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Postural control strategies during single limb stance following acute lateral ankle sprain

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ABSTRACT

Background: Single-limb stance is maintained via the integration of visual, vestibular and somatosensory afferents. Musculoskeletal injury challenges the somatosensory system to reweight distorted sensory afferents. This investigation supplements kinetic analysis of eyes-open and eyes-closed single-limb stance tasks with a kinematic profile of lower limb postural orientation in an acute lateral ankle sprain group to assess the adaptive capacity of the sensorimotor system to injury.
Methods: Sixty-six participants with first-time acute lateral ankle sprain completed a 20 second eyes-open single-limb stance task on their injured and non-injured limbs (task 1). Twenty-three of these participants successfully completed the same 20 second single-limb stance task with their eyes closed (task 2). A non-injured control group of 19 participants completed task 1, with 16 completing task 2. 3-dimensional kinematics of the hip, knee and ankle joints, as well as associated fractal dimension of the center-of-pressure path were determined for each limb during these tasks.
Findings: Between trial analyses revealed significant differences in stance limb kinematics and fractal dimension of the center-of-pressure path for task 2 only. The control group bilaterally assumed a position of greater hip flexion compared to injured participants on their side-matched "involved"(7.41 [6.1°] vs 1.44 [4.8]°; $\eta^2 = .34$) and "uninvolved" (9.59 [8.5°] vs 2.16 [5.6°]; $\eta^2 = .31$) limbs, with a greater fractal dimension of the center-of-pressure path (involved limb = 1.39 [0.16°] vs 1.25 [0.14°]; uninvolved limb = 1.37 [0.21°] vs 1.23 [0.14°]).
Interpretation: Bilateral impairment in postural control strategies present following a first time acute lateral ankle sprain.

1. Introduction

Balance is a generic term describing the dynamics of body posture to prevent falling (Winter, 1995). Information about body posture in single-limb stance (SLS) with respect to the force of gravity is provided to the central nervous system by vestibular, visual and somatosensory afferents (McCollum et al., 1996). Redundancies between structurally different sensory afferents [otherwise known as 'degeneracies' (Glazier and Davids 2009)] can combine in a variety of ways to produce similar efferent motor responses; this allows the sensorimotor system to simplify a task within a limited number of movement strategies (Nashner, 1979). Selective reweighting of these degeneracies by the central nervous system is then based on the availability of reliable information (McKeon et al., 2012). As a result, it is possible for the functioning somatosensory system to produce a motor output contingent with maintaining balance in the presence of altered visual, vestibular and/or somatosensory signals (McCollum et al., 1996). Despite this, some deterioration in the efferent response may become evident in simple postural control tasks when sensorimotor afferents are compromised (Winter, 1995).

Kinematic (Huurnink et al., 2014; Liu et al., 2012) and center of pressure (COP) (Prieto et al., 1996) analyses have been previously used to quantify the motor response associated with distorted sensory environments during single limb stance in a variety of populations. The underlying premise of these investigations is that in instances of sensorimotor compromise, the motor apparatus is organized in such a way as to adopt suitable compensatory postural orientation strategies (Pintsaar et al., 1996) which are reflected in the COP path trajectory features. A number of measures are currently available with which to characterize the COP path trajectory. However, traditional measures such as

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those that determine the area, length and velocity of the COP path have often yielded inconsistent or contradictory findings (McKeon and Hertel, 2006a) and have questionable reliability (Doyle et al., 2005). Furthermore, a newly developed measure of COP excursion called time-to-boundary (TTB) has shown potential in a number of studies (Hertel and Olmsted-Kramer, 2007; McKeon and Hertel, 2006b), but is limited by the requirement that participants must assume a foot placement contingent with assumptions required to calculate the value, which may restrict the observation of natural balance strategies and postural orientations. In contrast, fractal dimension (FD) is a technique which has previously been used in COP analyses (Błaszczyk and Klonowski, 2001; Cimolin et al., 2011; Doherty et al., 2014a; Doyle et al., 2005; Manabe et al., 2001; Prieto et al., 1996) to provide an indication of the complexity of the COP signal by describing its shape. Briefly, a straight line would have a fractal dimension equal to 1; a line so convoluted as to completely fill a plane has a dimension approaching the dimension of the plane (i.e. equal to 2; the standard dimension of a plane), and a line that 'piles up in the plane' by repeatedly crossing and re-crossing itself can have a fractal dimension of >2 (Katz and George, 1985). FD has previously been utilized successfully in COP analysis to characterize the stability of the postural control system (Błaszczyk and Klonowski, 2001; Doherty et al., 2014a).

