Ankle angle variability during running in athletes with chronic ankle instability and copers

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A B S T R A C T

Background: Individuals with chronic ankle instability (CAI) demonstrate altered ankle kinematics during running compared to uninjured individuals; however, little is known about differences between individuals with CAI and those who recover successfully from an index sprain (copers).

Methods: Thirty-two young male athletes with prior ankle sprain were investigated, eighteen with CAI and fourteen copers. Instrumented running analysis was performed on a treadmill at two velocities: moderate (2.63 ± 0.20 m/s, rate of perceived of exertion = 14/20); and high velocity (3.83 ± 0.20 m/s). Mean ankle kinematics and stride-to-stride variability were analyzed applying the statistical parametric mapping method.

Results: At both running velocities, no statistically significant differences in mean ankle kinematics were observed. At high running velocity, athletes with CAI demonstrated significantly increased frontal plane variability at 17–19% of the running gait cycle (p = 0.009). Additionally, large between-group effect sizes (Hedges' g ≥ 0.8) may potentially indicate increased frontal plane variability during initial contact and terminal swing, as well as decreased variability in sagittal plane at 34–35% in CAI. A similar tendency existed at moderate velocity, with large effect sizes indicating decreased dorsiflexion at 75–89% in CAI, as well as an increased frontal plane variability at 16–25%, and 97–99%.

Discussion: Compared to copers, individuals with CAI demonstrate increased variability of ankle kinematics - mainly in the frontal plane and particularly during stance phase - while mean ankle kinematics seems minimally affected. Increased ankle variability at high running velocity may best reflect persisting sensorimotor control deficits in athletes with chronically instable ankles.

1. Introduction

Ankle sprains are among the most common sports injuries [1], with the highest recurrence rate of all lower extremity injuries [2]. Approximately 40%–70% of individuals develop chronic ankle instability (CAI), which is characterized by long term impairments and a high risk of re-injury [2]. Besides mechanical insufficiencies of the joint, the development of CAI has been largely attributed to changes in the sensorimotor system [3].

In this context, the investigation of dynamic movement mechanics (i.e. running) is of high relevance since non-contact ankle sprains are highly prevalent [2]. A cadaver study of simulated gait suggested that inadequate foot positioning during walking or running may represent a possible injury mechanism [4]. While it is plausible that sensorimotor deficits in CAI contribute to changes in running patterns [5], empirical data is scarce [3,6]. The available studies indicate that individuals with CAI exhibit increased plantarflexion during stance [7,8] and swing phase [9], as well as a more inverted ankle during stance [9] and swing [7,10] during running compared to healthy controls. In contrast, Hamacher et al. [11] and Ridder et al. [12] couldn't find any differences in ankle kinematics between individuals with CAI and healthy controls during running. Aside from ankle kinematic patterns, investigating stride-to-stride variability provides important insight into motor control adaptations [13]. Altered variability during walking and running has been demonstrated in CAI compared to uninjured individuals, and has been attributed to disturbed proprioception [11,14–18].

However, while this evidence is derived from comparing individuals with CAI and uninjured controls, studying injured athletes who

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successfully return to preinjury functional levels (copers), may be more conclusive in elucidating mechanisms for developing CAI [19]. Thus, comparing copers to individuals with CAI is suggested to be a stronger approach for drawing clinically relevant conclusions and to understand the development of long-term injury consequences [19]. Compared to healthy individuals, copers demonstrate increased eversion angles in stance phase during walking, but not during running [12,20]. Additionally, no differences in running ankle kinematics were found between persons with CAI and copers [12,21,22]. To obtain a better insight into the potential long-term injury consequences on the sensorimotor system and to draw useful therapy conclusions it is necessary to investigate, if the altered variability is also persistent in copers. However, no data on differences in ankle stride-to-stride variability during running between athletes with CAI and copers exists. Thus, the aim of the present study was to compare frontal and sagittal plane running kinematics and stride-to-stride variability between athletes with CAI and copers. It was hypothesized that athletes with CAI would demonstrate larger stride-to-stride variability but no differences in ankle kinematics compared to copers.

