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Inter-joint coordination strategies during unilateral stance 6-months following first-time lateral ankle sprain

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ABSTRACT

Background: Longitudinal analyses of participants with a history of lateral ankle sprain are lacking. This investigation combined measures of inter-joint coordination and stabilometry to evaluate eyes-open (condition 1) and eyes-closed (condition 2) static unilateral stance performance in a group of participants, 6-months after they sustained an acute, first-time lateral ankle sprain in comparison to a control group.

Methods: Sixty-nine participants with a 6-month history of first-time lateral ankle sprain and 20 non-injured controls completed three 20-second unilateral stance task trials in conditions 1 and 2. An adjusted coefficient of multiple determination statistic was used to compare stance limb 3-dimensional kinematic data for similarity in the aim of establishing patterns of lower-limb inter-joint coordination. The fractal dimension of the stance limb centre of pressure path was also calculated.

Findings: Between-group analyses revealed significant differences in stance limb inter-joint coordination strategies for conditions 1 and 2, and in the fractal dimension of the centre-of-pressure path for condition 2 only. Injured participants displayed increases in ankle–hip linked coordination compared to controls in condition 1 (sagittal/frontal plane: 0.15 [0.14] vs 0.06 [0.04]; $\eta^2 = .19$; sagittal/transverse plane: 0.14 [0.11] vs 0.09 [0.05]; $\eta^2 = 0.14$) and condition 2 (sagittal/frontal plane: 0.15 [0.12] vs 0.08 [0.06]; $\eta^2 = 0.23$), with an associated decrease in the fractal dimension of the centre-of-pressure path (injured limb: 1.23 [0.13] vs 1.36 [0.13]; $\eta^2 = 0.20$).

Interpretation: Participants with a 6-month history of first-time lateral ankle sprain exhibit a hip-dominant coordination strategy for static unilateral stance compared to non-injured controls.

1. Introduction

The high prevalence of lateral ankle sprain (LAS) in a wide variety of activity types (Doherty et al., 2014a) has motivated a large body of research designed to evaluate the movement patterns which develop as a consequence of this acute injury. These movement patterns are typically assessed by means of laboratory analyses of prescribed tasks such as static unilateral stance, whereby kinematic and stabilometric measures are utilised to quantify postural control (Doherty et al., 2014b,c; Evans et al., 2004; Hertel et al., 2001).

Postural control during unilateral stance emerges from a dynamic interaction between feedback mechanisms and a central motor programme (McCollum et al., 1996). Feedback mechanisms originate as sensory afferents which include visual, vestibular and somatosensory components (McCollum et al., 1996). A decay in somatosensory afferents, as may occur with acute LAS injury (Freeman, 1965), combined with loss of visual input, has previously been shown to challenge the ability of the central nervous system to reweight available information with an appropriated postural control response (Evans et al., 2004; McKeon et al., 2012). With respect to acute LAS, it has been reported that this manifests as a deterioration of eyes-closed unilateral standing balance capability, with less effective utilisation of the supporting base and an altered kinematical orientation, on both the injured and non-injured limbs (Doherty et al., 2014c).

The high potential for patients with a history of LAS to suffer recurrence (Anandacoomarasamy and Barnsley, 2005; Konradsen et al., 2002) has prompted researchers to theorise that recovery or the onset of chronicity following this injury is dependent on the type of postural control strategies adopted in the year following the acute injury (Wikstrom et al., 2010, 2012); patients who subjectively report the continuum of residual symptoms collectively labelled 'chronic ankle instability' (CAI) (Delahunt et al., 2010), or those 'copers' who recover with no

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relapse (Wikstrom and Brown, 2014), are considered to adopt unique postural control strategies conducive with their injury outcome (Wikstrom et al., 2010). However, the research evaluating these postural control strategies at a specific time point occurring in the period between the acute episode (<2 weeks following injury) and the determination of recovery/chronicity (>1 year following injury), is sparse.

