Scand J Med Sci Sports 2014: ••: ••–••
doi: 10.1111/sms.12390

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Single-leg drop landing movement strategies 6 months following first-time acute lateral ankle sprain injury

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Accepted for publication 18 November 2014

No research exists predicating a link between acute ankle sprain injury-affiliated movement patterns and those of chronic ankle instability (CAI) populations. The aim of the current study was to perform a biomechanical analysis of participants, 6 months after they sustained a first-time acute lateral ankle sprain (LAS) injury to establish this link. Fifty-seven participants with a 6-month history of first-time LAS and 20 noninjured participants completed a single-leg drop landing task on both limbs. Three-dimensional kinematic (angular displacement) and sagittal plane kinetic (moment of force) data were acquired for the joints of the lower extremity, from 200 ms pre-initial contact (IC) to 200 ms post-IC. Individual joint stiffnesses and the peak magnitude of the vertical component of the ground reaction force (GRF) were also computed. LAS participants displayed increases in hip flexion and ankle inversion on their injured limb (*P* < 0.05); this coincided with a reduction in the net flexion-extension moment at the hip joint, with an increase in its stiffness (*P* < 0.05). There was no difference in the magnitude of the peak vertical GRF for either limb compared with controls. These results demonstrate that altered movement strategies persist in participants, 6 months following acute LAS, which may precipitate the onset of CAI.

The biomechanics literature is replete with a large quantity of investigations, which have performed laboratory analyses of dynamic movement tasks in cohorts with musculo-skeletal impairment. For example, researchers have sought to evaluate the movement patterns of participants with a history of lateral ankle sprain (LAS) using dynamic movement tasks across the spectrum of this injury: those who have recovered fully 1 year following their acute LAS (known as 'copers'; Brown et al., 2008, 2009, 2012), those who are suffering the chronic sequelae associated with LAS [collectively described by the umbrella term of 'chronic ankle instability' (CAI)] for a minimum of 1 year following the first acute episode (Brown et al., 2006, 2008, 2010, 2011, 2012; Delahunt et al., 2006; Gribble & Robinson, 2009; Terada et al., 2013), and those with a current acute LAS injury (Doherty et al., 2014b, in press). There is a gap in the biomechanics literature, however, as the movement patterns, which characterize individuals after they have sustained an acute LAS injury, but have yet to develop CAI or proceed to full recovery, have not been characterized or established to date. We believe it to be plausible for example that participants with a 6-month history of a first-time LAS injury constraint might display coordination strategies evolved from those adopted in the acute phase of their injury (Doherty et al., 2014b) and potentially akin to their coper and CAI counterparts.

Typically, the periods of interest for researchers during dynamic movement tasks include those in which movement is terminal and the final constraint of the task is relative stasis (such as in drop landings), or those in which acceleration is manipulated by the participant, and movement is nonterminal (such as is in drop jumps and cutting maneuvers; Schmitz & Shultz, 2010). A number of recently published laboratory analyses have revealed the dichotomy of demands dictated by the terminal and nonterminal components of a given dynamic movement task (Bates et al., 2013a,b). Terminal and non-terminal jumping movement tasks are utilized in laboratory analyses of participants with a history of ankle sprain as they are seen to mimic the demands of activities which typically lead to injurious events; for example, participants of sports such as volleyball and basketball are at a significantly greater risk for LAS injury compared with participants of sports such as soccer or field hockey (Doherty et al., 2014d), likely due to the greater jumping and landing requirements of the former sports. Typically, these types of analyses quantify the organization and control of the motor apparatus by the sensorimotor system [otherwise known as coordination (Bernstein, 1967)] using kinematic and kinetic profiling. It has been argued that these studies, which quantify the energetics of coordination, are the most informative of all biomechanical analyses of musculo-skeletal impairment because they conceptualize the force responsible for producing observed movement patterns (Norcross et al., 2010).

For example, a recent energetic analysis completed in our laboratory during a terminal movement landing task elucidated that participants with a first-time acute LAS injury constraint rely on their hip joint complex to absorb the forces of landing more so than noninjured participants (Doherty et al., 2014b). They do so by adopting a position of greater hip flexion during the landing descent with reduced flexion moment during floor contact, potentially in the aim of reducing the 'stiffness' of landing (Doherty et al., 2014b). These findings illustrated the capacity of the sensorimotor system to reweight dependence on each of the lower extremity joints according to the demands of the task and the immediate capabilities of the individual, in what is known as the 'energy absorption strategy' (Norcross et al., 2010). Furthermore, the bilateral nature of the observations made in this analysis lends to the hypothesis that acute ankle sprain may cause impairment of centrally mediated motor control pathways (Hass et al., 2010; Wikstrom et al., 2010).

Thus, in contrast to ankle sprain copers (Wikstrom & Brown, 2014), it is likely that the sensorimotor system of individuals suffering from CAI develop inappropriate coordination strategies, which fail to effectively exploit the degrees of freedom available to their motor apparatus using suitable energetics (Brown & Mynark, 2007). Evaluating participants with a 6-month history of first-time acute LAS may elucidate certain coordination and energy absorption strategies, which may persist following acute injury, and which may be precursors to those that belie CAI or coper status.

Therefore, the aim of this study was to perform a biomechanical energetic analysis of a group with a 6-month history of ankle sprain injury during a terminal movement, drop land (DL) task. The current study is in continuation of one previously described (Doherty et al., 2014b), which together form part of a larger study on the coordination strategy predictors of CAI or coper status during a terminal landing task. For the current study, we hypothesized that participants with a 6-month history of first-time LAS would display movement patterns similar to their acutely injured counterparts, when compared with a noninjured group: (a) they would adopt a position of increased hip flexion during landing descent, which would persist into floor contact on both their previously injured, and noninjured limbs; (b) this would manifest in a reduction in the flexion moment of the hip moment of force profile, thus resulting in greater overall hip joint stiffness compared with controls; (c) this hip-dominant strategy would be conducive to a reduction in the peak vertical ground reaction force (vGRF) of landing. Furthermore, in light of the evidence presented during a similar task in CAI populations, we hypothesized that the group with a 6-month history of LAS would display positions of increased knee flexion (Caulfield & Garrett, 2002) and ankle inversion (Delahunt et al., 2006) during landing.

