Lower limb landing biomechanics in subjects with chronic ankle instability

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http://dx.doi.org/10.1249/MSS.0000000000000525

Abstract:

Objective: Literature on lower limb kinematic deviations in subjects with chronic ankle instability (CAI) during landing tasks is limited and not consistent. Several studies only report joint angles at defined events rather than considering the whole kinematic curve which might obscure possibly relevant information. Therefore, the main goal of this study was to evaluate landing kinematics of the lower limb in subjects with CAI using curve analysis. **Methods:** Lower limb kinematics of 56 subjects (28 subjects with self-reported CAI and 28 matched healthy controls) were measured during a barefoot forward and side jump protocol. Kinematic data were collected in a laboratory setting using an eight-camera optoelectronic system. Ground reaction forces were registered by means of a force plate built into the landing zone. After completion of each task, difficulty level and subjective stability at the ankle joint were documented using a visual analogue scale. To compare between groups, Statistical Parametric Mapping was used to assess group differences between mean joint angles over the entire impact phase. **Results:** SPM analysis of kinematical curves of the hip, knee, and ankle showed no significant differences between the subjects with CAI and the control group independent of jump direction. Subjects with CAI did report higher feelings of instability for both landing tasks and a higher difficulty level for the forward jump. **Conclusion:** Our results showed no altered lower limb kinematics in subjects with CAI compared to a healthy control group during a forward and side jump landing task. Therefore, these results question the hypothesis of kinematic deviations as part of an underlying mechanism of CAI.

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Doi: http://dx.doi.org/10.1249/MSS.0000000000000525

Introduction

A recent systematic review with meta-analysis on ankle sprain epidemiology calculated a cumulative incidence rate between 6.94 (males) and 13.6 (females) sprains per 1000 exposures, with the highest incidence for indoor or court sports.[10] Although an ankle sprain is considered a common temporary musculoskeletal injury, a relatively high proportion of those patients develop chronic ankle instability (CAI). CAI is characterized by recurrent ankle sprains, 'giving way', and feelings of instability at the ankle joint, whether or not combined with mechanical laxity.[16] In addition, CAI has been associated with a decreased level of sports participation and the development of ankle osteoarthritis.[2, 25, 35] As for now, an unclear mechanism of combined proprioceptive deficits, neuromuscular changes, muscle strength, postural control and central adaptations is believed to be the origin of this pathology.[19, 20]

In subjects with CAI, lower limb kinematics during dynamic landing situations are being used to evaluate the presence of kinematic deviations at the ankle joint, as well as at the more proximal knee and hip joints.[4, 8, 18] The additional evaluation of proximal joints is based on kinetic chain theories, which stresses the interplay between proximal and distal segments during functional activities. Recently, studies focusing on proximal factors have identified relationships between proximal dysfunctions and lower extremity injuries.[5, 37] Furthermore, biomechanical research has indicated that joint kinematics are influential in the capability of modifying and absorbing impact forces during landing tasks.[40] Therefore, kinematic adaptations might be inefficient to deal with the rapid and very high loading forces, possibly increasing the susceptibility for injury, e.g. in chronic ankle instability

Literature on proximal kinematic deviations in subjects with CAI during landing tasks is limited and not consistent. Nine relevant studies have been identified reporting divergent results. Table 1 outlines an overview of these studies on this topic which illustrates the diversity in design and results. At the level of the hip, Delahunt et al. were the only to identify less external rotation in the prelanding phase during a vertical drop in subjects with CAI[8]. Both higher and lower degree of knee flexion have been identified during a landing task[4, 15] as well as no significant differences at all.[8, 9] Even at the ankle joint, where studies have confirmed the hypothesis of a more inverted and plantar flexed position of the foot[8, 9], controversy remains with opposing results.[24, 28] Since several studies only report joint angles at defined events during dynamic tasks[4, 15, 18, 23, 24, 26, 28] instead of considering the whole kinematic curve this might result in a focus bias and obscure possibly relevant information.[30] The limited and contradicting evidence from the available literature indicates the need for more studies

Table 1. Literature overview on lower limb kinematics during landing tasks in subjects with CAI compared to controls

