Title: Locomotive biomechanics in persons with chronic ankle instability and lateral ankle sprain copers.

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Abstract

Objectives: To compare the locomotive biomechanics of participants with chronic ankle instability (CAI) to those of lateral ankle sprain (LAS) copers.

Design: Cross-sectional study

Methods: Twenty-eight participants with CAI and 42 LAS copers each performed 5 self-selected paced gait trials. 3-D lower extremity temporal kinematic and kinetic data were collected for these participants from 200ms pre- to 200ms post-heel strike (period 1) and from 200ms pre- to 200ms post-toe off (period 2).

Results: The CAI group displayed increased hip flexion bilaterally during period 1 compared to LAS copers. During period 2, CAI participants exhibited reduced hip extension bilaterally, increased knee flexion bilaterally and increased involved limb ankle inversion. They also displayed a bilateral decrease in the flexor moment pattern at the knee.

Conclusions: Considering that all of the features which distinguished CAI participants from LAS copers were also evident in our previously published research (within 2-weeks following acute first-time LAS); these findings predicate a potential link between these features and long-term outcome following first-time LAS. Clinicians must be cognizant of the capacity for these movement and motor control impairments to cascade proximally from the injured joint up the kinetic chain and recognise the value that gait re-training may have in rehabilitation planning to prevent CAI.

Key words: ankle joint [MeSH]; biomechanical phenomena [MeSH]; kinematics [MeSH]; kinetics [MeSH]; gait [MeSH]; joint instability [MeSH]

Introduction

It has been posited that the high potential for recurrence following an initial lateral ankle sprain (LAS) injury during gait is predicated by inappropriate positioning of the lower extremity joints in the loading-unloading transitions between stance and swing.[1-4] These patterns materialise immediately following the injury[5], and may persist into chronicity.[6] Chronic ankle instability (CAI) is the name given to the cluster of chronic symptoms that may develop following an initial LAS, with ankle joint instability and LAS recurrence residing at the epicentre of this injury‘s chronic paradigm[7]. During walking gait, laboratory analyses have revealed that individuals with CAI exhibit a more inverted position of the foot at heel strike (HS)[2] and toe-off (TO)[1], as well as an increased rate of change in inversion over the course of the former event[1], compared to non-injured controls. In other research, it has been documented that individuals with CAI also exhibit increased ankle joint plantar flexion around HS and TO compared to non-injured controls.[3,4]

Recently however the value of comparing or matching a non-injured control to an individual with CAI has been questioned as the former does not possess the same injury exposure, thus undermining their suitability for such analyses.[8] This is of particular pertinence in light of the availability of a more appropriate comparison group: those individuals who sustain a LAS but do not develop the chronic sequalae of CAI (herein referred to as LAS copers) .[8] Such a comparison would provide added insight as to the _coping mechanisms‘ of gait motor control and movement that preside long-term outcome.[9] A recent position-statement by the International Ankle Consortium (IAC) has advocated the need for this comparison[7], while Wikstrom and Brown[10] have outlined the necessary inclusionary criteria for a LAS coper group.

A number of publications comparing individuals with CAI to LAS copers during components of the gait cycle have recently been published.[11,12] De Ridder et al.[11] delineated different components of motion at the ‗involved' (previously sprained) foot-ankle complex using a multi-segmental model and recorded no differences between CAI participants and LAS copers during the stance phase of gait. Brown et al.[12] in an analysis which included both ankle and knee motion, observed a reduction in joint angular displacement at the ankle in the sagittal plane in CAI participants compared to LAS copers during walking. These analyses combine to advance current understanding of the emergent movement and motor control patterns belying CAI or LAS coper status. However, the LAS copers recruited for these studies were not defined according to recently published recommendations.[10] Thus, we believe there is significant potential for expansion on these constructs with the use of a bilateral model of kinematic and kinetic parameters to evaluate participants with CAI in comparison to LAS copers around HS and TO.

Therefore, the aim of the current study was to perform an exploratory analysis of the locomotive kinematic and kinetic profiles of participants with CAI and those of a LAS coper group 1-year following first-time LAS injury.

