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Author(s)	Doherty, Cailbhe; Bleakley, Chris J.; Hertel, Jay; Ryan, John; Sweeney, Kevin T.; Delahunt, Eamonn
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Authors:

Cailbhe Doherty[1]

Chris Bleakley[3]

Jay Hertel[4]

Brian Caulfield[1]

John Ryan[5]

Kevin Sweeney[1]

Eamonn Delahunt[1,2]

1. School of Public Health, Physiotherapy and Population Science, University College Dublin, Dublin, Ireland.
2. Institute for Sport and Health, University College Dublin, Dublin, Ireland.
3. Sport and Exercise Sciences Research Institute, Ulster Sports Academy, University of Ulster, Newtownabbey, Co. Antrim, Northern Ireland.
4. Department of Kinesiology, University of Virginia, Charlottesville, VA, United States.
5. St. Vincent's University Hospital, Dublin, Ireland.

Address for Correspondence:

Cailbhe Doherty

A101
School of Public Health, Physiotherapy and Population Science
University College Dublin
Health Sciences Centre
Belfield
Dublin 4
Ireland
Email: cailbhe.doherty@ucdconnect.ie
Telephone: 00 353 1 7166671
Fax: 00 353 1 716 6501

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Running title: Inter-joint coordination following ankle sprain

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 lateral ankle sprain and 20 non-injured controls completed three 20-second stance task trials in conditions 1 and 2. An adjusted coefficient of multiple determination statistic was used to compare stance limb 3-D kinematic data for similarity in the aim of establishing patterns of inter-joint coordination. The fractal dimension of the stance limb center 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 center-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]; $\eta^2 = .43$; sagittal/transverse plane: 0.14 [0.11] vs 0.09 [0.05]; $\eta^2 = 0.38$) and condition 2 (sagittal/frontal plane: 0.15 [0.12] vs 0.08 [0.06]; $\eta^2 = 0.48$), with an associated decrease in the fractal dimension of the center-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 LAS present with a hip-dominant coordination strategy for static unilateral stance compared to non-injured controls.

Key words: ankle joint [MEsH]; biomechanics [MEsH]; kinematics [MEsH]; kinetics [MEsH]; postural balance [MEsH]

1.0 Introduction

The high prevalence of ankle sprain in a wide variety of activity types [1] 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 the coordination of postural control [2-5]. Postural control during unilateral stance emerges from a dynamic interaction between feedback mechanisms and a central motor program [6]. Feedback mechanisms originate as sensory afferents which include visual, vestibular and somatosensory components [6]. A decay in somatosensory afferents, as may occur with acute ankle sprain injury [7], 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 coordination response [4,8]. With respect to acute ankle sprain, 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 [3].

The high potential for patients with a history of ankle sprain to suffer recurrence [9,10] has prompted researchers to theorise that recovery or the onset of chronicity is dependent on the type of coordination strategies adopted in the year following the acute injury [11-13]; patients who subjectively report the continuum of residual symptoms collectively labelled ‘chronic ankle instability’ (CAI) [14], or those ‘copers’ who recover with no relapse [15], have both been shown to adopt unique coordination strategies conducive with their injury outcome [11,13]. However, the research evaluating these coordination strategies at a specific time point occurring in the period between the acute episode (<2 weeks following injury) and the determination of recovery/chronicity (>1year following injury), is sparse.

Bernstein described coordination as the process of incorporating redundant motor system degrees of freedom into a controllable unit [16]. Traditionally in laboratory analyses of static unilateral stance, kinematical data from isolated joints (e.g. angular displacement) are presented as a function of time [3,17] to identify the contributing role of each lower-extremity joint to the coordination of postural control. For example, Tropp and Odenrick[18] observed a central role of the ankle joint in postural corrections during single-limb standing, while Doherty et al. [3] 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). However, it has recently been suggested that evaluating inter-joint coordination relationships between segments of the motor apparatus may further advance current understanding of the coordination strategies supporting human postural control in environments of sensory decay [19,20]. Indeed no research currently exists evaluating the inter-joint coordination strategies of a group following first-time, acute lateral ankle sprain (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, which can only occur a minimum of 1 year following the initial injury [14,15,21].