2. Methods

2.1. Participants

Thirty-two male athletes (mostly team sport) were recruited for the study, eighteen with CAI and fourteen copers (Table 1). All participants were male, aged between 18 and 35 years, and conducted at least 2 h of competitive sport per week. In addition, subjects had to report a minimum of one significant ankle sprain according to the definition of Gribble et al. [23], i.e. the sprain i) had occurred at least 12 months prior to the study enrolment, ii) was associated with inflammatory symptoms (e.g. pain or swelling), iii) led to at least one interrupted day of desired physical activity, iv) the most recent injury had occurred more than 3 months prior to the study enrollment. Exclusion criteria were surgery of the lower extremities or acute injury of the lower extremities during the last three months. Participants were classified as having CAI if they met the following criteria [23]: i) at least two episodes of "giving way" prior to the study enrolment and/or ii) two or more sprains to the same ankle and/or iii) self-reported ankle instability using the Cumberland Ankle Instability Tool (CAIT) cutoff < 24. Copers were defined according to the criteria recommended by Wikstrom et al. [19], if they: i) had returned to at least moderate-level weight-bearing physical activities for a minimum of 12 months; ii) presented a minimal level of self-reported disability defined as a score of ≥ 28 in the CAIT or a Foot and Ankle Ability Measure (FAAM) and FAAM- sports subscale (FAAM-S) score not lower than 99% and 97%, respectively. Participants gave written informed consent prior to participation, and the study was approved by the local ethics committee.

Table 1
Subjects' demographics.

	CAI (n = 18) M; [SD]	Coper (n = 14) M; [SD]	p-value
Age (years)	24.7 [3.0]	25.5 [3.7]	0.490
Height (cm)	185.2 [6.5]	183.1 [5.8]	0.353
Weight (kg)	81.2 [10.1]	80.5 [7.6]	0.837
Sport (hrs/week) [*]	4.9 [2.7]	3.9 [1.8]	0.352
# of ankle sprains	2.4 [1.5]	1.4 [0.5]	**0.033**
# of giving way episodes [§]	3.7 [3.8]	0.5 [1.3]	**0.001**
FAAM (%)	94.3 [9.5]	99.3 [1.5]	**0.001**
FAAM-S (%)	84.7 [9.2]	99.2 [1.5]	**< 0.001**
CAIT	21.9 [3.4]	28.1 [1.7]	**< 0.001**

Bold numbers indicate statistical significance (p < 0.05).
   [*] Handball: n = 11; Soccer: n = 12; Others: n = 9; [§]12 month prior to the study; FAAM = Foot and Ankle Ability Measure; FAAM-S = Foot and Ankle Ability Measure Sport; CAIT = Cumberland Ankle Instability Tool.

2.2. Data collection

Running analyses were performed shod on a spilt-belt treadmill (Bertec Corporation, Columbus, USA) with integrated force plates sampling at 1000 Hz. All participants were equipped with the same shoe model in different sizes (Adidas Duramo 6, adidas AG, Herzogenaurach, Germany). Three-dimensional analysis was conducted using an eight-camera motion capture system (Qualisys AB, Gothenburg, Sweden) with 8 Oqus cameras sampling at 200 Hz. To analyze ankle motion, the shank was defined by markers above the medial and lateral femoral epicondyles as well as medial and lateral malleoli [24]. Clusters of four markers were placed laterally on each shank for tracking. Foot markers were placed on the shoes above the first, second and fifth metatarsal heads and on the aspect of the Achilles tendon insertion of the calcaneus. To have a standardized marker placement and because of the difficulty to palpate bony landmarks when wearing shoes, the placement of the heel marker was additionally aligned on the height of shoe sole.

Ankle kinematics were analyzed at two different running velocities (moderate and high), in order to evaluate movement patterns at different levels of physical stress and to better reflect typical physical demands during sport participation. Each participant started the protocol at a velocity of 2.22 m/s. Running velocity was progressively increased by 0.14 m/s every 30 s until the participant reached a moderate rate of perceived of exertion (RPE) using the Borg-Scale (Borg = 14). After reaching the target RPE, participants maintained the velocity for two minutes and the last 60 s were recorded for data analysis (moderate velocity). Subsequently, running velocity was increased by 1.2 m/s. Participants maintained this higher velocity for another 1.5 min and the last 60 s were recorded (high velocity). The running velocity progression was based on pilot trials showing that this was the velocity and duration the participants could reach and sustain.