Methods

All participants were recruited from a University affiliated hospital emergency department within 2-weeks of sustaining a first-time, acute LAS injury. Twelve months following recruitment, 83% (seventy-one) of the original eighty-six participants attended our laboratory to complete the current test protocol. Data has previously been published detailing an evaluation of these participants within 2-weeks[5] of recruitment completing the same protocol. The participant exclusion criteria have previously been described.[5] Furthermore, to be included in the study, participants must have reported to partake in a minimum of 1.5 hours of physical activity per week.

Self-reported ankle instability was assessed for all participants on arrival to the laboratory prior to completion of the current test protocol with the Cumberland Ankle Instability Tool (CAIT)[13]; individuals with a score of <24 were designated as having CAI[7] while participants with a score ≥24 were designated as LAS copers in the avoidance of false positives for this group.[14] To be designated as a LAS coper, participants also must have reported to have returned to pre-injury levels of activity and function, with no injury recurrence.[10] Secondly, the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) were utilised as a means to evaluate the level of self-reported disability, but was not used as an inclusion criterion for either group.

Based on the CAIT, twenty-eight participants were designated as having CAI, and forty-two as LAS copers. One participant was excluded from the original group of seventy-one because they scored ≥24 on the CAIT but reported having not returned to pre-injury levels of sport participation. Participant characteristics and questionnaire scores are presented for the seventy included individuals in Table 1. Participants provided written informed consent, and the study was approved by the University Human Research Ethics Committee. .

Collection methods for this study have been previously documented.[5] Briefly, gait data acquisition was made using 3 Codamotion cx1 units (Charnwood Dynamics Ltd, Leicestershire, UK). The Codamotion cx1 units were fully integrated with two AMTI walkway embedded force plates (Watertown, MA) and time synchronized. Participants were familiarised with the testing procedures prior to commencement and a neutral stance trial was used to align the participant with the laboratory coordinate system and to function as a reference position for subsequent kinematic analysis.[15] During testing, participants walked barefoot across the 10 m walkway at a self-determined speed. Five _clean‘ gait cycles, defined by both the participant‘s feet landing fully on each of the force plates, were identified and saved for future analysis. Prior to data analysis all values of force were normalised with respect to each subject‘s body mass (BM).

Kinematic data acquisition was made at 250 Hz and kinetic data at 1000 Hz. Kinetic and kinematic data were passed through a fourth-order zero phase Butterworth low-pass digital filter with 40Hz and 6-Hz cut-off frequencies respectively.[16] A full description of the kinematic model underlying this analysis has been previously published.[17] Internal joint moments at the hip, knee and ankle were calculated using a standard inverse dynamics approach.[18] Kinematic and kinetic data relating to two periods for both limbs were analysed using the Codamotion software: period 1 extended from 200ms pre-HS to 200ms post-HS (coinciding with terminal swing, HS, loading response and mid-stance) and period 2 extended from 200ms pre-toe off (TO) to 200ms post-TO (coinciding with terminal stance, pre-swing, TO and initial swing). These time windows were chosen for analysis as they are commonly used to investigate CAI-associated movement pattern anomalies during gait[2,3,6], likely because accurate positioning at HS and TO is conducive to safe locomotion. For example, increased plantar flexion as well as inversion of the ankle joint stand to increase ground reaction force moments about the sub-talar joint with significant potential for re-sprain of the injured ankle.[19,20]

A vertical component GRF threshold of 10N with the force plate was used to identify initial foot contact (for HS) and last foot contact (for TO).[21]

Time-averaged angular displacement (in 3-dimensions) and moment of force (in the sagittal plane) profiles were plotted for the hip, knee and ankle joints for each limb of all participants in the specified gait periods.[6] Frontal plane ankle joint moments were also calculated in the specified time-periods to identify the energetics contributing to the observed foot-position around HS and TO.

The average of participants‘ five trials for all variables was processed to compare group mean profiles (i.e. CAI *vs* LAS coper). For both the CAI and LAS coper groups, the limb to which the ankle sprain was incurred at the time of recruitment was labelled as __involved‘‘ and the opposite limb as __uninvolved‘‘.