Methods

Design

As part of the larger study conducted in our laboratory, 57 participants (34 males and 21 females, mean age of 22.6 years, mean height of 1.72 meters, mean body mass of 74.7 kg) were recruited at convenience from a university-affiliated hospital emergency department (ED) within 2 weeks of sustaining a first-time acute LAS injury, and attended a single testing session 6 months after sustaining this injury in which all data for this study were acquired. On discharge from the ED, all LAS participants were provided with basic advice on applying ice and compression for one week: they were each encouraged to weight-bear and walk within the limits of pain. Activities of daily living were encouraged.

Testing procedures for these participants in the acute phase of their injury have previously been reported (Doherty et al., 2014b). An additional convenience group of 20 participants (15 males and five females, mean age of 22.6 years, mean height of 1.73 meters, mean body mass of 71.4 kg) with no prior history of LAS was recruited from the hospital catchment area population using posters and flyers to act as a control group. All participants were at least recreationally active, reporting a minimum of 1.5 h of cardiovascular activity per week. Recruitment of all participants was completed between March 1, 2012 and the September 29, 2013. Participants provided written informed consent on arrival to the testing laboratory and the study was approved by the university's institutional review board.

Instrumentation

On arrival to the testing site, all participants were required to complete two questionnaires: the Cumberland Ankle Instability Tool (CAIT) was used to assess overall ankle joint function and symptoms (Hiller et al., 2006), and the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) were used to quantify ankle-related function, patient reported symptoms and functional ability (Carcia et al., 2008).

Collection methods for this study have been previously documented (Doherty et al., 2014b). Briefly, following completion of the questionnaires, each participant was instrumented with the Codamotion bilateral lower limb gait setup (Charnwood Dynamics Ltd, Leicestershire, UK) and asked to perform three DLs on both limbs, following a practice period. The DL task began with participants standing barefoot on a 0.4 m high platform with their test leg initially held in a non-weightbearing position and their knee flexed. Participants were then required to drop forward onto the test leg, landing on a force plate in front of the platform. Upon landing, participants were required to balance as quickly as possible on the test leg and hold this position for approximately 4–6 s. Vertical displacement of the sacrum at the beginning of each trial was assessed following completion. This was performed to ensure that participants stepped off the platform as opposed to jumping upward.

Kinematic data acquisition during trials of the DL was made at 200 Hz using three Codamotion cx1 units and kinetic data at 1000 Hz using two fully integrated AMTI (Watertown, Massachusetts, USA) walkway embedded force plates. The Codamotion cx1 units were time synchronized with the force plates. Kinematic data were calculated by comparing the angular orientations of the coordinate systems of adjacent limb segments using the angular coupling set "Euler Angles" to represent clinical rotations in three dimensions (Winter, 2009). Marker positions within a Cartesian frame were processed into rotation angles using vector algebra and trigonometry (CODA mpx30 User Guide, Charnwood Dynamics Ltd). A neutral stance trial was recorded for each participant prior to completion of the DL protocol and served as a reference position for subsequent kinematic data analyses and to align the subject with the laboratory coordinate system (Wu et al., 2002). The variables of interest were identified during the period from 200 ms pre-initial contact (IC) to 200 ms post-IC for the three successful DL trials for each subject on each limb. Kinematic and kinetic data were analyzed using the Codamotion software and then converted to Microsoft Excel file format with the number of output samples per trial set at 100 + 1 in the data-export option of the Codamotion software, which represented the timeframe of interest during the DL trial as 100%, for averaging and further analysis. Thus, 1% of a DL trial represented a 4 ms time interval. GRF data were passed through a third-order Butterworth low-pass digital filter with a 20-Hz cut-off frequency (Winter, 2009).

The vertical component of GRF (force plate registered vertical GRF greater than 10 N) was used to identify IC.

Time-averaged three-dimensional angular displacement profiles for the hip (flexion-extension; adduction-abduction; internal-external rotation), knee (flexion-extension; varus-valgus; internal-external rotation), and ankle joints (dorsiflexion-plantar flexion; inversion-eversion; foot internal-external rotation) were calculated for each limb of all participants from 200 ms pre-IC to 200 ms post-IC. Maximum flexion for the hip, knee, and ankle was calculated as the difference between the joint angle at ground contact and the peak joint angle.

Inverse dynamics were then used to calculate time averaged, sagittal plane hip, knee, and ankle moments from the kinematic and force plate data.

Sagittal plane hip, knee, and ankle torsional joint stiffnesses were calculated as the change in normalized net internal moment (Nm) divided by the change in angular position (degrees) from initial contact to peak flexion excursion (Nm/kg/degrees) during the defined landing phase (Farley & Morgenroth, 1999; Schmitz & Shultz, 2010).

Finally, absolute peak magnitude of the vertical component of the GRF within the first 200 ms post-IC was also calculated for all participants. Prior to data analysis, all values of force were normalized with respect to each subject's body mass (BM).

Statistical analyses

For the LAS group, the limb with the recently incurred LAS was labeled as "involved" and the noninjured limb as "uninvolved." In all cases, the limbs in the control group were side matched to the LAS group; for each control subject, one limb was assigned as "involved" and one as "uninvolved" so that an equal proportion of right and left limbs were classified as "involved" and "uninvolved" in both the LAS and control groups.

To determine whether the LAS group would have persistent disability and poorer self-reported function, scores on the CAIT and subscales of the FAAM were compared with the control group using a multivariate analysis of variance. The independent variable was group (LAS vs control). The dependent variables were CAIT score, FAAMadl score, and FAAMsport score for the involved limb. The significance level for this analysis was set a priori with a Bonferroni adjusted alpha level of $P < 0.017$.

Between-group differences in involved and uninvolved limb three-dimensional, time-averaged angular displacement profiles and sagittal plane moment of force profiles for the hip, knee, and ankle were tested for statistical significance using independent-samples *t*-tests for each data point. The significance level for these analyses was set *a priori* at $P < 0.05$ (Hopkins et al., 2009). Effect sizes were not calculated for the temporal kinematic and kinetic profiles secondary to the number of separate comparisons for each variable.