Author	Task	Planes	Time frame	Ankle	Knee	Hip
Caulfield et al.	Vertical drop	S	(-)100ms-(+)200ms	↑ DF ((-)10ms-(+)20ms)	↑ FL ((-)20ms- (+)60ms)	/
Delahunt et al.	Vertical drop	F+S+H	(-)200ms-(+)200ms	↑ INV ((-)200ms-(-)95ms), ↓ DF ((+)90-(+)200ms)	NS	↓ EXT ROT ((-)200-(-)55ms)
Delahunt et al.	Lateral hop	F+S+H	(-)200ms-(+)200ms	↓ EV ((-)45ms-(+)95ms)	NS	NS
Gribble et al.	Forward jump	S	(-)100ms, TD, peak	NS	↓ FL	NS
Gribble et al.	Forward jump	S	TD	NS	↓ FL	NS
Kipp et al	Land-and-cut	F+S+H	TD, peak	NS	/	/
Lin et al.	Stop jump (bilat)	F+S+H	(-)200ms-(+)200ms	↑ INV (at (+)140ms)	/	/
Monteleone et al.	Med/lat hop	F+S+H	8 timepoints during flight and landing	NS	/	/

F=Frontal, S=Sagittal, H=Horizontal, TD=Touch down, (-) indicates prior to TD, (+) indicates after TD, DF=Dorsiflexion, PF=Plantar flexion, INV=Inversion, EV=Eversion, EXT ROT=External rotation, ↑ indicates 'more' in subjects with CAI compared to controls, ↓ indicates 'less' in subjects with CAI compared to controls, NS signifies no significant differences between groups, / signifies not measured in the study

focusing on overall lower limb biomechanics during dynamic landing tasks in order to identify underlying mechanisms for CAI.

The main goal of the current study was to evaluate landing kinematics at the ankle, knee and hip joints in subjects with CAI compared to a healthy control group during a frontal plane and sagittal plane directed task. To avoid focus bias, the use of statistical parametric mapping (SPM), extensively used in brain research[13, 22, 32] enabled us to perform a comprehensive curve analysis during the whole pre- and post landing phase.

Methods

Population

A total of 56 subjects participated in this study, including 28 subjects with CAI (10 men and 18 women) and 28 healthy controls (10 men and 18 women). Population characteristics are presented in table 2. Subjects in the CAI group met all of the following inclusion criteria: a history of a significant ankle sprain resulting in participation limitations for at least 3 weeks, repetitive ankle sprains, episodes of giving way, and feelings of instability and weakness around the ankle joint. The healthy control group had no history of an ankle sprain. Exclusion criteria were fractures or surgery at the ankle joint in the past. Overall, subjects were at least recreationally active defined by a minimum of 1.5 hours of cardiovascular activity a week and had no lower limb complaints at the moment of testing. Subjects of the control group were matched to subjects with CAI based on age, sex, height, weight and limb dominance. This study was approved by the ethics committee of the Ghent university hospital and all subjects signed the informed consent before participation.

Table 2. Population characteristics

	CAI (n=28)	Control (n=28)
Age (yrs)	22.3 (2.7)	22.5 (1.6)
Height (m)	1.73 (0.10)	1.72 (0.10)
Weight (kg)	71.0 (10.6)	66.5 (9.4)
BMI	23.8 (2.8)	22.5 (2.1)
FADI	88.2 (7.2)	99.7 (0.7)*
FADI-S	69.9 (9.6)	99.4 (1.5)*
Time to last sprain (months)	4.5 (4.2)	N/A
Duration of complaints last sprain (weeks)	5.2 (6.1)	N/A
# sprains annually	5.6(3.6)	N/A
Ankle orthotics (tape/brace) during sports	19/28	1/28
Insoles	7/28	6/28

BMI=Body Mass Index; FADI=Foot and Ankle Disability Index; FADI-S=Foot and Disability Index Sports subscale; * signifies significant group difference with p<0.001)

Instruments

Kinematic data were collected in a laboratory setting using an eight-camera optoelectronic system (250Hz, OQUS 3, Qualisys). Ground reaction forces were registered by means of a force plate (250Hz, Advanced Mechanical Technology, Inc., Watertown, MA) built into the landing zone.