Between-group differences in involved and uninvolved limb angular displacement and moment of force temporal profiles were tested for statistical significance using independent-samples t-tests for each data point for each period of gait. This mechanism of data analysis has been previously published.[2,5,6] The significance level for these temporal analyses was set a priori at $p < 0.05$.

Results

Between groups differences were noted in sagittal plane kinematics for the hip (periods 1 and 2; Figure 1A, Figure 1B) and knee (period 2; Figure 1C), and in frontal plane kinematics at the ankle (period 2; Figure 1D).

No differences were noted in the moment of force profiles for period 1. During period 2, between groups differences were noted at the knee only (Figure 2B).

Discussion

This study identified several movement patterns that distinguish CAI participants from LAS copers. During period 1, CAI participants displayed increased hip flexion bilaterally. During period 2 CAI participants displayed reduced hip extension (bilaterally), increased knee flexion (bilaterally) and increased ankle inversion (_involved‘ limb only). The underlying energetics of these movements was quantified with the moment of force profiles. On this basis, only during period 2 did CAI participants exhibit different motor control patterns to LAS copers, where a bilateral reduction in flexion moment at the knee was noted.

The participants in the current study were recruited within 2-weeks of sustaining a first-time acute LAS, and tested 1-year following recruitment wherein they were designated as CAI or LAS coper. Only recently have LAS copers started to be utilised as a comparison group for CAI participants [11,12], thus this study provides novel insight into the _coping‘ mechanisms in walking gait which may predicate outcome following first-time LAS injury via its analysis of time-homogenous CAI and coper cohorts.

With regards to the current results, the bilateral increase in hip flexion angle displayed by CAI participants, which persisted across almost the entirety of period 1 seems not to have manifested in the moment of force profiles (where no between-groups differences were evident). That an increase in hip flexion angle was not accompanied by alterations in its associated energetics may have been potentiated by three things. First, the forces that caused the observed kinematics were not analysed (i.e. they may have manifested outside the observed time-frames, or in different planes); second, and in recognition that it is futile to analyse the kinetic chain in its separate components, these differences could be reflective of changes at other lower extremity joints.[22,23] Finally, subtle kinematic strategies adopted elsewhere in the lower extremity may have compensated sufficiently and masked the kinetics required to enable these strategies. It is likely that the answer lies in a combination of these three potentialities. However, that the increase in hip flexion around HS was followed by a decrease in hip extension around TO in the CAI group can be intuitively linked and points to _flexor dominance‘ movements at this joint in this group. Similarly, the increase in knee flexion during period 2 may have been a necessary adjustment for a less flexed hip to enable TO.

Based on the current findings, it is possible that CAI participants develop proximal alterations in kinematic strategies following their injury[5], some of which are likely to play a role in the development of chronicity. While we did not observe any differences between CAI and LAS coper participants in the current study for some parameters, we believe these patterns are linked with those previously documented in these participants when they were compared to non-injured controls.[5] Namely, the aforementioned decrease in hip extension prior to TO in the CAI group compared to LAS copers in the current study (~12 degrees extension vs ~18-20 degrees extension) was previously evident in the LAS group compared to controls[5] (~12 degrees extension vs ~15-18 degrees extension). However, whereas in the acute paper this pattern was under lied by a reduction in the flexion moment at the hip[5], no such reduction was evident in the current study. This flexion moment normally serves to ‗pull‘ the extended hip forward in preparation for swing.[16] On this basis we previously hypothesised that because the hip of injured participants was less extended, less hip flexion moment was required to ‗pull‘ the hip forward.[5] Similarly we believed that the reduction in the plantar flexion moment or ‗push‘ produced at the ankle was linked with this hip position: because injured participants‘ hips were less extended, ‗push-off‘ at the ankle and the ‗pull‘ at the hip were both reduced.[5] This combined to lend to a hypothesis that injured participants were minimising joint loading by avoiding the extremes of joint motion and the motor patterns required to achieve these.[5] Alternatively, the injured participants may also have been unable to achieve the necessary closed kinetic chain dorsiflexion necessary just prior to TO to achieve adequate hip extension due to pain or swelling. With regard to the current study, the subsidence of the motor patterns underpinning the reduction in hip extension may represent the continuation of some of the "learned" movement patterns which manifested following injury[5] (and which may have preceded it), but which have since become redundant. Furthermore, the better outcome of LAS copers may be contingent on the –re-learning‖ of pre-injury gait strategies, or the development of new ones comparable to those of non-injured controls.