Therefore, the purpose of this study was to evaluate the coordination of 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 the coordination of 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 [20,22] was used to establish inter-joint coordination between the hip, knee and ankle joints in all planes of motion. ACMD analysis provides a mechanism by which continuous waveform data can be evaluated for similarity [22], thus establishing the relationship between movement patterns at different joints, in different planes of motion. The measure of stabilometry utilised was the fractal dimension (FD) of the centre of pressure (COP) path [23]. FD has previously been used to evaluate unilateral standing balance in participants with acute LAS injury [2,3] 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 [24]. We hypothesised that participants with a recent history of ankle sprain 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 hypothesized 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).

2.0 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. 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 (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 utilized to quantify self-reported function and participant reported symptoms [25], and the Cumberland Ankle Instability Tool (CAIT) was utilized to evaluate ankle joint function and painful symptoms [26].

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 joints were collected for each participant, with subsequent placement of lower limb markers and wands as described by Monaghan et al. [27]. 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 [28]. 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 both limbs were not included in the analysis. 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 degrees abduction, 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 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) 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 were made using the ACMD statistic [22] 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. For example, frontal plane hip motion was compared with frontal, sagittal and transverse plane knee motion, before being compared with the same relative movements at the ankle joint. 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) [22]. The same data processing procedure was performed for both eyes-open and eyes-closed unilateral stance, on both limbs. See Figure 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 wascenter of pressure (COP) (the location of the vertical reaction vector on the surface of a force-plate) path for each reach trial. The COP is a bivariate distribution, jointly defined by the antero-posterior (AP) and medio-lateral (ML) coordinates which in a time series define the COP path relative to the origin of the force platform [24]. COP data acquired from trials of the unilateral stance were used to compute FD of the combined AP and ML COP path using an algorithm previously published and described by Prieto et al [24]. 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 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[29]. Kinematic and COP data were analysed using the Codamotion software, with the following axis conventions: x axis = frontal-plane motion; y = sagittal-plane motion; 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’’. 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.

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 bonferonni 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 were adjusted for multiple tests using the Benjamini-Hochberg method for false discovery rate (<5%) [30] 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 (involved and uninvolved) in each condition. The significance level for this analysis was set a priori with a Bonferroni adjusted alpha level of 0.025.

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

3.0 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 squared = 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). Similarly 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. Joint motion ranges for both conditions of unilateral stance are detailed in 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 squared = 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).

4.0 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 coordination strategies that can be used either independently or in conjunction by the central motor program based on the feedback received from sensory afferents in order to achieve adaptable control of the COP within the supporting base [31]: 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 [31,32]. It is plausible that a decay of sensory afferents (as may occur with injury [6,8]), 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 [33]. The results of the current study can be seen to conform to the propositions first made by Nashner and McCollum, and as such we believe it appropriate to evaluate these coordination strategies within the context of their theoretical framework.

The use of the ACMD statistic to establish normative similarities in 3-dimensional inter-joint movement patterns for the lower extremity during eyes-open and eyes-closed unilateral stance 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 [20]. This group with a history of LAS, who reported significantly decreased function on their previously injured (involved) limb, displayed increased hip-ankle 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. These results may indicate the utilisation of a more hip-dominant balance strategy in the LAS group, perhaps due to the local somatosensory compromise associated with reduced ankle joint function, which was further confounded (and subsequently compensated for), by removal of visual afferents. These theories are supported on inspection of the joint range values, where the LAS group displayed significantly greater transverse plane ankle motion in the eyes-open condition, and significantly greater sagittal plane hip motion in the eyes-closed condition.

Despite the stasis sought as part of the constraints of the unilateral stance tasks used in the current study, an unremitting synchrony of postural adjustments is required to maintain equilibrium throughout their course. An impaired ability to correct any disequilibrium created by these postural adjustments using the ankle strategy secondary to inadequate ankle function 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 [34]), and which possesses a greater availability of non-distorted somatosensory afferents; specifically, we refer to the strategy of the hip. Tropp and Odenrick [18] 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 [18]. Perhaps the initial balance deficits associated with pain and swelling that presented in the acute phase of LAS injury [3], persisted into the weeks and months following; an acute distortion of somatosensory afferents [35] manifested in an immediate impairment in ankle joint function [3,36], potentially forcing the adoption of the more proximal hip strategy [3,18], and this may have persisted 6-months following the injury, as evidenced by the current findings. That the LAS group displayed increased inter-joint coupling in 79% of all cases for both the involved limb in both the eyes-open and eyes-closed conditions suggests a reduced ability for separate components of the kinetic chain to function independently following the initial injury.