2.3. Data analysis and statistics

Kinematic data of the ankle were processed and calculated using Visual3D (C-Motion, Germantown, MD, USA), low-pass filtered using a fourth order Butterworth filter with a cut-off frequency of 12 Hz. Ground contact was detected based on a threshold of 80 N on the vertical ground reaction force component. A biomechanical model with two lower body segments (feet and shank) was defined and kinematics were calculated in Visual3D to determine three-dimensional joint angles (Cardan rotational sequence X-Y-Z, representing respectively dorsi-/plantar flexion, eversion/inversion, ab-/adduction). Gait cycles were normalized from 0% to 100% with the first and last point reflecting the initial ground contact. Additionally, the habitual foot strike pattern was quantified by determining the strike index (SI) [25]. Mean ankle kinematics and its intra-individual stride-to-stride standard deviation (running variability) were calculated for each participant for the most affected ankle [11].

The statistical parametric mapping (SPM; version 0.4) method was applied [26] to identify possible differences between the CAI and coper group throughout the entire running gait cycle using MATLAB (R2017a, MathWorks Inc., Natick, MA, USA). Normality of the data were tested before performing the SPM by applying the Shapiro-Wilk statistic. For ankle kinematics, data showed normal distribution. T-tests (SPM {t}) over the normalized time series were used to determine significant group differences involving four steps (for detailed description see De Ridder et al. [12] or http://www.spm1d.org/). For ankle variability, data did not show normal distribution and consequently the non-parametric permutation procedure of the SPM was applied [27]. Additionally, effect sizes were calculated using Hedges' g to interpret group differences, which is recommended as a more meaningful approach in comparative studies [28].

For group demographics, injury data and self-reported ankle function normal distribution was tested using the Shapiro-Wilk test. The

normally distributed data were compared using unpaired *t*-tests. Differences in non-normally distributed data were analyzed using the Mann-Whitney-Test. Analyses were performed in SPSS (Version 23, IBM, Armonk, NY, USA) and the significance level set at p ≤ 0.05.

3. Results

Demographic characteristics, injury data and self-reported ankle function are presented in Table 1. No significant group differences existed for any of the demographic variables. With respect to self-reported ankle function and stability, the CAI group had significantly lower scores in the FAAM (p = 0.001) and the FAAM-S (p < 0.001) as well as in the CAIT (p < 0.001). Running velocities normalized to body size [29] did not significantly differ between groups (moderate: p = 0.074, high: p = 0.101), with 2.68 (± 0.19) m/s for the CAI and 2.54 (± 0.19) m/s for the coper group at moderate running speed, and 3.88 (± 0.19) m/s and 3.74 (± 0.19) m/s at high running speed, respectively. The increase in running velocity was also reflected in the RPE (CAI: 17.1 ± 1.1; Coper: 16.8 ± 1.1) and did not differ significantly between the groups (p = 0.425). Twenty-five of the thirty-two participants could be classified as potential rearfoot runners, whereas seven were mid- or forefoot runners indicated by a negative or positive SI, respectively. All participants with a positive SI were individuals with CAI. In one participant the determination of the SI was not possible due to problems with calculating the center of pressure location, however visual observation revealed a rearfoot strike pattern.

3.1. Ankle kinematics

Ankle kinematics throughout the running gait cycle did not show any statistically significant differences in sagittal (Fig. 1), frontal (supplementary Fig. 1), and transversal plane (supplementary Fig. 2) for either of the two running velocities.

Large between-group effects, potentially indicating clinically meaningful differences, existed only in the sagittal plane with increased plantarflexion at 75–89% of the gait cycle (g = -0.81 – -1.03) during moderate velocity (Fig. 1).

3.2. Stride-to-stride variability of ankle kinematics

Significant group differences existed for inversion/eversion variability at high running velocity, with the CAI group demonstrating increased variability at 17–19% of the gait cycle (p = 0.009).

Additionally, large effect sizes indicated several potential clinically relevant group differences. In sagittal plane (Fig. 2), the CAI group demonstrated decreased intra-individual plantar-/dorsiflexion variability during the high velocity, indicated by large between-group effect sizes at 34–35% (g = -0.82 – -0.88) of the gait cycle.

In frontal plane (Fig. 3), inversion/eversion variability was higher in athletes with CAI at 16–25% (g = 0.82–1.08), and 97–99% (g = 0.85 – 0.90) of the gait cycle during moderate velocity. During high velocity, large between-group effects indicated a higher variability in the CAI group at 0% (g = 0.82), 10–27% (g = 0.82–1.24), and 92–100% (g = 0.81 – 0.98). No group differences existed in the transversal plane (supplementary Fig. 3).