The bilateral increase in knee flexion that CAI participants displayed during period 2 was predicated by what is now a feature common with the 2-week[5] paper: a decrease in the knee flexion moment ~ 200-180ms pre-TO. At the terminal part of stance the knee transitions from an extended to a flexed position in preparation for swing. The extensor moment dominance at the knee during this time period (following TO) represents eccentric contraction of the quadriceps to minimise the amount of flexion that transpires. [16,24]Whether the reduced knee flexion moment in the CAI group is representative of a more rigid strategy to accommodate _push-off‘ in late stance or is a corollary to the decrease in hip extension is unknown based on the current data. The roles of the lower extremity musculature in this mechanism may be relevant, as could the associated ground reaction forces; future analyses are required to confirm these speculations. Furthermore, the presence of bilateral differences (at the hip and knee) in the current CAI cohort may reflect the propensity for cyclical movements such as gait to illicit global movement alterations in the maintenance of locomotive safety and efficiency[22], or an injury induced alteration in central control mechanisms[25], or both.

One of the _unilateral features‘ displayed by CAI participants was a position of greater ankle joint inversion following TO, something that was evident in these participants when they were grouped together in the 2-week paper. [5] At 2-weeks following their initial LAS, participants adopted a bilateral position of ~ 2 degrees of inversion around TO[5]; this was seemingly magnified (to ~ 3-5 degrees) in the CAI group in the current study and provokes the question as to whether this motor pattern preceded their sprain, or manifested soon after and subsequently predicated their current condition.

To our knowledge, this is the first instance in which an increased position of ankle joint inversion has been observed in CAI participants compared to LAS copers during walking gait. However, Brown et al[12]did previously detail greater overall inversion displacement in a CAI cohort compared to copers, which supports our findings. Increased inversion is a feature that has been reported previously when comparing patients with CAI to non-injured controls during walking[2,6] and running[1] and is considered one of the primary contributory anomalous patterns that presides injury recurrence. A more inverted position around the sub-talar joint axis is recognised as potentiating injury recurrence by influencing the capacity for an external load to force the ankle into the extremes of this motion[20] wherein the normally protective bony restrictions are disabled.[26] CAI participants have been shown to activate their peroneus longus (PL) prior to HS earlier than non-injured controls.[27,28] If this finding is projected to the current cohorts, and because it distinguishes CAI participants from LAS copers, then it may have the apparently paradoxical effect in preventing the normal medial displacement of the centre of pressure during early stance, which then continues into TO[5,29] _ENREF_39, thus manifesting in greater inversion. Participants with a history of LAS have previously been shown to apply greater loading through the lateral column of their foot during the latter part of stance[28,30], which lends to this theory. Furthermore, we previously hypothesised that the damage to the calcaneofibular ligament which likely coincided with the initial LAS event increased the available morphological range at the ankle.[5] Although mechanical testing for ligamentous laxity was not used to stratify LAS participants in the current study or those previously described (which is in line with the recommendations recently published by the IAC[7]), CAI participants may have had greater mechanical laxity, equating to greater morphological compromise and thus greater inversion around TO.

While our results are important, this study is not without limitations. Firstly, we have speculated about a number of key movement and motor control patterns which may or may not predict outcome. This paper cannot confirm or refute these speculations due to its design. However, this analysis is part of a larger longitudinal one designed to tackle this issue, and will likely inform the choice of dependent variables for the latter investigation. Second, while we believe we have presented an analysis of what we consider to be the key loading-unloading phases of the gait cycle, it is possible that an analysis of the entire gait cycle may have yielded additionally informative information relevant to the LAS outcome paradigm. However, these time periods were chosen on the basis of previously published research in this area [2,5,6]_ENREF_17, and clearly chart important events around which the motor apparatus interacts with its external environment as it transitions between open and closed kinetic chain systems.

