UCLouvain

Faculté des sciences de la motricité

# Dynamic task multi-segment foot kinematics and kinetics in participants with chronic ankle instability

Narrative Review

Auteur : WALTZING Florian
Promoteur : PETERS-DICKIE Jean-Louis
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## Table des matières

# 1. Introduction

Ankle joint-related issues stand as some of the most prevalent occurrences among human injuries. Specifically, ankle sprains appear to be one of the leading reasons for visits to hospital emergency rooms with an estimate of 2 to 7 sprains per 1000 person-years, possibly underreported due to primary care visits or self-care (Anderson et al., 2011; Gribble et al., 2016).

About 85% of ankle sprains are caused by hyperflexion, inversion, and internal rotation trauma, primarily resulting in injury to the lateral ligaments (Hintermann, 1999). Lateral ankle sprains (LAS) rank as one of the most prevalent injuries sustained in sports and physical activities (Hertel & Corbett, 2019). Ankle sprains are frequently observed in sports, such as football, basketball, tennis, and volleyball, due to mechanisms including player-to-player contact, forceful plantar flexion, and sudden rapid inversion. Beyond sports, physically active groups, like the military, also face a high risk of ankle sprains. Between 1998 and 2006, the US Armed Services conducted an 8-year cohort study, revealing an approximate rate of 0.4 sprains per 1000 exposures, rates similar to sports like softball, hockey and baseball (Cameron et al., 2010; Hootman et al., 2007).

Ankle injuries pose a challenge as they are frequently not properly managed, either left untreated or without adequate guidance for patients, sometimes both (Hiller et al., 2012; McKay et al., 2001). Additionally, studies indicate a high likelihood of ankle sprain recurrence. It is approximated that as many as 40% of individuals who suffer their first LAS are at risk of developing chronic ankle instability (CAI) (Gribble et al., 2016). CAI is identified in patients who have experienced their first LAS more than 12 months prior, displaying a tendency for repeated ankle sprains, frequent occurrences of the ankle feeling unstable, pain, swelling, reduced range of motion (ROM), weakness, and diminished self-reported functional abilities (Hertel & Corbett, 2019).

Copers are seen as the opposite to CAI on a spectrum of clinical outcomes proposed by Hertel & Corbett (2019). The definition of Copers is based on 3 components: (1) an initial severity assessment of LAS necessitating protective measures such as an ankle brace or immobilization for a week, or both; (2) absence of chronic ankle instability (CAI) symptoms, such as disability or instability episodes, and by successfully resuming moderate weight-bearing activity for at least a year without recurring injuries or feelings of instability; (3) a time-related aspect since the injury occurred, as well as minimal, if any, self-reported disability. A genuine Coper resumes pre-injury physical activities unchanged. If activities are adjusted due to the injury, full recovery has not occurred. Some adapt to prevent symptoms but do not fully recover as they do not return to pre-injury activity levels and thus are not considered true Copers (Hertel & Corbett, 2019).

Ankle sprains are also considered to be a financial toll on society. This presents itself through societal, direct healthcare, and indirect costs. In the Netherlands, ankle sprains incur substantial economic costs, with a mean cost per injury around €820 (2010) similarly to the United Kingdom (UK), where single ankle sprains are estimated to cost up to £940 (2007). These numbers being from a while ago, costs probably have risen as of these studies (Cooke et al., 2009; De Boer et al., 2014). The overall societal expense averages around $11,925 per ankle injury in the USA, covering direct clinical expenses and employer-related costs. Direct healthcare costs include consultations, diagnostics, and medications. Indirect costs, resulting in about 6.9 workdays lost and an average of 318€ in productivity impact per injury, significantly add to this burden. In the long-term, CAI imposes financial strains due to recurrent healthcare expenses and productivity limitations (Hupperets et al., 2010; Knowles et al., 2007). Notably, most patients needing surgery for severe ankle joint arthritis have a history of LAS, which make up around 80% of cases. People with CAI are more likely to develop early post-traumatic osteoarthritis, suggesting that CAI plays a big role in starting ankle joint damage, which can lead to expensive surgeries, such as ankle replacements, driving the costs related to ankle sprains even higher (Dahmen et al., 2021; Golditz et al., 2014; Valderrabano et al., 2009).

Over the last 60 years, our comprehension of the elements contributing to CAI has progressed. In 1965, Freeman et al. introduced the initial comprehensive theory of ankle instability. They created the term "functional instability", defining it as "the incapacity that patients describe when they mention their foot's tendency to 'give way' in the months and years following their initial ankle sprain". Pain and swelling were also occasionally reported in such patients (Freeman, 1965). In 2011, a refined model for categorizing patients with CAI into 7 subgroups, based on mechanical instability, perceived instability, and recurrent sprains, was proposed (Hiller et al., 2011). While Hiller et al.'s model advanced understanding, emerging evidence in areas like self-reported function, quality of life, movement patterns, and injury paradigms highlighted the need for an updated model. In 2019, Hertel et al. presented an article with the aim to present this updated model, offering a contemporary framework for understanding CAI causes and assisting clinicians in evaluating and treating patients with both LASs and CAI. The updated model of CAI comprises eight key components, including primary tissue injury, motor-behavioral impairments across various domains, personal and environmental factors, interactions among components, and a spectrum of clinical outcomes. Every patient with CAI typically experiences initial damage to specific ligaments. While not all impairments are present in each patient, these characteristics collectively define CAI. The model hypothesizes how these elements interact to shape diverse clinical outcomes, ranging from fully successful recovery (Coper) to persistent instability (CAI) (Hertel & Corbett, 2019).

Motor-behavioral impairments in CAI involve muscle issues, activity choices and altered motion patterns. These aspects affect the motor side of sensorimotor function. Most impairments in this category align with the biopsychosocial model, except reduced physical activity, which includes both physiological and intentional behavioral components. Among the motor-behavioral impairments, altered movement patterns are frequently reported. It is important to note that in most of the existing literature, the foot is considered as a unique segment in the assessment of altered lower limb kinematics and kinetics.

Motion analysis is essential for assessing in-vivo human biomechanics. This analysis comprises two primary elements: kinematics, which measures the position, orientation, and motion of human body segments and joints, and kinetics, which defines the mechanical forces and moments required to generate these movements (Cappozzo et al., 2005; Robertson et al., 2013). Several articles have been concluded identifying alternated movement patterns in different activities such as walking, running, cutting, and landing for example, in individuals with CAI (Deschamps et al., 2016; Drewes et al., 2009; Lin et al., 2011). For running and walking tasks for example, a systematic review was conducted in 2017 by Moisan et al., in which they identified increased rearfoot inversion and ankle joint inversion, a more externally rotated shank as well as increased forefoot inversion and decreased ankle joint dorsiflexion during a walking cycle for the CAI groups compared to the control group. During running, a more inverted rearfoot, greater plantar flexion in the ankle as well as other kinematic alternations were observed. The ankle of subjects with CAI is found to be more plantar flexed and in higher inversion compared to controls, which could increase the risk of recurrent sprains (Chinn et al., 2013; Koldenhoven et al., 2019, 2022; Moisan et al., 2017).

During side-cutting tasks, participants with CAI exhibited altered kinematics, displaying lower inversion angles not only in the ankle but also alterations in the hip joints. They also showed altered ankle-joint kinetics, including reduced ankle-eversion moments and increased ankle plantar-flexion moment. These alterations are believed to represent a protective strategy, aiming to minimize ankle joint loading in potentially hazardous situations and thereby reduce injury risks (Fuerst et al., 2018; Koshino et al., 2016; Simpson et al., 2020). In 2017, Moisan et al. (2017) did a systematic review analyzing kinetic and kinematic alterations in subjects with CAI. However, most of the included studies regard the foot as one single rigid segment, which is not representative of the fact that the foot has 26 bones (Ficke & Byerly, 2023). In their systematic review, only 3 of the articles regarding walking and running considered the foot as a multi-segmented body part.

Initial biomechanical models such as for example the “Plug in Gait” consider the foot as a mono-segmented, the foot being linked to the tibia via the ankle joint (Kadaba et al., 1990). Even though this model brings limitations with it, such as neglecting internal foot movements and reduction of the anatomical degrees of freedom, one-segmented foot models are still used daily when analyzing kinematics and kinetics and lower limb evaluations (Moore & Dixon, 2014; Thompson et al., 2014).

In the 1990’s, literature emerged to start studying the foot as a multi-segmented body part, resulting in multi-segmented foot models (MSFM) (Kidder et al., 1996; Leardini et al., 1999). Since then, various research teams like De Ridder et al. (2013), Deschamps et al. (2015) and Northeast et al. (2018) for gait and running analysis, and Kunugi et al. (2021) focusing on side-cutting tasks, have documented biomechanical alterations in ankle and foot joints using such MSFM. Taking into account the foot's number of bones, considering it as a rigid single-segmented body part, instead of a multi-segmented one, could induce wrong ideas on how the feet actually move (Pothrat, Authier, et al., 2015). This is where newer models like the Rizzoli Foot Model (RFM) were created (Leardini et al., 2007). The RFM, which is a multi-segmented model, is used for assessing foot movement during the gait cycle. The RFM divides the foot into 4 separate segments by placing markers around the tibiotarsal, Chopart, Lisfranc and metatarsophalangeal joints. Other validated MSFM include the Oxford foot model, the Ghent foot model or the Milwaukee foot model. The Oxford foot model is described with a rearfoot (calcaneus and talus), a forefoot (five metatarsals) and a hallux (proximal phalanx of the hallux) whilst the Ghent model comprises the rearfoot, midfoot, lateral forefoot, medial forefoot, and hallux (Carson et al., 2001a; De Mits et al., 2012). For every model, captions are usually done via reflective markers placed on the feet captured by multi-camera motion capture systems (Carson et al., 2001a; De Mits et al., 2012; Wright et al., 2011). While these models are commonly considered reliable, it is crucial for clinicians and researchers to possess a thorough understanding of these models and their proper implementation to ensure consistent and trustworthy results (Deschamps et al., 2011, 2012; Leardini et al., 2019; Yoo et al., 2022).

Different statistical methods are used to compare kinetic and kinematic curves between groups of participants. One method is to consider isolated metrics such as peak values, or values at key moments of stance. However, such methods reduce continuous data into discrete parameters, which can lead to false conclusions (Pataky, 2010). Statistical Parametric Mapping (SPM) in locomotor analysis is a method that maps statistical measures onto specific body regions or coordinates. It helps detect subtle differences or abnormalities in movement patterns across conditions or groups, aiding in understanding various disorders or treatment effects. It is a powerful tool to analyze complex movement data, commonly used in both research and clinical settings and can also be used to analyze subtle alterations of kinetics and kinematics (Honert & Pataky, 2021; Mestanza Mattos et al., 2023).

Moreover, Moisan et al. (2017) only considered walking and running. Given the widespread participation in running and walking activities leading to common injuries, research efforts should be directed toward these areas (van Poppel et al., 2021). However, other tasks like side-cutting may be more demanding on the feet, and more representative of sports involving changes of direction (Hootman et al., 2007).

This review aimed to examine the altered movement patters, particularly multi-segment kinetics and kinematics, among individuals with CAI compared to copers and healthy controls during dynamic tasks and more precisely to answer the question: “What sorts of alterations of movement patterns, specifically kinematics and kinetics, are exhibited by individuals with chronic ankle instability during various dynamic tasks considering the foot as multi-segmented, during running and other dynamic horizontal component focused tasks?”.