Independent samples, two-sided *t*-tests were undertaken to compare matched limbs (LAS involved vs control involved; LAS uninvolved vs control uninvolved) for significant differences in sagittal plane hip, knee, and ankle torsional stiffness in the time interval from IC to 200 ms post-IC, and differences in the magnitude of the peak vertical GRF in the time interval from IC to 200 ms post-IC during the DL task. The significance level for these analyses was set *a priori* at $P < 0.025$ (2 × limb).

Associated effect sizes (η^2) were calculated for all discrete variables with 0.01 = small effect size, 0.06 = medium effect size and 0.14 = large effect size. (Cohen, 1988) All statistical analyses were performed with IBM SPSS Statistics 20 (IBM Ireland Ltd, Dublin, Ireland).

Results

With regard to the questionnaires, there was a statistically significant main effect for the combined dependent variables, F (3, 63) = 14.80, $P < 0.01$, Wilks' lambda = 0.59, partial eta squared = 0.41. The means and standard deviations of the CAIT and subscales of the FAAM for the LAS and control groups are presented in Table 1.

Time-averaged three-dimensional kinematic profiles comparing matched limbs (LAS involved vs control involved; LAS uninvolved vs control uninvolved) revealed that the LAS group displayed altered movement patterns compared with control participants in sagittal plane hip motion on both limbs, sagittal plane knee motion on the uninvolved limb, and frontal plane ankle motion on the involved limb. Kinematic profiles for the hip, knee and ankle joints are detailed in Figs 1–3, respectively.

Time-averaged sagittal plane kinetic profiles comparing match limbs (LAS involved vs control involved; LAS uninvolved vs control uninvolved) revealed between-group differences for the hip moment profile on the involved limb only. Sagittal plane kinetic profiles for the hip, knee, and ankle are presented in Fig. 4.

There was significantly greater sagittal plane hip joint stiffness on the involved limb in the LAS group

Table 1. Participant self-reported function and disability questionnaire scores (mean ± SD) for the involved limb of LAS and control groups

Group	CAIT (/30)	FAAMadl (%)	FAAMsport (%)
LAS	21.44 ± 5.90[a]	95.78 ± 5.82[a]	83.72 ± 13.41[a]
Control	30 ± 0.00	100 ± 0.00	100 ± 0.00

[a]Significantly different from control group.

CAIT, Cumberland Ankle Instability Tool; FAAM, Foot and Ankle Ability Measure; LAS, lateral ankle sprain.

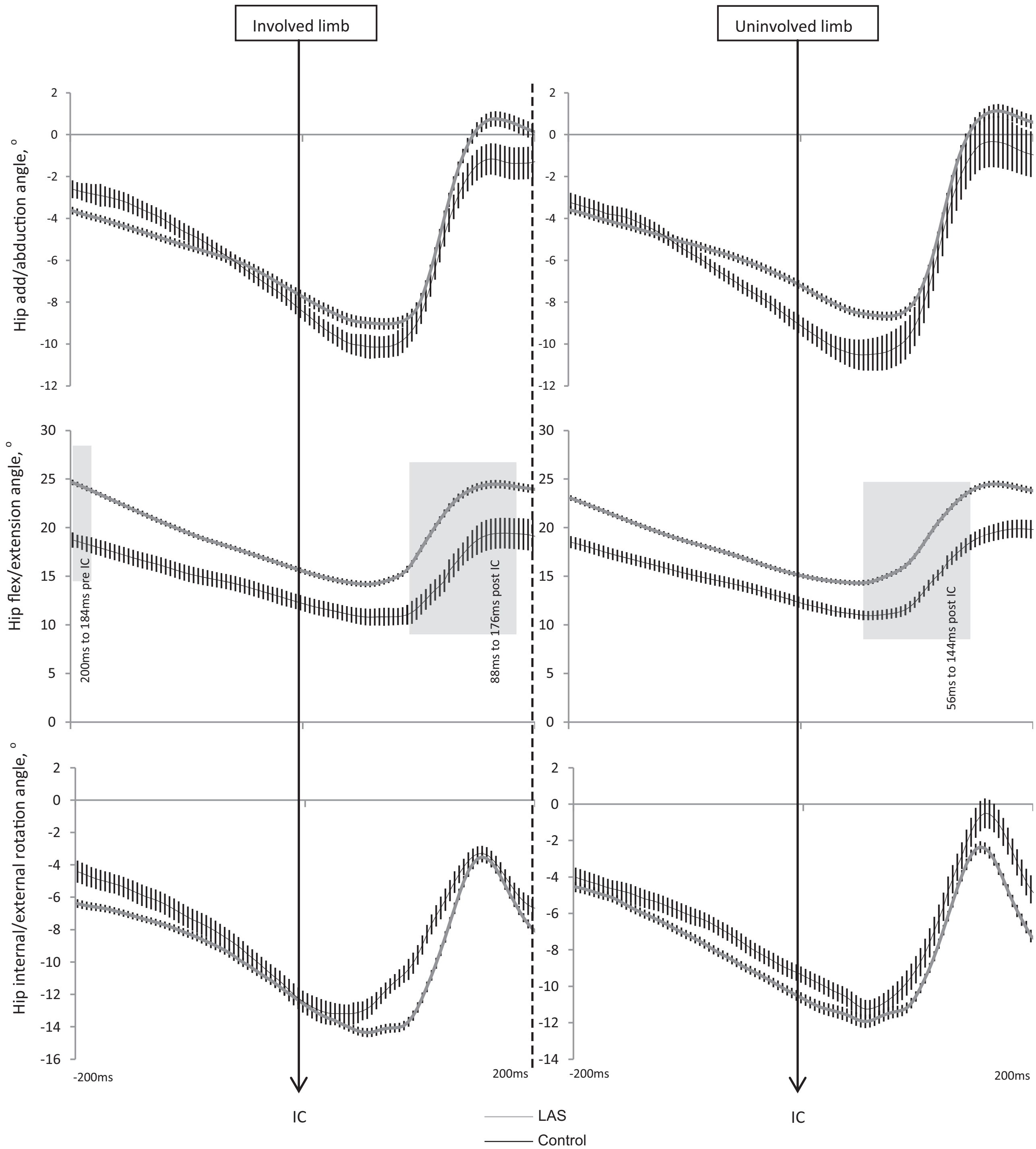

Fig. 1. Hip joint adduction-abduction, flexion-extension, and internal-external rotation during performance of the drop land task from 200 ms pre-IC to 200 ms post-IC for the involved and uninvolved limbs of LAS and control groups. Adduction, flexion, and internal rotation are positive; abduction, extension, and external rotation are negative. Values are mean ± SEM. Black line with arrow = initial contact (IC). LAS, lateral ankle sprain. Shaded area = area of statistical significance.