Conclusions

These findings predicate a potential link between features which manifest early in the pathological process of LAS and long-term outcome. Clinicians must be cognizant of the capacity for these movement and motor control impairments to cascade proximally from the injured joint up the kinetic chain and recognise the value that gait re-training may have in rehabilitation planning to prevent CAI.

Practical implications

- Aberrant kinematics and energetics characterize individuals with acute lateral ankle sprain, some of which persist into chronicity.
- These persistent aberrancies are evident bilaterally and at joints proximal to the injured ankle
- Gait retraining may be an important component of rehabilitation following lateral ankle sprain injury.

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to report.

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Figure legends

Figure 1. Average $\pm$SEM) hip flexion-extension (A: period 1; B: period 2), knee flexion-extension (C: period 2) and ankle inversion-eversion (D: period 2) angular displacement during periods 1 and 2 of the gait cycle (200ms pre-HS/TO to 200ms post-HS/TO) for the involved and uninvolved limbs of CAI and coper groups. Flexion and inversion are positive; Extension and eversion are negative. Black line with arrow = HS/TO. Shaded area = area of statistically significant difference between CAI and LAS coper groups. Abbreviations: HS = heel strike; TO = Toe off; CAI = chronic ankle instability; LAS = lateral ankle sprain.

Figure 2. Average $\pm$SEM) hip flexion-extension (A), knee flexion-extension (B), ankle plantarflexion-dorsiflexion (C) and ankle inversion-eversion (D) moments of force during period 2 of the gait cycle (200ms pre-TO to 200ms post-TO) for the involved and uninvolved limbs of CAI and coper groups. Extension, plantar-flexion and inversion moments are positive; Flexion, dorsiflexion and eversion moments are negative. Black line with arrow = TO. Shaded area = area of statistically significant difference between CAI and LAS coper groups. Abbreviations: TO = Toe off; CAI = chronic ankle instability; LAS = lateral ankle sprain.