Traditionally in laboratory analyses of static unilateral stance, kinematical data from isolated joints are presented as a function of time (Doherty et al., 2014c; Huurnink et al., 2014) to identify the movement patterns underlying postural control. For example, Tropp and Odenrick, (1988) observed a central role of the ankle joint in postural corrections during single-limb standing, while Doherty et al. (2014c) identified the important role of the hip in maintaining balance with an increasing number of task constraints (i.e. transition from eyes-open to eyes-closed single-leg stance). Thus, the postural control strategies in maintaining upright unilateral stance are typically conceptualised as movement patterns at individual joints. However, it has recently been suggested that evaluating inter-joint 'coordination' pattern relationships between segments of the motor apparatus may further advance the conceptualisation of postural control, particularly in environments of sensory decay (Liu et al., 2012; Wheat and Glazier, 2005). Indeed no research currently exists evaluating the inter-joint coordination strategies of a group following first-time, acute LAS injury in maintaining postural control during unilateral stance in the presence and absence of visual input, prior to the establishment of CAI or coper status (Delahunt et al., 2010; Gribble et al., 2013; Wikstrom and Brown, 2014).

Therefore, the purpose of this study was to evaluate postural control in a group of participants in which recovery or recurrence is yet to be established following first-time, acute LAS. Measures of platform stabilometry and 3-dimensional kinematics of inter-joint coordination were combined to evaluate postural control during static unilateral stance in the presence and absence of visual input in a group 6 months after sustaining a first-time, acute LAS, on both their involved and uninvolved limbs. An "adjusted coefficient of multiple determination (ACMD)" statistic (Kadaba et al., 1989; Liu et al., 2012) was used to establish inter-joint coordination between the hip, knee and ankle joints in all planes of motion. Liu et al. (2012) previously used ACMD to compare movement patterns of inter-joint coordination in a healthy group during unilateral stance in the eyes-open and eyes-closed conditions. ACMD analysis provides a mechanism by which waveform data can be evaluated for similarity (Kadaba et al., 1989), thus establishing the relationship between movement patterns at different joints (Liu et al., 2012). The measure of stability utilised was the fractal dimension (FD) of the centre of pressure (COP) path (Katz and George, 1985). FD has previously been used to evaluate unilateral standing balance in participants with acute LAS injury (Doherty et al., 2014b,c, in press) and describes the complexity of the COP signal, thus giving an indication of the extent to which a person utilises the base of support available to them (Prieto et al., 1996). We hypothesised that participants with a recent history of LAS injury would have reduced self-reported function and ability compared to a group with no recent injury history as their recovery would not be complete. Furthermore, it was hypothesised that these participants would display inter-joint coordination patterns contingent with increased reliance on the proximal strategies of the hip joint to maintain unilateral stance stasis (thus compensating for reduced control at the ankle), and that they would display reduced FD of the stance limb COP path (indicating a limited ability to utilise the available base of support).

2. Methods

2.1. Participants

A convenience group of sixty-nine participants (forty-four males and twenty-five females; age = 22.78 [4.12] years; height = 1.72 [0.09] m; body mass = 76.6 [13.6] kg) were recruited from a University affiliated hospital Emergency Department within 2-weeks of sustaining a first-time acute LAS injury, to take part in testing procedures for the current investigation, which took place 6 months following recruitment. A similar analysis completed on these individuals in the acute phase of their injury (which detailed measures of ankle sprain severity) has been previously published (Doherty et al., 2014c). An additional convenience sample of twenty participants (fifteen males and five females, age = 22.6 [1.7] years; height = 1.73 [0.1] m; body mass = 71.4 [11.29] kg) with no prior history of LAS were recruited from the hospital catchment area population using posters and flyers to act as a control group. All participants signed an informed consent form prior to testing and all testing procedures were approved by the Institutional Review Board where the study was completed. None of the subjects had a history of severe lower extremity injury causing prolonged absence from activity or surgery (excluding the recently sustained LAS for the injured group), vestibular lesions or any other pathology that would impair their motor performance.

2.2. Protocol

All participants were required to complete questionnaires relating to ankle joint function and disability on arrival to the testing laboratory: the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) were utilised to quantify self-reported function and participant reported symptoms (Carcia et al., 2008), and the Cumberland Ankle Instability Tool (CAIT) was utilised to evaluate ankle joint function and painful symptoms (Hiller et al., 2006).

