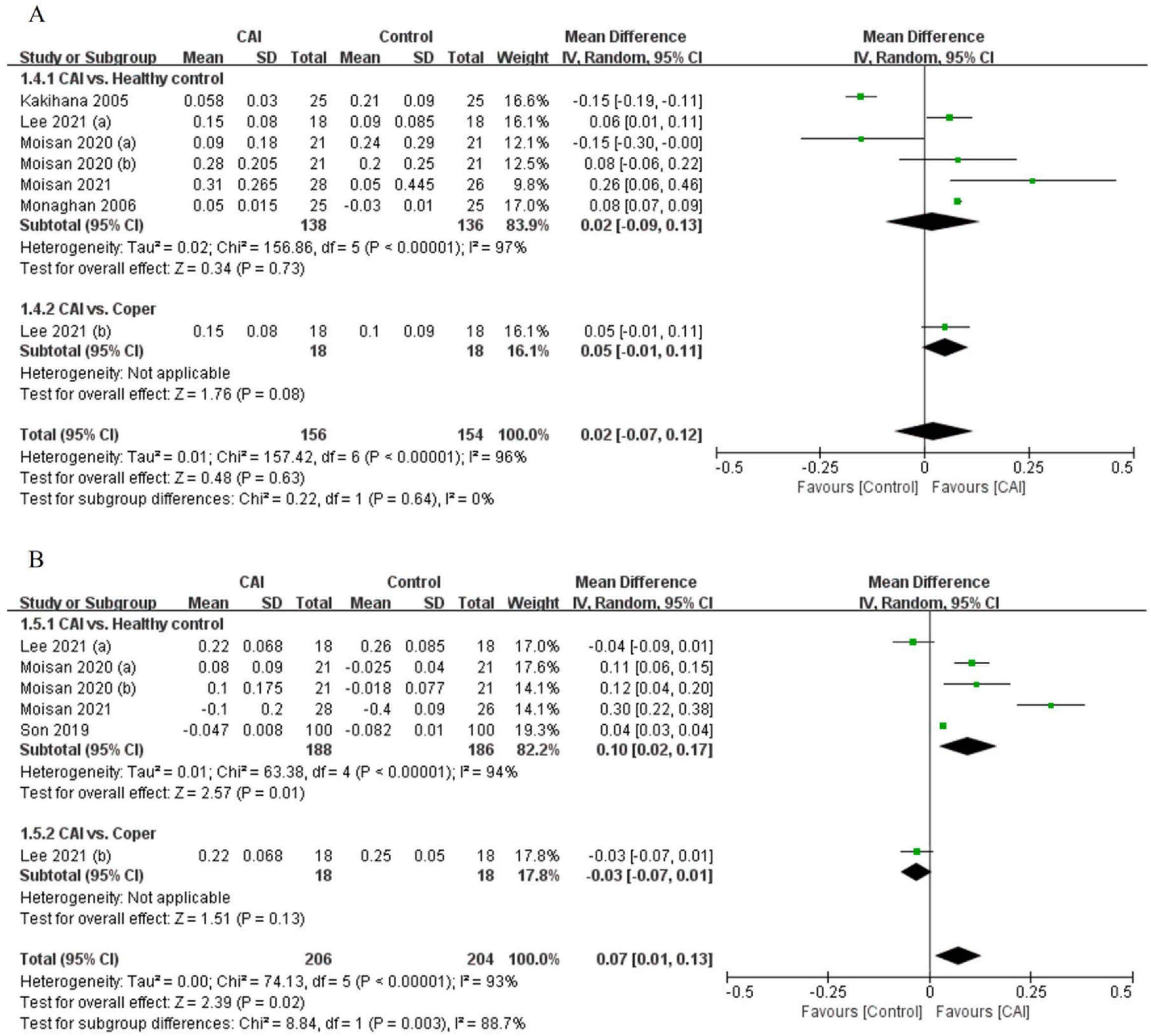

Fig. 3. Ankle eversion moment (A) and knee valgus moment (B) during walking between CAI and controls. "Favours": Indicates that the value of this group is higher when there is a significant difference between the two compared groups. CAI: people with chronic ankle instability.

are asymptomatic with normal function [22,23,25], the observed variations may not solely stem from the injury/condition but may also include pre-existing disparities. Whether CAI causes abnormal gait due to ankle instability, or having an abnormal gait predisposes individuals to CAI, requires future investigation.