4. Discussion

The aim of this study was to compare ankle kinematics and its variability between athletes with CAI and copers. Based on the results of the SPM analyses no differences in ankle kinematics, but in intra-individual stride-to-stride variability existed between groups. Individuals with CAI exhibited a significantly higher variability in frontal plane during stance at high running velocity. Furthermore, large between-group effect sizes suggested potential clinically relevant differences that should receive further attention in future studies. First, a
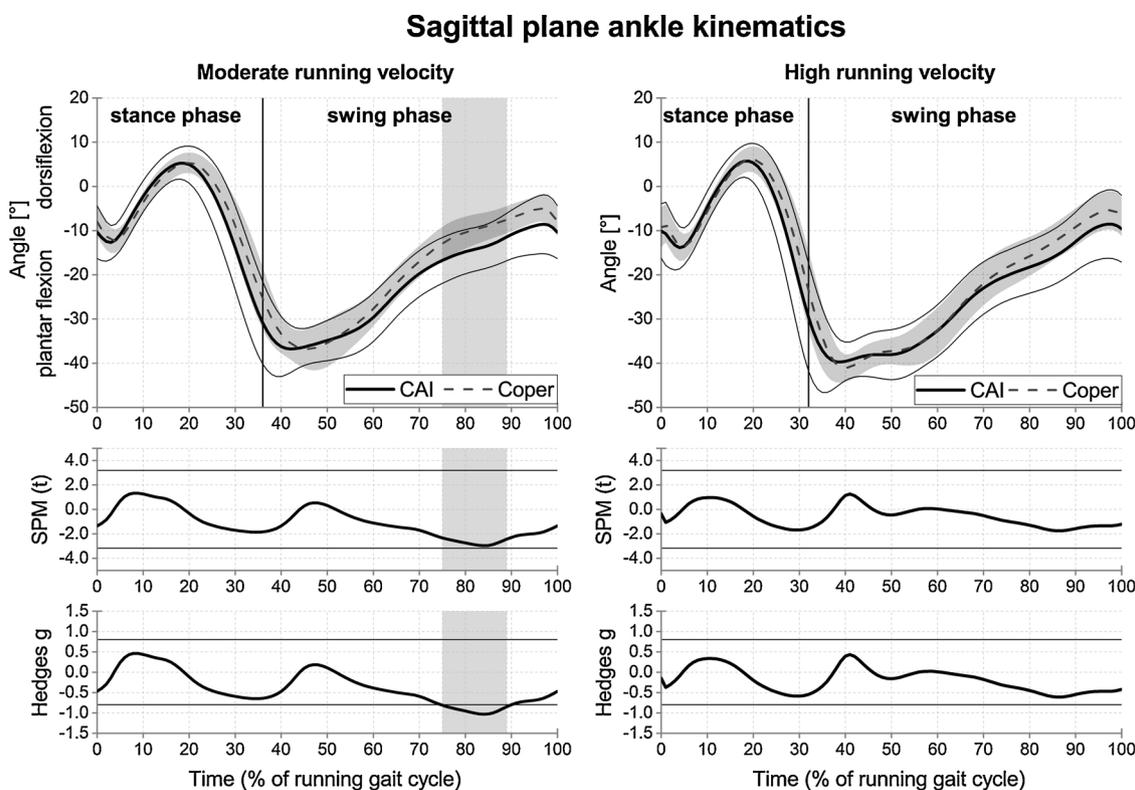
Sagittal plane ankle kinematics

Fig. 1. Mean sagittal plane ankle kinematics with standard deviation at moderate (left column) and high running velocity (right column) with effect size Hedges'g and the results of the statistical parametric mapping method (SPM) in athletes with chronic ankle instability (CAI) and those who developed no chronic conditions after an initial ankle sprain (copers).