Experimental procedure

Baseline anthropometric characteristics of all subjects were registered at the beginning of the testing procedure. All subjects completed a medical questionnaire, the foot and ankle disability index (FADI) and its sports subscale (FADI-S). In case of bilateral ankle instability, the most unstable ankle was selected for analysis in our study protocol based on the subject's subjective indication. To match the tested ankle of an individual control subject to a subject with CAI, limb dominance was taken into account (i.e. if the non-dominant ankle was selected for the subject with CAI, in accordance the non-dominant ankle was included for the matched control subject).

The functional protocol used in the current study is based on the study of Sell et al.[34] All tasks were performed barefooted. First, subjects performed a forward jump with a jump distance standardized to 40% of subject's height while jumping over a 30cm high hurdle. Push off had to be performed on both feet while subjects were instructed to land on the tested ankle on an indicated spot on the force plate. Hands were free during the flight phase, but had to be placed on the hips immediately after landing and balance had to be maintained for 5 seconds. Maintaining balance was defined by keeping the hands on the hips, no shifts of the tested ankle and no contact between the contralateral limb and the tested limb nor with the ground. Secondly, a lateral side jump was performed over a distance of 33% of subject's height over a 15cm high hurdle. Prerequisites were identical to that of the forward jump. For each task 5 successful trials were captured. After completion of each task, difficulty level and subjective stability at the ankle joint were documented using a visual analogue scale (VAS).

Kinematic data were collected using the 'Liverpool John Moores University' (LJMU) model.[36] This model tracks feet, upper and lower legs, pelvis and trunk. However, the trunk was not included in the current study. To track these 7 segments, 38 spherical reflective markers were placed on anatomical landmarks, along with tracking markers according to the LJMU model. A static trial was performed to define the model. Separate trials were performed for calculation of the functional hip joint centres[33] and knee joint axes.[3, 31]

Data analysis

Kinematic and kinetic data was processed using Visual 3D (C-motion, Germantown, MD). Inter-joint motion was calculated using Euler rotations (X-Y-Z).[39] Rotation around the X-, Y- and Z-axis defined respectively flexion/extension (hip and knee joint) and plantar-/dorsiflexion (ankle joint) in the sagittal plane, ab-/adduction (hip and knee joint) and in-/eversion (ankle joint) in the frontal plane, and internal/external rotation (hip and knee joint) and ab-/adduction (ankle joint) in the transversal plane. The time interval for analysis extended from 200ms prior to touch down (TD) and 200ms after. Event detection was based on the vertical component of the ground reaction force (threshold set at 15 N). Marker data was filtered using a fourth order Butterworth low-pass filter at 15Hz. The raw force data were filtered by a critically damped low-pass filter at 15Hz.

A curve analysis, one-dimensional statistical parametric mapping (SPM)[12, 29], of mean joint angles of the ankle, knee and hip during the impact phase was performed to compare between groups. SPM allows the calculation of the traditional t statistics, subsequently referred to SPM{t}, over the entire normalized time-series. For this analysis, two-sample t-tests were performed, with $\alpha=0.05$ corrected to 0.0055 for each joint (n=3) and plane (n=3) to maintain the family-wise error rate. Firstly, SPM{t} statistic was calculated from the mean joint angles for the entire impact phase.[29] Secondly, the temporal smoothness of SPM{t} based on its average temporal gradient was estimated.[12] Subsequently, the threshold of SPM{t} was computed using Random Field Theory[1] above which only alpha=0.55% of the data would be expected to reach had the test statistic trajectory resulted from an equally smooth random process. Any clusters of SPM{t} that exceeded this threshold were considered significantly different. Individual probability values were calculated for each supra-threshold cluster, which indicate the probability that a cluster of a given height and size could have resulted from an equivalently smooth random process. All SPM analyses were implemented in Python 2.7 using Canopy 1.1 (Enthought Inc., Austin, USA).

Results

SPM analysis of kinematical curves of the hip, knee, and ankle showed no significant differences between the subjects with CAI and the control group independent of jump direction. Figure 1 and 2 illustrate joint kinematics and statistical results of respectively the forward jump and the side jump.

