Title	Lower Limb Interjoint Postural Coordination One Year after First-Time Lateral Ankle Sprain
Authors(s)	Doherty, Cailbhe, Bleakley, Chris J., Hertel, Jay, Caulfield, Brian, Ryan, John, Sweeney, Kevin T., Patterson, Matthew, Delahunt, Eamonn
Publication date	2015-11-01
Publication information	Doherty, Cailbhe, Chris J. Bleakley, Jay Hertel, Brian Caulfield, John Ryan, Kevin T. Sweeney, Matthew Patterson, and Eamonn Delahunt. "Lower Limb Interjoint Postural Coordination One Year after First-Time Lateral Ankle Sprain." Wolters Kluwer, November 1, 2015. https://doi.org/10.1249/MSS.0000000000000673.
Publisher	Wolters Kluwer
Item record/more information	http://hdl.handle.net/10197/10903
Publisher's version (DOI)	10.1249/MSS.0000000000000673

Title: Inter-joint postural coordination 1-year following first-time ankle sprain injury.

Running title: Inter-joint coordination after ankle sprain

Abstract word count: 248

Word count: 4907

4 tables

0 figures

Authors:

Cailbhe Doherty[1]

Chris Bleakley[3]

Jay Hertel[4]

Brian Caulfield[1]

John Ryan[5]

Kevin Sweeney[6]

Matthew R Patterson[6]

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.
6. Insight Centre for Data Analytics, University College Dublin, 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

Conflicts of Interest and Source of Funding:

No conflicts of interest were associated with the authors and the results of this research. This study was supported by the Health Research Board (HRA_POR/2011/46) as follows: PI – Eamonn Delahunt; Co-investigators – Chris Bleakley and Jay Hertel; PhD student – Cailbhe Doherty).

ABSTRACT

Introduction: Longitudinal analyses of participants with a history of first-time lateral ankle sprain are lacking. This investigation combined measures of inter-joint coordination and stabilometry to evaluate static unipedal stance with eyes-open (condition 1) and eyes-closed (condition 2) in a group of participants with chronic ankle instability compared to ankle sprain ‘copers’ (both recruited 12-months after sustaining an acute first-time lateral ankle sprain) and a group of non-injured controls.

Methods: Twenty-eight participants with chronic ankle instability, forty-two ankle sprain ‘copers’ and twenty non-injured controls completed three 20-second single-limb stance 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 inter-joint coordination. The fractal dimension of the stance limb center of pressure path was also calculated.

Results: Between-group analyses revealed that participants with instability displayed notable increases in ankle-hip linked coordination compared to both copers (0.52 [1.05] vs -0.28 [0.9] p = 0.007) and controls (0.52 [1.05] vs -0.63 [0.64] p = 0.006) in condition 1 and to controls (0.62 [1.92] vs 0.1 [1.0] in condition 2.. Participants with instability also exhibited a decrease in the fractal dimension of the center-of-pressure path during condition 2 compared to both controls and copers. **Conclusion:** Participants with chronic ankle instability present with a hip-dominant strategy of eyes-open and eyes-closed static unipedal stance. This coincided with reduced complexity of the stance-limb center of pressure path in the eyes-closed condition only.

Key words: ankle joint [MeSH]; biomechanical phenomena [MeSH]; kinematics [MeSH]; kinetics [MeSH]; postural balance [MeSH]

INTRODUCTION

Lateral ankle sprain (LAS) injury pervades a variety of activities, with between 0.88 [CI 95%: 0.73 – 1.02] and 7 [CI 95%: 6.82 – 7.18] injury events occurring per 1,000 exposures, depending on the activity type (11). The prevalence of this injury in a wide range of sports and activities is further complicated by its capacity to deteriorate into an array of chronic sequalae and injury recurrence, collectively termed “chronic ankle instability (CAI)”(15-17), which has been linked to limitations in future physical activity participation (1).