# 2. Methods

## *2.1 Protocol*

This narrative review followed the principles of a 'systematized' narrative review. Such a review design incorporates some elements of a systematic review without comprising a complete systematic review. As such, this systematized narrative review among others included a systematic literature search across multiple databases using keywords, without limitations on time (Greenhalgh et al., 2018).To conduct a targeted search, a search equation was developed using various keywords. As PubMed uses its own vocabulary, the terms needed to be transformed to match 'Mesh Terms'. The PICO (*Population, Intervention, Comparator, Outcome*) criteria method was used to identify keywords (**Table 1**).

**Table 1:** Search terms using the PICO criteria method

| ***PICO*** | **Key term** | **Synonyms** |
|---|---|---|
| ***Population*** | Chronic ankle instability | CAI, Persistent ankle instability, Long-term ankle weakness, Ankle sprain, ankle injury |
| ***Intervention*** | Run; jog; jogging; sprint ; Side-cutting; cutting task; change of direction | |
| **Comparison** | Control, Coper | Healthy individual |
| **Outcome** | Kinematics, kinetics, biomechanics, movement pattern, validated multi-segmented foot model | / |

The combination of these keywords with the boolean operators 'AND' and 'OR' formed the equations listed in **Table 2**. As PubMed uses its own vocabulary, it was necessary to transform the terms to find them in the form of 'Mesh Terms' and add them to the basic synonyms.

**Table 2 :** Search Query

| Database | Search Query |
|---|---|
| **PubMed** | ("ankle injuries"[MeSH Terms] OR “ankle injury”[Title/Abstract] OR "ankle instability"[Title/Abstract] OR "ankle sprain"[Title/Abstract] OR ankle sprains[Title/Abstract] OR "CAI"[Title/Abstract] OR "chronic ankle instability"[Title/Abstract] OR "ankle injuries"[Title/Abstract] OR "ankle weakness"[Title/Abstract]) AND ("biomechanical phenomena"[MeSH Terms] OR "kinematic*"[Title/Abstract] OR "kinetic*"[Title/Abstract] OR "biomechanic*"[Title/Abstract] OR "biomechanical phenomena"[Title/Abstract] OR “motion capture”[Title/Abstract]) AND ("multisegment*"[Title/Abstract] OR "multi segment*"[Title/Abstract] OR multi-segment*[Title/Abstract] OR "rizzoli"[Title/Abstract] OR "oxford"[Title/Abstract] OR "ghent"[Title/Abstract] OR "Milwaukee"[Title/Abstract] OR "Rao"[Title/Abstract] OR "Heidelberg"[Title/Abstract] OR "MSFM"[Title/Abstract] OR "foot segment*"[Title/Abstract] OR "multisegmental"[Title/Abstract] OR rearfoot[Title/Abstract] OR midfoot[Title/Abstract] OR forefoot[Title/Abstract] OR 3DMFMs[Title/Abstract] OR 3DMSFM[Title/Abstract] OR MSFMs[Title/Abstract] OR “foot joint”[Title/Abstract] OR “foot joints”[Title/Abstract]) |
| **Embase** | ('ankle injury':ti,ab,kw OR 'ankle injuries':ti,ab,kw OR 'ankle instability':ti,ab,kw OR 'ankle instabilities':ti,ab,kw OR 'ankle sprain':ti,ab,kw OR 'ankle sprains':ti,ab,kw OR 'cai':ti,ab,kw OR 'ankle weakness':ti,ab,kw OR 'ankle injury'/exp OR 'ankle instability'/exp OR 'ankle sprain'/exp) AND ('biomechanical phenomena':ti,ab,kw OR 'biomechanical phenomenon':ti,ab,kw OR 'kinematic':ti,ab,kw OR 'kinematics':ti,ab,kw OR 'kinetic':ti,ab,kw OR 'kinetics':ti,ab,kw OR 'biomechanic':ti,ab,kw OR 'biomechanics':ti,ab,kw OR ‘biomechanics’/exp OR 'kinematics'/exp OR 'kinetics'/exp OR ‘motion capture’:ti,ab,kw OR ‘motion capture’/exp) AND ('multisegmental':ti,ab,kw OR 'multisegment':ti,ab,kw OR |

| | |
|---|---|
| | 'multisegmented':ti,ab,kw OR 'multisegments':ti,ab,kw OR 'multi-segment':ti,ab,kw OR 'multi-segmented':ti,ab,kw OR 'multi-segments':ti,ab,kw OR 'rizzoli':ti,ab,kw OR 'oxford':ti,ab,kw OR 'ghent':ti,ab,kw OR 'milwaukee':ti,ab,kw OR 'rao':ti,ab,kw OR 'heidelberg':ti,ab,kw OR 'msfm':ti,ab,kw OR 'msfms':ti,ab,kw OR 'foot segment':ti,ab,kw OR 'foot segments':ti,ab,kw OR '3dmsfms':ti,ab,kw OR '3dmsfm':ti,ab,kw OR 'foot joint':ti,ab,kw OR 'foot joint'/exp 'forefoot':ti,ab,kw OR 'midfoot':ti,ab,kw OR 'rearfoot':ti,ab,kw OR 'forefoot'/exp OR 'midfoot'/exp OR 'rearfoot'/exp) |
| **Google Scholar** | (“Ankle Injury” OR “ankle injuries” OR “ankle instability” OR “ankle instabilities” OR “ankle sprain” OR “ankle sprains” OR “cai” OR “ankle weakness”) AND (“biomechanical phenomena” OR “biomechanical phenomenas” OR “motion capture”) AND (“kinematic” OR “kinematics” OR “kinetic” OR “kinetics biomechanic” OR “biomechanics”) AND (“multisegmental” OR “multisegment” OR “multisegmented” OR “multisegments” OR “multi-segment” OR “multi-segmented” OR “multi-segments” OR “rizzoli” OR “oxford” OR “ghent” OR “Milwaukee” OR “Rao” OR “Heidelberg” OR “MSFM” OR “MSFMS” OR “Foot segment” OR “foot segment” OR “foot segments” OR "Forefoot" OR "Midfoot" OR " Rearfoot" OR "3DMSFMs" OR "3DMSFM" OR “foot joint” OR “foot joints”) |

### *2.2 Eligibility criteria*

After conducting the article search, inclusion and exclusion criteria, as outlined in **Table 3** below, were established to select the most relevant articles for this study.

Articles involving participants of all age groups diagnosed with chronic ankle instability compared to Copers and/or healthy individuals were considered for inclusion.

Only experimental studies employing validated MSFMs were included. To be included, articles needed to encompass dynamic tasks such as running, jogging, side-shuffling and other similar tasks with a horizontal jump component. Tasks with a main vertical component such as a vertical-jump and single legged drop jump were excluded. Articles had to include kinetic or kinematic results.

Articles included in this review were all written in either English or French.

Systematic reviews, case-reports and expert opinions were excluded.

There was no time frame selected, articles up to April 2024 were included.

**Table 3:** Inclusion and exclusion criteria

| Inclusion | Exclusion |
|---|---|
| All ages<br>Chronic ankle instability<br>Validated Multisegmented foot models<br>Running, Side-cutting, side-jump<br>Kinematics, kinetics<br>Use of a MSFM | ReviewsExperts OpinionCase Reports<br>Dynamic vertical tasks<br>walking |

### *2.3 Study Selection*

The search across the three databases and the selection of articles were conducted by a single reviewer.

Records were identified through three databases using the search equations (see **Table 2**) and were managed with Rayyan and Zotero (Ouzzani et al., 2016). In the Rayyan online app: duplicate articles were removed., a first screening was conducted on the articles by analyzing each title and abstract, leading to the exclusion of articles not meeting the PICO criteria or were not available in English or French. During the second screening articles of which the full text was not available were excluded. Furthermore, reviews and case reports were excluded as well as studies without a validated MSFM or studies having no participants with CAI. This selection process and the justifications of articles excludes at full-text stage are graphically represented in **Figure 1** (*3.1 Study selection).*

### *2.4 Data extraction*

Once all the articles were selected, a summary table was used to extract all the relevant data. Annex (x) contains information on the studies, including:

- Author and year of publication
- Study type
- Score obtained using Downs and Black Checklist
- Sample size
- Participant characteristics

### *2.5 Risk of bias in studies*

To assess the methodological quality and biases of the selected studies, the modified Downs & Black quality index was applied to all articles. This checklist consists of 27 items grouped into 5 subgroups. These items are used to evaluate different criteria grouped into data reporting (10 items), external validity (3 items), internal validity (7 items for biases and 6 items for confounding factors), and statistical power (1 item). Each question is scored as 0 or 1, except for one question in the *reporting* section, which is scored on a 2-point scale (*item 5*). The original Downs & Black scale was initially scored out of 32 points, with the statistical power question (*item 27*) accounting for 5 points (Downs & Black, 1998). In the modified scale, this question was reduced to 1 point. The modified Downs & Black quality scale used in this review is therefore scored out of a maximum of 28 points, and each included article receives a quality grade based on the obtained score (O'Connor et al., 2015).

These quality grades are categorized as:

- "Excellent" (26-28 points);
- "Good" (20-25 points);
- "Fair" (15-19 points);
- "Poor" (≤14 points)

# 3. <u>Results</u>

## *3.1 Study selection*

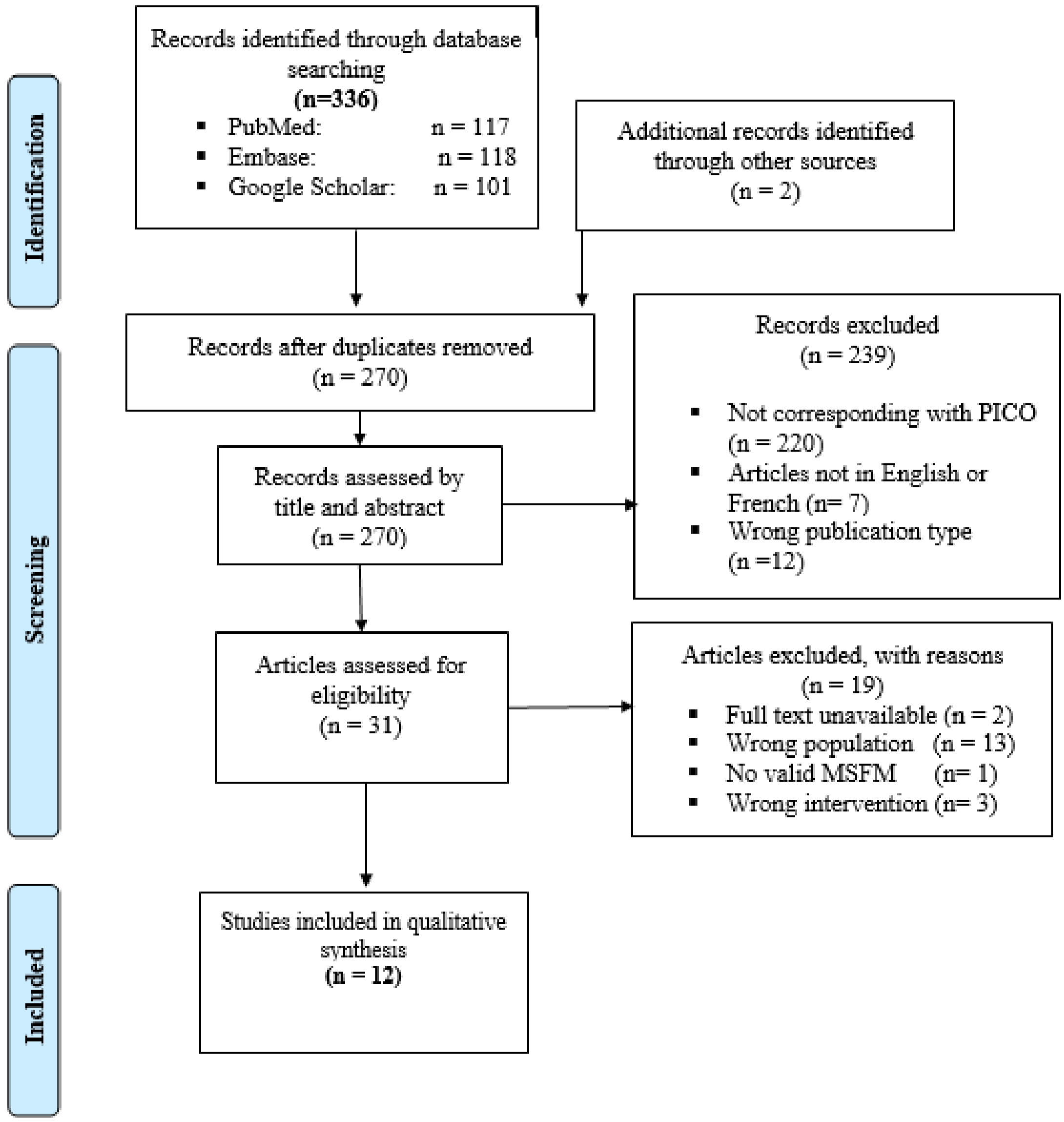
In total, 336 articles were identified through the search queries across the different databases (117 on PubMed, 118 on Embase and 101 on Google Scholar). Duplicates were removed, leaving 270 articles after deduplication. A first screening by analyzing each title and abstract, lead to the exclusion of 239 irrelevant articles. Then, a further screening was performed on the remaining 31 articles. The full text was not available for two articles. The inclusion and exclusion criteria (**Table 3**) resulted in 19 articles that did not meet these criteria.