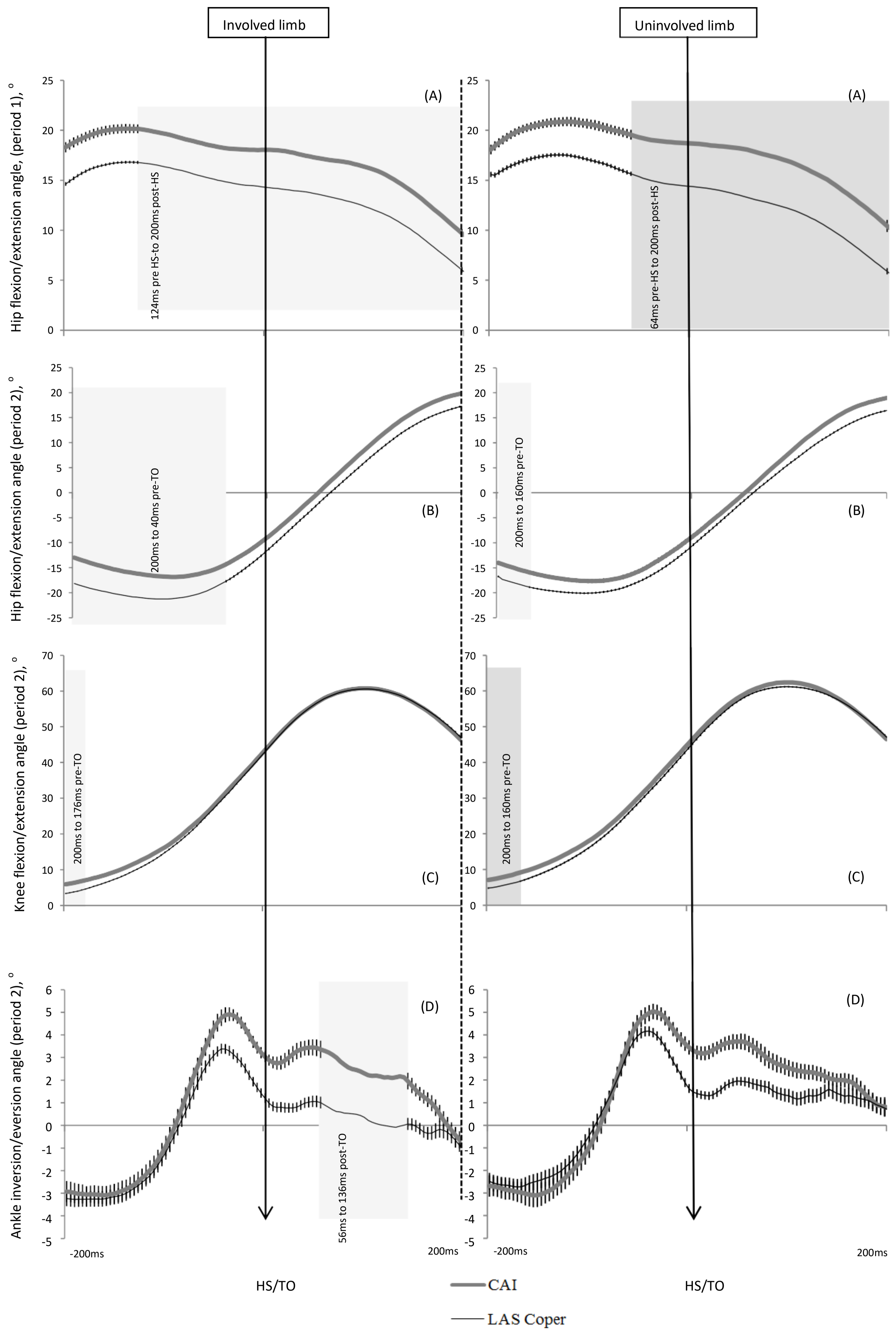
Table 1

Table 1. Participant anthropometrics, self-reported disability and function questionnaire scores (mean and 95% CI) for the involved limb of CAI and LAS coper groups.

		Anthropometrics:								Questionnaires					
		Gender		Age (years)		Body mass (kg)		Height (m)		CAIT (/30)		FAAMadl (%)		FAAMsport (%)	
	n	Males	Females	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI
CAI	28	17	11	23.21 (4.31)	21.62 to 24.81	75.53 (14.54)	70.14 to 80.91	1.72 (0.08)	1.69 to 1.75	22.32 (1.85)	20.03 to 23.61	95.71 (1.35)	93.62 to 97.81	85.50 (6.11)	79.19 to 91.81
LAS coper	42	26	16	22.74 (4.23)	21.42 to 24.07	73.43 (12.01)	69.66 to 77.20	1.73 (0.10)	1.70 to 1.76	27.88 (2.07)	27.23 to 28.52	98.01 (3.73)	96.85 to 99.16	90.55 (15.83)	85.64 to 95.45