Although CAI is considered a multifaceted condition with a range of consequences, persistent deficits in single-limb stance (SLS) postural control strategies are well established in individuals with CAI (18, 25, 36), and may be consequent upon a potential change in neural signalling following the initial ankle joint trauma (14). This theory has since been tested in previous studies comparing individuals with a history of LAS to uninjured controls (13, 35, 37), with a new hypothesis emerging whereby the long-term outcome following LAS is dependent upon the success or failure of the newly adopted post-LAS postural control strategies (33, 34). This has yet to be confirmed however, as there is currently an absence of longitudinal investigations which prospectively track the restoration or degradation of postural control strategies after an initial LAS.

More recently, ankle sprain ‘copers’, who have a history of LAS and experience a restoration of pre-injury levels of function in the year following initial injury (15, 33), have been compared to individuals with CAI during SLS (36); this is considered to provide a stronger, more relevant comparison in laying the foundation for longitudinal analyses and the development of clinical outcome models for the CAI paradigm (33). Recently published material from our laboratory was developed according to this paradigm: individuals with an acute, first-time LAS were evaluated in comparison to a non-injured control group during eyes-open and eyes-closed SLS using kinematic and kinetic measures of joint position and platform stabilometry respectively (7). A follow-up analysis of these same individuals 6-months following the initial assessment revealed a hip-dominant postural control strategy prevailing during the prescribed tasks of SLS, again in comparison to non-injured controls (9). In this latter investigation, an adjusted coefficient of multiple determination (ACMD) statistic was utilised to evaluate waveform similarity between lower extremity 3-D joint angular displacements in the determination of inter-joint 'coupling' strategies during 20 seconds of eyes-open and eyes-closed SLS (9). We believe novel insight was gained by combining these laboratory measures: the increase in observed coupling between sagittal plane hip and frontal plane ankle motion in LAS participants underpinned a hypothesis that these individuals adopt a hip-dominant strategy in the maintenance of single-limb postural control, perhaps to compensate for a dysfunctional ankle joint (9). This theory is in agreement with the model of human postural control proposed by Nashner and McCollum, in which an 'ankle strategy' is appropriated to the fine tuning of static postural control, and a 'hip strategy' is employed to tackle more substantial postural control disturbances (28); the LAS group in the aforementioned studies were considered to have reduced capacity to utilise their ankle strategy, thus adopting the more proximal hip strategy in its place (7, 9).

The measure of platform stabilometry employed in the aforementioned investigations from our laboratory was the fractal dimension (FD) of the center of pressure (COP) path. The FD is a unit-less measure that conceptualises the complexity of the COP path using a value between 1 (a straight line or low complexity) and 2 (a convoluted line or high complexity)(23). In addition to a hip-dominant kinematical strategy, LAS participants were also shown to display a bilaterally reduced FD of the COP path during eyes-closed SLS within 2 weeks of incurring their initial injury (7), and on their involved limb only 6 months following their initial sprain (9). This was interpreted as a reduced ability to utilise the available base of support on removal of visual afferents (6, 7, 9).

The current study is a continuation of those previously described and forms part of a larger longitudinal analysis of the LAS cohort. Specifically, we sought to complete the 12-month follow-up of the individuals we previously alluded to who completed the 2-week and 6-month evaluations, thus allowing for participant segregation as CAI or ankle sprain "coper" status. Kinematic and stabilometric measures were combined to compare stance limb inter-joint coordination and COP path complexity during eyes-open and eyes-closed SLS between individuals with CAI, ankle sprain "copers" and a separately recruited non-injured control group of participants. We hypothesised that individuals with CAI would exhibit the same hip-dominant coupling strategies for completing eyes-open and eyes-closed SLS which were documented 6-months previously, , whereas "coper" and control participants would not due to a superior capacity to employ an ankle-based balance strategy in isolation. Furthermore, we hypothesised that during eyes-closed SLS CAI participants would exhibit poorer postural control ability, as evidenced by a reduced FD of the COP path.