After completion of the questionnaires, participants were instrumented with the Codamotion bilateral lower limb gait set-up (Charnwood Dynamics Ltd, Leicestershire, UK). Anthropometric measures required for the calculation of internal joint centres of the lower extremity were collected for each participant, with subsequent placement of lower limb markers and wands as described by Monaghan et al. (2006). A neutral stance trial was used to align the subject with the laboratory coordinate system and to function as a reference position for subsequent kinematic analysis which is in accordance with the International Society of Biomechanics' guidelines (Wu et al., 2002). Participants then performed three, 20 second trials of quiet unilateral stance barefoot on a force-plate with their eyes open on both limbs, each separated by a 30 second break period. Following another 2 minute rest period, these participants then attempted to complete the unilateral stance task with their eyes closed. Participants were required to complete a minimum of three practice trials on each limb for each condition prior to data acquisition. Participants who were unable to complete a full trial of unilateral stance after five attempts on the relevant limb were not included in the analysis for that limb. The test order between legs was randomized. For both conditions of unilateral stance, subjects were instructed to stand as still as possible with their hands resting on their iliac crests while adopting a postural orientation most natural to them; the position of the non-stance limb was not dictated in the sagittal plane as part of experimental procedures. Trials were deemed invalid if the subject lifted their hands off their iliac crests, placed their non-stance limb on the support surface, moved their non stance hip into a position >30° abduction, adducted their non-stance limb against their stance limb for support or if the foot placement assumed by the participants relative to the support surface changed in any way over the course of a trial. In addition a trial was deemed failed in the eyes closed condition if the subject opened their eyes at any point.

2.3. Kinematic and kinetic data processing

Three Codamotion cx1 units were used to provide information on 3 dimensional angular displacements at the hip, knee and ankle joints for both limbs during the unilateral stance task. Two AMTI (Watertown, MA, USA) walkway embedded force-plates were used to acquire kinetic data. Kinematic and kinetic data acquisition was made at 100 Hz. 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. Marker positions within a Cartesian frame were processed into rotation angles using vector algebra and trigonometry.

Pairwise comparison of 3-dimensional temporal angular displacement waveforms for the hip, knee and ankle joints of the stance limb was made using the ACMD statistic (Kadaba et al., 1989) in the aim of quantifying the similarity of a given pair of waveforms during both conditions of unilateral stance. There were three joint pairs (hip/knee, hip/ankle, and knee/ankle) each operating separately in three dimensions, with twenty-seven resultant ACMD values for each trial of unilateral stance. The mean ACMD from three trials of unilateral stance was used as a representative ACMD for each participant. ACMD values ranged from 0 (no similarity) to 1 (two identical curves) (Kadaba et al., 1989). The same data processing procedure was performed for both eyes-open and eyes-closed unilateral stances, on both limbs. See Fig. 1 for a representative depiction of an ACMD value between two angular displacement waveforms.

Furthermore, mean values of all joint angular ranges (maximum value–minimum value) during testing in each task were computed for comparisons between LAS and control participants.

The kinetic data of interest was the centre of pressure (COP) (the location of the vertical reaction vector on the surface of a force-plate) path for each trial (Prieto et al., 1996). COP data acquired from trials of unilateral stance were used to compute the FD of the COP path using an algorithm previously published and described by Prieto et al. (1996). FD was calculated based on the 20 second interval for each unilateral stance trial, and averaged across the three trials for each participant on each limb. The COP time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5 Hz cut-off frequency (Winter, 2009). Kinematic and COP data were analysed using the Codamotion software, with the following axis conventions: x axis = frontal-plane motion; y = sagittal-plane motion; and z = transverse-plane motion, and then converted to Microsoft Excel file format. Temporal data were set with the number of output samples per trial at 2000 + 1 in the data-export option of the Codamotion software, which represented the complete unilateral stance trial as 100%, for averaging and further analysis.

2.4. Data analysis and statistics

For the LAS group, the limb injured at the time of recruitment was labelled as "involved" and the non-injured limb as "uninvolved". 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 matched as "involved" and "uninvolved" in both the LAS and control groups. For all outcomes, we calculated mean (SD) scores for the involved and uninvolved limbs in the LAS group, and mean (SD) scores for the left and right limbs in the control group.

To determine whether the LAS group would demonstrate decreased function compared to the control group a multivariate analysis of variance was undertaken. 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 $P < 0.017$.