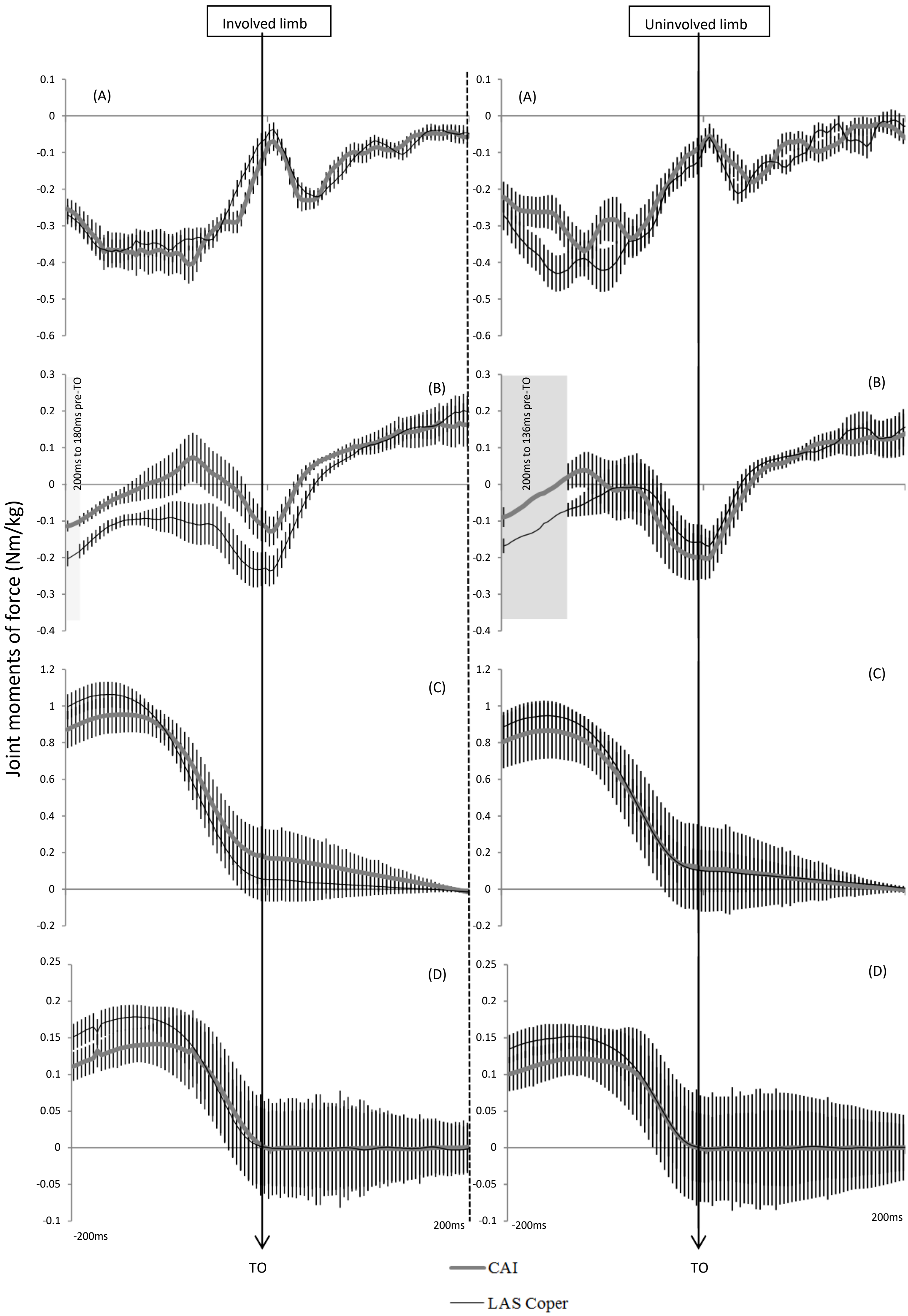
Abbreviations: CAI = chronic ankle instability; LAS = lateral ankle sprain; CAIT = Cumberland Ankle Instability Tool; FAAMadl = activities of daily living subscale of the Foot and Ankle Ability Measure; FAAMsport = sport subscale of the Foot and Ankle Ability Measure. CI = confidence interval.

Figure 1



Involved limb
Uninvolved limb
Hip flexion/extension angle, (period 1), °
124ms pre HS-to 200ms post-HS
64ms pre-HS to 200ms post-HS
(A)
Hip flexion/extension angle (period 2), °
200ms to 40ms pre-TO
200ms to 160ms pre-TO
(B)
Knee flexion/extension angle (period 2), °
200ms to 176ms pre-TO
200ms to 160ms pre-TO
(C)
Ankle inversion/eversion angle (period 2), °
56ms to 136ms post-TO
(D)
-200ms
200ms
HS/TO
CAI
LAS Coper

Figure 2


Involved limb
Uninvolved limb
Joint moments of force (Nm/kg)
(A)
(A)
(B)
(B)
(C)
(C)
(D)
(D)
200ms to 180ms pre-TO
200ms to 136ms pre-TO
-200ms
200ms
-200ms
200ms
TO
TO
CAI
LAS Coper