METHODS

Participants

As part of the larger longitudinal study conducted in our laboratory, eighty-two individuals presenting with a first-time acute LAS were recruited from a University-affiliated hospital emergency department. All LAS participants were provided with the same basic advice on applying ice and compression on discharge from the hospital ED: they were each encouraged to weight-bear and walk within the limits of pain. Whether participants sought additional formal medical healthcare services for council or rehabilitation of their LAS was recorded on arrival to the testing laboratory but not controlled as part of the current study.

These individuals were required to attend three test sessions and complete a number of movement tasks within 2-weeks of sustaining their initial injury, with further follow-up at 6 months and 12 months. Testing procedures for these participants in the acute phase of their injury has previously been reported (6, 8, 10). A total of seventy-one of the original eighty-two participants returned for the third test session (i.e. 12 month follow-up); the current investigation relates to the data collected for these individuals at this time-point. An additional convenience group of twenty participants with no prior history of LAS were also recruited from the hospital catchment area population using posters and flyers to act as a control group. Participant characteristics for the individuals included in the current analysis are presented in Table 1. The following exclusion criteria were utilised for both limbs (where applicable) at the time of recruitment: (1) no previous history of ankle sprain injury (excluding the initial acute LAS episode for the CAI and coper groups); (2) no other severe lower extremity injury in the last 6 months; (3) no history of ankle fracture; (4) no previous history of major lower limb surgery; (5) no history of neurological disease, vestibular or visual disturbance or any other pathology that would impair their motor performance. Participants provided written informed consent, and the study was approved by the University Human Research Ethics Committee.

LAS participants' designation as CAI or coper status was completed according to recently published guidelines (15). Self-reported ankle instability was confirmed with the Cumberland Ankle Instability Tool (15); individuals with a score of <24 were designated as having CAI while "copers" were designated with a score of ≥ 24, to avoid the potential for false positives in this group (39). Additionally, to be designated as a coper, participants must have returned to pre-injury levels of activity and function (36). Finally, the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) were utilised as a means to evaluate general self-reported foot and ankle function (15). All participants completed the CAIT and subscales of the FAAM on arrival to the testing laboratory.

Based on these criteria, twenty-eight of the LAS participants were designated as having CAI, and forty-two as "copers" (Table 1). One 'coper' participant was excluded because he did not return to pre-injury levels of activity participation.

Protocol

Collection methods for this study have been previously documented (9). Briefly, following the collection of anthropometric measures required for the calculation of internal joint centres of the lower extremity joints, each participant was instrumented with the Codamotion bilateral lower limb gait set-up according to the manufacturer guidelines (Charnwood Dynamics Ltd, Leicestershire, UK). 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 (40). Participants then 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 rest period. Following another 2 minute rest period, participants then attempted to complete three 20 second SLS trials 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 (6, 21). 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 the SLS task, participants 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 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 as failed in the eyes-closed condition if the subject opened their eyes at any point.

Kinematic and Kinetic Data Processing

Three Codamotion cx1 units were used to acquire data on 3-D angular displacements at the hip, knee and ankle joints for both limbs during the SLS tasks. 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 and COP data were analysed using the Codamotion software 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.

Pairwise comparison of 3-D temporal angular displacement waveforms for the hip and ankle joints of the stance limb were made using the ACMD statistic (22) to determine the similarity of a given pair of waveforms during both conditions of SLS. The pairing of ankle and hip motion was completed in three dimensions, with nine resultant ACMD values for each individual SLS trial. The mean ACMD from three trials of unilateral stance was used as a representative ACMD for each participant for the eyes-open and eyes-closed conditions separately, with subsequent calculation of group (CAI; coper; control) means. ACMD values ranged from 0 (no similarity) to 1 (two identical curves) (22).

The kinetic data of interest was the COP, the location of the vertical reaction vector on the surface of a force-plate) path (30). COP data acquired from trials of the unilateral stance were used to compute FD of the COP path using an algorithm previously published and described by Prieto et al (30). 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 and grouped accordingly. The COP time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency(38).

