

Multi-segment foot landing kinematics in subjects with chronic ankle instability

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Abstract

Background: Chronic ankle instability has been associated with altered joint kinematics at the ankle, knee and hip. However, no studies have investigated possible kinematic deviations at more distal segments of the foot. The purpose of this study was to evaluate if subjects with ankle instability and copers show altered foot and ankle kinematics and altered kinetics during a landing task when compared to controls. **Methods:** 96 subjects (38 subjects with chronic ankle instability, 28 copers and 30 controls) performed a vertical drop and side jump task. Foot kinematics were obtained using the Ghent Foot Model and a single segment foot model. Group differences were evaluated using Statistical Parametric Mapping and analysis of variance. **Results:** Subjects with ankle instability had a more inverted midfoot position in relation to the rearfoot when compared to controls during the side jump. They also had a greater midfoot inversion/eversion range of motion than copers during the vertical drop. Copers exhibited less plantar flexion/dorsiflexion range of motion in the lateral and medial forefoot. Furthermore, the ankle instability and copers group exhibited less ankle plantar flexion at touch down. Additionally, the ankle instability group demonstrated a decreased plantar flexion/dorsiflexion range of motion at the ankle compared to the control group. Analysis of ground reaction forces showed a higher vertical peak and loading rate during the vertical drop in subjects with ankle instability. **Interpretation:** Subjects with chronic ankle instability displayed an altered, stiffer kinematic landing strategy and related alterations in landing kinetics, which might predispose them for episodes of giving way and actual ankle sprains.

Keywords: ankle instability, 3D kinematics, foot segments, impact phase.

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1. Introduction

Ankle sprains are one of the most frequently observed sport injuries, representing between 10-30% of all registered musculoskeletal injuries [1]. In 80% of the cases the sprain involves an inversion trauma with damage to the lateral ligaments [1]. In the United States, up to 27,000 ankle sprains occur daily [2]. As a consequence of sustaining an initial ankle sprain, many patients experience residual symptoms such as pain, swelling, and even re-sprains. Moreover, up to 53% of all patients report a residual condition described as chronic ankle instability (CAI) [3]. CAI has been defined as the repetitive occurrence of instability, resulting in numerous ankle sprains [4]. In view of the high incidence, the impact on sports participation [5;6], and long term degenerative consequences [7], it is necessary for clinicians to gain a better understanding of the underlying mechanisms.

Ankle sprains often occur during activities which involve jumping, landing and turning, e.g. during sports such as basketball, volleyball and soccer [8]. Inadequate joint control during landing in particular might be a key factor as biomechanical research indicates that ankle joint kinematics can reveal detriments in the capacity to modify and control the high loading associated with landing [9]. Differences in the timing and magnitude of ground reaction forces (GRF) between subjects with CAI and controls have also been reported [10;11]. In addition, research on landing kinematics in subjects with CAI revealed several kinematic differences not only at the level of the ankle, but also at more proximal joints, i.e. the knee and the hip [10;12;13]. For the ankle joint, a more inverted position of the ankle has been shown during the postlanding phase of a stop-jump landing task [14] and during the pre- and postlanding phase of lateral hop [15], as well as a greater ankle dorsiflexion prior to and post landing in a single leg jump [12]. Notwithstanding some conflicting results, possibly caused

by the different tasks observed, the observation of lower limb joint kinematics may well offer a window into the underlying mechanisms of CAI.

Although current research has focused on kinematics at the ankle and more proximal joints in subjects with CAI, to the author's knowledge no studies have investigated the kinematic adaptations during landing distal to the ankle, i.e. at the foot. Previous research during landing has modeled the foot as one rigid segment. This assumption ignores the functional anatomy of the ankle-foot complex, yet mid- and forefoot characteristics have been acknowledged to potentially play a role in the mechanism of an ankle sprain [16]. In addition, rearfoot and medial forefoot kinematics have been shown to differ between subjects with CAI and healthy controls during gait [17]. Insight in foot function during landing tasks could therefore be enhanced by the use of multi-segment foot models [18]. Moreover, with the forefoot being first in contact with ground during landing, differences in foot segment kinematics may also influence the ankle and more proximal joints in the kinetic chain. Multi-segment foot kinematics might also reveal impaired force dissipation strategies at touch down, which could put a subject with CAI at increased risk for re-spraining their ankle.

The goal of this study was to identify differences in ankle and multi-segment foot kinematics during the impact phase of a landing task in subjects with CAI compared to a control group. In addition, single segment foot kinematics were also calculated to allow comparison of results with existing literature. To further understand the CAI mechanism, we also included a copers group who had previously sustained an ankle sprain but had not experienced any negative effects following their rehabilitation, and had since returned to their pre-injury sporting level. For this copers group, subjects with a recent ankle sprain were chosen with the aim of identifying active coping strategies in the period during which an individual is most

susceptible to sustain a resprain. For some reason these subjects had not developed a chronic condition as of yet and therefore were interesting to consider as a separate group. Based on the ankle sprain mechanism, a more inverted ankle joint position was hypothesized in subjects with CAI. Furthermore, based on previous multi-segment foot research [17], a more inverted medial forefoot was expected in subjects with CAI. Vertical ground reaction force (GRF) patterns were also evaluated to reveal whether peak force and loading rate were altered.