Musculoskeletal injury has the potential to challenge postural stability via a direct disturbance of somatosensory afferents, consequently challenging the system to reweight information to produce a suitable efferent response, and has been shown to manifest in bilateral balance deficits following acute lateral ankle sprain (LAS) (Wikstrom et al., 2010). The high incidence and prevalence of LAS in a number of activity types are of significant concern for clinicians (Doherty et al., 2014b) and despite a number of studies presenting COP analyses of participants with acute LAS injury during SLS (Evans et al., 2004; Fridén et al., 1989; Hertel et al., 2001; Holme et al., 1999; Leanderson et al., 1996), no current investigation has supplemented these analyses with a kinematic profile of postural orientation. Additionally, no previous research has explored the capacity of the somatosensory system to further adjust and reweight the already distorted somatosensory afferents when compounded by an absence of visual input during the same task, in this group.

Therefore, the purpose of the current investigation was to assess the effects of first time acute LAS on balance using kinematic and COP analyses in the presence and absence of visual afferents (i.e. eyes-open and eyes-closed SLS). We hypothesized that acute LAS would result in an increase in participant self-reported disability and would manifest in a bilateral modification of postural kinematic orientation strategies when compared to control subjects, which would be reflected by COP trajectory measures sensitive to eyes-open and eyes-closed SLS. Such an analysis may serve to elucidate the strategies used by a somatosensory system challenged not only in organizing distorted somatosensory afferents secondary to injury, but also in coping without previously available visual degeneracies (Overstall et al., 1977).

2. Methods

2.1. Participants

A convenience sample of sixty-six participants (forty-three males and twenty-three females) were recruited from a university-affiliated hospital Emergency Department within 2 weeks of sustaining first-time LAS for the current investigation. The following inclusion criteria were applied to all potential participants: (1) no previous history of ankle sprain injury (excluding the recent acute episode for the injured group); (2) no other lower extremity injury in the last 6 months; (3) no history of ankle fracture; (4) no previous history of major lower limb surgery; and (5) no history of neurological disease, vestibular or visual disturbance or any other pathology that would impair their motor performance. An additional convenience group of nineteen uninjured participants (fifteen males and four females) with no prior history of LAS were recruited from the hospital catchment area population using posters and flyers to act as a control group. Participants were required to sign an informed consent form approved by the University Human Research Ethics Committee upon arrival at the University biomechanics laboratory.

2.2. Questionnaires

Self-reported disability and participant reported symptoms as measures of LAS severity were assessed using the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) (Carcia et al., 2008). Overall ankle joint function and painful symptoms were evaluated using the Cumberland Ankle Instability Tool (CAIT) (Hiller et al., 2006).

2.3. Swelling

Ankle joint swelling was assessed using the figure-of-eight method (Esterson, 1979). High intra-rater and inter-rater reliability has been reported using this technique (ICC = 0.99) (Tatro-Adams et al., 1995). To determine the degree of swelling, the mean value (of 2 measures) was subtracted from the mean value of the non-injured ankle. For control participants the mean value of the non-dominant limb was subtracted from the mean value of the dominant limb.

2.4. Procedures

Prior to completion of the 20 second SLS task, participants were instrumented with the Codamotion bilateral lower limb gait set-up (Charnwood Dynamics Ltd, Leicestershire, UK). Following collection of specific anthropometric measures required for the calculation of internal joint centers at the hip, knee and ankle joints, lower limb markers and wands were attached, 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 as recommended in previously published literature (McLean et al., 2007). Kinematic data acquisition was made at 1000 Hz using 3 Codamotion CX1 units and kinetic data at 100 Hz using 2 AMTI (Watertown, MA) walkway embedded force-plates. The Codamotion CX1 units were time synchronized with the force-plates.

2.5. Single-limb stance trials

Participants performed three, 20 second trials of quiet SLS 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 SLS 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 SLS after five attempts on both limbs were not included in the analysis. The test order between legs was randomized. For both conditions of SLS, 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 subjects 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, and adducted their non-stance limb against their stance limb for support or lifted their forefoot/heel. In addition a trial was deemed as failed in the eyes closed condition if the subjects opened their eyes at any point.

2.6. Data processing of kinematics and COP measures

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. Discrete whole-trial averaged joint angular position values were calculated for the hip, knee and ankle joints in the sagittal, transverse and frontal planes of motion, producing nine 'joint position' dependent variables of interest for each limb.