Data Analysis and Statistics

For both LAS groups (CAI and coper), the limb injured at the time of recruitment was labelled as ‘‘involved’’ and the non-injured limb as ‘‘uninvolved’’. With regards to the control group, limbs were randomly assigned as ‘‘involved’’ and ‘‘uninvolved’’ in all cases. For all outcomes, we calculated mean (SD) scores for the involved and uninvolved limbs of the CAI, coper and control groups.

A principal component analysis (PCA) was performed to reduce the dimensionality of the kinematic data. Specifically, the nine ‘latent’ variables of inter-joint coordination were reduced into significant components. This was performed separately for the eyes-open and eyes-closed conditions. Preliminary analyses (scree test and parallel analysis) informed our decision to retain three components for the eyes-open condition and two components for the eyes-closed condition.

To test our hypothesis that the CAI group would display hip-dominant strategies of inter-joint coordination , the components derived from the ACMD ‘latent’ variables were compared between groups using a 2-way MANOVA for each condition (eyes-open and eyes-closed). The independent variables were group (CAI; coper; control) and limb (involved; uninvolved). The dependent variables were the three extracted components for the eyes-open condition and the two extracted components for the eyes-closed condition. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices, and multicollinearity with no serious violations noted. An alpha-level of $p < 0.05$ was used to determine significant differences for each analysis (19). Post-hoc comparisons were completed using a Tukey HSD test where appropriate. The significance level for post-hoc analyses was set with a bonferroni adjusted alpha of $p < 0.017$ for the eyes-open condition (0.05/3 components) and $p < 0.025$for the eyes-closed condition (0.05/2 components)(20).

In order to test our hypothesis that the CAI group would display reduced COP path trajectory FD during the SLS task compared to copers and controls, a two-way between-groups analysis of variance was conducted separately for each condition (eyes-open and eyes-closed). The independent variables were group (CAI; coper; control) and limb (involved; uninvolved). The dependent variable was FD of the COP path. The significance level for this analysis was set a priori at $p < 0.05$. Post-hoc comparisons were completed using a Tukey HSD test where appropriate. The significance level for post-hoc analyses was set at $p < 0.05$ for both conditions.

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

RESULTS

All participants completed the eyes-open SLS task on both limbs. Thirty-six percent of CAI participants (10 of 28), 76% of copers (33 of 42) and 85% of controls (17 of 20) completed the SLS task with their eyes-closed on both their ‘involved’ and ‘uninvolved’ limbs.

Regarding inter-joint coordination, there was a statistically significant main effect for group in the eyes-open [$F\ (3,322) = 2.585$, $p = 0.018$; Wilks’ Lambda = 0.91] and eyes-closed [$F\ (3,220) = 3.58$, $p = 0.008$; Wilks’ Lambda = 0.88] conditions. When the results of the dependent variables were considered separately, the only components to reach statistical significance at the bonferroni adjusted alpha levels were components 3 (which loaded heavily on the inter-joint coordination between sagittal plane hip and frontal plane ankle motion, and sagittal plane hip and transverse plane ankle motion) in the eyes-open condition [F(2,321) = 6.508, p = 0.002, $\eta_p^2 = 0.074$] and 2 (which loaded heavily on the inter-joint coordination between sagittal plane hip motion and ankle motion in all three dimensions, and frontal plane hip motion and sagittal plane ankle motion) in the eyes-closed condition [F(2,219) = 4.125, p = 0.019, $\eta_p^2 = 0.069$]. Post-hoc analysis and inspection of the mean scores revealed that CAI participants exhibited lower mean scores for component 3 in the eyes-open condition, most notably on their involved limb (M = -0.52, SD = 1.05) compared to both copers (M = 0.28, SD = 0.9, p = 0.007) and controls (M = 0.63, SD = 0.64, p = 0.006). Due to the negative correlation between component 3 and its latent variables, this represented an increase in ankle-hip linked coordination. With regards to the eyes-closed condition, post-hoc analyses revealed that CAI participants exhibited greater mean scores for component 2 compared to controls only (p = 0.024). This was evident on both their involved (CAI: M = 0.62, SD = 1.92; Control = 0.1, SD = 1.0) and uninvolved (CAI: M = 0.07, SD = 1.19; Control = -0.34, SD = 0.66) limbs. Due to the positive correlation between this component and its latent variables, this too represented an increase in ankle-hip linked coordination.