In order to test our hypothesis that the LAS group would display bilateral changes in inter-joint coordination patterns as determined using the ACMD statistic for pairwise comparison between 3 dimensional joint angular displacement curves, we undertook a series of independent samples t-tests comparing: involved limb vs control, and uninvolved limb vs control for the eyes-open and eyes-closed conditions. Furthermore, the mean joint range of motion in both conditions was computed for all joints in all planes for comparison between LAS and control groups. The significance level for these analyses was adjusted for multiple tests using the Benjamini–Hochberg method for false discovery rate (<5%) (Benjamini and Hochberg, 1995) in two groups (ACMD and joint ranges) each with two levels (eyes-open and eyes closed).

In order to test our hypothesis that the LAS group would display altered COP path trajectory FD during unilateral stance, an independent samples, two-sided t-test was undertaken for each limb in each condition. The significance level for this analysis was set a priori with a Bonferroni adjusted alpha level of $P < 0.025$.

All data were analysed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA).

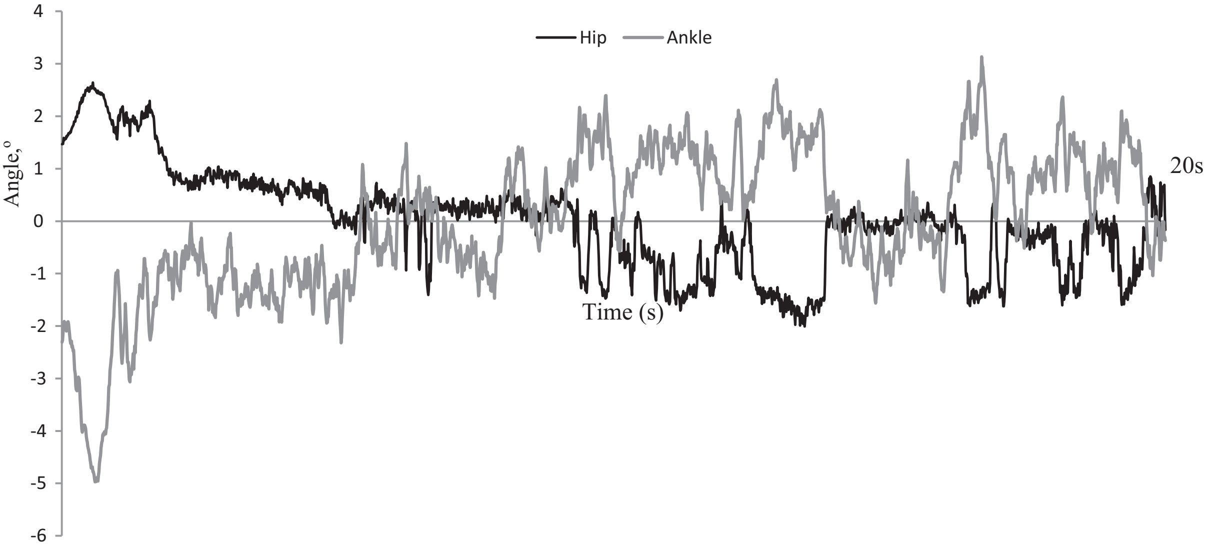

Fig. 1. Frontal plane ankle and hip motion recorded during unilateral stance with eyes open. Eversion and adduction are positive; inversion and abduction are negative. Two curves showed similar changes in the same direction (ACMD = 0.74).

3. Results

Regarding self-reported function and disability, a statistically significant main effect was observed for the combined dependent variables, F (3, 72) = 14.81, $P < 0.01$, Wilks' Lambda = 0.61, partial $\eta^2 = 0.38$. Questionnaire scores with details of relevant statistical analyses for the LAS and control groups are detailed in Table 1.

All participants completed the eyes-open SLS task on both limbs. Of the sixty-nine participants in the LAS group, thirty-eight (23 males & 15 females) completed the SLS task with their eyes-closed on both their involved and uninvolved limbs. Of the twenty participants in the control group, seventeen (12 males & 5 females) completed the SLS task with their eyes-closed on both limbs.