2. Methods

2.1. Subjects

A total of 96 participants took part in this study (table 1). Thirty-eight subjects with CAI (19 males and 19 females, 5 (SD 3) months to last sprain, 10 (SD 13) sprains annually), 28 copers (14 males and 14 females, 11 (SD 5) months to last sprain) and 30 controls (12 males and 18 females) were recruited. All subjects in the CAI group met the following inclusion criteria: (1) a history of at least one ankle sprain which resulted in pain, swelling, and stiffness prohibiting participation in sport, recreational or other activities for at least three weeks; (2) repeated ankle sprains; (3) presence of giving way; (4) a feeling of weakness around the ankle, and (5) a decreased functional participation (recreational, competitive or professionally) as a result of the ankle sprains. The copers were defined as subjects with a history of an ankle sprain in the last two years, but who had no characteristics of CAI. Subjects in the control group had no lower leg injuries in the past two years. All subjects had to perform at least 1.5 hours of cardiovascular activity per week. Exclusion criteria were a history of ankle fracture or surgery, lower limb pain at the time of testing, an ankle sprain in

the last 3 months, and equilibrium deficits. This study was approved by the local ethics committee and all subjects signed the informed consent.

2.2 Experimental procedure

Baseline characteristics were registered for all subjects. The Foot and Ankle Disability Index (FADI) and its sport subscale (FADI-S) were completed by all participants to assess the disability of the ankle during daily living [19]. Group characteristics are summarised in table 1.

All subjects performed two landing tasks. First, subjects carried out a single leg vertical drop from a 40cm high box. They were instructed not to jump, but rather to step down and to maintain balance for three seconds, starting out on the opposite leg to control drop height and land onto the force plate. Hands had to be kept on the hips throughout the whole trial and subjects were asked to look straight forward. Trials were discarded if the subject jumped from the box, if the foot shifted after landing, if hands were used to restore balance, if there was contact between both legs in an attempt to keep balance, or if the contralateral foot touched the ground. Each subject performed 3 vertical drops. Second, after 5min rest, subjects performed a maximal side jump. They started in a single leg stance on their contralateral foot, were asked to push off and jump maximally sideways and land with their tested leg on the force plate. The foot position upon landing had to be perpendicular to the line of movement to eliminate compensation by external rotation of the foot. A jump was discarded if the subject required any corrections following landing as described above. Each subject performed 3 side jumps. Subjects were permitted a period of practice prior to testing.

All subjects were barefooted during testing and none complained of any discomfort during the functional tasks. In the CAI group, the most unstable ankle based on the subject's medical history, was investigated. For the copers, the ankle sprained most recently was selected. And in the control group the tested ankle was chosen randomly.

Spherical reflective surface markers (7mm) were placed on anatomical landmarks according to the Ghent Foot Model. This six-segment model tracked the shank, rear foot, midfoot, medial and lateral forefoot, and the hallux as individual functional segments. The single segment foot was defined by markers on the calcaneus, the lateral malleolus, and the head of the first and fifth metatarsal head. A 6 camera opto-electronic system (500Hz, OQUS 3, Qualysis, Gothenburg, Sweden) was synchronized with a force plate (500Hz, AMTI, Watertown, Massachusetts) embedded underneath the landing zone. A visual record was captured by means of a normal video camera (Sony, 25Hz).

2.2. Data analysis

Visual 3D (C-motion, Germantown, MD) was used to process the kinematic and kinetic data (QTM, Qualisys). Marker data were filtered using a fourth order Butterworth low-pass filter at 15Hz, with 50 points reflected. Euler rotations (X-Y-Z, representing respectively dorsi-/plantar flexion, eversion/inversion, ab-/adduction) were used to calculate motion between the defined segments in the different planes [20]. Joint kinematics were calculated for the impact phase which was defined from touch down (TD) until maximal dorsiflexion in the ankle joint (maxDF). The vertical component of the ground reaction force (with a 15N threshold) was used for event detection. A curve analysis, one-dimensional statistical parametric mapping

(SPM) [21;22], of mean joint angles of the GFM and single segment foot model during the impact phase was performed to compare between groups. SPM allows the calculation of the traditional F and t statistics, subsequently referred to as SPM{F} or SPM{t}, over the entire normalized time-series. For this analysis a SPM ANOVA followed by post-hoc SPM t-tests if appropriate, were used with alpha maintained at 0.05 throughout. The analysis procedure comprises the following steps. (1) Using SPM ANOVA a SPM{F} ('F-value curve') was calculated for the complete time series. (2) The temporal smoothness of the data based on the average temporal gradient was estimated. (3) Random Field Theory was used to calculate the threshold of SPM{F} above which only alpha=5% of the data would be expected to reach had the test statistic trajectory resulted from an equally smooth random process. (4) Individual probability values were calculated for each supra-threshold cluster based on the probability that a cluster of a given height and size could have resulted from an equivalently smooth random process. If statistical significance was reached in the SPM{F} then the original data were further analysed with three pairwise post-hoc SPM t-tests, using the same processes (1 to 4) as described above to establish the significance of the SPM{t} in paired groups.

Additionally, range of motion (ROM) was determined for each joint in all planes during the impact phase. Furthermore, peak forces (normalized to body weight), time to peak forces and loading rate (normalized peak force/time to peak force) were calculated for the vertical component of the GRF. The raw force data were filtered by a critically damped low-pass filter at 15Hz. Between group differences for ROMs, peak forces, time to peak force and loading rate were analyzed by means of a Oneway ANOVA. Post hoc comparisons with a Bonferroni correction were performed to identify group differences. Alpha was set 0.05 and statistical analysis of these parameters was performed in SPSS 21 (SPSS Inc., Chicago, Illinois 60606, U.S.A.)

Reliability analysis to evaluate internal consistency (Cronbach's alpha) of motion kinematics over trials indicated in general a good to excellent consistency for all segments in all planes (vertical drop: ROM $\alpha > 0.797$, curves $\alpha > 0.849$; side jump: ROM $\alpha > 0.643$, curves $\alpha > 0.815$).