Kinetic data acquired from the trials of SLS were used to compute the FD of the COP path. The COP is a bivariate distribution, jointly defined by the antero-posterior (AP) and medio-lateral (ML) coordinates which in a time series define its path relative to the origin of the force platform (Prieto et al., 1996). The local COP origin for the stance limb was defined by the arithmetic means of the AP and ML time series (Prieto et al., 1996). The COP has previously been shown to be a valid and reliable measure of postural control mechanisms in static balance tasks (Le Clair and Riach, 1996). The AP and ML time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency. We adopted an algorithm previously published by Katz and George (1985) and described in the seminal paper by Prieto et al. (1996) to calculate FD:

$$\mathrm{FD} = \log(\mathrm{N})/\left(\log(\mathrm{Nd})/\left(\sum_{n=1}^{N-1}\left[(\mathrm{AP}[n+1]-\mathrm{AP}[n])^2+(\mathrm{ML}[n+1]-\mathrm{ML}[n])^2\right]^{\frac{1}{2}}\right)\right)$$

where N = the number of data points included in the analysis and d = the maximum distance between any two points (n) on the COP path. FD was calculated based on the 20 second interval for each SLS trial, and averaged across the three trials for each participant on each limb.

2.7. Data analysis and statistics

For the LAS group, the injured limb was labelled as "involved" and the non-injured limb as "uninvolved". In all cases the limbs in the control group were side matched to the injured 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. 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. Participant characteristics and swelling were compared between the LAS and control groups using multivariate analysis of variance. The dependent variables were age, mass, sex, height and ankle joint swelling. The independent variable was status (injured vs non-injured). The significance level for this analysis was set a priori with a Bonferroni alpha level of $P < 0.01$.

In order to test our hypothesis that acute LAS would manifest bilateral changes in COP path trajectory FD and kinematic measures of postural orientation, we undertook a series of independent samples t-tests for each outcome comparing: involved limb vs control, and uninvolved limb vs control. The significance level for analyses were adjusted for multiple tests using the Benjamini–Hochberg method for false discovery rate (<5%) (Benjamini and Hochberg, 1995). All data were analyzed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Participant characteristics

Regarding participant characteristics and swelling there was a statistically significant difference between the LAS and control groups on the combined dependent variables, $F(78,5) = 5.04$; $P = 0.000$; Wilk's Lambda = 0.76; and partial eta squared = 0.24. When the results of the dependent variables were considered separately, swelling ($F[1, 82] = 18.392$, $P = 0.000$, partial eta squared = 0.18) was the only difference to reach statistical significance. An inspection of the mean scores indicated that injured participants had increased swelling on their involved limb compared to controls. Participant characteristics, swelling and questionnaire scores are detailed in Table 1.

3.2. Single-limb stance trials

All participants completed the eyes-open SLS task on both limbs. Of the sixty-six participants in the LAS group, twenty-three (12 males & 11 females) completed the SLS task with their eyes-closed on both their involved and uninvolved limbs. Of the nineteen participants in the control group, sixteen (12 males & 4 females) completed the SLS task with their eyes-closed on both limbs.

3.3. Single-limb stance kinematics

There was a significant difference in eyes-closed SLS kinematics between the LAS and control groups for the involved and uninvolved limbs. Multiple testing with a false discovery rate of less than 5% revealed that control group exhibited increased hip flexion compared to the LAS group on both the involved and uninvolved limbs. The magnitude of the differences in the means for the involved limb was 5.96° (95% CI: −9.49° to −2.43°) and 7.4° (95% CI: −11.98° to −2.87°) for the uninvolved limb. Means (SD) for each joint in each plane of motion, with corresponding *t*-test statistics are detailed in Table 2. Between-group comparisons of the kinematic profile for the involved and uninvolved limbs are detailed in Figs. 1 and 2 ('k-flake graph').

3.4. Single-limb stance COP

There was a significant difference in eyes-closed SLS FD scores between the LAS and control groups for the involved and uninvolved limbs. Multiple testing with a false discovery rate of less than 5% revealed that the LAS group displayed reduced FD of the COP path trajectory compared to the control group on both their involved and uninvolved limbs. Between-group comparisons for FD scores for the involved and uninvolved limbs are detailed in Table 3.

4. Discussion

The results of the present study demonstratea significant difference between the postural orientations utilized by participants with first time acute LAS compared to non-injured controls, during eyes-closed

Table 1
Participant characteristics and questionnaire scores [mean (SD) with 95% CIs] for the LAS and control groups.