Regarding inter-joint coordination, the LAS group displayed significantly increased similarities in joint angular motions based on ACMD values between sagittal plane hip motion and both frontal and transverse plane ankle motion on their involved limb compared to control participants in the eyes open condition (Table 2). In the eyes-closed condition, the LAS group displayed significantly increased similarities in joint angular motion based on ACMD values between sagittal plane hip motion and frontal plane ankle motion on their involved limb compared to control participants (Table 3). LAS participants also displayed significantly greater transverse plane range of ankle motion compared to controls in the eyes-open condition, and significantly greater sagittal plane range of hip motion compared to controls in the eyes-closed condition (Table 4).

Regarding the kinetic variables of interest, LAS participants displayed reduced stance limb FD compared to control participants on their involved limb in the eyes closed condition only (1.23 [0.13] vs 1.36 [0.13]; t(56) = −0.66, $P = 0.001$, two-tailed). The magnitude of the differences in the mean (mean difference = −0.13, 95% CI: −0.21 to −0.05) was large ($\eta^2 = 0.20$). There was no significant difference between LAS and control participants' stance limb FD in the eyes open condition for the involved (1.15 [0.20] vs 1.23 [0.12]; t(86) = −1.69, $P = 0.09$, two tailed) or uninvolved (1.12 [0.25] vs 1.03 [0.28]; t(86) = 1.26, $P = 0.21$, two tailed) limbs. There was no significant difference between LAS and control participants' stance limb FD in the eyes closed condition for the uninvolved limb (1.21 [0.25] vs 1.26 [0.19]; t(56) = −0.66, $P = 0.51$, two tailed).

4. Discussion

The findings of the current investigation illustrate that participants with a 6-month history of LAS display increased ankle–hip linked joint coordination during unilateral stance in both the presence and absence of vision. Nashner and McCollum were the first to propose the existence of two postural control strategies that can be used either independently or in conjunction by the central motor programme based on the feedback received from sensory afferents in order to achieve adaptable control of the COP within the supporting base (Nashner and McCollum, 1985): the synchronous exploitation of torques around the ankle joint that constitutes the 'ankle strategy' is appropriate for subtle changes in postural control while a 'hip strategy', which generates shear forces around the hip joint, compensates for more substantial disturbances in equilibrium (Hwang et al., 2009; Nashner and McCollum, 1985). It is plausible that a decay of sensory afferents (as may occur with injury (McCollum et al., 1996; McKeon et al., 2012)), forces the adoption of strategies more appropriate for safely maintaining balance, although this may still manifest in an alteration, and deterioration, in standing postural control (Winter, 1995).

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	21.60 [5.79][a]	95.80 [5.83][a]	87.05 [17.73][a]
Control	30 [0.00]	100 [0.00]	100 [0.00]

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.

[a] Significantly different from control group.

The use of the ACMD statistic to establish normative similarities in 3 dimensional inter-joint coordination of lower extremity movement patterns during eyes-open and eyes-closed unilateral stances using the control group in the current study has allowed for the determination of a number of injury-affiliated alterations present in the group with a 6 month history of LAS (Liu et al., 2012). This group with a history of LAS, who reported significantly decreased function on their previously injured (involved) limb, displayed increased hip–ankle linked inter-joint coordination patterns compared to the control group in both conditions of unilateral stance. Specifically, there was greater 'coupling' of sagittal plane hip motion and both frontal and transverse plane ankle motion in the eyes-open condition. Similarly, in the eyes-closed condition, there was greater coupling of sagittal plane hip motion and frontal plane ankle motion. This coupling coincided with significantly greater transverse plane ankle motion in the eyes-open condition, and significantly greater sagittal plane hip motion in the eyes-closed condition for LAS participants.