compared with the control group in the time period from IC to 200 ms post-IC (Table 2) based on the a priori *P*-value. Stiffness values for the involved and uninvolved limbs are depicted in Fig. 5.

There was no significant difference in the magnitude of the peak vertical GRF in the 0–200 ms post-IC time interval for either the involved or uninvolved limbs (Table 3).

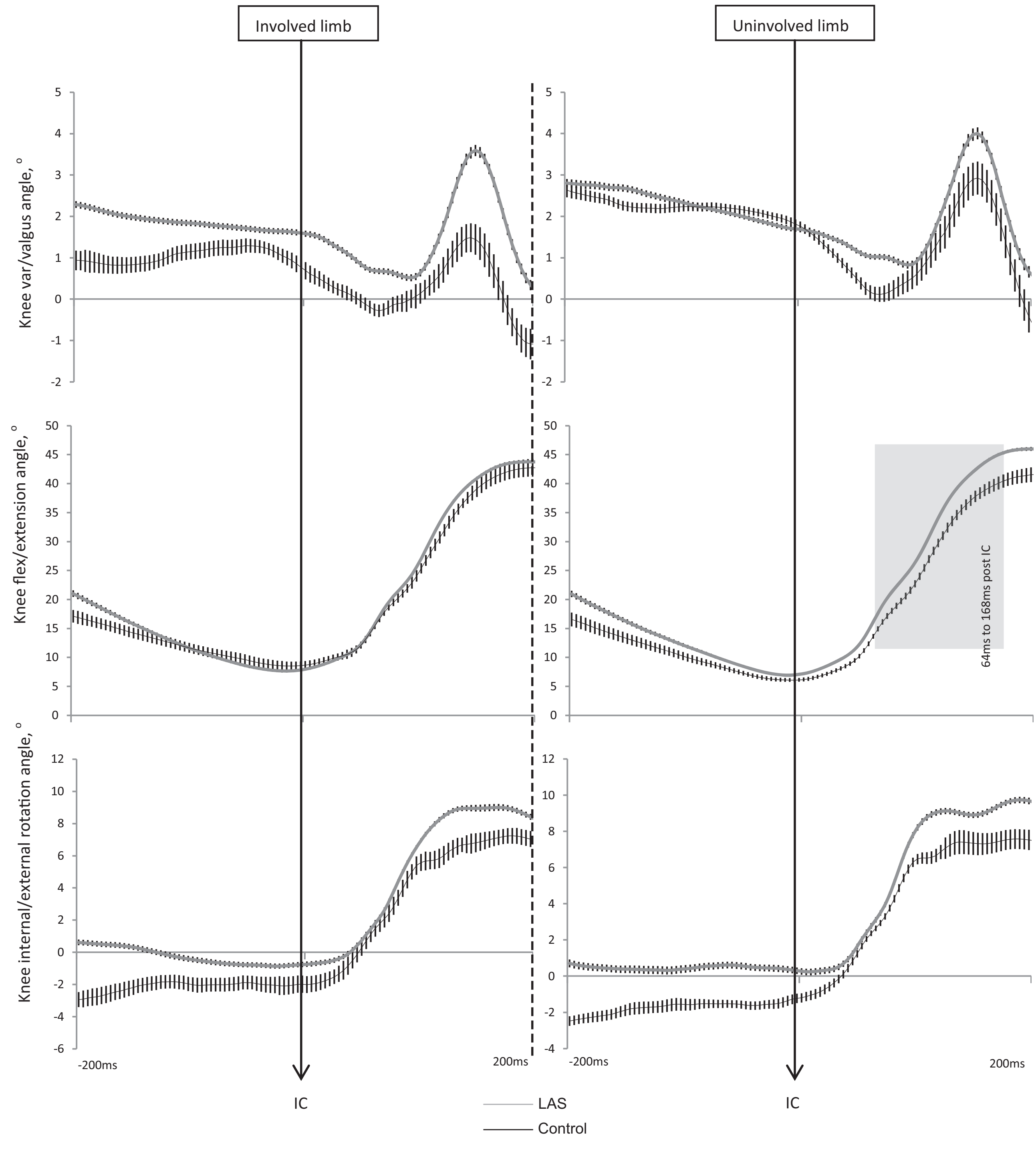

Fig. 2. Knee joint varus-valgus, flexion-extension, and internal-external rotation during performance of the drop land task from 200 ms pre-IC to 200 ms post-IC for the involved and uninvolved limbs of LAS and control groups. Varus, flexion, and internal rotation are positive; valgus, extension, and external rotation are negative. Values are mean ± SEM. Black line with arrow = initial contact (IC). LAS, lateral ankle sprain. Shaded area = area of statistical significance.

Discussion

The findings of the current study both confirm and rebuke our experimental hypotheses. The participants with a 6-month history of first-time LAS injury displayed movement patterns and energetics akin to when they were acutely injured and to their CAI counterparts. Specifically, they displayed bilateral increases in hip flexion and reduced post-IC hip flexion moment on the involved limb, which were both noted in this group in the acute phase of their injury (Doherty et al., 2014b). They also exhibited increased pre-IC ankle inversion and knee flexion, which were observed in CAI populations by Delahunt et al. and Caulfield et al., respectively (Caulfield & Garrett, 2002; Delahunt et al., 2006).