3. Results

3.1. Curve analysis

3.1.1. Vertical drop

The single segment foot (in relation to the shank) showed a less inverted position from approximately 10%-100% of the impact phase for both the CAI group ($p < 0.001$) and coper group ($p < 0.001$) compared to the control group (fig. 1). During this period, the single segment foot was progressing towards a maximally inverted position. In addition, the CAI group (approx. 10-100%, $p < 0.001$) and coper group (approx. 15-20%, $p < 0.05$) displayed a more adducted position of the hallux (in relation to the medial forefoot) in comparison to the control group. In the CAI and coper group the hallux slightly adducted at the beginning of the impact phase before remaining in a stable position (supplementary file 2, fig.3). Adduction for the hallux signifies motion towards the subject's center sagittal plane.

3.1.2. Side jump

A less plantar flexed position was found for the single segment foot and the rearfoot at touch down between both the CAI group (respectively approx. 0-10%, $p < 0.05$; approx. 0-10%,

$p < 0.05$) and coper group (respectively. approx. 0-10%, $p < 0.05$; approx. 0-15%, $p < 0.05$) compared to the control group (fig. 2). In addition, the coper group displayed a more dorsiflexed position of the rearfoot at the end of the impact phase from approximately 60-100% ($p < 0.05$) (fig. 2). The rearfoot also displayed a significantly less inverted position from approximately 0-55% in the CAI group compared to the control group ($p < 0.05$) (fig. 1). During this phase, the rearfoot first inverted before everting which continued throughout the remainder of the impact phase. Furthermore, the CAI group had a more inverted position of the midfoot (in relation to the rearfoot) for approximately the whole impact phase (10%-100%) compared to the control group (fig. 3). After initially inverting, the midfoot showed eversion until the end of the impact phase. Finally, the medial forefoot (in relation to the midfoot) in the coper group showed a more inverted position from approximately 55-100%, during which slight eversion takes place, in comparison to the control group ($p < 0.05$) (fig. 4).

3.2. Range of Motion

Significant ANOVA results are presented in table 2. Post hoc analysis on the **vertical drop** data showed a significantly smaller ROM for single segment foot plantar-/ dorsiflexion in the CAI group compared to the control group ($p = 0.020$). Single segment foot abduction/adduction and rearfoot plantar-/dorsiflexion ROM did not reach significance level in post hoc analysis. Furthermore, the coper group displayed a smaller plantar-/dorsiflexion ROM in the lateral forefoot ($p = 0.030$), medial forefoot ($p = 0.017$) and hallux compared to the control group ($p = 0.028$). Finally, the midfoot showed less eversion/inversion ROM in the coper group compared to the CAI group ($p = 0.038$). For the **side jump**, the CAI group displayed less ROM in the single segment foot as well as the rearfoot for plantar-/dorsiflexion and ab-/adduction compared to the control group (PF/DF: resp. $p = 0.010$ and 0.045 ;

ABD/ADD: resp. $p=0.003$ and 0.004). The copers group again displayed a smaller plantar-/dorsiflexion ROM in the lateral forefoot ($p=0.030$), and medial forefoot ($p=0.017$) compared to the control group. Finally, the hallux showed less eversion/inversion ROM in the copers group compared to the CAI group ($p=0.039$).

3.3. Ground reaction force

The CAI group displayed a higher peak vertical GRF ($p=0.019$), they reached this vertical peak faster ($p=0.021$), and had a higher loading rate ($p=0.008$) than the control group for the vertical drop. Means and ANOVA results are presented in table 2. For the side jump, no significant differences were found.

There was no significant difference between the control group, copers and CAI group regarding the time to reach the maxDF during the vertical drop (0.24s (SD 0.05), 0.23s (SD 0.07) and 0.22s (SD 0.05) respectively, $p=0.288$) and the side jump (0.24s (SD 0.05), 0.22s (SD 0.05) and 0.22s (SD 0.05) respectively, $p=0.342$). Significant post-hoc analysis results for curve analysis, ROM, and GRF are presented below (supplementary file 1 presents all means, ANOVA results and post hoc results for ROM and GRF; supplementary file 2, which represents the kinematic curves for each segment in each plane and post hoc SPM comparisons).

4. Discussion

To our knowledge, this was the first study to explore multi-segment foot landing kinematics and kinetics in subjects with CAI, copers and controls. Differences were found between subjects with CAI, copers and controls in the rearfoot, midfoot, medial/lateral forefoot, hallux, and in vertical GRF parameters. We did not, however, find a more inverted ankle position and more inverted medial forefoot as hypothesized. Overall, we identified similar differences in the sagittal plane kinematics during the impact phase between groups for both the vertical drop and side jump. Subjects with CAI and copers, seem to display less plantar flexion upon impact. This could be a compensatory strategy by protecting them from a possible ankle sprain, as further explained below. For the CAI group, this strategy could be counterproductive as their stiffer landing pattern (a smaller ROM) with higher loading rates may make them more susceptible to episodes of giving way and ankle sprains.