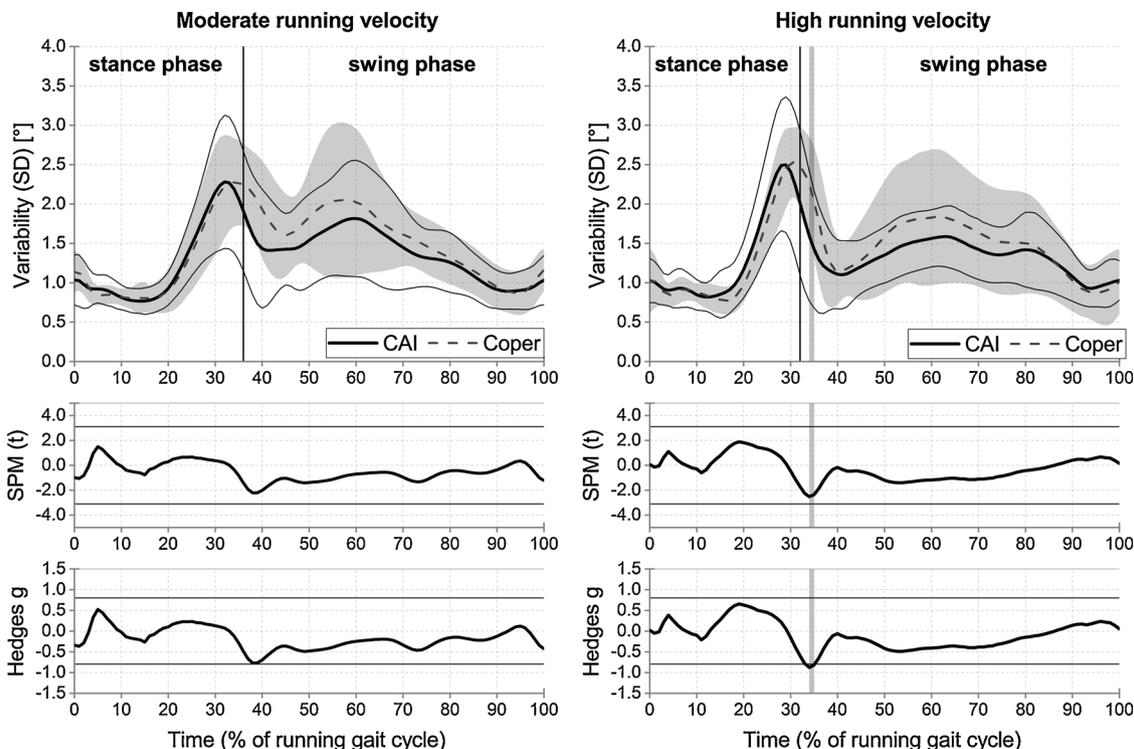## Sagittal plane ankle stride-to-stride variability

Fig. 2. Mean sagittal plane ankle motion variability (stride-to-stride variability) with standard deviation at moderate (left column) and high running velocity (right column) with effect size Hedges'g and the results of the statistical parametric mapping method (SPM) in athletes with chronic ankle instability (CAI) and those who developed no chronic conditions after an initial ankle sprain (copers).

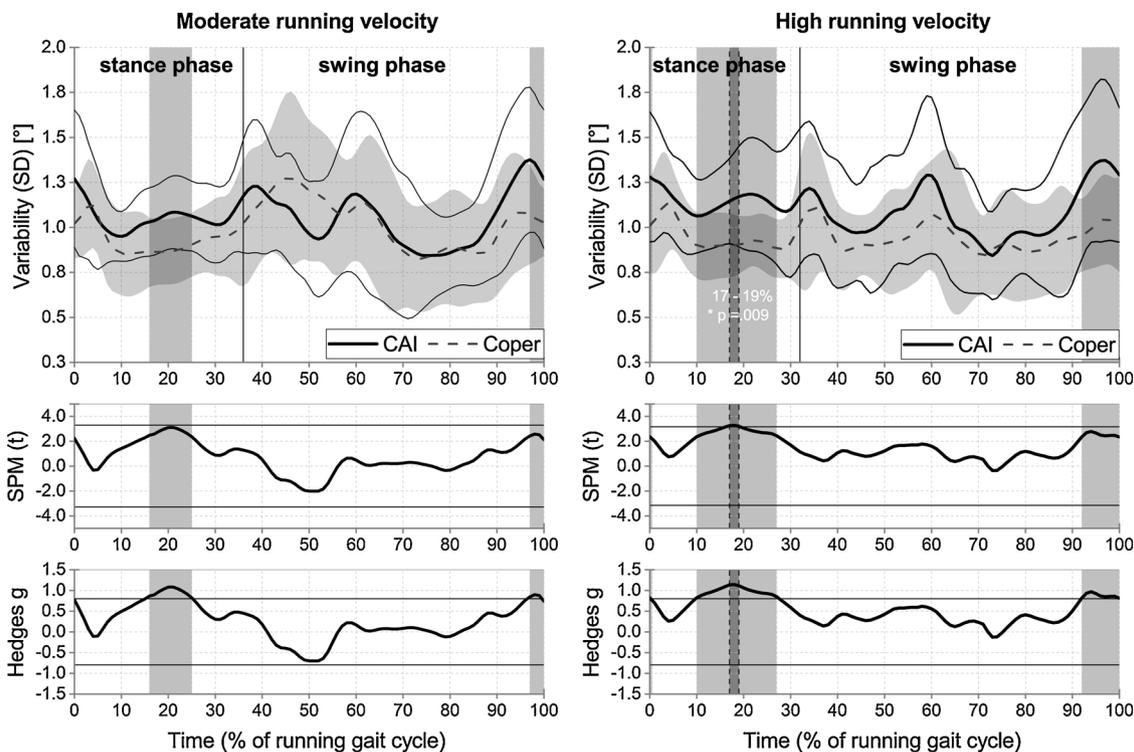## Frontal plane ankle stride-to-stride variability