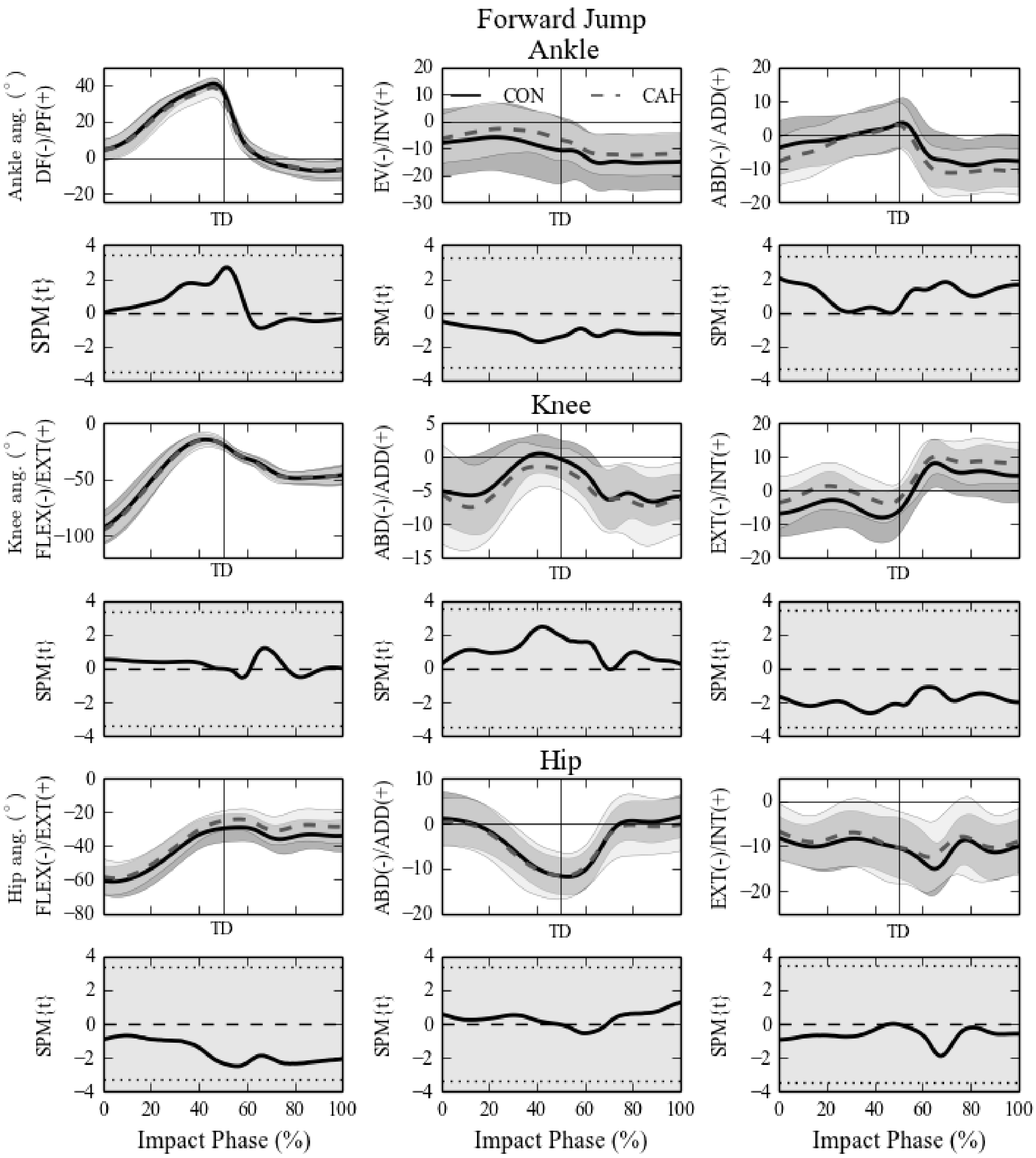

Figure 1. Lower limb kinematic comparison during the forward jump (CAI =dashed --; CON =solid __). Mean kinematic trajectories with standard deviation clouds with underneath the Statistical Parametric Mapping results are presented for each joint. "SPM{t}" is the trajectory Student's t statistic or, equivalently, the mean difference curve normalised by sample-size normalised variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t} that exceeded this threshold were considered significantly different. No significant findings were reported. DF=dorsiflexion; PF=plantar flexion; FLEX=flexion; EXT=extension; EV=eversion; INV=inversion; ABD=abduction; ADD=adduction; EXT=external rotation; INT=internal rotation;TD=touch down.