The evaluation of multi-segment foot landing kinematics showed differences between our subjects with CAI, copers and controls during landing tasks which could not be detected with a single segment foot. Previous research found a more inverted medial forefoot during the stance phase of gait in subjects with CAI, which reflects a mechanically less stable position [23]. This mechanism was, however, not observed during our landing tasks in subjects with CAI. This might be attributed to the function of the m. peroneus longus as it has been shown that the m. peroneus longus muscle is already more activated in the prelanding phase during a drop landing compared to walking or running conditions [24]. This could account for the differences in results between the functional tasks, even though an impaired function of the m. peroneus longus has been ascribed to CAI [15;25;26] Our multi-segment foot landing kinematics did show that subjects with CAI displayed a more inverted position of the midfoot

throughout most of impact phase (10%-100%) compared to controls during side jump and more midfoot in/eversion ROM compared to copers during vertical drop. The midfoot fulfills an important role in coupling rearfoot and forefoot motion [27]. Further research might elucidate the impact of midfoot kinematics observed in the current study by investigating the forefoot and rearfoot coupling in CAI. Furthermore, differences in hallux kinematics have been observed: for the vertical drop a more adducted hallux position for subjects with CAI (10%-100% of impact phase) and copers (15%-20% of impact phase) compared to controls, and less plantar-/dorsiflexion ROM in the coper group compared to controls, and for the side jump a smaller eversion/inversion ROM in the coper group compared to the subjects with CAI. These varying results between conditions and groups hamper a clear interpretation on the possible underlying mechanisms regarding hallux kinematics. Future research is necessary to further elucidate the contribution of intrinsic foot mechanisms in CAI and to study their consistency during other functional movements. Monitoring muscle activity combined with the multi-segment foot kinematics might provide deeper insight in the described mechanisms.

Overall, in the sagittal plane, subjects with CAI displayed significantly less plantar flexion upon impact in both the rearfoot and single segment foot models for the side jump compared to the control group. And although not significantly different, the kinematic data of the vertical drop also suggests a similar pattern. These findings correspond with the results of Caulfield and Garrett [12], who found a less plantar flexed ankle before, at, and post landing after a similar vertical drop. They argued that less plantar flexion might be a protective mechanism to restrain the lateral ligament complex from harmful stretch. In addition, a model driven study suggested that increased plantar flexion at touch down might be the primary mechanism, more so than the frontal plane subtalar joint angle, for increasing susceptibility to

ankle sprains [28]. Subjects with CAI might, therefore, try to limit plantar flexion at touch down as a protective strategy. However, this protective strategy can at the same time be counterproductive as their total ROM during the impact phase in the sagittal plane was reduced in the single segment foot for both the vertical drop and side jump, and in the rearfoot for the sidejump. In addition, the ROM of transverse plane movements for the side jump was also limited in the single segment foot and the rearfoot in subjects with CAI. This more rigid strategy might suppress the capacity to react appropriately to external perturbations, and might have a negative influence on vertical impact forces as discussed further on.

In the frontal plane, a less inverted rearfoot angle was seen in the CAI group at touch down during the side jump, and in the single segment foot towards the end of the impact phase for the vertical drop and the side jump. These findings are consistent with previous results using a multi-segment foot model during gait, indicating a less inverted position of the rearfoot during midstance [17]. Based on the pathomechanics of an ankle sprain, including plantar flexion-adduction-inversion of the ankle joint, the less inverted position suggests a compensation for the risk of sustaining an ankle sprain rather than causation. A prospective study by Willems et al. [29] using plantar pressure measurements during running found an increased medial loading of the foot and a trend towards higher eversion excursion in subjects susceptible for an ankle sprain. They suggested that this more medial foot roll-off may be the result of a compensation mechanism for possible ankle sprains [29]. This compensation mechanism might also cause the lower inversion angles found in the current study. Our results, therefore, do not confirm previous findings in literature indicating a more inverted position of the ankle in the landing phase [14;15].

Although not the primary aim of the current manuscript, differences in kinematics between the single segment foot and the rearfoot in relation to the shank are worth consideration. Notwithstanding similar results for the single segment foot and the rearfoot between groups, such as plantar flexion angle around touch down and ROM during the impact phase, also divergent kinematics can be observed. Firstly, the ROM values are higher in the single segment foot compared to the rearfoot in all planes (table 2 and supplemental file 1). This may not be a surprise when the marker set up is considered as the most distal markers of the single segment foot were placed on the distal end of MT1 and MT5. The single segment foot therefore does not only describe the dorsiflexion motion at the ankle joint, but also at the more distal joints, i.e. medial and lateral forefoot. Although not purely summative, this does influence the single segment foot kinematics and similar observations can be made for the motion in other planes. Not only ROM is affected, but also the shape of the curves between the single segment foot and the rearfoot, and especially in the frontal plane (supplemental file 2). These differences seem to be the result of the combination of rearfoot, midfoot and forefoot kinematics which are over simplified in the single segment foot model. As motion in the frontal plane is important in the ankle sprain mechanism, the impact of a single segment foot (with markers on the forefoot) when describing kinematic results should not be underestimated. Future research should focus on the validity of the use of a single segment foot to describe ankle kinematics.

The CAI group exhibited both an earlier, as well as a higher peak vertical GRF, during the vertical drop which has been observed previously [10;11]. This suggested that the CAI group is exposed to higher loading rates [30], as supported by our results, and which would match our earlier notion of a stiffer landing pattern. We checked this by calculating Pearson correlation coefficients and a significant correlation was found between the plantar-

/dorsiflexion ROM of the single segment foot, and the load rate, defined as the normalized peak vertical GRF divided by the time to peak vertical GRF ($p < 0.001$, $r = -0.689$) (fig 4) [30]. Increased loading rates may increase the risk for sustaining an ankle injury because of limited capacity to absorb this higher loading. Several studies have indicated neuromuscular insufficiencies in the preparatory and response phase in subjects with CAI which might prevent them from adequately controlling the foot complex to accommodate for these forces [26;31;32]. Figure 4 also shows that within the CAI group, there is substantial variation in stiffness of the landing, which may help focus treatment for those individuals with CAI who show increased landing stiffness. For the side jump, no significant differences were found in force dissipation between the study groups. A possible explanation for this dissimilarity in results between conditions could be attributed to movement direction. Logically, a vertical drop will have greater impact on the vertical GRF than will a side jump movement, and could therefore be more sensitive to group differences.