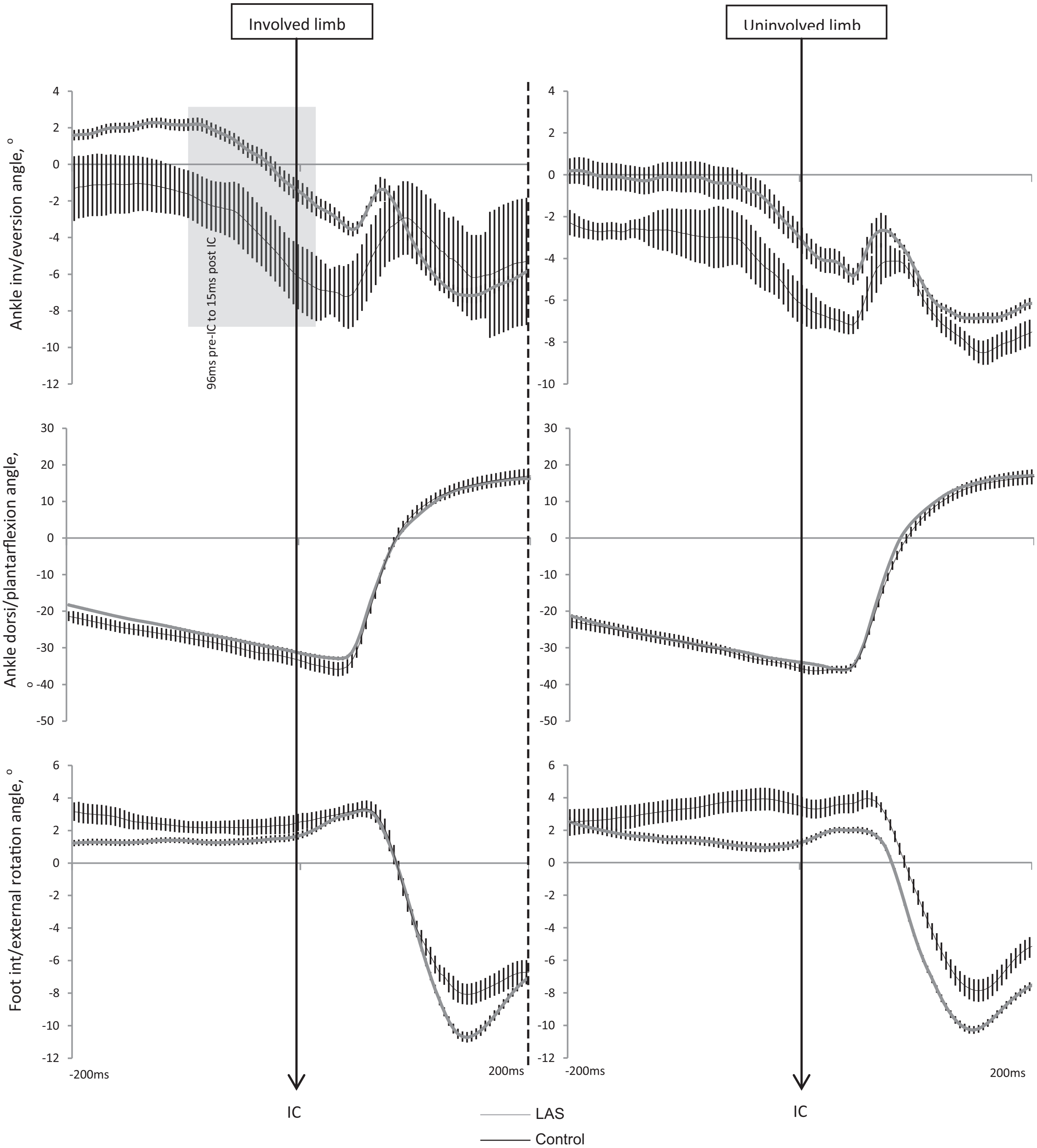

Fig. 3. Ankle joint inversion-eversion, dorsiflexion-plantar flexion, and foot internal-external rotation during performance of the drop land task from 200 ms pre-IC to 200 ms post-IC for the involved and uninvolved limbs of LAS and control groups. Inversion, dorsiflexion, and internal rotation are positive; eversion, plantar flexion, and external rotation are negative. Values are mean ± SEM. Black line with arrow = initial contact (IC). LAS, lateral ankle sprain. Shaded area = area of statistical significance.

However, a number of the patterns of energy absorption displayed by these injured participants have either not been reported during a terminal landing task (increased stiffness at the hip joint), or were contrary to previous findings by Doherty et al. 2014b [no reduction in the peak vGRF. Furthermore, because the confidence interval of the difference did not cross zero for the between-groups comparison of hip joint stiffness on the uninvolved limb and the effect size was moderate, we would consider it probable that the observed difference was meaningful.

These coordination and energy absorption strategies can be interpreted as the continuation of coping strategies adopted in the acute phase of injury (Doherty et al.,