Despite the 'static' nature of the unilateral stance tasks, postural adjustments are continually required to maintain successful balance. The presence of redundancies among various kinematical combinations allows the sensorimotor system to simplify such tasks by using a limited number of postural strategies in a process of self-organisation (Glazier and Davids, 2009). The strategies preferred by the system at any given time are dependent on its current architecture and previous experience (Thelen, 1995). Thus, a LAS and the subsequent 6-month interval may represent a new constraint that caused a re-organisation of postural adjustment strategies whereby previous redundancies were exploited to compensate for alterations in sensorimotor architecture. For instance, a deterioration in ankle–joint function following LAS impairs the sensorimotor system's ability to maintain unilateral stance balance using ankle-dominant strategies of postural control. This may require the motor apparatus to adopt another strategy, one which can more suitably compensate for the increased joint ranges presenting at distal parts of the kinetic chain (which have the capacity to be magnified proximally (Fong et al., 2011)), and which possesses a greater availability of non-distorted somatosensory afferents. Specifically, we refer to the strategy of the hip. Tropp and Odenrick (1988) previously established the importance of ankle joint function in maintaining unilateral stance. This ankle strategy is limited by the foot's ability to exert torque in contact with the supporting surface (Tropp and Odenrick, 1988). Perhaps the initial balance deficits which were evident in the acute phase of LAS injury (Doherty et al., 2014c), persisted into the following weeks and months. The acute distortion of somatosensory afferents (Freeman et al., 1965) manifested in an immediate impairment in ankle joint function (Djupsjöbacka, 2008; Doherty et al., 2014c). This may have forced the adoption of a more proximal hip-based postural control strategy (Doherty et al., 2014c; Tropp and Odenrick, 1988), which could have persisted 6-months following the injury. This is evidenced by the current findings, which seemingly lend to greater dependence on the hip joint for the postural adjustments of unilateral stance. That the LAS group displayed increased inter-joint coupling in both the eyes-open and eyes-closed conditions may suggest a reduced ability for separate components of the kinetic chain to function independently following the initial injury, as they become 'locked together' in the aim of achieving greater static stability. Alternatively, it may be the case that the hip-locked movement patterns of LAS participants preceded their sprain, and they are simply continuing a strategy which they are accustomed to. The reduction in involved limb FD that was exhibited by LAS participants with their eyes closed during unilateral stance suggests that they were unable to sufficiently utilise the available base of support in this condition when confined to a hip-

Table 2
Mean ACMD values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open condition.

Eyes open																
	Joint pair	Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Involved	F/F	.22	.15	.15	.12	0.043	.21	.18	.14	.12	0.152	.20	.17	.15	.14	0.285
	F/S	.19	.15	.16	.12	0.390	.25	.22	.25	.23	0.984	.20	.17	.18	.14	0.601
	F/T	.26	.17	.21	.17	0.224	.21	.17	.16	.11	0.240	.18	.15	.12	.10	0.154
	S/F	.15	.14	.06	.04	0.000[a]	.21	.18	.12	.11	0.050	.20	.17	.15	.08	0.102
	S/S	.22	.17	.18	.14	0.311	.57	.23	.60	.22	0.590	.32	.22	.27	.16	0.338
	S/T	.14	.11	.09	.05	0.001[a]	.18	.14	.11	.10	0.058	.17	.14	.11	.08	0.085
	T/F	.33	.22	.33	.21	0.943	.24	.20	.28	.17	0.412	.24	.18	.26	.15	0.610
	T/S	.18	.13	.17	.13	0.691	.23	.18	.16	.13	0.091	.23	.17	.17	.15	0.151
	T/T	.42	.23	.41	.22	0.901	.39	.24	.41	.21	0.792	.28	.21	.27	.17	0.970
Uninvolved	F/F	.20	.13	.19	.15	0.664	.21	.21	.15	.13	0.209	.23	.16	.16	.13	0.093
	F/S	.18	.14	.25	.20	0.133	.23	.18	.22	.16	0.866	.16	.13	.20	.14	0.342
	F/T	.26	.18	.24	.17	0.652	.18	.15	.17	.13	0.793	.19	.14	.13	.09	0.076
	S/F	.15	.12	.11	.08	0.203	.15	.15	.19	.15	0.254	.19	.14	.20	.14	0.652
	S/S	.20	.15	.23	.12	0.460	.54	.23	.57	.23	0.699	.31	.20	.25	.16	0.204
	S/T	.15	.12	.13	.15	0.415	.11	.11	.16	.09	0.089	.20	.14	.14	.09	0.058
	T/F	.31	.22	.26	.16	0.218	.24	.19	.17	.14	0.119	.22	.17	.20	.20	0.606
	T/S	.15	.11	.16	.11	0.742	.19	.15	.23	.16	0.287	.13	.10	.16	.11	0.369
	T/T	.41	.22	.32	.23	0.105	.34	.22	.38	.29	0.598	.30	.21	.23	.19	0.140

Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

[a] Denotes statistically significant between-groups difference; '/' denotes comparison between two joints/planes of motion.

dominant postural control strategy (Doherty et al., 2014c; Prieto et al., 1996). However, in consideration of the absence of between-group differences for the eyes-open condition despite the utilisation of a similar hip-dominant strategy, it is clear that there is no linear relationship between stance limb FD and postural control ability. For instance, too large an FD has previously been attributed to an inability to synergistically modulate sensory afferents in producing an efferent response (Cimolin et al., 2011) while too small an FD has previously been linked with insufficient utilisation of the available base of support (Prieto et al., 1996). COP analyses are merely surrogate measures of postural control, and often mask the complex strategies that belie them, particularly in instances of unilateral stance (Liu et al., 2012). Furthermore, FD has previously failed to distinguish between an acute LAS and control groups in the eyes open condition (Doherty et al., 2014c), but has made distinctions between these groups when visual afferents have been removed (Doherty et al., 2014b; Doherty et al., 2014c). In the current situation we would consider that the ineffective ankle strategy of LAS participants limited their ability to utilise the available base of support; one manifestation of this was a reduction in FD, which coincided with greater range of movement at the hip. Another potential manifestation of this would have been a normal value of FD, maybe due in part to the increase in rotational movements at the ankle (as is evident in the eyes open condition). That both of these conditions were characterised by a hip-dominant strategy as determined using the

Table 3
Mean ACMD values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-closed condition.

Eyes closed																
	Joint pair	Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Involved	F/F	.26	.19	.18	.12	0.135	.25	.22	.22	.22	0.657	.22	.21	.20	.15	0.750
	F/S	.23	.21	.12	.12	0.051	.25	.23	.19	.13	0.178	.18	.12	.13	.10	0.200
	F/T	.33	.18	.23	.12	0.067	.23	.17	.24	.24	0.853	.17	.15	.15	.13	0.676
	S/F	.15	.12	.08	.06	0.000[a]	.13	.12	.11	.09	0.557	.21	.21	.22	.19	0.856
	S/S	.26	.23	.24	.19	0.857	.56	.25	.45	.20	0.149	.39	.26	.33	.20	0.410
	S/T	.11	.12	.11	.08	0.970	.14	.16	.11	.12	0.437	.13	.17	.16	.09	0.521
	T/F	.43	.24	.36	.27	0.330	.29	.22	.25	.25	0.526	.24	.20	.36	.26	0.087
	T/S	.18	.18	.11	.10	0.094	.20	.20	.20	.12	0.881	.16	.18	.15	.15	0.797
	T/T	.45	.26	.42	.33	0.717	.39	.28	.36	.27	0.709	.33	.24	.31	.32	0.840
Uninvolved	F/F	.25	.17	.26	.19	0.798	.18	.17	.11	.13	0.089	.23	.22	.24	.18	0.946
	F/S	.20	.16	.16	.13	0.369	.25	.21	.18	.15	0.238	.20	.17	.19	.13	0.830
	F/T	.35	.17	.29	.16	0.190	.16	.15	.15	.15	0.700	.16	.13	.12	.10	0.200
	S/F	.09	.09	.08	.06	0.560	.14	.14	.11	.09	0.394	.20	.17	.19	.16	0.751
	S/S	.23	.20	.19	.19	0.495	.58	.24	.52	.22	0.373	.37	.26	.28	.22	0.199
	S/T	.15	.13	.09	.07	0.066	.14	.15	.08	.07	0.038	.15	.15	.11	.07	0.182
	T/F	.40	.28	.37	.23	0.672	.28	.21	.18	.16	0.102	.20	.18	.29	.20	0.092
	T/S	.14	.15	.16	.11	0.543	.17	.15	.16	.14	0.821	.14	.15	.14	.11	0.858
	T/T	.52	.24	.43	.25	0.245	.35	.21	.38	.25	0.707	.39	.24	.27	.20	0.075

Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

[a] Denotes statistically significant between-groups difference; '/' denotes comparison between two joints/planes of motion.

Table 4
Mean joint angular range values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open and eyes-closed conditions. Values are reported in degrees.