When observing the copers group against the CAI group, the copers group displayed a lower in/eversion ROM of the midfoot during the vertical drop. As addressed above, the midfoot plays an important role in the forefoot and rearfoot coupling and differences in ROM might be influential. However, the absolute ROM difference is lower than 1° (table 2), questioning clinical relevance of this observation. Furthermore, the copers differentiated themselves from the CAI group primarily by virtue of their differences with the control group. For the side jump, a similar lower plantar flexion angle as seen in the CAI group was registered for the rearfoot and the single segment foot. Unlike the CAI group however, the copers didn't significantly decrease ROM in the single segment foot and rearfoot during the impact phase. They did in fact have more dorsiflexion at the end of the impact phase for the side jump compared to the controls, indicating a more close packed position, which is considered a

locked and therefore stable position of the joint [33]. This could protect them from possible episodes of giving way and ankle sprain events. On the other hand, copers displayed a more inverted medial forefoot during the second half of the impact phase during the side jump, associated with a less stable position. This could be attributed to an impaired function of the m. peroneus longus as demonstrated during gait [17]. Furthermore, the coper group had significantly less ROM in the medial and lateral forefoot for both vertical drop and side jump compared to the control group. The underlying mechanism of these findings is unclear to the authors, but might be part of coping strategy explaining why some develop CAI after an ankle sprain whilst others do not.

Some methodological limitations should be recognized. Both jumping conditions occurred barefooted so this could be considered when comparing and extrapolating study results given that shod versus barefoot landings may alter impact forces that modulate stiffness strategies [34]. Any possible difference in foot type between groups was not accounted for by means of e.g. foot posture index. This could be complementary to the kinematic evaluation in explaining our findings. However, there were no similar results found in multi-segment foot kinematics between conditions advocating for task specific differences rather than static differences. Additionally, kinematic offset differences would have no impact on our main findings regarding ROM and kinetic findings. For the side jump protocol, a maximal effort/distance jump was chosen to provoke subjects' landing control capabilities. Jump distance was not taken into account in the study results and may have differed between groups. Similar foot landing kinematics were found in the vertical drop and maximal side jump conditions, indicating that both tasks offer a means to recognize group effects. Whether a maximal side jump is necessary, or a submaximal distance jump could suffice, is uncertain. Fleischmann et al. [35] found no differences in angular displacement at the ankle joint during

landing jumps at different distances, so for now we could consider that submaximal jumps may well have revealed the same group effects, yet this still needs to be seen. Furthermore, given the exploratory nature of the current study, the alpha level in the SPM analyses was not corrected for the dependent planes of joint motion, as in a previous paper [17]. This more liberal approach was chosen as it prevents that potentially weak phenomena would immediately be dismissed at this early stage of multi-segment foot model explorations. For data collection, due to technical limitations of the capturing volume, centre of mass determination and pre-impact kinematics were not registered. This means that joint moments and center of mass position could not be calculated and important pre-impact kinematic landing differences could have been missed. Future research should therefore also include e.g. pre-landing observations if possible, particularly if that were to involve the study of muscle (pre-)activations.

5. Conclusions

Subjects with CAI displayed an altered, stiffer foot landing kinematic strategy and adapted kinetic landing characteristics compared to a control group, which might predispose them to episodes of giving way and actual ankle sprain events. The use of a multi-segment foot model might open a window for identifying possible influencing distal factors related to chronic ankle instability, e.g. deviating midfoot kinematics. When observing single segment foot results against multi-segment foot results, data shows that the single segment foot may comprise more than only rearfoot kinematics. Single segment foot kinematics in the literature should therefore be interpreted with caution. Further research is warranted to increase insight into foot and ankle kinematics during functional tasks, and gain a better understanding of underlying mechanisms of CAI.

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Table 1: Group mean (SD) for demographic variables.

	CON (n=30)	COP (n=28)	CAI (n=38)
Age (yrs)	25.7 (1.8)*	20.3 (1.9)*	22.1 (3.4)*
Height (cm)	173.6 (9.4)	177.6 (10.2)	175.4 (8.3)
BMI	21.8 (1.8)	22.1 (1.7)	23.1 (3.4)
FADI	100 (0.0) ^l	99.0 (2.4) ^l	89.2 (7.2) ^l
FADI-S	100 (0.0) ^T	96.2 (4.8) ^T	72.7 (10.2) ^T

Differences between groups are non-significant ($p>0.05$) except for age for control (CON) in comparison with CAI and copers (COP) ($p<0.001$), and between CAI and COP ($p=0.018$). FADI^l (Functional Ankle Disability Index) and FADI-S^T (Functional Ankle Disability Index-Sport subscale) score were significantly lower in the CAI group compared to both the control group and the copers group ($p<0.001$).*

Table 2. Mean (SD) and significant ANOVA results for Range of Motion (ROM) and vertical ground reaction force (GRF).