In the end, all 12 articles were included in this review. 2 articles obtained a "Fair" assessment whilst 10 articles obtained "Good". A summary of the articles' Downs and black scorings can be found in the annexes (**Annex 2.1 & Annex 2.2**).

The PRISMA flow diagram below (**Figure 1**) provides an overview of the selection process. It shows the number of articles identified, included, and excluded based on the various criteria chosen (Moher et al., 2009).

Two other articles known by the reviewers were added due to their eligibility (C. Herb et al., 2024; Tamura et al., 2023).

**Figure 1 :** Prisma Flow Diagram




### *3.2 Characteristics of selected studies*

Considering the 12 studies included in this narrative review, 10 focus on running or jogging tasks and 2 articles analyze dynamic horizontal tasks such as side-cutting or side-shuffles. In total, 463 subjects participated in the various studies including 200 participants with a CAI. In most articles studies used healthy individuals as control groups and few studies also included copers for comparison (De Ridder et al., 2013a, 2015; Watanabe et al., 2022; Yu et al., 2024). Most of articles used the "Cumberland Ankle Instability Tool (CAIT) as inclusion criteria, based on the International Ankle Consortium recommendations in 2014 (Gribble et al., 2014). The CAIT assesses whether the individual reports perceived instability. The CAIT is a validated and reliable measurement tool based on 9 items with a maximum score of 30 and ≤24 as a cutoff score indicating perceived ankle instability (Wright et al., 2014) Individuals scoring 27 or lower are likely to have functional ankle instability whilst a score of 28 or higher means that they are unlikely to (Gribble et al., 2014; Hiller et al., 2006)(**Annex 5 Cumberland Ankle Instability Tool).** Differences and study characteristics have been in tabular form in the Annex (**Annex 3 Study Characteristics**).

### *3.2.1. Running Tasks (303 subjects including 138 CAI)*

The first article from Tamura et al. (2023) is a case-control study with 22 male college soccer players with a right foot dominance for the strike (left leg support). Depending on their CAIT scores, the individuals were put in either a CAI (n=12; mean age= 20.6 ± 0.9) or Control (n=10; mean age 29.3 ± 0.9) group. 9mm reflective markers were used in order to create the hindfoot and forefoot according to the Oxford foot model. After a standardized warm-up, the participants performed five laps barefoot at a self-selected, comfortable speed on a 30-meter runway covered with hard carpet and force plates in the laboratory. The hip, knee, ankle, foot angles and ground reaction force (GRF) were analyzed. In order to compare groups, SPM was used.

28 subjects (13 CAI, M/F:6/7, mean age 26.9 ± 6.8; 15 control M/f: 8/7, mean age: 23.6 ± 4.7) jogged barefoot at 9.66km/h on a treadmill in an observational study (C. Herb et al., 2013). 15 second clips were recorded for analysis. Reflective markers were attached according to the Oxford Foot Model. Exactly 15 strides were extracted for vector-coding analysis. Stride-to-stride variability (VCV), which reflects the consistency of the ratio and magnitude of coupled motion over multiple strides, ratio, and magnitude of coupled motion were examined in order to analyze shank-rear foot coupling during jogging. Herb et al. (2013), used SPM for between group comparisons.

The third, cross-sectional, study (Watanabe et al., 2022) recruited 35 males in 3 subgroups (CAI n=13, mean age: 21.0 ±1.3; Coper n=12, mean age: 20.2 ±0.8; Control n=10, mean age: 20.8 ±1.7). 9.5mm markers were attached according to the Rizzoli foot model. 100 total barefoot strides were collected on a treadmill at a given speed (3.5 m/s). 50 rearfoot strike strides out of the 100 strides were randomly analyzed for 4 intra-foot couplings (1. RearFoot-Shank vs. Midfoot-RearFoot sagittal, 2. RearFoot-Shank vs. MidFoot-RearFoot frontal, 3. MidFoot-RearFoot vs. ForeFoot-MidFoot sagittal, and 4. MidFoot-RearFoot vs. ForeFoot-Midfoo frontal). The coupling angle represents a spatial relationship from which coordination patterns can be identified.

The fourth study analyzing running tasks also used the Rizzoli foot model with 9.5mm markers (Deschamps et al., 2016) to compare a CAI group (n= 15, mean age: 22 ± 2.7; M/F= 6/9) to a control group (n=12; mean age: 23.6 ± 4.1; M/F= 4/8). Participants were asked to run barefoot at a constant speed of 3.3 m/s and adopt heel-strike running on a 10m lab-runway. The order of the different test conditions was randomly assigned. Every condition was repeated until at least three valid trials were registered. Kinematic data were created between the Rizzoli defined segments; shank (Sha), calcaneus (Cal), midfoot (Mid), metatarsus (Met) and hallux as rigid segments. Other variables analyzed were the talocrural kinematics (Sha-Foo) and the foot progression angle. Comparison between groups was done via SPM.

For the fifth article, a 15-marker model based on the Cleveland Model was used by Kim et al. (2017) in order to do a case-control study on neuromuscular training on foot kinematics in 21 Korean female elite hockey players (CAI n= 12, mean age: 26 ± 2.4; Control n=9, mean age: 27 ± 2.5). In addition to their daily field hockey training, athletes with CAI participated in a progressive 6-week rehabilitation program (5 sessions per week) focusing on postural stability, strength, plyometrics, and speed/agility drills. CAI and control were compared at the beginning and end of the 6 weeks. Participants were instructed to walk barefoot 10m at their comfortable normal walking speed and then to run at 7 km/h on a treadmill.

Inversion and eversion were analyzed in the frontal plane during heel strike, midstance and toe touch phases.

The sixth article analyzing a running task from Deschamps et al. (2018) is a case control study with the identical participants as Deschamps et al. (2016). The Rizzoli Foot Model was used. Participants were asked to run barefoot with a midfoot or forefoot striking pattern on a laboratory walkway at 3.3m/s. Participants had 3 test trials. The data collection stopped after 3 valid tests were performed (midfoot strike pattern, constant step frequency, correct running speed. Foot joint rotations between the shank and calcaneus (Sha-Cal), calcaneus and midfoot (Chopart), midfoot and metatarsus (Lisfranc), and calcaneus and metatarsus (Cal-Met) were computed for each running condition in all three planes (sagittal, frontal, and transverse). The flexion/extension values of the hallux were also calculated. Shank-foot kinematics (Sha-Foo), the foot progression angle and planar angles of the hallux were also computed. Comparison between groups was also done via SPM.

De Ridder et al's (2013) case-control study is the seventh running task study in this review. This study includes 77 participants in total for a CAI, Coper and Control group (CAI n= 29, mean age: 21.9 ± 3.3, M/F= 15/14; Coper n=24, mean age: 20.3 ± 1.9, M/F: 12/12; Control n=24, mean age: 25.8 ± 1.9, M/F: 10/14). De Ridder et al. used the Ghent Foot Model. Data were collected using a barefoot midfoot strike pattern at a constant speed of 3.5 m/s on a laboratory-runway. Subjects familiarized themselves with the test procedure by performing at least three practice trials. The actual test was repeated until three usable trials were captured. The dependent variables calculated for this study included the various segments of the Ghent Foot Model and the joint angles of the rigid foot. Rotation around the X-, Y-, and Z-axis defined the plantarflexion/dorsiflexion (sagittal plane), inversion/eversion (frontal plane), and abduction/adduction (transverse plane) motions, respectively. Comparison between groups was done via SPM.

Lilley et al.'s (2018) case-control study constitutes the eights' study and includes 27 participants (CAI n= 13, mean age: 23.8 ± 5.1, M/F: 4/9; Control n= 14, mean age: 21.8 ± 2.3, M/F: 4/10). Participants wore customized shoes in order to properly attach the reflective markers. Participants were given a 4-minute familiarization period before recording three 15-second clips of data for processing on a treadmill at 2.68 m/s. 15 consecutive strides were extracted for statistical analysis. VCV was calculated for knee sagittal-ankle (sagittal), knee sagittal-ankle (frontal), hip frontal-ankle (sagittal) and hip frontal-ankle (frontal) pairs.

The next case-control study included 27 participants (CAI n=15, Mean Age: 22 ± 2.7, M/F: 6/9; Control n=12, Mean Age: 23.6 ± 4.1, M/F: 4/7) (Deltour et al., 2021). The Rizzoli Foot Model was used for the reflective markers. Participants were instructed to run barefoot with a heel strike pattern at a constant speed of 3.3 m/s on a 10m-walkway in the laboratory. The swing phase from the gait cycle was excluded from analysis. ROM as well as kinematic coupling between the different segments and vertical GRF were calculated.

The last running task study includes 39 participants (CAI n=20, Mean age: 24.7 ± 5.9, M/F= 7/13; Control n=19, Mean age: 23.1 ± 3.8, M/F= 8/11) and is a case control study from 2024 using the Oxford foot model (C. Herb et al., 2024). The subjects wore customized shoes to attach the reflective markers. Following the warm-up, they jogged barefoot at a self-selected pace for 3–4 min and then speed was increased on the treadmill to 9.66 km/h. During jogging, 3-fifteen second clips were collected for analysis. Fifteen complete strides were extracted for statistical analysis. The study measured the kinematics in the transverse, frontal, and sagittal planes of the ankle, knee, and hip, as well as the joint moments and GRFs in the medial-lateral, anterior-posterior, and vertical directions. SPM was used to identify differences between data.