		Hip					Knee					Ankle				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Eyes open																
Involved	F	4.82	4.39	3.86	3.70	0.378	2.85	5.91	2.03	1.82	0.546	12.40	19.96	5.70	2.35	0.009
	S	5.01	5.15	3.27	2.69	0.150	7.41	9.55	5.27	3.01	0.327	5.57	6.95	4.17	2.66	0.384
	T	6.71	4.73	5.80	3.97	0.437	6.09	8.54	4.27	3.26	0.354	8.64	4.45	6.04	1.84	0.000[a]
Uninvolved	F	11.12	8.93	9.51	6.08	0.502	4.14	7.13	4.22	4.27	0.964	16.39	12.84	11.22	5.64	0.120
	S	9.32	7.42	10.13	9.36	0.732	11.25	8.75	9.69	6.28	0.513	8.13	4.57	6.63	3.36	0.232
	T	12.40	6.10	14.16	8.37	0.389	8.34	6.53	7.58	5.81	0.686	15.47	7.32	12.51	4.95	0.138
Eyes closed																
Involved	F	5.07	4.37	3.24	1.64	0.007	2.51	3.18	2.11	1.77	0.594	16.63	45.30	8.70	11.73	0.442
	S	5.33	5.21	3.19	1.06	0.003[a]	8.44	11.18	5.93	2.88	0.104	11.28	44.56	4.30	2.43	0.487
	T	6.32	3.26	5.14	2.89	0.150	5.31	5.38	6.58	4.84	0.349	11.33	19.99	7.77	4.31	0.433
Uninvolved	F	10.49	8.80	10.98	12.82	0.871	3.73	4.28	3.35	3.61	0.762	25.45	56.52	21.01	21.10	0.770
	S	8.40	4.96	8.69	6.75	0.861	11.32	7.15	8.06	5.65	0.120	7.95	4.66	11.93	16.31	0.367
	T	11.27	5.25	11.95	7.19	0.702	6.80	3.76	14.13	20.42	0.188	14.50	7.16	18.44	14.13	0.318

Abbreviations: LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

[a] Denotes statistically significant between-groups difference.

ACMD analyses suggests that the specific movements at each joint played an important role in the trajectory of the stance limb FD, a theory confirmed in consideration of the joint range values. In summary we theorise that reduced control at the ankle was compensated for in the eyes-closed condition by greater movements at the hip joint with a coinciding hip-dominant strategy and a reduced FD, while in the eyes-open condition, the same lack of control at the ankle manifested in a greater local rotational movement (directly affecting the complexity of COP patterns), and despite a similar hip-dominant balance strategy, an FD within normal ranges.

Whether the deficits observed in the current sample and the apparent hip-locked postural control strategies preceded or occurred as a result of injury, and contribute to chronicity or recovery, is unknown due to the design of the current study. Herein lies a significant limitation of the current investigation: future analyses would benefit from following participants after testing procedures are completed to determine the movement patterns most likely to contribute to the onset of CAI, or recovery. However, the current study forms one part of a longitudinal analysis designed to tackle this issue. It is also important to note the limitation of the range of motion measure utilised in this analysis: it is possible that the 'locked' postural control strategy of LAS participants resulted in a reduction in the apparent range of motion at the relevant joint. However, we believe that evaluating joint range of motion in the context of the inter-joint coordination statistic overcomes this limitation.

The primary implication of the current findings for clinicians is that postural control strategies continue to be altered 6-months following acute ankle sprain injury, with the hip seemingly playing a significant compensatory role for the injured ankle. Reweighted dominance on hip joint strategies may have a local 'detraining' effect at the ankle. If the ankle is then unable to fulfil its primary role in completing the local movement subtleties required for normal unperturbed standing balance (Nashner and McCollum, 1985), this may contribute to instability. Thus, clinicians must devise rehabilitation protocols with these issues in mind, and must consider the importance of administering these protocols in the months following the injury if self-reported functional deficits persist.

5. Conclusions

In conclusion, the results of the current study suggest that participants with a 6-month history of LAS report reduced ankle joint function and increased disability compared to uninjured controls, and that this manifests in a hip-dominant postural control strategy during tasks of eyes-open and eyes-closed unilateral stance.

Conflicts of interest

No conflicts of interest were associated with the authors and the results of this research.

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