Fig. 3. Mean frontal plane ankle motion variability (stride-to-stride variability) with standard deviation at moderate (left column) and high running velocity (right column) with effect size Hedges'g and the results of the statistical parametric mapping method (SPM) in athletes with chronic ankle instability (CAI) and those who developed no chronic conditions after an initial ankle sprain (copers).

decreased dorsiflexion during swing phase in the CAI group existed during moderate velocity. In frontal plane, variability during terminal swing phase was higher in athletes with CAI compared to copers during both velocities. Conversely, the CAI group demonstrated lower plantar-/dorsiflexion variability during initial swing at high velocity.

4.1. Ankle kinematics

In the present sample, results were mostly in line with previous research, showing no differences in running ankle kinematics between CAI and copers [12,20–22]. Large between-group effect sizes indicated only the tendency for an increased plantarflexion in swing phase during moderate running velocity.

When considering evidence from studies comparing CAI individuals to healthy controls, the results showed decreased dorsiflexion during stance [7,8] as well as increased plantarflexion during swing phase in CAI [9]. A cadaver study simulating gait showed that swing-phase collision (involuntary collision of the foot with the ground that leads to a progression from an unloaded to a loaded condition of the ankle) could lead to an increased risk of ankle sprain [4]. Further, Brown et al. [22] reported a lower minimum metatarsal height as a measure of ground clearance 250 ms pre-heel strike in persons with CAI compared to copers. Although they did not observe differences in plantarflexion, the large between-group effects seen in the present study may suggest a possible injury mechanism in the CAI group. An increased plantarflexion could result in a reduced foot-ground distance and contribute to a higher risk of swing phase collision. On the other hand, this pattern may indicate a coping strategy of the coper group to avoid swing phase collision due to inadequate dorsiflexion. However, due to the lack of statistically significant differences and the missing consistency with previous studies this interpretation remains highly speculative and further studies have to investigate, if these findings can be generalized in larger scaled studies.

4.2. Intra-individual variability of ankle kinematics

High levels of intra-individual variability in repetitive movements (e.g. running) under constant conditions are often interpreted to be pathologic due to deficient sensorimotor control [30]. A recent review reported increased variability during repetitive movements in persons with a lower limb musculoskeletal injury [31]. Altered gait or running variability of the ankle could already be seen in persons who developed CAI compared to healthy individuals [11,14–18]. All authors discussed that altered proprioception in CAI may explain the altered variability that may lead to inconsistent movement pattern.

Whilst there was no difference in frontal plane ankle kinematics in the present study, the CAI group showed a significantly increased frontal plane ankle variability at stance during the high running velocity. These findings support the results by Hamacher and colleagues [11] who applied the same method to assess variability differences in individuals with CAI and healthy controls. The higher variability during stance may indicate a limited stability of the ankle and consequently an altered sensorimotor control. It has been suggested that the inconsistent movement pattern is caused by altered neuromuscular recruitment [18]. Hamacher et al. [11] hypothesized that the recurrent ankle sprains in CAI could be causal to the instable running pattern (higher variability) that might mediate the effect of altered proprioception on recurrent giving-way episodes or spraining. In other words, the higher frontal plane ankle variability during stance may explain the recurrent episodes of giving ways and feelings of instability in CAI. Remarkably, during moderate running velocity athletes with CAI showed a less pronounced tendency for increased fontal plane variability during stance, whereas during high velocity, this difference became statistically significant. Even if this remains speculative, the more pronounced results during situation with maximal stress (high velocity) compared to situations with sub-maximal stress (moderate velocity), may indicate

poor adaptability of the sensorimotor system particularly under higher demands in athletes with CAI [30].