### *3.2.2. Horizontal tasks (162 subjects including 60 CAI)*

The first study for horizontal tasks is a case control study and includes 66 males (CAI n=22 Mean age: 22.59 ± 1.92; Coper n=22 Mean age: 22.45 ± 2.02; Control n=22 Mean age: 23.50 ± 2.50) (Yu et al., 2024). Yu et al. (2024) used a 5 segment

8 Degree Of Freedom (DOF) foot model for their study (H. Kim & Kipp, 2019). After task-familiarization, participants performed the side-cutting task barefoot. They were required to walk at a self-selected speed, step onto a force plate with the involved limb and with the other limb to step out in a 45° direction. The stance phase which means from initial to final ground contact was analyzed. Joint angles, joint moments GRF of the foot–ankle complex were calculated. Comparison between groups was done via SPM.

The second study is a cross-sectional study from De Ridder et al. (2015) and includes 96 participants (CAI n=38, Mean age: 22.1 ± 3.4, M/F= 19/19; Coper n=28, Mean age: 20.3 ± 1.9, M/F= 14/14; Control n=30, Mean age: 25.7 ± 1.8, M/F= 12/18). They used the Ghent Foot Model and participants did the task barefooted. The participants performed a maximal side jump task, beginning with a brief familiarization period. They initiated from a single-leg stance on the foot opposite to the tested leg, pushed off maximally sideways, and landed on the force plate with the tested leg. Rotations between the foot models' different segments were calculated as well as ROM and peak forces. Kinematics were calculated for the impact phase only which consisted of the moment of touchdown to the moment of maximal ankle joint dorsiflexion. SPM was used for statistical analysis.

## *3.3. Results of selected studies*

### *3.3.1. Running Studies*

*Sagittal Plane Kinematics*

In the articles examining running tasks, significant differences in sagittal plane kinematics have been noted between individuals with CAI and healthy controls. Deschamps et al. (2016) found that CAI individuals exhibited decreased dorsiflexion angles during early stance phases (6% to 8%) at the talocrural joint (CAI: 10.5° ± 2.3°, Control: 13.2° ± 1.8°) and increased inversion angles towards the late stance (99% to 100%) (CAI: 18.3° ± 3.1°, Control: 14.7° ± 2.5°) compared to controls. This pattern indicates compromised ankle dorsiflexion and increased inversion during running.

Furthermore, Deschamps et al. (2018) noted increased sagittal plane ROM at the shank-foot joint (single-segment foot model) during the absorption phase (CAI: 12.4° ± 2.1°, Control: 10.1° ± 1.9°) in CAI-barefoot conditions compared to controls.

*Frontal Plane Kinematics and kinetics*

During the early stance phase, Watanabe et al. (2022) observed CAI exhibited a significantly higher proportion of eversion at the Chopart joint compared to Coper (CAI: 12.7% ± 2.7%, Copers:5.4% ± 2.2%). Lisfranc also showed greater inversion in CAI.

In the mid-stance phase, De Ridder et al. (2013) highlighted kinematic alterations, in the eversion of the rearfoot and inversion of the medial forefoot. CAI individuals showed increased eversion of the rearfoot (CAI: 8.2° ± 1.7°, Control: 5.5° ± 1.4°) from 56% to 73% of the stance phase. Additionally, there was greater inversion at the medial forefoot (CAI: 13.7° ± 2.5°, Control: 3.9° ± 1.8°) from 56% to 91% of the stance phase (De Ridder et al., 2013).

During the late stance phase, Watanabe et al. (2022) found that CAI participants exhibited less rearfoot inversion compared to Copers, with rearfoot inversion angles recorded at 51.0° ± 8.8% for CAI versus 23.9° ± 7.7% for Copers from 54% to 86% of the stance phase.

Modified kinematics at the ankle joint (single-segment foot model) were also identified during the different stance phases.

Herb et al. (2024) reported that during the early stance phase, CAI participants demonstrated consistently greater ankle inversion angles compared to controls, with a mean difference of 4.56°, Deschamps et al. (2016) found that individuals with CAI had decreased dorsiflexion angles at the talocrural joint from 6% to 8% of the running cycle (6.2° ± 1.5% in CAI vs. 8.7° ± 1.2% in controls) as well as increased inversion angles (CAI: 12.4° ± 2.1%, Control: 8.9° ± 1.8%). Furthermore, Deschamps et al. (2016) noted more adduction at the calcaneus from 38% to 41% of the stance phase in CAI (CAI: 7.8° ± 1.6%, Control: 5.5° ± 1.3%)

In the late stance phase, Herb et al. (2024) consistently reported greater ankle inversion angles throughout various phases of a running task (from 20% to 92% of the stance phase) in CAI participants (Mean difference: 4.56°). He noted increased eversion moments at the ankle from 95% to 100% (Mean difference: 74.58 Nm/kg) in the CAI group during running.

*Transverse Plane Kinematics*

Deschamps et al., 2018 explored rotational movements at the shank-calcaneus joint (25% to 28%) in CAI individuals during running, revealing increased rotational ROM. This indicates challenges in controlling foot alignment and rotational movements during propulsion and weight transfer phases.

Deschamps et al., 2016 showed additional differences in transverse plane kinematics during running. Their study revealed increased internal rotation at the foot progression angle (34-36%) and greater adduction of the calcaneus (38-41%) among CAI participants.

*Joint Coupling and Variability During Jogging*

Lilley et al., (2018) investigated knee-ankle and hip-ankle joint couplings during jogging. They found that knee-ankle sagittal coupling in CAI individuals showed lower variability in joint coupling (VCV) from 19% to 26% (mean difference: -0.09 ± 0.06) and 60% to 80% (mean difference: -0.09 ± 0.08) compared to controls. Additionally, knee-ankle frontal coupling exhibited lower VCV in CAI from 20% to 23% of the gait cycle (mean difference: -0.07 ± 0.05). Hip-ankle frontal coupling showed significant reductions in VCV from 45% to 49% (mean difference: -0.15 ± 0.08), 51% to 53% (mean difference: -0.13 ± 0.06), and 61% to 70% (mean difference: -0.08 ± 0.06), highlighting challenges in hip-ankle coordination.

Herb et al. (2014) identified, against his initial hypothesis, that CAI displayed significantly lower coupling angles (θ) during their jogging trial at 9.66 km/h compared to control individuals. Specifically, during the early-stance phase, the CAI group had a θ of 47.2 ± 3.5° versus 60.3 ± 4.1° for the controls. Results were similar for the midswing (CAI = 39.4 ± 2.3°, Control = 51.3 ± 2.2°) and late-swing phases (CAI = 52.8 ± 3.6°, Control= 61.8 ± 2.3°). Lower θ values indicate increased relative rearfoot motion. There were no significant differences in VCV during jogging between the groups.

Summary of results during running

In the **sagittal plane**, studies (Deltour et al., 2021; Deschamps et al., 2016, 2018) reveal decreased dorsiflexion angles during early stance and increased inversion angles towards late stance in CAI participants. Increased sagittal plane ROM at the shank-foot joint during the absorption phase is noted in CAI individuals compared to controls.

In the **frontal plane**, greater ankle inversion angles and altered eversion moments are consistently observed in CAI participants (C. Herb et al., 2024; C. C. Herb et al., 2016; Watanabe et al., 2022). CAI individuals also demonstrate increased adduction at various joints, indicating compromised frontal plane control.

In the **transverse plane**, increased internal rotation at the foot progression angle and greater adduction at the shank-calcaneus joint are reported (Deltour et al., 2021; Deschamps et al., 2016, 2018) suggesting difficulties in maintaining foot alignment during dynamic tasks.

Regarding **joint coupling and variability**, CAI individuals exhibit lower variability in knee-ankle and hip-ankle joint couplings during jogging (Lilley et al., 2018; Herb et al., 2016), reflecting impaired movement adaptation. Taping reduces variability and stabilizes joint movements in both CAI and healthy individuals.

### *3.3.2. Side Cutting and Side Jumping Studies*

Yu et al. (2024) investigated the stance phase of side-cutting. They found notable differences at the subtalar joint. Copers exhibited more eversion angles compared to those with CAI throughout 5–100% of the stance phase. Additionally, during 81–100% of the stance phase, copers showed greater eversion angles compared to the control group.

De Ridder et al. (2015) focused on a side-jumping task. Both CAI and copers displayed a less plantarflexed position compared to controls during the initial 0–10% of the gait cycle, with copers showing this less plantarflexed rearfoot position up to 15% of the cycle. Copers exhibited a more dorsiflexed rearfoot position from 60–100% of the gait cycle. CAI individuals had less inversion from 0–55%, with the rearfoot initially inverting and then everting throughout the impact phase. During the entire impact phase (10-100%), relative to the rearfoot, the midfoot was more inverted in CAI. Copers displayed a more inverted medial forefoot position relative to the midfoot from 55–100%, with slight eversion compared to controls.

When analyzing ROM, De Ridder et al. (2015) also highlighted less amplitude in the single-segment foot and the rearfoot for plantar-/dorsiflexion and ab-/adduction compared in CAI. Copers had reduced plantar-/dorsiflexion ROM in both the lateral and medial forefoot, with the hallux showing less eversion/inversion ROM compared to CAI individuals.

Summary of findings during changes of direction

Both studies noted variations in eversion and inversion pattern. Yu et al. (2024) emphasized greater eversion in copers during cutting, whereas De Ridder et al. (2015) noted less inversion in CAI individuals and distinctive inversion patterns in copers during side-jumping.

Reduced ROM in CAI individuals was a consistent finding across both studies.

## 4. Discussion

CAI is a common condition following an ankle sprain, characterized by recurrent ankle sprains and persistent symptoms such as pain and perceived instability. The goal of our review was to investigate the biomechanical alterations associated with CAI during dynamic tasks such as running and side-cutting, utilizing advanced analytical methods including MSFMs and SPM. By comparing CAI, Copers and healthy individuals, we aimed to uncover specific kinematic and kinetic alterations that may contribute to the persistent instability experienced by these individuals.

The use of MSFM in our analysis allowed for a detailed examination of foot mechanics by considering multiple segments, rather than treating the foot as a single rigid unit. This approach provides understanding of intra-foot movements and their impact on overall running and side-task mechanics (Stone, 2023)

Additionally, employing SPM enabled us to analyze continuous data throughout defined movement cycles, offering a nuanced view of biomechanical patterns and deviations (Pataky, 2010).

**Kinematics**

During running and jogging, CAI participants demonstrated altered rearfoot mechanics, including increased rearfoot inversion. These findings align with other studies, who also reported more rearfoot inversion in CAI individuals during jogging tasks (Drewes et al., 2009). This consistency in kinematic patterns suggests that CAI affects neuromuscular control of the ankle and lower limb, potentially leading to recurrent ankle sprains and instability. Following a 6-week neuromuscular training program, elite hockey players with CAI demonstrated significant changes in ankle position, with increased inversion during running (E. Kim et al., 2017). This finding contrasted with earlier studies, which showed no significant changes after a shorter, 4-week training period (Coughlan & Caulfield, 2007; McKeon et al., 2009). Differences may be attributed to Kim's et al. (2017) study design, including elite athletes only as well as a longer training duration, which seems more effective for inducing physiological adaptations.

However, Tamura et al. (2023) found no significant differences in ankle kinematics during the running stance phase, which contrasts with findings of altered rearfoot mechanics in other studies. They explain this lack of alterations via their chosen population (soccer players). Soccer players generally have better sprinting, jumping, and balance compared to untrained individuals and thus may be able to compensate CAI with superior lower extremity function (Taylor et al., 2017).

In fact, study by Hoch & Mckeon (2014), reports a reflex latency as well as electromechanical activation delay in the peroneus longus muscle in individuals with CAI. As the peroneus longus muscle's roles are plantarflexion as well as ankle eversion, the muscles alterations is considered to be one of LAS's causes.