Group	Age (years)	Mass (kg)	Height (m)	Swelling (cm)	CAIT (/30)	FAAMadl (%)	FAAMadl (%)
LAS	23.22 (4.95); [95% CI: 22.01 to 24.45]	75.84 (14.48); [95% CI: 72.28 to 79.40]	1.73 (0.10); [95% CI: 1.71 to 1.76]	1.11 (.85); [95% CI: 0.90 to 1.32]	11.85 (7.91); [95% CI: 9.61 to 13.55]	68.50 (18.65); [95% CI: 63.77 to 73.16]	32.11 (23.85); [95% CI: 32 to 45.22]
Control	22.53 (1.68); [95% CI: 21.72 to 23.34]	71.55 (11.31); [95% CI: 66.01 to 77.01]	1.75 (0.08); [95% CI: 1.71 to 1.78]	0.25 (.34); [95% CI: 0.08 to 0.41]	30 (0.00); [95% CI: 30 to 30]	100 (0.00); [95% CI: 100 to 100]	100 (0.00); [95% CI: 100 to 100]

LAS = lateral ankle sprain.

Table 2
Discrete kinematic variable values (mean [SD] in degrees) for the hip, knee, ankle and foot for the involved and uninvolved limbs of the ankle sprain (injured) and side-matched limbs of the control (non-injured) groups during the performance of eyes open and eyes closed SLS. Add/abd = adduction (positive)/abduction (negative); flex/ext = flexion (positive)/extension (negative); int/ext = internal (positive)/external rotation (negative); var/val = varus (positive)/valgus (negative); inv/ev = inversion (positive)/eversion (negative); dor/pla = dorsiflexion (positive)/plantarflexion (negative). *indicates statistical significance.

		Involved			Uninvolved		
		Injured	Non-injured		Injured	Non-injured	
Eyes open							
Hip	Add/abd	4.05 (4.38)	4.18 (4.43)	t(83) = 0.11, p = 0.91, η^2 = .00	5.53 (6.21)	2.77 (5.13)	t(83) = 1.77, p = 0.08, η^2 = .039
	Flex/ext	1.51 (8.21)	3.57 (5.36)	t(83) = −1.03, p = 0.31, η^2 = .01	4.96 (3.91)	3.91 (5.94)	t(22.7) = −.73, p = 0.48, η^2 = .025
	Int/ext rot	1.82 (4.84)	5.03 (9.1)	t(21.02) = 1.48, p = 0.15, η^2 = .11	1.71 (6.93)	−0.09 (5.57)	t(83) = 83, p = 0.30, η^2 = .013
Knee	Var/val	0.64 (1.71)	0.87 (1.26)	t(83) = 0.54, p = 0.59, η^2 = .00	1.15 (5.50)	−0.15 (2.55)	t(65.84) = 1.45, p = 0.15, η^2 = .03
	Flex/ext	5.69 (6.38)	7.66 (10.33)	t(22.09) = 0.79, p = 0.44, η^2 = .031	1.33 (1.02)	6.90 (8.49)	t(18.15) = 2.85, p = 0.01, η^2 = .50
	Int/ext rot	1.06 (4.08)	−0.95 (7.62)	t(21.05) = 1.10, p = 0.28, η^2 = .06	6.53 (10.14)	1.85 (4.95)	t(83) = 1.94, p = 0.05, η^2 = .046
Ankle	Inv/ev	−0.19 (4.24)	−1.37 (5.59)	t(83) = 0.99, p = 0.32, η^2 = .012	1.39 (3.56)	−0.79 (5.51)	t(22.49) = 1.63, p = 0.12, η^2 = .013
	Dor/pla	6.01 (3.22)	7.6 (6.1)	t(20.97) = 1.09, p = 0.28, η^2 = 0.06	3.93 (3.43)	5.99 (5.33)	t(22.45) = 1.6, p = 0.12, η^2 = 0.13
Foot	Abd/add	−4.36 (4.78)	−4.56 (6.36)	t(83) = 0.14, p = 0.88, η^2 = 0.00	0.79 (4.75)	−4.89 (4.6)	t(83) = 0.58, p = 0.56, η^2 = 0.00
Eyes closed							
Hip	Add/abd	4.96 (3.5)	4.85 (2.98)	t(37) = 0.10, p = 0.9, η^2 = .00	4.64 (4.38)	2.71 (5.21)	t(37) = 1.25, p = 0.22, η^2 = .04
	Flex/ext*	1.44 (4.76)	7.41 (6.11)	t(37) = −3.42, p = 0.001*, η^2 = .34	2.16 (5.61)	9.59 (8.45)	t(37) = −3.3, p = 0.002*, η^2 = .31
	Int/ext rot	0.58 (5.08)	4.96 (11.41)	t(19.17) = 1.44, p = 0.17, η^2 = .12	−0.54 (6.9)	−2.62 (4.91)	t(37) = 1.04, p = 0.31, η^2 = .031
Knee	Var/val	0.26 (1.6)	0.32 (1.95)	t(37) = −0.09, p = 0.93, η^2 = .00	0.37 (2.19)	−0.11 (2.45)	t(37) = 0.64, p = 0.53, η^2 = .01
	Flex/ext	9.11 (8.25)	11.77 (9.29)	t(37) = 0.94, p = 0.35, η^2 = .025	8.08 (6.49)	15.60 (16.19)	t(18.39) = 1.76, p = 0.09, η^2 = .19
	Int/ext rot	2.63 (3.29)	0.46 (8.92)	t(17.86) = 0.93, p = 0.37, η^2 = .054	2.61 (5.51)	3.78 (5.72)	t(37) = 0.64, p = 0.52, η^2 = .01
Ankle	Inv/ev	−1.18 (5.56)	−0.42 (6.6)	t(37) = 0.39, p = 0.70, η^2 = .00	−2.2 (4.27)	−1.79 (10.4)	t(37) = −0.17, p = 0.87, η^2 = .00
	Dor/pla	7.85 (4.11)	9.72 (5.91)	t(37) = −1.17, p = 0.25, η^2 = 0.03	8.04 (4.64)	10.4 (9.23)	t(37) = 1.05, p = 0.25, η^2 = 0.04
Foot	Abd/add	−4.01 (4.77)	−4.89 (6.34)	t(37) = 0.49, p = 0.63, η^2 = 0.01	−6.32 (4.48)	−5.62 (4.7)	t(37) = 0.47, p = 0.64, η^2 = 0.00