ROM	Vertical Drop (°)			
	CON	COP	CAI	P-value
Rigid Foot DF/PF	48.90 (5.51)*	47.48 (5.18)	45.09 (5.85)*	0.022*
Rigid Foot ABD/ADD	11.32 (3.15)	11.18 (3.19)	9.60 (2.89)	0.045
Rearfoot DF/PF	35.10 (4.71)	35.07 (4.07)	32.61 (4.99)	0.048
Midfoot EV/IN	2.01 (0.66)	1.85 (0.65) ^l	2.48 (1.36) ^l	0.030 ^l
Lateral forefoot DF/PF	28.90 (4.15) ^T	25.78 (3.88) ^T	27.33 (4.43)	0.021 ^T
Medial forefoot DF/PF	26.32 (5.44) ^T	22.23 (5.14) ^T	23.73 (5.06)	0.019 ^T
Hallux DF/PF	28.34 (5.32) ^T	23.08 (4.29)	25.54 (7.43)	0.032 ^T
	Side Jump (°)			
	CON	COP	CAI	P-value
Rigid Foot DF/PF	43.05 (7.82)*	40.46 (6.16)	37.91 (6.59)*	0.013*
Rigid Foot ABD/ADD	13.60 (4.23)*	12.06 (4.11)	10.35 (3.40)*	0.005*
Rearfoot DF/PF	30.19 (5.54)*	28.93 (4.22)	27.28 (4.43)*	0.049*
Rearfoot ABD/ADD	8.35 (2.52)*	7.28 (2.27)	6.50 (2.00)*	0.006*
Lateral forefoot DF/PF	23.86 (5.69) ^T	20.61 (4.68) ^T	21.91 (5.13)	0.034 ^T
Medial forefoot DF/PF	19.53 (6.47) ^T	14.93 (5.68) ^T	16.46 (5.32)	0.024 ^T
Hallux EV/IN	23.16 (6.81)	28.44 (7.65) ^l	22.15 (8.65) ^l	0.035 ^l
GRF	Vertical Drop			
	CON	COP	CAI	P-value
Time to peak vertical GRF (sec)	0.061 (0.015)*	0.055 (0.011)	0.052 (0.012)*	0.021*
Peak vertical GRF (/BW)	2.976 (0.401)*	3.197 (0.473)	3.273 (0.449)*	0.023*
Loading rate ((N/BW)/sec)	52.40 (16.46)*	61.63 (18.70)	66.85 (21.17)*	0.010*

CON=control group; COP=coper group; CAI=chronic ankle instability group; DF=dorsiflexion; PF=plantar flexion; EV=eversion; IN=inversion; ABD=abduction; ADD=adduction; BW=body weight; N=Newton. Post hoc results ($p \leq 0.05$) are labeled with * for a significant difference between CAI and CON, with ^T between COP and CON, and with ^l between COP and CAI.

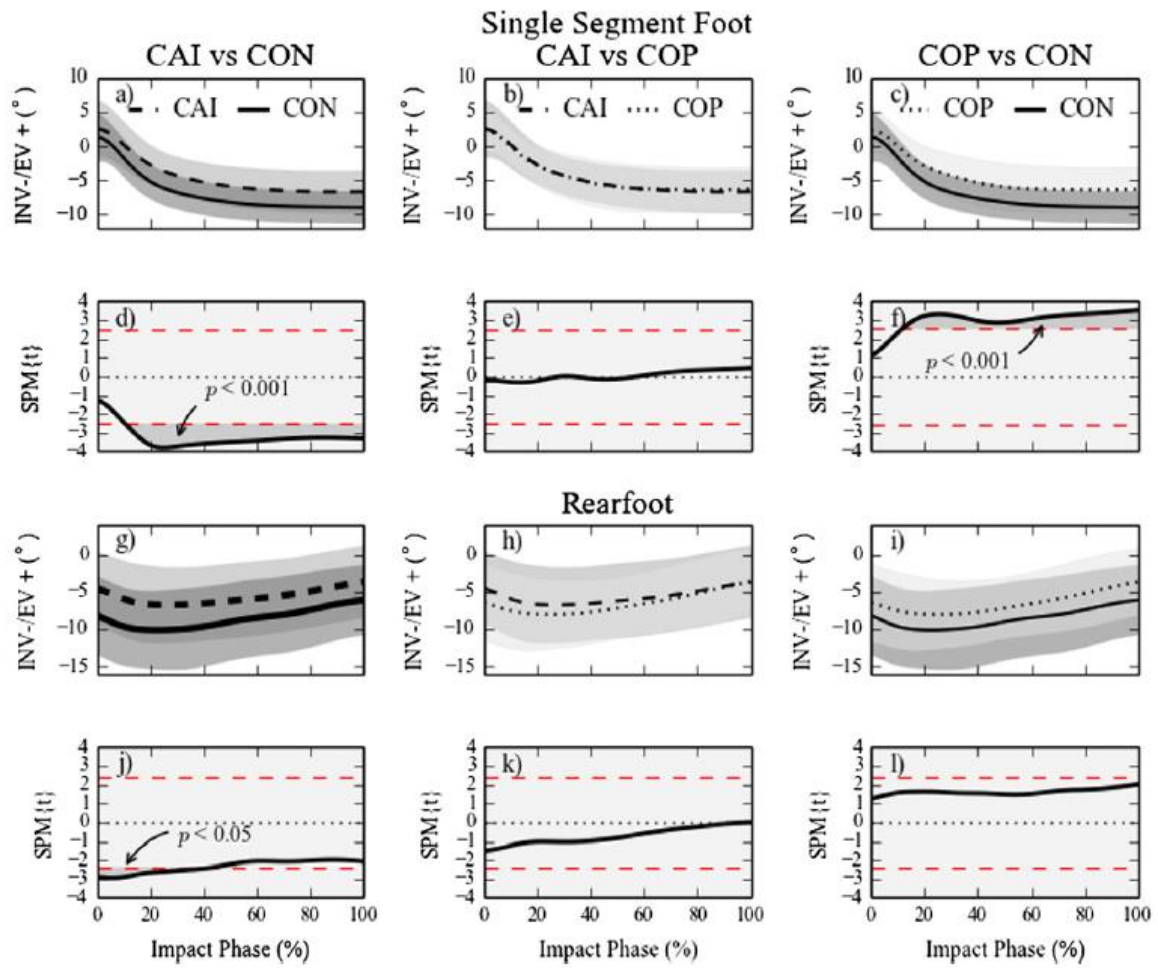


Figure 1. Kinematic between-group comparison in the frontal plane of the single segment foot during a vertical drop landing and the rearfoot during a side jump landing. (a,b,c) (g,h,i) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) (j,k,l) Statistical Parametric Mapping results; "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance, and p values indicate the likelihood that a random process of the same temporal smoothness would be expected to produce a supra-threshold cluster of the observed size.