In De Ridder et al. (2015), they identified reduced plantar flexion during the impact phase in CAI and Copers compared to healthy. Reduced plantar flexion might serve as a protective strategy to decrease the risk of ankle sprains. However, for individuals with CAI, this approach might be counterproductive as their stiffer landing pattern, characterized by a smaller ROM and higher loading rates, could increase their vulnerability to episodes of instability and recurrent ankle sprains. This study highlights that even copers show differences compared to healthy individuals, although they are often regarded as having recovered from their initial injury.

The more everted foot position in Yu et al.'s (2024) coper group during various phases indicated better neuromuscular control compared to the CAI group. Copers seem to use both open- and closed-loop control. Open-loop control involves anticipatory muscle activation based on prior knowledge, without sensory feedback. For ankle stability, muscles activate before ground contact to ensure proper joint positioning and stiffness. This preparation helps prevent injury by maintaining stability during movements like walking and landing. Closed-loop control involves reflex responses to maintain stability by reacting to sensory feedback. In ankle stability, proprioceptive signals from ligaments trigger muscle reflexes to correct instability. Damage to these ligaments impairs this feedback, causing delayed muscle responses and increasing the risk of the ankle "giving way" (Gutierrez et al., 2009; Johansson et al., 1991; Myers et al., 2003).

During side-cutting, CAI individuals exhibited increased ankle inversion and reduced dorsiflexion at initial contact, consistent with Moisan et al. (2018), who similarly reported increased ankle inversion and decreased dorsiflexion in CAI subjects during gait tasks. This suggests a persistent pattern of altered kinematics across various locomotor tasks.

**Kinetics**

Herb et al. (2024) found increased ankle eversion moments and plantar flexion moments in CAI participants, which align with De Ridder et al. (2013) who reported elevated eversion of the rearfoot and inversion of the medial forefoot during running. The increased eversion moments reported by Herb et al. (2024) may reflect altered loading patterns and compensatory mechanisms in CAI individuals. The observed plantar flexion moments further reinforce previous studies indicating that CAI can lead to altered force distribution and muscle activation patterns. CAI potentially use a corrective motor-control strategy where greater inversion during mid-stance through mid-swing is compensated by greater eversion forces prior to the subsequent stride. Earlier peroneal activation is hypothesized to be due to faulty inversion position of the ankle needing greater muscle activity. Earlier activation of peroneals may induce faster muscle fatigue and decrease the ability of correct initial joint position at contact (Gribble & Robinson, 2009).

During running and jogging, CAI participants showed slight reduced peak vertical GRFs, suggesting a possible protective mechanism to minimize impact forces. This finding contrasts with some previous studies that reported increased vertical GRFs in CAI individuals. Tamura et al. (2023) observed that lower lateral GRFs during running might suppress ankle inversion, potentially explaining the lack of observed differences in kinematic patterns compared to healthy controls in their study. Differences in task conditions and participant characteristics could account for these discrepancies, highlighting the complexity of CAI's effects on kinetic parameters.

Our kinetic analysis revealed that CAI is associated with increased lateral GRFs and decreased medial GRFs during side-cutting tasks. This lateral shift in load distribution could increase the risk of lateral ankle sprains. Moisan et al. (2018) reported mixed findings regarding kinetic alterations in CAI individuals, indicating variability in responses across different tasks and studies. This variability might be attributed to the dynamic and demanding nature of side-cutting tasks, which could exacerbate kinetic deviations in CAI individuals.

This review identified relatively few studies that investigated multi-segment foot kinetics. Indeed, obtaining such data is even more challenging than multi-segment foot kinematics, because kinetics require a pressure plate or two force plate, and subsequent analyses that are time-consuming (Deschamps et al., 2020).

**Injury risk and functional limitations**

The biomechanical changes observed CAI, including increased ankle inversion, altered ROM, and disrupted peroneal muscle activity, are linked to a higher risk of recurrent ankle sprains (Hoch & Mckeon, 2014; Kobayashi et al., 2016).

Altered kinematics, including changes in peroneal muscle activity, can impact functional performance, affecting activities such as running and side cutting. These deviations in biomechanics and muscle function can reduce athletic performance and hinder daily tasks, highlighting the need for targeted rehabilitation (Deschamps et al., 2016; Ruiz-Alias et al., 2023). Consistent with previous studies, reduced dorsiflexion angles of the ankle joint in CAI and copers compared to healthy participants were observed which results in a less stable joint during the stance phase (Chinn et al., 2013; Drewes et al., 2009; Wright et al., 2016). Ankle sprains also lead to lateral tibiotalar joint destabilization via structural impairments in ligamentous tissue (Brockett & Chapman, 2016; Yu et al., 2022).

The more everted foot position in the coper group during various phases indicated better neuromuscular control compared to the CAI group. Copers seem to use both open- and closed-loop control to maintain foot stability, activating ankle joint musculature before ground contact and utilizing reflex arcs after touchdown to counteract stretch (Gutierrez et al., 2009). In contrast to Copers using the open- and closed-loop control as explained earlier, CAI with damaged proprioceptive ligamentous structures, experience impaired proprioception and balance control, leading to worse sports performance (Han et al., 2015).

**MSFM vs. Mono-Segment Analysis**

MSFMs have become essential in the study of foot mechanics, offering a detailed representation by considering multiple segments such as the rearfoot, midfoot, and forefoot. This approach captures subtle inter-segmental movements that a mono-segment analysis might overlook, providing a more comprehensive understanding of foot biomechanics.

A significant advantage of MSFM is its increased accuracy and detail. By considering the movements of individual foot segments, these models detect nuanced changes in foot mechanics, which is crucial for understanding complex conditions CAI. Carson et al. (2001) highlighted that MSFMs could reveal abnormalities in foot function missed by single-segment models. This level of detail can also be beneficial in clinical settings for diagnosing and treating specific foot pathologies, designing orthotics or planning surgeries with higher precision (Carson et al., 2001a; Leardini et al., 2019; Pothrat, Authier, et al., 2015).

Moreover, MSFMs enhance biomechanical analysis by improving our understanding of how different foot segments interact during movement. Leardini et al. (2007) demonstrated that these models significantly improve the analysis of foot kinematics, allowing for the identification of biomechanical issues that single-segment models might miss. Potrath et al. (2015) further supported this by comparing a mono-segmented foot models with the Oxford Foot Model in assessing ankle kinematics in children with normal versus flat feet. The mono-segmented model often showed exaggerated ankle motion, while the MSFM provided a more accurate representation.

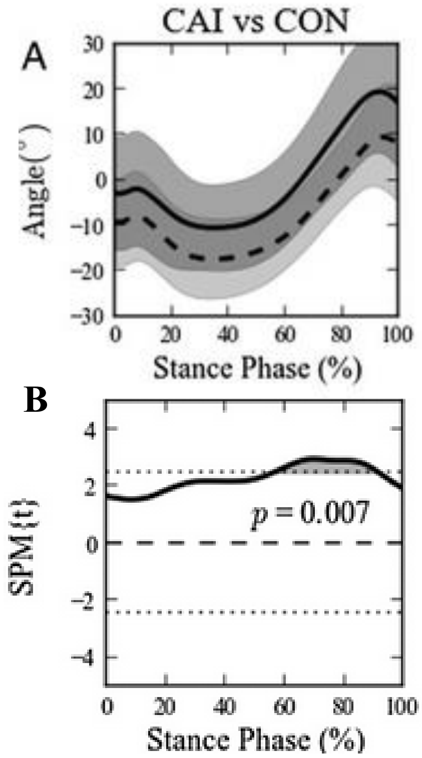
Despite their advantages, MSFMs do also have drawbacks. Their complexity requires sophisticated equipment and computational power, which can be a barrier in clinical settings, thus being potentially less practical for a routine clinical use compared to a mono-segment model. The setup and analysis process for MSFMs is also more time-consuming due to the need for multiple markers on the foot, making it less efficient for clinicians with tight schedules (Leardini et al., 2021).

When using MSFMs, deciding between barefoot analysis and wearing shoes with cut-outs for markers is important. Barefoot analysis shows natural foot mechanics without the influence of shoes. However, it does not reflect how shoes affect foot movement, which is crucial for real-world understanding. Shoes with cut-outs for markers allow foot mechanics to be observed while wearing footwear, but making these custom shoes can be time-consuming and expensive, and the amount of holes in the shoe may alter its structure (Schultz et al., 2021).

### SPM in lower limb biomechanics

SPM has been increasingly adopted in sports biomechanics to analyze continuous data, offering advantages over traditional discrete point analysis (Yona et al., 2024). The SPM technique provides a method of analysis for complex biomechanical data. SPM can reveal detailed kinetic and kinematic patterns throughout the movement cycle, providing insights into technique improvement and training effectiveness or pathological alterations. This method is particularly valuable for analyzing complex movements like running, cutting, and jumping, which involve continuous and dynamic changes in lower limb mechanics as their individual values in the cycle are influenced by the point before. The continuous nature of human movement requires coordination across all lower-extremity joints and in multiple planes of motion. By examining continuous movement patterns, SPM can identify phases of the gait cycle where biomechanical deviations occur, informing more effective interventions (Pataky, 2010)

Studies using SPM have identified specific kinematic characteristics linked to improved performance and injury prevention. For example, SPM has been used to analyze kinematic differences between healthy and injured populations, providing valuable information for developing targeted rehabilitation programs. SPM can also help give insights into the influence of shoes or explain the differences between sex or skill (Boyne et al., 2021; Ruiz-Alias et al., 2023). Research on CAI using SPM has revealed altered ankle kinematics and joint coupling, which may predispose individuals to recurrent injuries. In this way, SPM avoids that each point of gait is assessed independently from the surrounding data points.




*An example of SPM analysis.*
*Kinematic between-group comparison (A) of the medial forefoot during running (CAI (dashed), coper (dotted), control (solid)) with SPM analysis underneath (D). SPM{t} is the trajectory of the Student's t statistic (De Ridder et al., 2013)*

**Limitations**

Our study has several limitations, including a small number of included articles, especially on side-cutting and side-jumping tasks, impacting the generalizability. Perceived instability among CAI participants might introduce selection bias, as those with greater instability are more likely to exhibit significant biomechanical alterations. Variability in inclusion criteria, such as using self-reported function as an including criteria, differing thresholds for the Foot and Ankle Ability Measure (FAAM) and CAIT questionnaires or reliance on self-reported instability, further affects consistency between studies.

Most studies were conducted in laboratory settings, such as treadmills, limiting ecological validity. Running speeds, wearing shoes or being barefooted and environment may impact findings in different studies.

Studies like Watanabe et al. (2022) and Yu et al. (2024) for example only used male participants. They decided to not include female participants as earlier studies determined that females were more prone to LAS than men (Doherty et al., 2014). This choice influences the ability of generalization of their findings and limits the results to a specific population.

MSFMs face several limitations that impact their accuracy. Marker placement errors can lead to incorrect data, making precise marker positioning essential. Additionally, Skin-Tracking Artifacts arise from three main factors: skin deformation, bone motion beneath the skin, and dynamic effects like the inertia of markers during movement can distort data (Okita et al., 2009). Capturing the interaction between different body segments remains a challenge.

The use of SPM requires larger sample sizes for adequate statistical power which is sometimes difficult to obtain for biomechanical studies due to logistical reasons and time (Harrison et al., 2020; Robinson et al., 2021).

Addressing these limitations would enhance the generalizability, comparability, and ecological validity of future CAI research, leading to more effective interventions and rehabilitation strategies. Future studies should elaborate on side-cutting, side-shuffling and side-jumping tasks with a main focus on horizontal forces in order to better understand alterations during that type of movements, often found in sports prone to ankle injuries such as basketball, football and tennis.