SLS: LAS participants assumed a position of reduced hip flexion compared to non-injured participants. This difference was observed bilaterally and the effect size was large for both limbs. The position of reduced hip flexion was associated with reduced complexity of the COP path, as illustrated by the smaller FD of the LAS group on both their involved and uninvolved limbs. There was no difference between postural

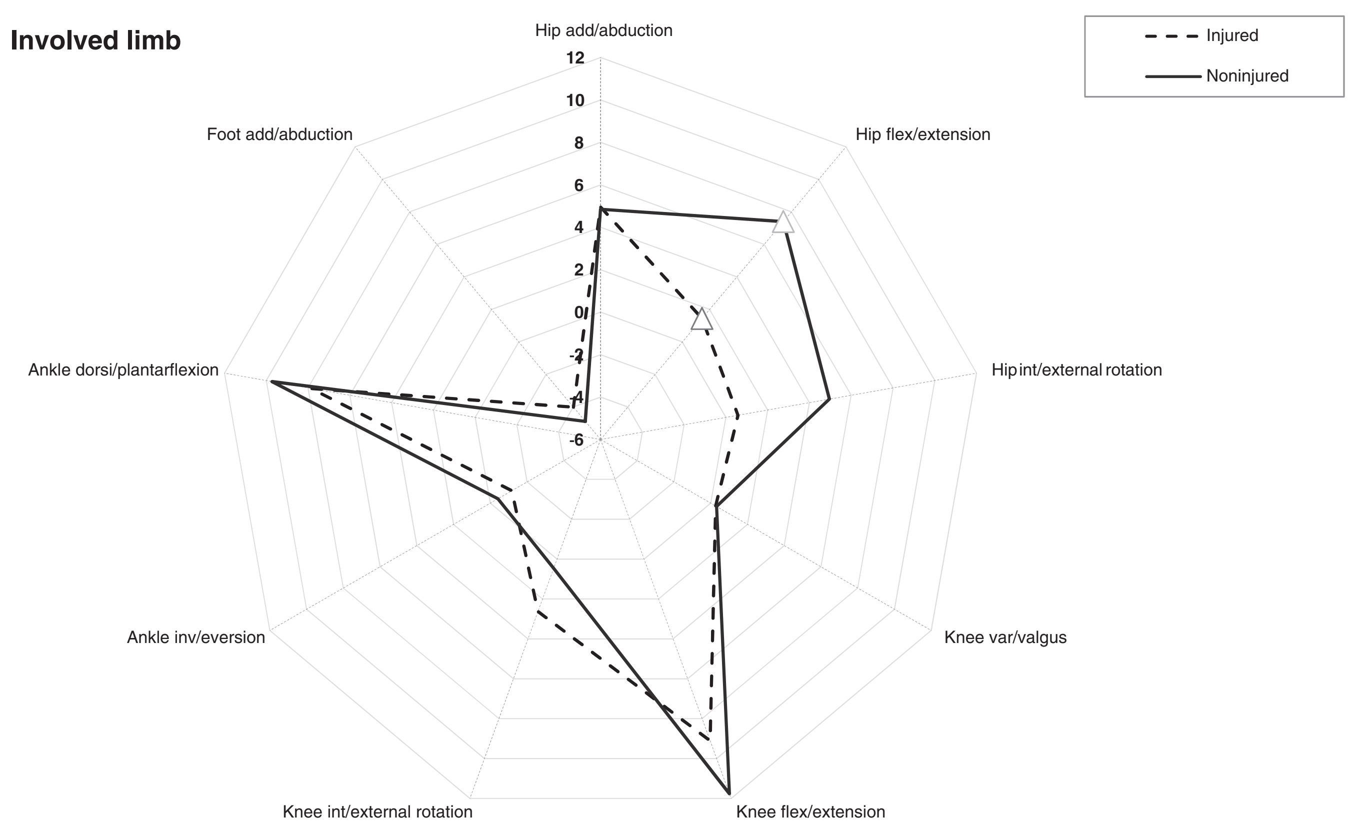

Fig. 1. K-flake graph depicting average joint position for the hip, knee and ankle for the involved limb of injured and non-injured participants. Δ indicates statistically significant between groups difference. Movements are listed in order of positive and negative values, with neutral equating to a value of 