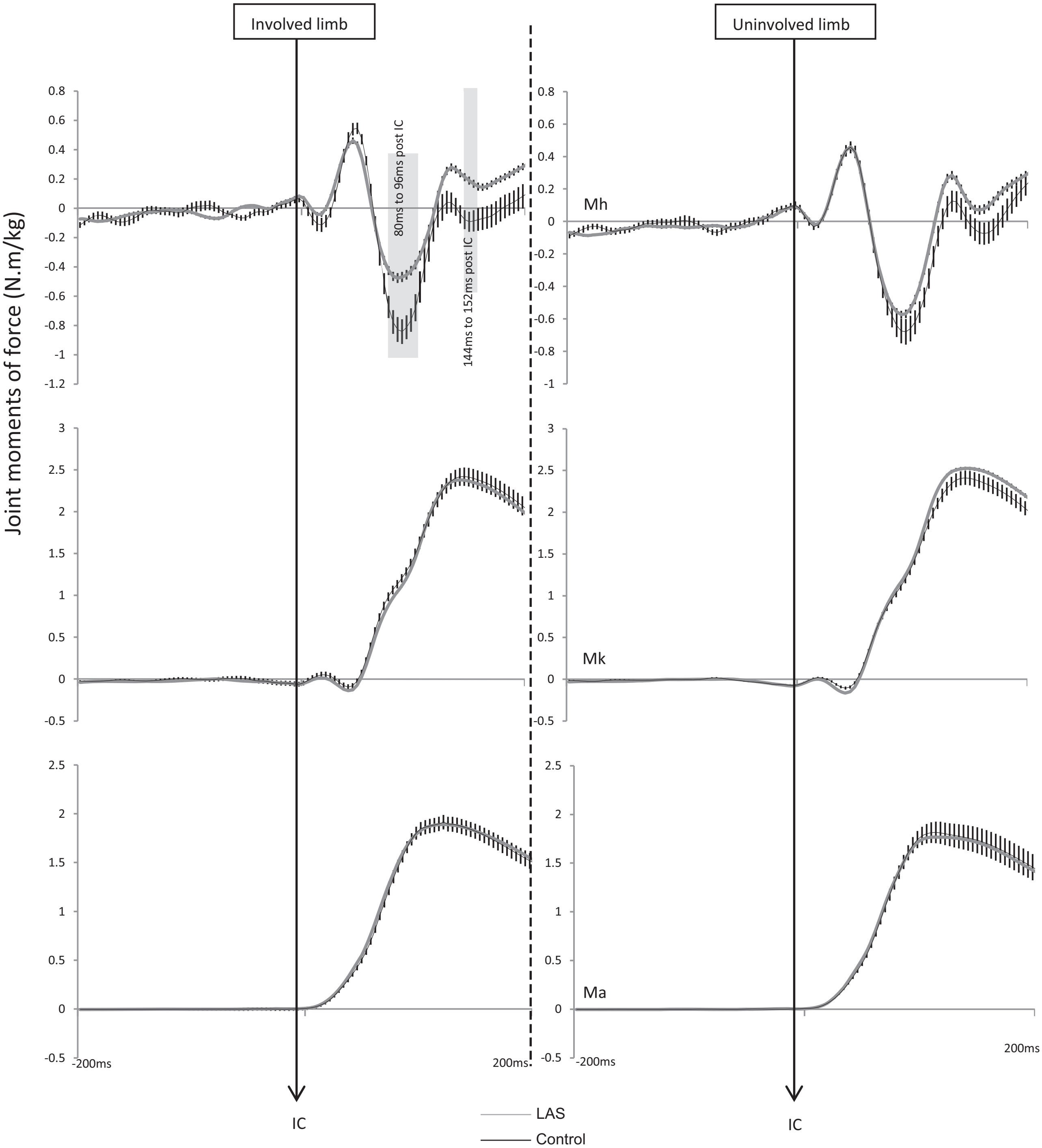

Fig. 4. Sagittal plane joint moment-of-force profiles for the hip, knee, and ankle during performance of the drop land task from 200 ms pre-IC to 200 ms post-IC for the involved limb of LAS and control groups. Extension and plantar flexion moments are positive; flexion and dorsiflexion moments are negative. Values are mean ± SEM. Black line with arrow = initial contact (IC). LAS, lateral ankle sprain. Shaded area = area of statistical significance. Mh , hip moment; Mk, knee moment; Ma, ankle moment.

2014b), in light of the persistence of reduced function reported by the LAS group (based on the CAIT and subscales of the FAAM). Whether the emergence of these coping strategies following injury is contingent with complete recovery or chronicity is unknown based on the current findings, however, this study is part of a larger longitudinal analysis designed to clarify this.

Importantly, in analyzing the results of the current study and those reported in previously mentioned publications of participants across the spectrum of LAS injury (CAI, coper, and acutely injured participants) a direct comparison to the coordination and energetics that characterize these groups must be performed with caution if the prescribed task is different

Table 2. Mean ± SD values, *P*-values, mean difference, 95% confidence interval (CI) of the difference, and associated effect sizes for sagittal hip, knee, and ankle torsional stiffnesses (Nm/kg/degrees)

Limb		LAS		Control				95% CI of the difference		
		Mean	SD	Mean	SD	*P*	Mean difference	Lower	Upper	η^2
Involved	Hip	0.01	0.06	−0.06	0.09	0.01[a]	0.07	0.02	0.11	0.16
	Knee	0.07	0.02	0.08	0.03	0.20	−0.01	−0.02	0.01	0.03
	Ankle	0.04	0.01	0.04	0.02	0.97	0.00	−0.01	0.01	0.00
Uninvolved	Hip	0.00	0.05	−0.04	0.07	0.03	0.04	0.00	0.08	0.08
	Knee	0.07	0.02	0.08	0.02	0.58	0.01	−0.02	0.01	0.01
	Ankle	0.03	0.01	0.03	0.01	0.88	0.00	−0.01	0.01	0.00

Stiffness values were calculated in the time period from initial contact to 200 ms post-initial contact during the drop land task.
[a]Indicates statistically significant difference.
LAS, lateral ankle sprain; CI, confidence interval; SD, standard deviation.

Table 3. Statistical output of peak post-IC vGRF analysis for LAS and control participants on their involved and uninvolved limbs during the DL task with associated effect sizes

Limb	LAS		Control						
	Mean (× BW)	SD	Mean (× BW)	SD	*P*	Mean difference	95% CI of the difference		η^2
Involved	2.44	0.23	2.48	0.24	0.48	−0.04	−0.17	0.08	0.01
Uninvolved	2.44	0.20	2.51	0.24	0.20	−0.07	−0.19	0.04	0.02

LAS, lateral ankle sprain; BW, body weight; DL, drop land; IC, initial contact; SD, standard deviation; vGRF, vertical ground reaction force.