The reduction in involved limb FD that presented in 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-dominant postural control strategy [3,24]. 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; too large an FD has previously been attributed to an inability to synergistically modulate sensory afferents in producing an efferent response [37] while too small a FD has previously been linked with insufficient utilisation of the available base of support [24]. COP analyses are merely surrogate measures of postural control, and often mask the complex coordination strategies that precede them, particularly in instances of unilateral stance [20]. Furthermore, FD has previously failed to distinguish between an acute LAS and control groups in the eyes open condition [3], but has made distinctions between these groups when visual afferents have been removed [2,3]. 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 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 by 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 greater local rotational movement (directly affecting the complexity of COP patterns), and despite a similar hip-dominant balance strategy, an FD within normal ranges.

The presence of bilateral postural control impairments in subjects with acute LAS during similar tasks of unilateral stance [3,4], and the absence of such deficits in the current sample suggests that acute LAS has the capacity to cause spinal-level inhibition through gamma motor neuron loop dysfunction [38], but that this does not always persist in the months following the acute episode [39]. Alternatively, it may be that a persistence of peripheral impairment with/without central impairment is sufficient to limit an individual’s capacity to maintain successful balance. Whether these deficits 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 study: 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.

The primary implication of the current findings for clinicians is that coordination 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. As the hip is more suited to synchronising the global movements of the head, arms and trunk with the lower extremities, 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 in completing the local movement subtleties required for normal unperturbed standing balance [31], this may contribute to instability. Thus, clinicians must devise rehabilitation protocols with these issues in mind.

5.0 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 balance strategy during tasks of eyes-open and eyes-closed unilateral stance.

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References

[1] Doherty C, Delahunt E, Caulfield B, Hertel J, Ryan J, Bleakley C. The Incidence and Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-Analysis of Prospective Epidemiological Studies. Sports Med 2014;44 (1) 123-140

[2] Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Balance failure in single limb stance due to ankle sprain injury: an analysis of center of pressure using the fractal dimension method. Gait & Posture 2014.

[3] Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Postural control strategies during single limb stance following acute lateral ankle sprain. Clinical Biomechanics 2014.

[4] Evans T, Hertel J, Sebastianelli W. Bilateral deficits in postural control following lateral ankle sprain. Foot Ankle Int 2004;25:833-839.

[5] Hertel J, Buckley W, Denegar C. Serial testing of postural control after acute lateral ankle sprain. J Athl Train 2001;36:363-368.

[6] McCollum G, Shupert C, Nashner L. Organizing sensory information for postural control in altered sensory environments. J Theor Biol 1996;180:257-270.

[7] Freeman MA. Instability of the foot after injuries to the lateral ligament of the ankle. J Bone Joint Surg Br 1965;47:669-677.

[8] McKeon PO, Stein AJ, Ingersoll CD, Hertel J. Altered plantar-receptor stimulation impairs postural control in those with chronic ankle instability. J Sport Rehabil 2012;21:1-6.

[9] Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. British journal of sports medicine 2005;39:e14; discussion e14.

[10] Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle inversion trauma. Scand J Med Sci Sports 2002;12:129-135.

[11] Wikstrom EA, Fournier KA, McKeon PO. Postural control differs between those with and without chronic ankle instability. Gait Posture 2010;32:82-86.

[12] Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Discriminating between copers and people with chronic ankle instability. J Athl Train 2012;47:136-142.

[13] Brown CN, Padua DA, Marshall SW, Guskiewicz KM. Hip kinematics during a stop-jump task in patients with chronic ankle instability. J Athl Train 2011;46:461-467.

[14] Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion criteria when investigating insufficiencies in chronic ankle instability. Med Sci Sports Exerc 2010;42:2106-2121.

[15] Wikstrom EA, Brown C. Minimum Reporting Standards for Copers in Chronic Ankle Instability Research. Sports Med 2014;44:251-268.