0 (for example, hip adduction is the positive value and hip abduction the negative value for hip frontal plane motion).

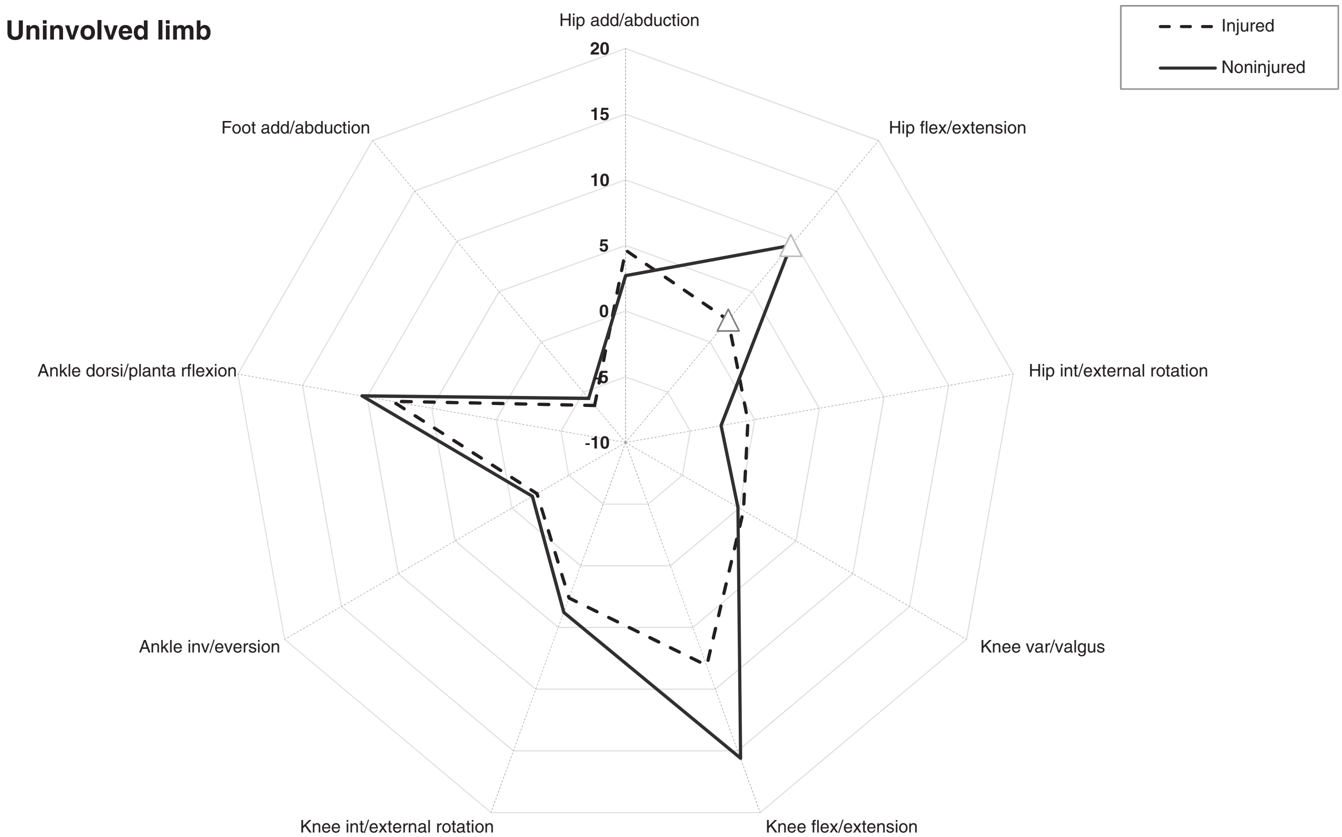

Fig. 2. K-flake graph depicting average joint position for the hip, knee and ankle for the uninvolved limb of injured and non-injured participants. Δ indicates statistically significant between groups difference. Movements are listed in order of positive and negative values, with neutral equating to a value of 0 (for example, hip adduction is the positive and hip abduction the negative value for hip frontal plane motion).

orientations as depicted by the kinematic variables and associated complexity of the COP path trajectory of the LAS group compared to the control group in the eyes-open condition.