## 5. Conclusion

This review aimed to examine the altered movement patterns, particularly multi-segment kinetics and kinematics, among individuals with CAI and copers during dynamic tasks, specifically focusing on running and horizontal component tasks.

In conclusion, CAI remains a significant issue characterized by recurrent sprains, persistent pain, and instability. Our narrative review identified kinematic and kinetic alterations in running and side-cutting tasks. Kinematic analyses reveal that CAI participants exhibit reduced dorsiflexion and increased inversion angles compared to healthy controls, with greater rearfoot inversion and shank external rotation during running, indicating impaired neuromuscular control. In horizontally focused tasks, CAI individuals also show decreased dorsiflexion and altered inversion/eversion patterns. In contrast, copers demonstrate superior neuromuscular control and more stable rearfoot positioning.

Kinetic analyses highlight disruptions in force distribution and compensatory mechanisms in CAI, with altered moments and GRFs underscoring the complexity of CAI's impact on dynamic movements. These kinematic and kinetic deviations contribute to a higher risk of recurrent ankle sprains and functional limitations. The compromised proprioception and neuromuscular control in CAI further exacerbate these risks, emphasizing the need for individualized rehabilitation strategies.

MSFMs provide a detailed understanding of foot biomechanics, offering valuable insights for accurate diagnosis and effective treatment planning. Addressing the biomechanical alterations associated with CAI through detailed assessments and advanced modeling techniques can enhance our understanding and management of the condition. Future research should address current limitations, such as small sample sizes and limited ecological validity.

# 6. Annexes

## Annex 1: Downs & Black quality Checklist

| | Reporting | Yes (1) | No (0) | N/A (/) | Unable to determine (0) |
|---|---|---|---|---|---|
| 1. | **Is the hypothesis/aim/objective of the study clearly described?** | | | | |
| 2. | **Are the main outcomes to be measured clearly described in the Introduction or Methods section?** *If the main outcomes are first mentioned in the results section, the question should be answered as no.* | | | | |
| 3. | **Are the characteristics of the subjects included in the study clearly described?** *In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and source for controls should be given.* | | | | |
| 4. | **Are the interventions of interest clearly described?** *Treatments and placebo (where relevant) that are to be compared should be clearly described.* | | | | |
| 5. | **Are the distributions of principal confounders in each group of subjects to be compared clearly described?** *A list of principal confounders is provided* | | | | |
| 6. | **Are the main findings of the study clearly described?** *Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions. (This question does not cover statistical test which are considered below)* | | | | |
| 7. | **Does the study provide estimates of the random variability in the data for the main outcomes?** *In non-normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported. If distribution data is not described, it must be assumed that the estimates used were appropriate and the question should be answered with yes.* | | | | |
| 8. | **Have all important adverse events that may be a consequence of the intervention been reported?** *This should be answered yes if the study demonstrates that there was a comprehensive attempt to measure adverse events. (A list of possible adverse events is provided).* | | | | |
| 9. | **Have the characteristics of subjects lost to follow-up been described?** *This should be answered yes where there were no losses to follow-up or where losses to follow-up were so small that findings would be unaffected by their inclusion. This should be answered no, where a study does not report the number of patients lost to follow-up.* | | | | |
| 10. | **Have actual probability values been reported ( e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?** | | | | |
| | External validity | | | | |
| 11. | **Were the subjects asked to participate in the study representative of the entire population from which they were recruited?** *The study must identify the source population for subjects and describe how the subjects were selected. Subjects would be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant population exists. Where a study does not report the proportion of the source population from which the subjects are derived, the question should be answered as unable to determine.* | | | | |
| 12. | **Were those subjects who were prepared to participate representative of the entire population from which they were recruited?** *The proportion of those asked who agreed should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population.* | | | | |
| 13. | **Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive?** *For the question to be answered yes, the study should demonstrate that the intervention was representative of that in use in the source population. The* | | | | |

## Internal Validity

14. **Was an attempt made to blind study subjects to the intervention they have received?**
*For studies where the patients would have no way of knowing which intervention they received, this should be answered yes.*
15. **Was an attempt made to blind those measuring the main outcomes of the intervention?**
16. **If any of the results of the study were based on "data dredging", was this made clear?**
*Any analyses that had not been planned at the outset of the study should be clearly indicated. If no retrospective unplanned subgroup analyses were reported, then answer yes.*
17. **In trials and cohort studies, do the analyses adjust for different lengths of follow-up, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?**
*Where follow-up was the same for all study subjects the answer should yes. If different lengths of follow-up were adjusted for by, for example, survival analysis the answer should be yes. Studies where differences in follow up are ignored should be answered no.*
18. **Were the statistical tests used to assess the main outcomes appropriate?**
*The statistical techniques used must be appropriate to the data. For example nonparametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described it must be assumed that the estimates used were appropriate and the question should be answered yes.*
19. **Was compliance with the intervention/s reliable?**
*Where there was noncompliance with the allocated treatment or where there was contamination of one group, the question should be answered no. For studies where the effect of any misclassification was likely to bias any association to the null, the question should be answered yes.*
20. **Were the main outcome measures used accurate (valid and reliable)?**
*For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work or that demonstrates the outcome measures are accurate, the question should be answered as yes.*

## Internal Validity – confounding (selection bias)

21. **Were the subjects in different intervention groups or were they recruited from the same population?**
*For example, patients for all comparison groups should be selected from the same hospital. The question should be answered unable to determine for cohort and casecontrol studies where there is no information concerning the source of patients included in the study.*
22. **Were study subjects in different intervention groups or were they recruited over the same period of time?**
*For a study which does not specify the time period over which patients were recruited, the question should be answered as unable to determine.*
23. **Were study subjects randomised to intervention groups?**
*Studies which state that subjects were randomized should be answered yes except where method of randomisation would not ensure random allocation. For example, alternate allocation would score no because it is predictable.*
24. **Was the randomised intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?**
*All non-randomised studies should be answered no. If assignment was concealed from patients but not from staff, it should be answered no.*
25. **Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?**
*This question should be answered no for trials if: the main conclusions of the study were based on analyses of treatment rather than intention to treat; the distribution of known confounders in the different treatment groups was not described; or the distribution of known confounders differed between*

*the treatment groups but was not taken into account in the analyses. In nonrandomized studies if the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analyses the question should be answered as no.*

26. **Were losses of subjects to follow-up taken into account?**
*If the numbers of subjects lost to follow-up are not reported, the question should be answered as unable to determine. If the proportion lost to follow-up was too small to affect the main findings, the question should be answered yes.*

**Power**

27. **Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?**
*Sample sizes have been calculated to detect a difference of x% and y.*

## Annex 2.1: Detailled Downs & Black checklist scores

| ***Items/author*** | (Tamura et al., 2023) | (Herb C. et al., 2014) | (Watanabe et al., 2022) | (Yu et al., 2024) | (Deschamps et al., 2016) | (Kim et al., 2017) | (Deschamps et al., 2018) | (De Ridder et al., 2013) | (Lilley et al., 2018) | (De Ridder et al., 2015) | (Deltour et al., 2019) | (Herb et al., 2024) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reporting** | | | | | | | | | | | | |
| 1. Is the hypothesis/aim/objective of the study clearly described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2. Are the main outcomes to be measured clearly described in the Introduction or Methods section? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3. Are the characteristics of the subjects included in the study clearly described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4. Are the interventions of interest clearly described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5. Are the distributions of principal confounders in each group of subjects to be compared clearly described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6. Are the main findings of the study clearly described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7. Does the study provide estimates of the random variability in the data for the main outcomes? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8. Have all important adverse events that may be a consequence of the intervention been reported? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9. Have the characteristics of subjects lost to follow-up been described? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10. Have actual probability values been reported ( e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001? | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| **External validity** | | | | | | | | | | | | |
| 11. Were the subjects asked to participate in the study representative of the entire population from which they were recruited? | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 12. Were those subjects who were prepared to participate representative of the entire population from which they were recruited? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 13. Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive? | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Internal Validity** | | | | | | | | | | | | |
| 14. Was an attempt made to blind study subjects to the intervention they have received? | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15. Was an attempt made to blind those measuring the main outcomes of the intervention? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 16. If any of the results of the study were based on "data dredging", was this made clear? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17. In trials and cohort studies, do the analyses adjust for different lengths of follow-up, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 18. Were the statistical tests used to assess the main outcomes appropriate? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 19. Was compliance with the intervention/s reliable? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20. Were the main outcome measures used accurate (valid and reliable)? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Internal Validity – confounding (selection bias)** | | | | | | | | | | | | |
| 21. Were the subjects in different intervention groups or were they recruited from the same population? | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 |
| 22. Were study subjects in different intervention groups or were they recruited over the same period of time? | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23. Were study subjects randomised to intervention groups? | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24. Was the randomised intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable? | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn? | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 26. Were losses of subjects to follow-up taken into account? | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Power** | | | | | | | | | | | | |
| 27. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%? | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **20** | **19** | **18** | **21** | **21** | **20** | **20** | **20** | **18** | **20** | **21** | **20** |

**Annex 2.2: Downs & Black checklist scores summary**

| Author + year | Reporting | External validity | Internal validity - bias | Internal validity- confounding (selection bias) | Power | Total Score |
|---|---|---|---|---|---|---|
| (Tamura et al., 2023) | 9 | 2 | 6 | 3 | 0 | 20 |
| (Herb C. et al., 2014) | 9 | 2 | 6 | 2 | 0 | 19 |
| (Watanabe et al., 2022) | 9 | 2 | 6 | 1 | 0 | 18 |
| (Yu et al., 2024) | 9 | 2 | 6 | 3 | 1 | 21 |
| (Deschamps et al., 2016) | 9 | 2 | 6 | 3 | 0 | 20 |
| (Kim et al., 2017) | 9 | 2 | 6 | 3 | 0 | 20 |
| (Deschamps et al., 2018) | 9 | 2 | 6 | 2 | 0 | 19 |
| (De Ridder et al., 2013) | 9 | 2 | 6 | 2 | 0 | 19 |
| (Lilley et al., 2018) | 9 | 2 | 6 | 1 | 0 | 18 |
| (De Ridder et al., 2015) | 9 | 2 | 6 | 2 | 0 | 19 |
| (Deltour et al., 2019) | 9 | 2 | 6 | 3 | 0 | 20 |
| (Herb et al., 2024) | 9 | 2 | 6 | 2 | 0 | 19 |