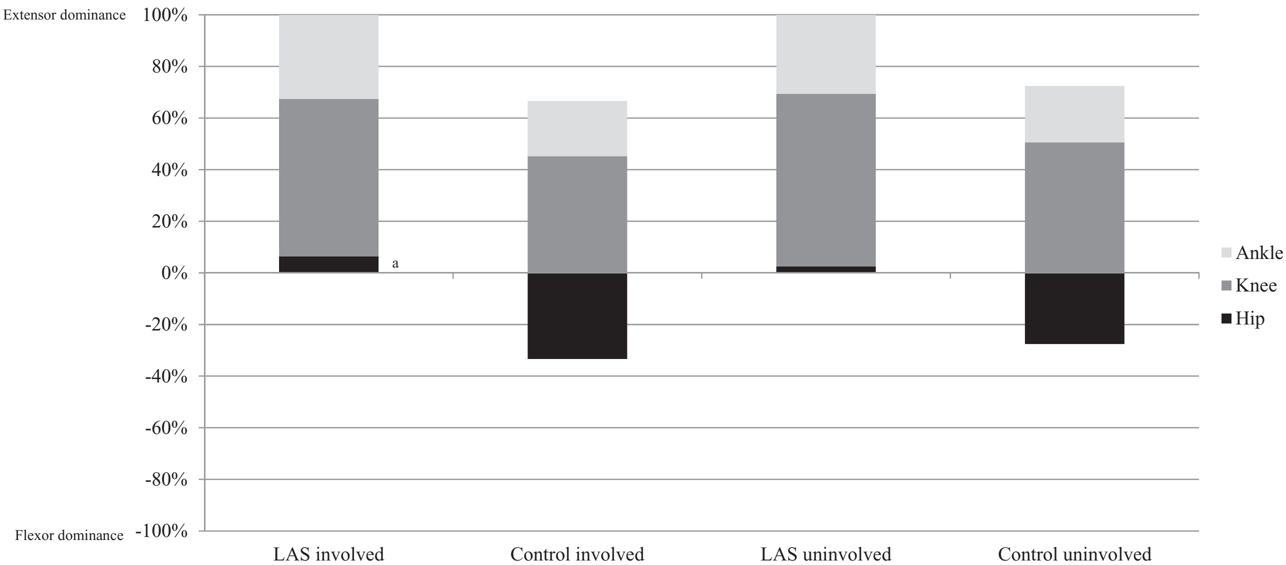

Fig. 5. LAS and control relative joint stiffness on the involved and uninvolved limbs during the drop land task. Positive values indicate extensor dominance (greater stiffness); negative values indicate flexor dominance (greater flexibility). LAS, lateral ankle sprain. [a]Indicates statistically significant difference from control participants at the *a priori* alpha level.

in nature (terminal vs nonterminal dynamic movement tasks).

Landing impact during the DL task is controlled by lower extremity coordination strategies designed to arrest the downward velocity of the body's center of mass in a safe and efficient manner (DeVita & Skelly, 1992). The nature of the joint-specific contributions to the absorption of this kinetic energy should ideally limit the transmission of excess force to capsuloligamentous structures such as the lateral ligament complex of the ankle joint (DeVita & Skelly, 1992), and exploit the geometry of the musculo-skeletal system with its controlling musculature (Farley & Morgenroth, 1999). The increased risk of injury recurrence in CAI populations (Attenborough et al., 2014) has been attributed to an increase or improper mediation of landing forces, secondary to the emergence of inappropriate coordination strategies following injury (Brown et al., 2010). Thus CAI populations are theorized to be vulnerable during landing as the preparatory and/or reactive coordination strategies devised by their sensorimotor system are poorly executed (Griller, 1972; Lees, 1981; Wikstrom et al., 2006); the current investigation provides a link as to how acute coordination strategies may be contingent with long-term outcomes during a terminal landing task.

The moment of force profiles in the current analysis give valuable insight into this integration of preparatory and reactive actions of the sensorimotor system (Winter, 1980). The sinusoidal trajectory of the hip joint moment following IC during this terminal landing task equates to a reduction in the net moment pattern at this joint when compared with that of the knee and ankle joints. As a result, smaller stiffness values were evident at the hip when compared with the knee and ankle, which did not fluctuate between extensor and flexor moments in the same manner as the hip. Thus, this extensor (≃ 50 ms post-IC)-flexor (≃90 ms post-IC)-extensor (≃160 ms post-IC) pattern at the hip may be the central joint strategy utilized to control the kinetic energy event associated with this terminal landing task, as the fundamental role of the knee and ankle, which displayed almost complete extensor dominance, was simply to prevent collapse of the lower extremity during descent via an eccentric extension and flexion moment, respectively. These patterns were also displayed in the acute phase of injury for these participants (Doherty et al., 2014b), and has shown to be evident during the terminal component of a drop vertical jump task (Doherty et al., 2014c).

That injured individuals displayed a reduced flexor moment at the hip joint (80 to 96 ms post-IC), which was soon followed by an increase in its extensor moment (144–152 ms post-IC) was reflected in the stiffness parameter for these participants: because the net moment pattern at the hip was positive for injured participants (increased extensor pattern, reduced flexor pattern compared with controls), hip stiffness was increased. In contrast, control participants had a negative net moment pattern at the hip (greater flexor pattern compared with the subsequent extensor pattern) with a resultant negative hip stiffness value or greater hip softness.

The results of the investigation pertaining to this LAS group's coordination strategies in the acute phase of their injury elucidated contrasting hip joint moment patterns to those displayed in the current study (when compared with control participants). A sequential pattern of reduced flexion moment (≃80 ms post-IC) followed by increased extension moment at the hip (≃150 ms post-IC) compared with controls in the current study was different, as participants in the acute phase of their injury actually displayed a reduced extension moment (≃50 ms post-IC) followed by the same pattern of reduced flexion moment (≃80 ms post-IC; Doherty et al., 2014b). It is likely that this reduction in the extension moment at the hip in the immediate impact phase of the landing (Lees, 1981) was an important contributor to the decrease in peak post-IC vGRF, which was evident in the latter study (Doherty et al., 2014b), and not in the current one. Whether the pattern consistent between the acute study and the current study (reduced hip flexion moment ≃80 ms post-IC) is appropriate to complete recovery following the initial LAS, or contributes to instability associated with CAI, is unknown based on the current findings; this can only be clarified at the 1-year follow-up.