Lower extremity kinematics

Meta-analysis showed that increased inversion is a common characteristic in CAI. This could be due to stretched or torn lateral ligaments resulting in loss of stability and increased joint mobility [43,44]. In addition, damage to proprioceptive feedback mechanisms caused by the sprain can impair ability to sense joint position and movements [45,46], and muscle weakness and altered neuromuscular control following an ankle sprain may not provide adequate stability during weight-bearing activities [47,48]. Increased inversion during walking could potentially lead to recurrent lateral ankle sprains [43], emphasizing the need for heightened attention to this in CAI management.

The available research has limited conclusions for angle changes in the knee joint. Although two studies reported differences in knee external rotation angle between CAI and healthy controls [41], a meta-analysis conducted on this specific angle showed high heterogeneity and lacked statistical significance.

Most studies either did not focus on hip angle changes or reported no significant differences between the CAI and control groups, and high heterogeneity among the studies prevented obtaining robust evidence. Admittedly, this meta-analysis was statistically significant, implying that individuals with CAI may have a larger hip adduction angle compared to non-CAI controls. This could result from increased ankle inversion, which necessitates spontaneous adjustment using the hip joint to correct the deviation upon landing during walking, leading to greater hip adduction [46,49,50], or be due to inadequate gluteal muscle strength and insufficient abduction causing increased tension in the hip adductor muscles and resulting in a larger angle [51].

Lower extremity kinetics

Joint moments serve as comprehensive indicators of coordinated muscle movements, and may provide insights into posture control strategies [13]. Comparison of ankle eversion moments has shown differences which favor CAI over healthy controls at certain walking phases [18,19,40], suggesting that upon landing during walking, individuals with CAI may require greater involvement of ankle eversion (the opposite direction to inversion) to correct the ankle joint, which implies that it may be more cognitively-demanding for individuals with CAI to maintain stability with associated increased risk of injury [52,53]. However, the meta-analysis yielded highly heterogeneous results, preventing a definitive conclusion.

In addition, three studies reported differences favoring CAI in knee valgus moments at certain phases during walking [7,18,41]. Despite the high heterogeneity, there were statistically significant differences in knee valgus moments between CAI groups and non-CAI controls, as well as healthy controls. An increased knee valgus moment may result in an abnormal motion of the knee joint, a potentially injury-prone movement pattern that can compromise stability [54–56]. This could be another compensatory mechanism similar to increased ankle inversion and hip adduction angle [57,58], and could be a self-adjustment in posture control to support actions during walking [57,59,60].

One study reported differences in hip abduction moments between CAI and healthy controls favoring CAI at certain phases and controls in others [7] along with significantly greater hip moments in flexion, extension, and adduction directions for individuals with CAI [7]. It is possible that individuals with CAI exhibit a preference for hip force strategies [61], and there were benefits from improving hip strength and neuromuscular control in individuals with CAI [57,61,62] suggesting that hip-focused training may have a greater impact on functional performance in individuals with CAI [63] given identified deficits in hip strength [51].

Study limitations

In this review, limitations included a restricted database search, with potential omissions from national databases like Chinese Wanfang and German Base. Secondly, the values obtained from linear graphs may lack precision. Thirdly, the walking protocols employed lacked standardization, including variations in experimental parameters such as filtering frequency and ground contact criteria. Fourthly, the inconsistencies in the measurement instruments used, such as force plates and motion capture systems, could affect recorded signals. Fifthly, the effect size discussion in the meta-analysis (e.g., ankle inversion angle, WMD: 3.71) was omitted since the minimal clinically important differences for these data have not been established, and the clinical significance the effect sizes represent needs further investigation. Lastly, the heterogeneity among individuals with CAI across studies, including variations in inclusion criteria, gender, age, height, and weight, may have influenced outcomes; population data extracted from individual studies may not fully represent the general population.

Conclusions

Individuals with CAI exhibit significantly greater ankle inversion and hip adduction angles during walking compared to non-CAI controls, with possible alterations in the knee valgus moment. These results, obtained through kinematic and kinetic analysis, may help explain the recurrent ankle sprains observed in CAI, and inform the inclusion of interventions that target hip abduction and ankle eversion in CAI rehabilitation and management.

Ethical approval: None required.

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Conflict of interest:

None declared.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.physio.2024.101420.

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