**Annex 3: Study Characteristics**

| **Author, year of publication** | Type of study | Downs&Black Score (/28) | Sample size (Male:Female genders)<br>Age: mean ± SD (year) | Characteristics |
|---|---|---|---|---|
| **(Tamura et al., 2023)** | Case control | 20 | N=22 (22:0)<br><br>CAI: n=12<br>Age: 20.6 ± 0.9<br><br>Control n=10<br>Age: 29.3 ± 0.9 | Inclusion criteria:<br>-male college soccer player<br>-Preferred kicking is the right leg<br>-Soccer experience of >6 years<br>-Age ≥18 years<br>-Absence of current pain in the lower extremities and lumbar region during daily activities and soccer practice<br>Cumberland Ankle Instability Tool (CAIT) scores: CAI ≤27; Control ≥ 28<br><br>Modalities: running five laps at a self-selected and comfortable speed on a 30-m runway on hard carpet |
| **(Herb C. et al., 2013)** | Case control | 19 | N=28 (14:14)<br>CAI n=13<br>Age: 26.9 ± 6.8;<br><br>Control n=15<br>Age: 23.6 ± 4.7 | Inclusion criteria :<br>all subjects: min 3 moderate or vigorous physical activities per week<br>Foot and Ankle Ability Measure Sport sub-scale (FAAM-Sport) scores: CAI<80%<br><br>Modalities:3 times 15second recordings on treadmill at 9.66 km/h, |

| | | | | |
|---|---|---|---|---|
| **(Watanabe et al., 2022)** | Cross-sectional | 18 | N=35 (35:0)<br>CAI n=13<br>Age: 21.0 ±1.3;<br><br>Coper n=12<br>Age: 20.2 ±0.8;<br><br>Control n=10<br>Age: 20.8 ±1.7) | Inclusion criteria :<br>active males aged 18-24yrs<br>- Cumberland Ankle Instability Tool (CAIT) scores:<br>Coper ≥ 28; CAI <24; Control =30;<br>- Identification of Functional Ankle Instability (IdFAI) scores:<br>Coper ≤10; CAI >11; Control =0<br><br>Modalities: . 100 total barefoot strides were collected on a treadmill at a given speed (3.5 m/s) |
| **(Yu et al., 2024)** | Case control | 20 | N= 66 (66:0)<br>CAI n= 22<br>Age: 22.59 ± 1.92;<br><br>Coper n= 22<br>Age: 22.45 ± 2.02<br><br>Control n= 22<br>Age: 23.50 ± 2.50 | Inclusion criteria :<br>males only<br>- Cumberland Ankle Instability Tool scores:<br>Coper 25-28; CAI ≤24; Control ≥ 28<br><br>Modalities: at self-selected speed, step onto a force plate with the involved limb and with the other limb to step out in a 45◦ direction |
| **(Deschamps et al., 2016)** | Cross-sectional | 21 | N=27 (10:17)<br>CAI n= 15,<br>Age: 22 ± 2.7<br><br>Control n=12<br>Age: 23.6 ± 4.1 | Inclusion criteria :<br>All subjects did at least 1.5h of cardiovascular activity per week<br>-Cumberland Ankle Instability Tool scores:<br>CAI ≤24; Control >24<br><br>Modalities: running on a 10m-runway at 11,8 km/h |

| | | | | |
|---|---|---|---|---|
| **(Kim et al., 2017)** | Case control | 20 | N=21 (0:21)<br>CAI n= 12<br>Age : 26 ± 2.4<br><br>Control n=9<br>Age: 27 ± 2.5 | Inclusion criteria :<br>korean elite women field hockey players<br>- Cumberland Ankle Instability Tool scores:<br>CAI ≤24; Control >24<br><br>Modalities: walk barefoot 10m at their comfortable normal walking speed and then to run at 7 km/h on a treadmill. |
| **(Deschamps et al., 2018)** | Case control | 20 | *identical to (Deschamps et al., 2016)* | *see (Deschamps et al. 2016)*<br><br>Modalities: run barefoot with a midfoot striking pattern on a treadmill at 3.3m/s. Participants had 3 test trials |
| **(De Ridder et al., 2013)** | Case control | 20 | N=77 (37:40)<br>CAI n= 29<br>Age: 21.9 ± 3.3<br><br>Coper n=24<br>Age: 20.3 ± 1.9<br><br>Control n=24<br>Age: 25.8 ± 1.9 | Inclusion criteria :<br>Control had no history of lower leg injury in the last 2yrs<br>Copers had an ankle sprain in the last 2 yrs but not experiencing ankle instability<br>All subjects did at leats 1.5hrs of c-v activity<br>Foot and Ankle Disability Index (FADI) and its sport subscale (FADI-S) for baseline functionality assessment<br><br>Modalities: speed of 3.5 m/s. The starting position for running was 10 meters before the force plate. familiarization via at least three practice trials. The actual test was repeated until three usable trials were captured |
| **(Lilley et al., 2018)** | Case control | 18 | N= 27 (8:19)<br>CAI n= 13<br>Age: 23.8 ± 5.1<br><br>Control n= 14<br>Age: 21.8 ± 2.3 | Inclusion criteria :<br>all participants were between 18 and 40 years old and active at least 3times per week<br>- Foot and Ankle Ability Measure Sport sub-scale (FAAM-Sport) scores:<br>CAI <85%; Control = 100%<br><br>Modalities: 4-minute familiarization period before recording three 15-second clips on a treadmill at 2.68 m/s |

| | | | | |
|---|---|---|---|---|
| **(De Ridder et al., 2015)** | Cross-sectional | 20 | N= 96 (45:51)<br>CAI n= 38<br>Age: 22.1 ± 3.4<br><br>Coper n= 28<br>Age: 20.3 ± 1.9<br><br>Control n=30<br>Age: 25.7 ± 1.8 | Inclusion criteria :<br>All subjects had to do at least 1.5h of cardiovascular activity per week<br>Copers: history of ankle sprain in the last 2 years, but no characteristics of CAI<br>Control: no lower leg injury in the last 2 years,<br><br>Modalities: Landing required the foot to be positioned perpendicular to the direction of movement to prevent compensation from external foot rotation. Jumps were excluded if any post-landing corrections were necessary, and each participant completed the task three times. |
| **(Deltour et al., 2019)** | Case control | 21 | N=27 (10:16)<br>CAI n= 15<br>Age: 22 ± 2.7<br><br>Control n=12<br>Age: 23.6 ± 4.1 | Inclusion criteria :<br>All subjects did at leats 1.5h of cardiovascular activity per week<br>Cumberland Ankle Instability Scores :<br>CAI ≤24; Control >24;<br><br>Modalities: barefoot run with a heel strike pattern at a constant speed of 3.3 m s− on a 10m laboratory-walkway |
| **(Herb et al., 2024)** | Case control | 20 | N= 39 (15:24)<br>CAI n= 20<br>Age: 24.7 ± 5.9<br><br>Control n= 19<br>Age: 23.1 ± 3.8 | Inclusion and exclusion based on the Internation Ankle Consortium only<br><br>Modalities: . Following the warm-up (3-4minutes), they jogged at a self-selected pace for 3–4 min, then speed was increased on the treadmill to 9.66 km/h. During jogging, 3-fifteen second clips were recorded for analysis |

**Annexe 4: Study Results**

| Author, year of publication | Dynamic Task | MSFM | Outcomes | Results |
|---|---|---|---|---|
| **(Tamura et al., 2023)** | Running: Stance phase | Oxford (Tibia (TB), Hindfoot (HF), Forefoot (FF), hallux (hx)) | **SPM:**<br>Hip & knee angles<br>Ground Reaction Force (GRF)<br>Varus,<br>Internal Rotation,<br>Ankle Dorsi Flexion,<br>HFTBA(HF vs TB) DorsiFlexion,<br>HFTBA Inversion,<br>FFHFA (FF vs HF) dorsiflexion<br>FFHFA Inversion | greater knee stiffness in the frontal plane<br>other outcomes: no other significant differences |
| **(Herb C. et al., 2013)** | Jogging | Oxford | **SPM:**<br>**Shank-rearfoot joint:**<br>VCV, ratio, and magnitude of coupled motion (inversion/eversion to internal/external rotation) | CAI group had significantly lower coupling angles during the early-stance phase (Control = 60.3 ± 4.1°, CAI = 47.2 ± 3.5°), midswing phase (Control = 51.3 ± 2.2°, CAI = 39.4 ± 2.3°), and late-swing phase (61.8 ± 2.3°, CAI = 52.8 ± 3.6°)<br>other outcomes: no other significant differences |

| | | | | |
|---|---|---|---|---|
| **(Watanabe et al., 2022)** | Running: Stance phase | Rizzoli (Rearfoot, midfoot, forefoot and shank) | rearfoot with respect to the shank (RF-SH),<br>midfoot with respect to the rearfoot (Chopart) and<br>forefoot with respect to the midfoot (Lisfranc):<br>plantarflexion/dorsiflexion,<br>eversion/inversion,<br>and abduction/adduction | In the frontal plane:<br>Chopart had significantly longer rearfoot inversion during late stance in Coper than CAI (coper=23.9 ± 7.7 %, CAI=51 ± 8.8 %)<br>During the late stance coper showed a significantly higher proportion of Chopart inversion and greater chopart angular amplitude, than the CAI group (coper=54 ± 7.7 %, CAI=27 ± 5.3 %,<br>During the early stance, Coper showed a significantly lower proportion of Chopart eversion and greater Lisfranc angular amplitude, than CAI (coper=5.4 ± 2.2 %, CAI=12.7 ± 2.7 %,<br>-Lisfranc showed greater inversion in CAI<br><br>other outcomes: no other significant differences |

| | | | | |
|---|---|---|---|---|
| **(Yu et al., 2024)** | Cutting: Stance phase | 5segments 8DOF (degree of flexion) 1 DOF at ankle joint which; 1 DOF at subtalar joint; 2 DOF at the chopart joint, 2 DOF at the tarsometatarsal joint; and 2 DOF at the metatarsophalangeal (MTP) joint (mainly focused on the 1st and 2nd MTP joints), | **SPM:** Joint Angles and Joint Moments for: **ankle joint:** plantarflexion and dorsiflexion; **subtalar joint:** eversion-inversion; **Chopart:** eversion-abduction-extension/inversion-adduction-flexion; **Lisfranc**: flexion-eversion/extension-eversion; **MTP:** plantarflexion/dorsiflexion and abduction/adduction | differences only existed in the subtalar joint, copers presented more eversion angles compared to CAI from 5–100% of the stance phase and had greater eversion angles compared to the control group during 81–100% of the stance phase<br><br>other outcomes: no other significant differences |

| | | | | |
|---|---|---|---|---|
| **(Deschamps et al., 2016)** | Running | Rizzoli (shank (Sha), calcaneus (Cal), midfoot (Mid), metatarsus (Met), hallux. The sagittal plane angle of the hallux (F2Ps). Shank-foot) | **GRF**<br>**SPM analysis for:**<br>**Footprogression angle Int/Ext**<br>**F2Ps:**<br>Dorsiflexion/plantarflexion angle<br>For the **Shank-Foot, Chopart, Lisfranc joints and Cal-Met**:<br>Dorsiflexion/plantarflexion<br>Inversion/Eversion<br>adduction/abduction | At the talocrural angle, a significantly decreased dorsiflexion angle from 6 to 8% and a significantly increased inversion angle from 99 to 100% of the running cycle was observed in the CAI Barefoot group compared to the control group<br>CAI barefoot showed significantly more internal rotation from 34-36% in the foot progression angle<br>At the Shank-Calcaneus angle, from 38–41% the CAI Barefoot group showed more adduction in the calcaneus.<br><br>other outcomes: no other significant differences |
| **(Kim et al., 2017)** | Running: Early stance phase | 15 marker model (Cleveland based) | Joint angular displacements were calculated for the ankle joints in the frontal planes during heelstrike, midstance and toetouch: inversion/eversion | CAI show less ankle eversion compared to control at heel strike contact and midstance during running<br>significantly more ankle inversion after 6-week neuromuscular training<br>a 24 week follow up showed that the obtained changes from the training were restored (heelstrike and midstance) |
| **(Deschamps et al., 2018)** | Running: Stance phase | Rizzoli (Shank and calcaneus (Sha-Cal), calcaneus and midfoot (Cal-Mid), midfoot and metatarsus (Mid-Met) and at last calcaneus and metatarsus (Cal-Met) hallux) and the medial longitudinal arch (MLA)) | **joint rotations in all three planes :**<br>Sha-Cal, Cal-Mid, Mid-Met, Cal-Met<br>**sagittal plane:**<br>dorsiflexion/plantarflexion,<br>**frontal plane:** inversion/eversion<br>**transverse plane:**<br>adduction/abduction<br>**The planar angle of the hallux;**<br>**medial longitudinal arch (MLA);**<br>**Sha-Foo kinematics (RoM)**<br>**foot progression angle**<br>**SPM:**<br>joint rotations and planar angle | CAI-BF(barefoot) vs control:<br>During the peak impact phase Chopart showed significantly less dorsiflexion from 6-12% in CAI-barefoot(7.2 vs 4,5)<br>during the absorption phase: CAI had increased sagital plane ROM at shank-foot joint (CAI-BF 12.4°, CTRL 10.1°), the shank.calcaneus joint (CAI-BF 9.5°, CTRL 7.6) and increased transverse ROM at the Shank-calcaneus (CAI-BF 3.8°, CTRL 2.2) during generation phase, CAI-BF had significantly more frontal-plane ROM at the Chopart joint. At 25-28% less plantar flexion at the Shank-foot joint for CAI-BF<br>more adduction at Sha-foo between 35-42% and 55-57% in CAI-bf<br>more adduction in Sha-Cal for 36-41%<br><br>other outcomes: no other significant differences |