The apparent importance of the hip in controlling the landing event based on the current observations is in agreement with the findings of DeVita and Skelly (1992), albeit the task prescribed in this instance was unipodal in nature, whereas theirs was bipodal, in addition to being performed from a greater height. Furthermore, in light of the findings of a number of studies during other movement tasks, it is plausible that individuals who have sustained a LAS injury generally increase weighted dominance on hip joint movement strategies. This has been shown to be evident during static postural control tasks (Doherty et al., 2014a), in fulfilling both slow (Doherty et al., in press) and fast dynamic movement tasks (Doherty et al., 2014c) and in reacting to significant balance perturbation (Beckman & Buchanan, 1995), this latter finding being further evidenced by alteration in the observed hip muscle activation onsets and patterns in the 'LAS' group (Bullock-Saxton, 1994). It is possible that the reduction in hip stiffness in injured participants observed in the current study may be strategic in shifting dependence to a joint ideally suited to the transmission of larger impact forces (Alexander & Ker, 1990), and away from the ankle joint, which is more suited to subtle alterations in postural control (Nashner & McCollum, 1985).

Inspection of the kinematic data for the hip reveals a preparatory (pre-IC) increase in hip flexion on the involved limb, a trait shared by these participants in the acute phase of their injury (Doherty et al., 2014b). That injured participants landed in increased hip flexion is counterintuitive to the decrease in the observed hip stiffness: Farley and Morgenroth (1999) report that if the leg is more extended at the instant of touchdown, the vGRF vector will be more closely aligned with the joints, simultaneously decreasing joint moments but increasing leg stiffness. However, describing the relationship of torsional joint stiffness and the position of the motor apparatus using a discrete point in such a linear fashion may be an oversimplification, as landing in a position of extreme hip flexion could theoretically increase the tension on passive and active structures crossing the joint, thus reducing the available range through which this joint can move, and increasing joint stiffness. That the increase in hip flexion displayed by injured participants in the current study was linked with an increase in hip stiffness compared with controls lends to this theory, and may be part of a strategy contingent with that of the acute phase data (Doherty et al., 2014b). This strategy has since become redundant, in consideration of the absence of a between-groups difference for the vGRF. Furthermore, because the impact forces of landing occur less than 30–50 ms post-IC (Nigg et al., 1981; DeVita & Skelly, 1992), and because the quickest potential reaction response by the sensorimotor system is insufficient to modify these forces, any attempt to reduce external impact must include some activity prior to contacting the landing surface (Lees, 1981; DeVita & Skelly, 1992); apart from the brief period of significant increase in hip flexion, the LAS group displayed no other preparatory coordination strategies in the sagittal plane. The reason predicating the observed increase in hip joint flexion in the LAS group may also lie in parameters not evaluated in the current study: both the increase in preparatory hip flexion and the coinciding decrease in post-IC hip flexion moment may be linked with greater flexion of the trunk. Increases in hip flexion during landing have previously been linked with greater concomitant active trunk flexion (Blackburn & Padua, 2008); the reduced hip flexion moment and subsequent increase in hip extension moment and hip stiffness may reflect the more flexed position of the trunk at IC in injured participants and the greater resultant force needed to extend out of this position during stabilization, respectively. While landing in a position of increased hip flexion is considered beneficial in minimizing risk to the knee joint complex (Frank et al., 2013), in this instance, this movement pattern could reflect the abandonment of the inverted pendulum model of postural control during landing stabilization, and may be potentially anomalous because it was linked with greater stiffness at this joint. The current study cannot confirm this however.

That these movement strategies were bilateral in nature (increase in hip flexion and hip joint stiffness) for the LAS group contradicts the identification of the noninjured limb as ‘uninvolved’. However, whether these movement patterns preceded or occurred as a result of the injury is irrelevant to this contradiction, and implicates centrally mediated motor control pathways (Hass et al., 2010; Wikstrom et al., 2010). On this basis, clinicians must recognize the importance of treating both limbs as ‘involved’ following LAS.

The final between-groups difference in involved limb kinematics was an increase in inversion at the ankle joint exhibited by the LAS group (starting 96 ms pre-IC). This may have occurred as a result of damage to the calcaneofibular ligament (CFL) when the injury was first sustained; the CFL is responsible for limiting inversion and frontal plane motion at the ankle, and is often injured in LASs (Stormont et al., 1985). This ligament was likely stretched or torn in the LAS group, thus increasing frontal plane motion during the DL task. This increased in frontal plane motion is potentially anomalous in its capacity to increase the risk of sustaining further injury; increased inversion about the ankle joint axis equates to an increase in the ground reaction force moments about the sub-talar joint with significant potential for re-sprain of the injured ankle (Wright et al., 2000; Tropp, 2002).

Our findings lend to the hypothesis that participants with a history of LAS exhibit a seemingly re-weighted dominance on their hip joint in the completion of the movement tasks (Bullock-Saxton, 1994; Beckman & Buchanan, 1995; Doherty et al., 2014b, c, in press). This advances current understanding of the compensatory mechanisms, which may lend to the onset of chronicity in groups with ankle sprain as, to the authors knowledge to date, no research has previously been conducted evaluating joint energetics and movement patterns in a group 6 months after they sustained their injury. In consideration of our findings, clinicians must be cognizant of the potential persistence of injury-affiliated movement patterns with a coinciding decrease in self-reported functional capacity even 6 months following LAS injury, and the capacity for these patterns to manifest bilaterally. The inability to determine whether the movement patterns observed in the current study are predictors of chronicity or recovery may be a significant flaw, but as we have previously alluded to, this analysis is part of a larger study designed to tackle such a dilemma. Further, it is possible that the ‘coping’ strategies displayed by the LAS group actually predicated their injury event in the first instance. Neither this study nor the longitudinal analysis this study forms part of can answer this question, which is a significant limitation.

Perspectives

This analysis has elucidated a continuation of certain landing movement patterns previously exhibited by a group with acute LAS injury (Doherty et al., 2014b), this time 6 months following the initial biomechanical evaluation. That many of these movement patterns are also exhibited by patients with CAI potentiates a link between the movement strategies adopted in the acute phase of injury and long-term outcome, although future longitudinal analyses of LAS participants are required to confirm this.

Key words: Ankle joint [MeSH], kinematics [MeSH], kinetics [MeSH], task performance and analysis [MeSH].

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