[16] Bernstein N. The Coordination and Regulation of Movements. London: Pergamon; 1967.

[17] Huurnink A, Fransz D, Kingma I, Verhagen E, van Dieën J. Postural stability and ankle sprain history in athletes compared to uninjured controls. Clin Biomech (Bristol, Avon) 2014;29:183-188.

[18] Tropp H, Odenrick P. Postural control in single-limb stance. J Orthop Res 1988;6:833-839.

[19] Wheat J, Glazier P. Movement system variability: Human kinetics; 2005.

[20] Liu W, Santos MJ, McIntire K, Loudon J, Goist-Foley H, Horton G. Patterns of inter-joint coordination during a single-limb standing. Gait and Posture 2012;36:614-618.

[21] Gribble P, Delahunt E, Bleakley C, Caulfield B, Docherty C, Fourchet F, et al. Selection criteria for patients with chronic ankle instability in controlled research: a

position statement of the International Ankle Consortium. The Journal of orthopaedic and sports physical therapy 2013;43:585-591.

[22] Kadaba M, Ramakrishnan H, Wootten M, Gainey J, Gorton G, Cochran G. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849:860.

[23] Katz MJ, George EB. Fractals and the analysis of growth paths. Bull Math Bio 1985;47:273-286.

[24] Prieto T, Myklebust J, Hoffmann R, Lovett E, Myklebust B. Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Trans Biomed Eng 1996;43:956-966.

[25] Carcia C, Martin R, Drouin J. Validity of the Foot and Ankle Ability Measure in athletes with chronic ankle instability. J Athl Train 2008;43:179-183.

[26] Hiller C, Refshauge K, Bundy A, Herbert R, Kilbreath S. The Cumberland ankle instability tool: a report of validity and reliability testing. Arch Phys Med Rehabil 2006;87:1235-1241.

[27] Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with chronic ankle instability compared to controls. Clin Biomech (Bristol, Avon) 2006;21:168-174.

[28] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. Journal of Biomechanics 2002;35:543-548.

[29] Winter D. Biomechanics and motor control of human movement. 4th ed. Hoboken, NJ: John Wiley and Sons; 2009.

[30] Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society 1995;51:289–300.

[31] Nashner L, McCollum G. The organization of human postural movements: a formal basis and experimental synthesis. Behav. Brain Sci 1985;8:135-172.

[32] Hwang S Fau - Tae K, Tae K Fau - Sohn R, Sohn R Fau - Kim J, Kim J Fau - Son J, Son J Fau - Kim Y, Kim Y. The balance recovery mechanisms against unexpected forward perturbation. Ann Biomed Eng 2009 37:1629-1637.

[33] Winter DA. Human balance and posture control during standing and walking. Gait and Posture 1995;3:193-214.

[34] Fong CM, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. J Athl Train 2011;46:5-10.

[35] Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional instability of the foot. J Bone Joint Surg Br 1965;47:678-685.

[36] Djupsjöbacka M. Fundamentals of Musculoskeletal Pain.2008.

[37] Cimolin V, Galli M, Rigoldi C, Grugni G, Vismara L, Mainardi L, et al. Fractal dimension approach in postural control of subjects with Prader-Willi Syndrome. J Neuroeng Rehabil 2011;20:8-45.

[38] Khin-Myo-Hla, Ishii T, Sakane M, Hayashi K. Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle. Foot Ankle Int 1999;20:554-559.

[39] Wikstrom E, Naik S, Lodha N, Cauraugh J. Bilateral balance impairments after lateral ankle trauma: a systematic review and meta-analysis. Gait Posture 2010;31:407-414.

Figure legends

Figure 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).

Table 1

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; 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;

Table 2

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.

	Joint pair	Eyes open														
		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*	.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*	.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

*Denotes statistically significant between-groups difference; ‘/’ denotes comparison between two joints/planes of motion. 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.

Table 3

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*	.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

*Denotes statistically significant between-groups difference; ‘/’ denotes comparison between two joints/planes of motion. 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.

Table 4

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.

		Eyes open														
		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
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*
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*	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

*Denotes statistically significant between-groups difference; Abbreviations: LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

Figure 1