| | | | | |
|---|---|---|---|---|
| **(De Ridder et al., 2013)** | Running: Stance phase | Ghent (shank, rear foot, midfoot, medial forefoot, lateral forefoot, and hallux) | **SPM for Joint angles:** Rigid foot and Ghent segments(plantarflexion/dorsiflexion (sagittal plane), inversion/eversion (frontal plane), and abduction/adduction (transversal plane) | rigid foot in relation to the shank:<br>Running:<br>significantly greater eversion of the rear foot in CAI, from 56% to 73% of the stance phase (average difference of 2.72°) and in the coper group, from 29% to 86% (average difference of 3.47°)<br>no significant difference during walking<br>Medial forefoot (in relation to the midfoot):<br>running:<br>CAI showed significantly more inversion (vs control) from 56% to 91% (average difference of 9.81°) during running. During this significant period, the medial forefoot everted until maximal before supinating at the end of stance phase. Coper showed significantly more inversion compared to control from 28% to 30% of the stance phase in running (average difference of 8.28°) |
| **(Lilley et al., 2018)** | Jogging | Pohl | **VCV for:** knee sagittal-ankle sagittal, knee sagittal-ankle frontal, hip frontal-ankle sagittal, hip frontal-ankle frontal | Jogging<br>Knee Sagittal-Ankle Sagittal Coupling:<br>Lower VCV in CAI compared to control from 19-26% (mean difference: −0.09 ± 0.06 and 60-80% (mean difference: −0.09 ± 0.08)<br>Knee Sagittal-Ankle Frontal Coupling:<br>Lower VCV in CAI from 20-23% of gait cycle (mean difference: −0.07 ± 0.05,)<br>Hip Frontal-Ankle Sagittal Coupling During Jogging:<br>Significant differences with lower VCV in CAI from 45-4% (mean difference: −0.13 ± 0.04), 51-53% (mean difference: −0.13 ± 0.06) and 61-70% (mean difference: −0.08 ± 0.06)<br>Hip Frontal-Ankle Frontal Coupling:<br>Significantly lower VCV in CAI from 45-49% of gait cycle (mean difference: −0.15 ± 0.08) |

| | | | | |
|---|---|---|---|---|
| **(De Ridder et al., 2015)** | Side-Jump:<br>Impact phase (TD to maxDF) | Ghent<br>(shank, rear foot, midfoot, medial forefoot, lateral forefoot, and hallux) | **SPM for Joint angles:**<br>Rigid foot and Ghent segments(plantarflexion/dorsiflexion (sagittal plane),<br>inversion/eversion (frontal plane),<br>and abduction/adduction (transversal plane)<br>**For all defined joints in all planes**:<br>ROM,<br>peak forces,<br>time to peak force,<br>loading rate (peak force/time to peak force) | **Foot and Rearfoot Position at Touchdown:**<br>Less plantar flexed position in both CAI and coper vs. control (0%-10%)<br>Coper shows less plantar flexed position of the rearfoot from 0-15% of gait cycle<br>**Rearfoot Position at End of Impact Phase:**<br>Coper displayed more dorsiflexed position from 60%-100%<br>**Rearfoot Inversion/Eversion:**<br>CAI showed less inverted position from 0%-55%<br>Rearfoot inverted then everted throughout the impact phase.<br>**Midfoot Position in CAI Group:**<br>More inverted position relative to rearfoot during the entire impact phase (10%-100%) compared to control<br>Initial inversion followed by eversion until the end of the impact phase.<br>**Medial Forefoot Position in Coper Group:**<br>More inverted position relative to midfoot from 55%-100%, with slight eversion compared to control<br><br>CAI showed **less ROM in the single-segment foot** as well as the rearfoot for plantar-/dorsiflexion and ab-/adduction compared to control.<br>Coper displayed a smaller plantar-/dorsiflexion ROM in the lateral forefoot and medial forefoot compared to Control<br>the hallux showed less eversion/inversion ROM for coper compared to CAI<br><br>for the other outcomes: no significant differences |

| | | | | |
|---|---|---|---|---|
| **(Deltour et al., 2019)** | Running: Stance phase | Rizzoli (shank (Sha), calcaneus (Cal), midfoot (Mid), metatarsus (Met), hallux. The sagittal plane angle of the hallux (F2Ps)) | **Joint Couple:**<br>-Sha-Cal Inversion/Eversion with Adduction/Abduction,<br>-Sha-Cal Inversion/Eversion with Cal-Met Dorsiflexion/Plantarflexion,<br>-Sha- Cal Inversion/Eversion with Cal-Met Inversion/Eversion,<br>- Sha-Cal Inversion/Eversion with Cal-Met Adduction/Abduction*.<br>**Comparison in 3 substance phases (Peak impact, absorption, generation):**<br>GRF, ROM | weaker joint coupling in CAI compared to Control, except for the Sha-Cal Inv/Eve with Cal-Met Add/Abd *<br><br>no other significal outcome |
| **(Herb et al., 2024)** | Running | Oxford | **SPM:**<br>frontal, sagittal and transverse-plane kinematics and joint moments of the ankle,<br>GRF in the anterior-posterior, medial-lateral and vertical directions during the stance-phase. | Running<br>in the frontal-plane, CAI group had greater ankle inversion from 20–92% (Mean difference:4.56°)<br>Greater eversion moments at the ankle were found in the CAI group from 95–100% (Mean difference:74.58Nm/kg)<br>CAI showed greater plantar flexion moments from 65–71% of gait (Mean difference:347.38 Nm/kg)<br><br>no other significal outcomes |

**Annex 5: Cumberland Ankle Instability Tool**

| | Left | Right | Score |
|---|---|---|---|
| 1. I have pain in my ankle | | | |
| Never | ☐ | ☐ | 5 |
| During sport | ☐ | ☐ | 4 |
| Running on uneven surfaces | ☐ | ☐ | 3 |
| Running on level surfaces | ☐ | ☐ | 2 |
| Walking on uneven surfaces | ☐ | ☐ | 1 |
| Walking on level surfaces | ☐ | ☐ | 0 |
| 2. My ankle feels unstable | | | |
| Never | ☐ | ☐ | 4 |
| Sometimes during sport (not every time) | ☐ | ☐ | 3 |
| Frequently during sport (every time) | ☐ | ☐ | 2 |
| Sometimes during daily activity | ☐ | ☐ | 1 |
| Frequently during daily activity | ☐ | ☐ | 0 |
| 3. When I make SHARP turns, my ankle feels unstable | | | |
| Never | ☐ | ☐ | 3 |
| Sometimes during running | ☐ | ☐ | 2 |
| Often when running | ☐ | ☐ | 1 |
| When walking | ☐ | ☐ | 0 |
| 4. When going down the stairs, my ankle feels unstable | | | |
| Never | ☐ | ☐ | 3 |
| If I go fast | ☐ | ☐ | 2 |
| Occasionally | ☐ | ☐ | 1 |
| Always | ☐ | ☐ | 0 |
| 5. My ankle feels UNSTABLE when standing on one leg | | | |
| Never | ☐ | ☐ | 2 |
| On the ball of my foot | ☐ | ☐ | 1 |
| With my foot flat | ☐ | ☐ | 0 |
| 6. My ankle feels unstable when | | | |
| Never | ☐ | ☐ | 3 |
| I hop from side to side | ☐ | ☐ | 2 |
| I hop on the spot | ☐ | ☐ | 1 |
| When I jump | ☐ | ☐ | 0 |
| 7. My ankle feels unstable when | | | |
| Never | ☐ | ☐ | 4 |
| I run on uneven surfaces | ☐ | ☐ | 3 |
| I jog on uneven surfaces | ☐ | ☐ | 2 |
| I walk on uneven surfaces | ☐ | ☐ | 1 |
| I walk on a flat surface | ☐ | ☐ | 0 |
| 8.Typically, when I start to roll over (or “twist”) on my ankle, I can stop it | | | |
| Immediately | ☐ | ☐ | 3 |
| Often | ☐ | ☐ | 2 |
| Sometimes | ☐ | ☐ | 1 |
| Never | ☐ | ☐ | 0 |
| I have never rolled over on my ankle | ☐ | ☐ | 3 |
| 9. After a typical incident of my ankle rolling over, my ankle returns to “normal” | | | |
| Almost immediately | ☐ | ☐ | 3 |
| Less than one day | ☐ | ☐ | 2 |
| 1 or 2 days | ☐ | ☐ | 1 |
| More than 2 days | ☐ | ☐ | 0 |
| I have never rolled over on my ankle | ☐ | ☐ | 3 |

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**OBJECTIVE:** To investigate the alterations in movement patterns, specifically kinematics and kinetics, exhibited by individuals with chronic ankle instability (CAI) during various dynamic tasks. The focus is on comparing these kinematics and kinetics in individuals with chronic ankle instability to Copers and healthy subjects, while considering the foot as multi-segmented, particularly during running and other dynamic horizontal tasks.

**METHOD:** A narrative review with a 'systematized' approach was conducted, following PRISMA guidelines and using the Downs and Black checklist for quality assessment. A comprehensive literature search was performed using PICO criteria and keywords related to CAI, kinematics, and kinetics.

**RESULTS:** 12 studies with 465 participants (198 CAI) were analyzed and showed alternated movement patterns in CAI individuals. During running tasks, they showed reduced dorsiflexion, increased inversion angles, greater rearfoot inversion, and shank external rotation compared to healthy controls. For side-cutting tasks, CAI demonstrated decreased dorsiflexion and altered inversion/eversion patterns. Kinetic analyses revealed disrupted force distribution and compensatory mechanisms

**CONCLUSION:** We highlight how chronic ankle instability alters movement patterns during dynamic tasks like running and side cutting. CAI participants show reduced dorsiflexion, increased inversion angles, and impaired neuromuscular control compared to healthy controls and copers. Kinetic analyses reveal disruptions in force distribution and compensatory mechanisms, increasing the risk of recurrent sprains and functional limitations. Detailed assessments using multi-segment foot models are crucial for accurate diagnosis and effective rehabilitation. Addressing the limited ecological validity of current studies is essential for improving treatment strategies and outcomes.

**UNIVERSITÉ CATHOLIQUE DE LOUVAIN**
**Faculté des sciences de la motricité**
Place Pierre de Coubertin, 1 bte L8.10.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/fsm**