Descriptive statistics for the ‘latent’ ACMD variables for the CAI, coper and control groups prior to PCA are presented in Table 3. Pattern and structure matrices for the PCA relative to the eyes-open and eyes-closed conditions are presented in Table 4.

Regarding the kinetic variables of interest, there was a statistically significant main effect for group in the eyes-closed condition [F (2,219) = 8.11, p = 0.001, $\eta_p^2 = 0.12$] only. Post-hoc analysis and inspection of the mean scores revealed that CAI participants exhibited lower FD of the COP path trajectory on their involved limb (M = 1.78, SD = 0.11) compared to both copers (M = 1.90, SD = 0.1, p = 0.045) and controls (M = 1.94, SD = 0.13, p < 0.001).

In an exploratory analysis, the concurrent validity of four variables deemed ‘significantly important’ (eyes-closed SLS task completion, component 3 in the eyes-open condition on the involved limb, and both component 2 and the FD of the COP path on the involved limb in the eyes-closed condition) in determining the extent of disability was established by calculating their respective Pearson correlation coefficients to CAIT score. This was performed for LAS participants only. The ability of each of these variables to determine outcome (CAI *vs* coper) was then tested for sensitivity and specificity. A cut-off value of 0.7 was adopted for the C-statistic in the sensitivity and specificity analyses.

There was no correlation between CAIT score and eyes-closed SLS task completion ($r = 0.004$, $p = 0.97$), component 3 ($r = 0.109$, $p = 0.39$), component 2 ($r = 0.213$, $p = 0.19$) or FD of the COP path ($r = 0.11$, $p = 0.39$).

However, eyes-closed SLS task completion was moderately predictive of outcome (CAI *vs* coper), with a C-statistic of 0.71 ($p = 0.003$); the resultant prediction equation yielded a sensitivity of 0.64 and a specificity of 0.78, with a positive likelihood ratio of 2.93.

To explain these findings, post-hoc analysis using independent samples t-tests were performed to compare the CAIT scores of the subgroups of CAI and coper participants who succeeded and failed at the eyes-closed SLS task. The p-value for this post-hoc analysis was set a priori with a bonferonni adjustment at $p < 0.025$. This analysis revealed that copers who were able to complete the task actually had significantly greater disability than those who couldn’t, and likewise for the CAI participants, thus explaining the capacity of task completion to predict outcome (CAI or coper), despite the absence of a correlation to CAIT score. The results of this post-hoc analysis for both sub-groups of CAI and coper participants are presented in Table 2. None of the other variables (components 2 and 3, FD of the COP path) were predictive of outcome based on the C-statistic.

DISCUSSION

The primary finding of this motion analysis investigation was that individuals with CAI exhibit greater 'coupling' of hip and ankle motion compared to both ankle sprain "copers" and non-injured controls during an SLS task. This increase in ankle-hip 'coupling' may represent a compensatory strategy to accommodate what is now a chronically unstable ankle in the CAI group (as determined using the CAIT). Furthermore, the CAI group also demonstrated a reduced FD of the COP path on their involved limb compared to both "copers" and controls in the eyes-closed condition of SLS. These findings are consistent with those previously published on this group as a whole within two-weeks of their injury (7), and 6-months following (9). Therefore, it is possible that the abatement of a hip-dominant postural control strategy may be conducive to superior outcome. The design of the current study however means that this cannot be confirmed.

To our knowledge, this is the first documented evaluation of postural control in a first-time LAS population exactly 12-months following initial injury using kinematical measures of inter-joint coordination and platform stabilometry. The advantage of the experimental design is that all LAS participants (CAI and coper) were recruited at the time of their first ankle sprain injury, thereby securing the homogenous subgroups of ankle sprain outcome. As we have alluded to, this study is part of a longitudinal analysis designed to develop an outcome model for the predictors of instability following ankle sprain injury.