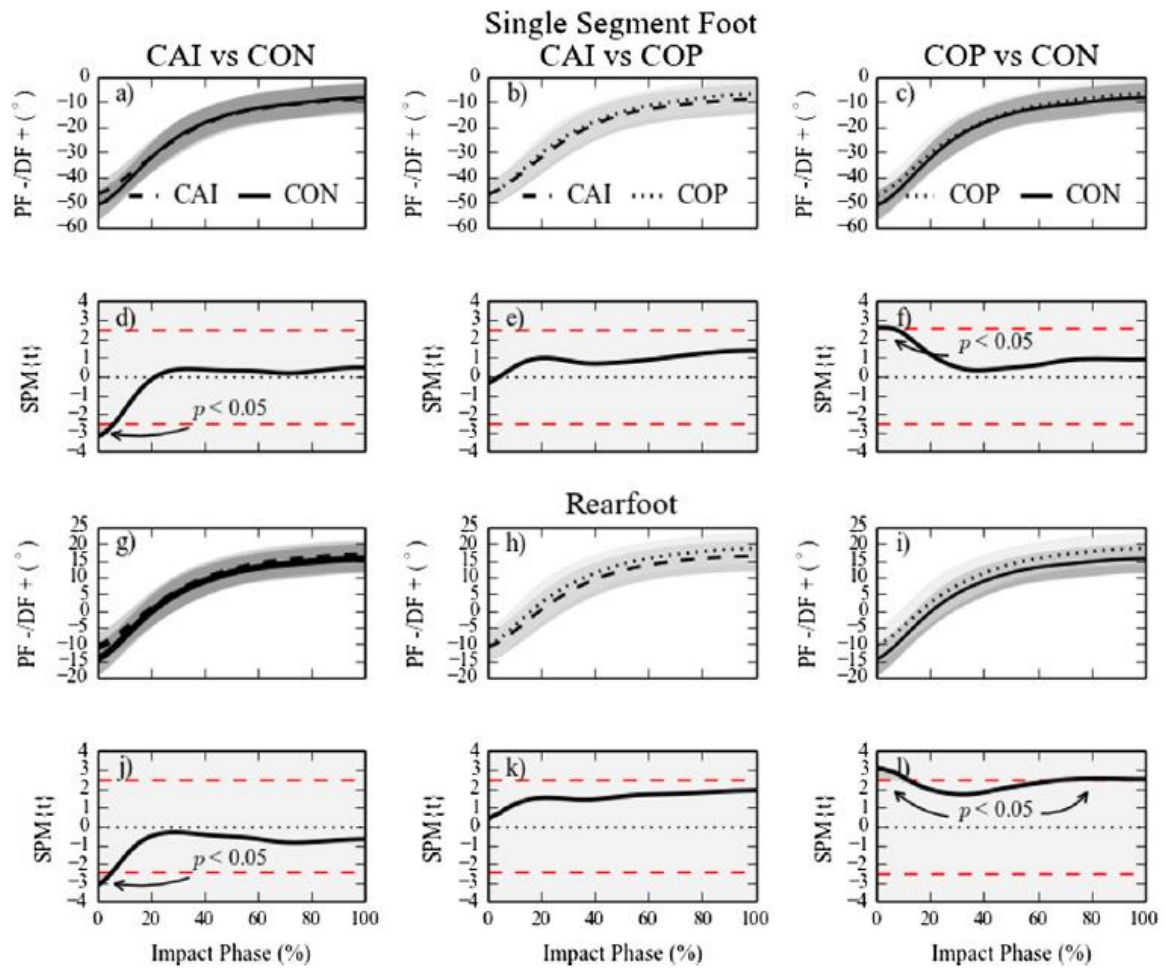


Figure 2. Kinematic between-group comparison in the sagittal plane of the single segment foot and the rearfoot during a side jump landing. (a,b,c) (g,h,i) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) (j,k,l) Statistical Parametric Mapping results.