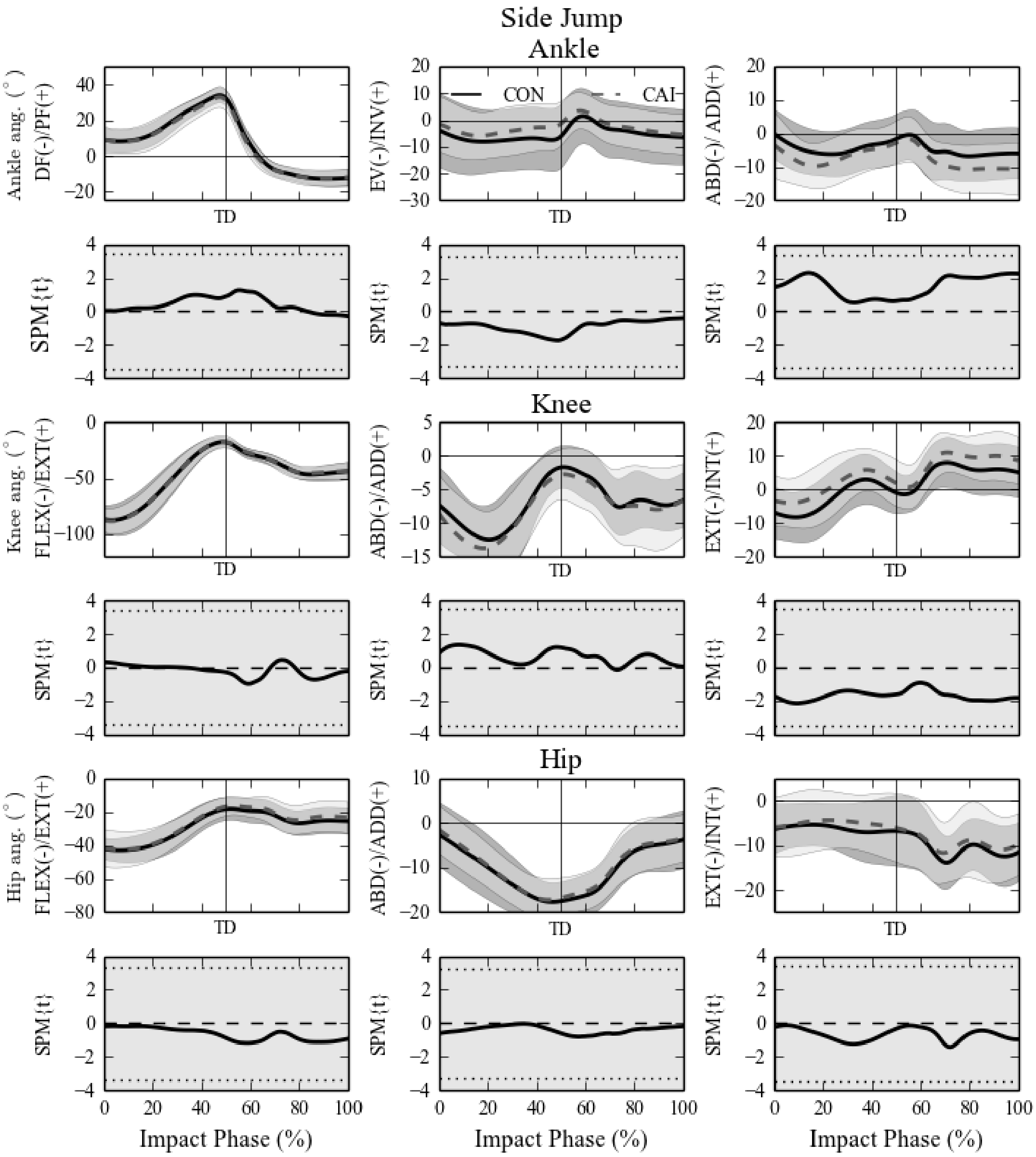

Figure 2. Lower limb kinematic comparison during the side jump (CAI =dashed --; CON =solid __). Mean kinematic trajectories with standard deviation clouds with underneath the Statistical Parametric Mapping results are presented for each joint. "SPM{t}" is the trajectory Student's t statistic.