This is the first analysis to combine stabilometric and kinematic measures of lower limb joint angular displacement during SLS in a group with first time acute LAS, as well as being the first to present an evaluation of the eyes-closed condition for this task in this group.

The FD measure utilized in the current study represents a reliable method of analyzing COP path trajectory (Doyle et al., 2005; Myklebust et al., 1995), whereby a change in FD may indicate a change in the postural control strategies for maintaining quiet stance (Doyle et al., 2005). FD has previously been shown to be a suitable means to characterize quite stance COP under a number of conditions as compared to more traditional measures (Doyle et al., 2005). Błaszczyk and Klonowski (2001) compared the COP path trajectory FD in healthy elderly participants in eyes-open bilateral stance to that of eyes-closed bilateral stance. The increase in FD that occurred on elimination of visual afferents led the authors to attribute a change in FD to a change in balance and postural stability. In pathological conditions, FD has been shown to be useful in evaluating postural instability in Parkinson and ataxia patients in bilateral stance in eyes open and eyes closed conditions (Manabe et al., 2001). Results from the research of Manabe et al. (2001) elucidated that the transition to eyes-closed stance corresponded with an increase in FD in pathological and control groups, with an associated higher FD in the pathological group. This was proportional to the severity of the condition in the pathological group. Cimolin et al. (2011) observed an increase in FD in participants with Prader–Willi Syndrome compared to healthy controls during bilateral stance with their eyes-open. They theorized that higher FD values may be interpreted as an inability of pathological patients to synergistically modulate the three sources of afferent information (i.e., the visual, vestibular and somatosensory systems) involved in maintaining balance.

In contrast to the findings reported in these analyses, we have observed a decrease in FD associated with pathology (acute LAS), which was present in the eyes-closed condition only, for both the involved and uninvolved limbs of injured participants. We offer two explanations for the contrasting results: differences in experimental methodology and subject sample separate the current investigation from those previously discussed. Specifically, we have assessed participants with first time acute LAS injury, who presented with significantly increased

Table 3
Fractal dimension scores [reported as mean (SD) with associated *P*-values and 95% CIs] for the LAS and control groups during eyes-open and eyes-closed single-limb stance.

Task		FD		*P*-value	95% confidence interval of the difference	
SLS	Participant	Involved limb	Uninvolved limb		Lower	Upper
Eyes open	LAS	1.18 (0.14)	1.15 (0.14)	0.38	−0.10	0.04
	Control	1.21 (0.13)	1.13 (0.15)	0.46	−0.04	0.10
Eyes closed	LAS	1.25 (0.14)	1.23 (0.14)	0.003	−0.23	−0.04
	Control	1.39 (0.16)	1.37 (0.21)	0.015	−0.23	−0.02

Abbreviations: LAS = lateral ankle sprain; FD = fractal dimension.

disability, pain and swelling on their involved limb (as opposed to participants with longstanding neurological impairment with no reported pain) during a task of eyes-closed single limb stance [in contrast to the bilateral, eyes-open stance task utilized in the investigations by Cimolin et al. (2011) and Manabe et al. (2001)], and have utilized Katz's algorithm for the calculation of FD in accordance with the procedures described by Prieto et al. (1996). With regard to the results observed in the current analysis, we theorize that a linear relationship between COP path trajectory and its associated FD does not exist; there may be an ideal FD which is specific to the constraints of the task and those limiting the individual, but it does not place on a scale where more or less is better or worse. In losing some of the available degeneracies via the distortion of somatosensory afferents, the postural control system of the injured participants has fewer available strategies with which to complete the prescribed task. While an increase in FD has previously been associated with the loss of visual afferents (Błaszczyk and Klonowski, 2001; Doyle et al., 2005), the lower FD within the constraints of this condition in the LAS group compared to the non-injured group in the current investigation may reflect a postural control system with fewer available strategies with which to complete the task. In essence the LAS participants were less able to utilize the base of support available to them, as evidenced by a reduced FD. This apparent impairment of postural control may have arisen from the presence of nociceptive input from the involved ankle which further compounded the distorted proprioceptive afferents at the joint level (Djupsjöbacka, 2008). That there was no difference in the eyes-open condition between LAS and control participants reflects that the presence of visual afferents sufficed to allow the postural control system of this injured group to optimally organize the network of constraints and degeneracies in a manner similar to that of the control group; several investigations have demonstrated that in circumstances where one or two sensory afferents are deficient, sufficient compensatory information can be provided by remaining sources for equilibrium to be maintained (Horak et al., 1990; Jørgensen et al., 2011; Nashner, 1971).