In addition to the increased variability during stance phase, Hamacher et al. [11] reported a higher frontal plane ankle variability during swing phase in individuals with CAI compared to healthy controls. Although the results in the current study were not statistically significant, a similar tendency for increased frontal plane ankle variability during terminal swing existed, supporting these results at least partly. The cadaver study by Konradsen and Voigt [4] showed that particularly swing-phase collision could lead to an increased risk of ankle sprain. Hamacher et al. [11] postulated that a collision of the lateral foot and the ground that leads to an inversion and plantarflexion in late swing phase is more likely in persons with CAI due to the increased variability. Furthermore, large between-group effect sizes in the present data indicated a tendency for increased frontal plane variability at heel-strike in the CAI group during high velocity. One could speculate that this may consequently increases the chances of improper foot positioning, thereby placing the ankle in an injury-prone situation, which however could not be confirmed by the cadaver study by Konradsen and Voigt [4].

Further, it has been suggested that not only increased but also decreased variability may be associated with pathological sensorimotor control and that an optimal state of variability is necessary for healthy and functional movement [32]. In the present study, a trend for decreased variability in the CAI group during initial-swing compared to copers in sagittal plane during high running velocity could be observed. In a study examining phase-dependent gait variability, it was shown that foot kinematic variability is relatively high in the initial-swing phase since the variability is not relevant to avoid swing phase collision in this phase [30]. The decreased variability of the CAI group in this phase may indicate a constrained sensorimotor system, which is less adaptable to environmental change. This has also been suggested in previous studies which have found decreased stride-to-stride variability during walking and running in CAI compared to healthy controls [14–17], and may contribute to the long-term consequences of CAI. However, since the effects seen in the current data lack statistical significance, this remains speculative.

5. Limitations

A major limitation of the present study is the relatively small sample size and the resulting limited statistical power. Consequently, the conservative p-value adjustment of the statistical parametric mapping approach [26] may have led to the lack of significant between-group findings. As a consequence, effect sizes were calculated to detect group differences with potential clinical relevance, which is recommended as a more meaningful approach in comparative studies [28]. However, small samples can lead to an overestimation of effects and may have a low reproducibility [33]. Hence, the present results need to be interpreted with caution.

Furthermore, only male athletes were included to have a more homogenous sample in this pilot study. Consequently, inferences on females cannot be drawn from the present data. Additionally, including potential habitual forefoot and midfoot runners could have influenced the results and the internal validity. It has been reported that ankle kinematics in sagittal and frontal plane can differ between forefoot, midfoot and rearfoot strikers during running [34]. However, a sub-analysis considering only rearfoot strikers (negative SI, n = 22) revealed similar results. A further limitation of this study is the use of a rigid-foot model. This model may have hidden differences in more distal joints of the foot, and a multi-segmented foot model, including more markers, would have provided the possibility of a more differentiated insight in the ankle/foot complex [11,12]. However, for reasons of ecological validity (i.e. habitual shod running in sports activities), and since the high impact forces when running barefoot have shown to change the running pattern [35], all running analyses were

performed shod. Thus, comparisons to studies positioning the markers directly on the skin have to be made with caution [36]. Lastly, the utilization of a standardized shoe model may not have reflected individual shoe habits in all participants (e.g. minimalist vs. maximalist shoes), thereby potentially affecting their running kinematics.

6. Conclusion

In the present study, differences in ankle kinematics between athletes with CAI and copers appeared to be minimal, whereas stride-to-stride variability in frontal plane during stance was significantly higher in CAI. This may indicate abnormal sensorimotor control in CAI, could explain feelings of giving way, and might present a potential re-injury risk factor. Additionally, large between-group effect sizes suggested potential differences in running variability between CAI and copers, particularly at high running velocity. This may indicate poor adaptability of the sensorimotor system particularly under higher demands in athletes with CAI and requires further attention and confirmation in larger scaled studies. Overall, the present findings emphasize the need for further studies comparing ankle kinematics and variability between CAI and copers.

Conflict of interest statement

None.

Ethical approval

Ethics committee of the Friedrich-Alexander-University Erlangen-Nürnberg (Re.-No. 4335)

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