No group differences (p>0.05) were found for any of the anthropometric variables or for the amount of trials needed to complete 5 successful trials for both the forward jump (CON: 9.8 (3.3), CAI: 10.6 (3.7)) and the side jump (CON: 9.6 (2.8), CAI: 8.6 (2.6)). VAS score analysis showed that subjects with CAI had higher feelings of instability in the ankle joint for both jump directions compared to the control group (forward jump: CAI: 4.55 (2.17) cm, CON: 0.54 (0.99) cm, p<0.001; side jump: CAI: 4.28 (2.09) cm, CON: 0.49 (0.95) cm, p<0.001). The perceived difficulty level of the landing task was significantly higher in subjects with CAI compared to the control group for the forward jump (CAI: 4.71 (2.04) cm, CON: 2.62 (1.68), p<0.001) but not for the side jump (CAI: 3.58 (2.32) cm, CON: 2.53 (1.91), p=0.069).

Discussion

The goal of our study was to present a comprehensive overview of lower limb kinematics of the hip, knee and ankle during both a forward jump and side jump landing task. Instead of focusing on particular time frames, the whole landing curve ranging from 200ms pre landing till 200ms post landing, including all three motion planes, was considered for analysis using SPM, accounting for curve smoothness and corrected for multiple testing. The main results of our study revealed that there were no significant differences in lower limb kinematics between subjects with CAI and healthy controls during the imposed tasks. This raises the question on the role of lower limb kinematics in the mechanism of chronic ankle instability. Exploring the available evidence in literature reveals the large diversity of included tasks, analyzed planes, time frames and, maybe most importantly, kinematic results (table 1).

In general, the observed absence of kinematical deviations at the level of the hip coincides with most of the scarcely available literature. We identified only four studies that evaluated hip kinematics during a landing task[8, 9, 15, 18] and only two of these analyzed all three motion planes before and after landing.[8, 9] One study of the latter two, by Delahunt et al. [8], reported less external rotation of the hip joint in the pre-landing phase during a vertical drop task. These authors attributed their finding to possible proximal neuromuscular impairments through central neural adaptations. However, a direct link between such impairments and altered kinematics has not been established yet. Our results are in agreement with all other studies evaluating hip kinematics during a landing tasks[9, 15, 18] as well as during gait.[7, 27] At this moment, available evidence does not support the involvement of deviating hip joint kinematics in the mechanism associated with CAI.

At the level of the knee, Caulfield et al. were the first to report kinematic deviations.[4] They found more knee flexion around touch down in subjects with CAI during a vertical drop task and attributed their findings also to central adaptation. These results, however, have not been confirmed since. On the opposite, Gribble et al. found less knee flexion prior to and at touch down during a forward jump task in subjects with CAI compared to a control group.[15, 18] They argued that a greater knee extension results in a longer period to dissipate forces after impact accounting for the increased time to stabilization they also observed. These studies of Caulfield et al. and Gribble et al. only considered the sagittal plane motion in their study design. As already indicated, our study results support neither of these findings on deviating knee kinematics during both a forward and side jump in all planes of motion, which is in agreement with Delahunt et al.[8, 9] Two additional studies on gait also reported no kinematic deviations at the knee joint [7, 27], whereas Drewes et al. found an increased external rotation of the shank during large portion of the gait cycle during both walking and running.[11] In summary, all deviating kinematic findings at the knee joints have not been confirmed in other studies prohibiting a clear message. Notwithstanding some studies support the involvement of the knee joint in those with CAI, these study results lack confirmation by e.g. our study results. More high quality studies are needed to be able to formulate a comprehensive message on the involvement of the knee joint in CAI.