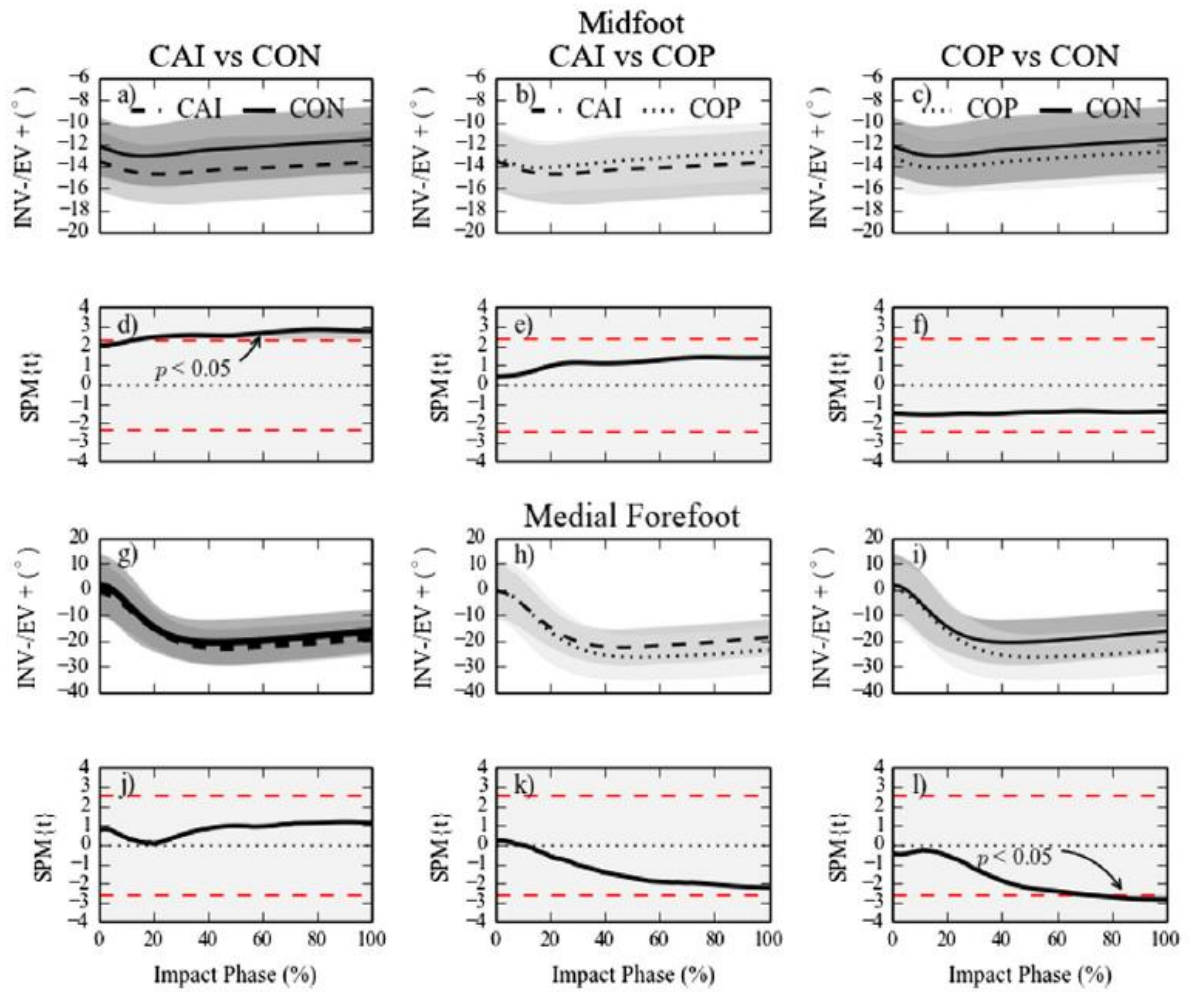


Figure 3. Kinematic between-group comparison in the sagittal plane of the midfoot and the medial forefoot during a side jump landing. (a,b,c) (g,h,i) Mean ankle joint kinematic trajectories with standard deviation clouds. (d,e,f) (j,k,l) Statistical Parametric Mapping results.

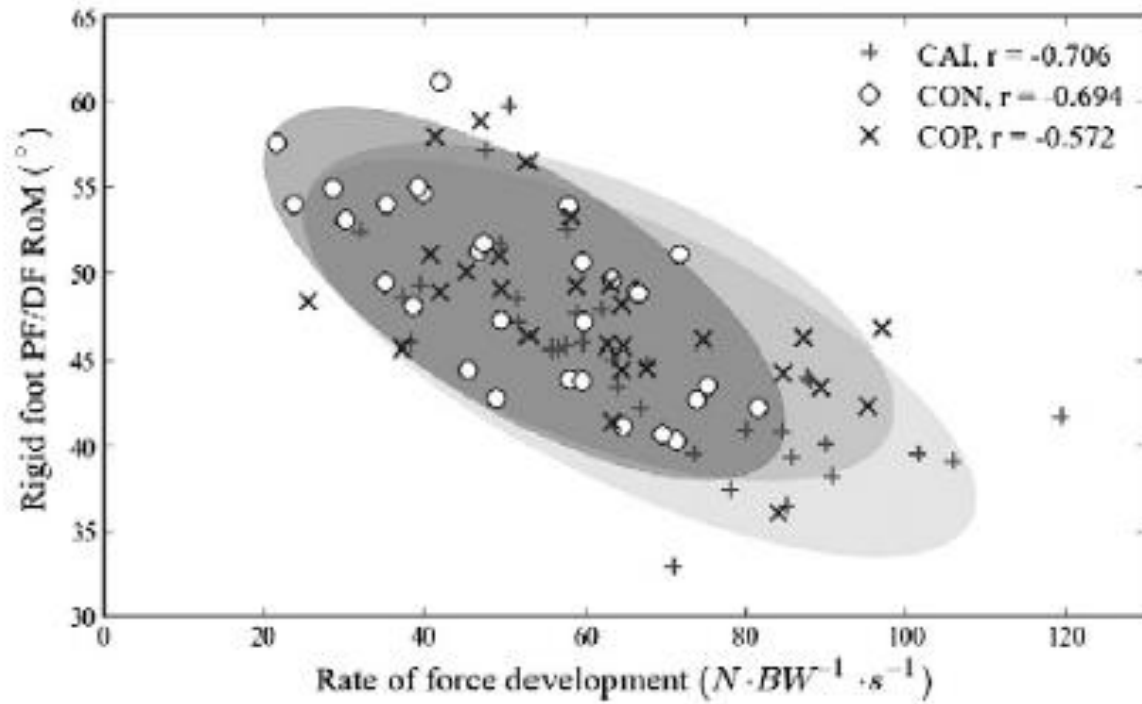


Figure 4. Scatterplot visualizing correlation between the dorsiflexion/plantar flexion range of motion (DF/PF ROM) and the rate of force development with co-variance cloud (2 SD) for each group (dark=CON, mediate=COP, light=CAI).

List of supplementary files

Supplementary file 1. Tables that present all means, ANOVA results and post hoc results for ROM and GRF.

Supplementary file 2. Figures that represent the kinematic curves for each segment in each plane and post hoc SPM comparisons not presented in the main body of the manuscript.