The non-significance of the between-group findings for the eyes-open condition is however in contrast with previous research (Evans et al., 2004; Fridén et al., 1989; Hertel et al., 2001; Holme et al., 1999; Leanderson et al., 1996) and may be due to methodological differences between these studies and the current investigation.

Although the SLS balance task is intended to be static in nature, every participant displayed some degree of movement over the course of each trial. Consequently, these time series represent an internally generated perturbation, as well as the organization of a postural control system in which the resultant ground reaction forces differ to the displacement of the segments of the kinetic chain to which they are coupled (Myklebust et al., 1995; Winter, 1995). The current research tackles this issue by supplementing measures of the COP path trajectory with an averaged 3-dimensional kinematic profile of lower limb alignment to discern the differences in joint position that accompany COP FD. Furthermore, conceptualization of the postural orientation that produced the observed FD makes the current findings more accessible to clinicians. The kinematic profiles can be seen to reflect the FD of the COP path: similar to the FD in the eyes-open condition, there were no differences in the average position assumed by LAS participants at the hip, knee or ankle joints in the sagittal, frontal or transverse planes of motion compared to control participants for either the involved or uninvolved limbs. However, in the eyes-closed condition, the reduced FD of LAS participants compared to control participants on both the involved and uninvolved limbs was linked to a bilateral decrease in hip flexion. The presence of bilateral impairments in subjects with acute LAS is well documented in the literature (Wikstrom et al., 2010), supporting the hypothesis that LAS has the capacity to cause spinal-level inhibition through gamma motor neuron loop dysfunction resulting in postural control impairment (Khin-Myo-Hla et al., 1999). The conscious perception of swelling and pain associated with the acute ankle sprain in the current sample during the full weight-bearing SLS task could be linked with this supraspinal inhibition, thus impairing postural control strategies when potential degeneracies became unavailable (i.e. in the eyes-closed condition). This is reflected in the bilaterally observed decrease in hip flexion and COP path trajectory FD in the injured group (with significant self-reported disability) compared to the non-injured group (with no self-reported disability). The ankle joint has a central role for maintaining equilibrium in SLS. The elimination of visual afferents disrupts this equilibrium, and corrections in healthy populations are then made at the hip (Tropp and Odenrick, 1988). We hypothesize that the natural transition from an inverted pendulum model (where the ankle has a central role in postural corrections) to a multi-segmental chain model (where the hip has a central role in postural corrections) on removal of visual afferents did not occur in the LAS group secondary to a change in the sensory environment due to injury (McCollum et al., 1996). In the eyes-open task for both groups, the sensorimotor system had the ability to shift reliance away from the affected area toward other available receptors, hence no between-group differences were observed.

The consequences of these bilaterally observed impairments in postural control are of significant importance considering their role in increasing the risk of re-spraining the injured ankle (McGuine et al., 2000; Tropp et al., 1984), and particularly in view of the equality of the observed effects on the involved and uninvolved limbs. The potential worth of a task of eyes-closed SLS as a simple yet challenging early-stage rehabilitation exercise should be noted; there is an inference from the current data that static balance rehabilitation tasks such as eyes-closed SLS is a challenging exercise for participants with acute LAS, and that an increase in eyes closed SLS FD may coincide with recovery, although this can only be confirmed with follow-up analyses.

It is however important to note that the simplicity of the kinematic analysis technique used in the current investigation must be considered a potential limitation. We chose to quantify a surrogate of the motor output using COP and averaged kinematic measures to provide a simple and immediately accessible conceptualisation of the sensorimotor response to distorted sensory afferents. Future research may benefit from more advanced analyses of movement variability and between-joint coupling during SLS to further advance current understanding. Furthermore, there was a representative gender disparity between males and females in the LAS and control groups; these convenience samples were composed of 35% and 21% males and females respectively. While no research has previously elucidated any between-groups differences for males and females during a static balance task using kinematic or kinetic outcome measures, the results of the current investigation must be considered in light of this disparity. With regard to future investigations, a follow-up period whereby participants with first time acute LAS are evaluated longitudinally in the determination of clinical outcome would be enlightening.

5. Conclusions

The postural control system of participants with first time acute LAS displays bilateral impairment when denied previously available sensory degeneracies, as evidenced by altered postural orientation strategies and reduced complexity of the COP path during eyes closed SLS. Future research is required to identify the variables that determine recovery or the onset of recurrent symptoms in patients with acute LAS injury.

Conflicts of interest and source of funding

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