In our study, no significant differences in ankle kinematics were identified in all planes of motion during both jump protocols. In literature, we identified 9 studies in which patients with CAI performed a landing task[4, 8, 9, 15, 18, 23, 24, 26, 28] describing ankle kinematics (see table 1). In the frontal plane, three landing studies reported an increased inversion angle in subjects with CAI. However these finding were found during different time periods of the landing phase, ranging from before touch down (200ms-95ms pre) during a vertical drop [8], around touch down (45ms pre - 95ms post) during a lateral hop[9], and in the post landing phase (at 140ms post) during a stop jump[26] (table 1). In agreement with our results, three studies described no significant frontal plane differences, i.e. during a mediolateral hop task[28], a forward jump[23] and a land-and-cut task[23]. In the sagittal plane, a more dorsiflexed ankle position has been described around touch down by Caulfield et al[4], however this was not confirmed in other studies. In addition, one study by Delahunt et al. described a less dorsiflexed ankle position at the end of the landing phase indicating a lesser closed packed position.[8] Overall, no differences have been reported on ankle kinematics in the transversal plane. Although Kipp and Palmieri-Smith found no differences in discrete ankle joint angles as aforementioned, they did find a higher inter-trial variability in the frontal and sagittal plane during a forward jump[23], and also a more complex control strategy represented by a more planar angular co-variation during a land-and-cut task[24] at the ankle joint using principal component analysis. These authors associated their findings to the mechanism of CAI. Future research should consider similar approaches to reveal motion patterns associated with CAI. In general, when considering all available evidence on ankle kinematics during landing tasks, it appears difficult to generalize individual study results on ankle joint kinematics in chronic ankle instability.

Based on the current available literature, it is difficult to make a general statement on the influence of lower limb kinematics in the mechanism associated with CAI. For each joint, different results have been reported or similar results in different timeframes during the event. Differences in the inclusion criteria between studies used to select subjects with CAI might partly account for these differences. Recently, the International Ankle Consortium has endorsed a number of inclusion and exclusion criteria in an attempt to guide future research on CAI. Although our study criteria were defined before this position statement, we believe our inclusion criteria to be to a large extent in line with the endorsed criteria (i.e. (1) significant ankle sprain, (2) 'giving way', recurrent sprains and feelings of instability, and (3) a self-reported foot and ankle function questionnaire). Furthermore, studies differ in included landing tasks, kinematic registration protocols and statistical analysis making comparison difficult. An overall limiting factor could be that, when looking at kinematics, only successful trials have been taken into account and that due to technical limitations data is gathered in a laboratory setting. This means that subjects are focused on the task at hand despite distractions or perturbations sometimes used. As subjects with CAI do not experience episodes of giving way continuously, the execution of this controlled landing task might obscure possible kinematic differences between subjects with CAI and healthy controls. It might be necessary to place the system into a state in which it is more challenged, i.e. a near episode of giving way. Although our study results did indicate higher feelings of instability and difficulty level during the performed tasks in subjects with CAI, no differences were found in lower limb kinematics. These subjective scales might not reflect the actual challenge imposed on the neuromuscular system or the actual challenge might not be discriminative in joint kinematics. Maybe induced fatigue is meaningful to be able to detect kinematic deviations during landing tasks.[6, 17] Also looking further into failed trials or kinematic control strategies might yield valuable information on CAI associated mechanisms.[14, 24, 38] Furthermore, although CAI has been associated with impaired proprioception, strength, and (supra)spinal motor control, a direct link between such impairments and altered kinematics has not been established yet.[19, 21] Therefore, more research is necessary to elucidate the role of lower limb kinematics in CAI.

Conclusion

The goal of our study was to provide a comprehensive overview of lower limb kinematics in subjects with CAI. Our results showed no altered lower limb kinematics in subjects with CAI compared to a healthy control group during a forward jump and side jump landing task. Therefore, these results do not support the hypothesis of kinematical deviations as part of a mechanism associated with CAI at this time.

Acknowledgements

No funding was received for this study and the results of the present study do not constitute endorsement by ACSM. The authors report no conflict of interest.

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