The use of "copers" provides a superior comparison group to individuals with CAI than non-injured controls because copers have had the same exposure, but are not characterized by the same symptom sequalae as those individuals who develop CAI (33). The addition of a non-injured control group in this report has however allowed us to identify that, based on the parameters utilised in the current investigation, LAS "copers" are no different to non-injured controls in their postural control strategies for eyes-open and eyes-closed SLS. This is evidenced by the absence of between-groups differences for copers and controls in this analysis, which is in agreement with previous findings during a similar task protocol (31, 36). It has recently been identified that this tripartite comparison between CAI, “coper” and control participants is needed in the context of ankle sprain research(33). Indeed, there are only a limited number of previous analyses which have evaluated movement patterns in these groups (4, 5, 31, 36, 37) with fewer still providing an analysis of SLS postural control using measures of platform stabilometry (31, 36). Wikstrom et al. (36) identified that ankle sprain coper participants’ stance limb COP paths exhibits a lower velocity in both the antero-posterior and the medio-lateral axes of the foot than individuals with CAI during a similar task. Shields et al.(31), demonstrated that the standard deviation of the COP path and it’s range were significantly lower in “copers” compared to subjects with CAI, a finding the authors interpreted as being demonstrative of better postural control predictability.

The issue regarding the application of these ‘traditional measures’ of COP excursion which quantify the length, area and velocity of the COP path, apart from their questionable reliability (12), is that they have previously yielded inconsistent or even contradictory findings in ankle sprain populations (26). By contrast, the FD measure utilised in the current analysis is a reliable measure (12) which has previously been successful in characterising a degeneration in stability of the postural control system in the transition from eyes-open to eyes-closed stance (3). Furthermore, because we have adopted the FD calculation in analysing the COP paths of these same participants during SLS within 2-weeks (7) of incurring their initial injury and 6-months later (9), its use enables us to directly compare our findings across time points relevant to the development of CAI or ankle sprain coper status.

Consistent with the investigations of these participants 2-weeks and 6-months following injury occurrence (7, 9), the findings of the current study revealed that individuals with poorer outcome (<24 on the CAIT in this study, ‘injured’ status in those previously described), exhibit reduced FD of the COP path compared to individuals with superior outcome (non-injured controls and “copers”), albeit in the eyes-closed condition only. This was previously interpreted as a reduced ability to utilise the available base of support during SLS, isolated to instances where the task condition dictated the removal of visual afferents (6). Similarly, the CAI participants in the current study also exhibited greater ‘coupling’ of hip-ankle joint coordination in the completion of eyes-closed SLS compared to controls, a finding consistent with the acute (2-week) and injury “twilight” (6-month) data.

.

That a lower proportion of the CAI group were able to complete the balance task in the eyes-closed condition prompted an exploratory analysis, whereby this dichotomous outcome and the other group-defining variables (components 3, 2 and the FD of the COP path) were separately correlated with CAIT score. Their capacity to predict outcome (CAI vs coper) was also evaluated. While the group-defining variables exhibited no correlation with CAIT score, and did not predict outcome, task completion was determined as predictive of CAI or coper status. . The moderate specificity and sensitivity that an ability to complete eyes-closed SLS had in predicting outcome, in the absence of a correlation to CAIT score, may be under-lied by a disability ‘cut-off’; the correlation between CAIT score and task ability is probably not linear, wherein it is possible that at a certain point, an individual’s ability to perform a difficult balance task (such as eyes-closed SLS) deteriorates drastically. Individuals below this cut-off have the potential to be equally likely to be unable to complete the task, whether they have “more” or “less” disability. Future analyses are required to elucidate such ‘cut-offs’ however.

The apparent difficulty CAI participants had in completing eyes-closed SLS may represent an impaired capacity to compensate and re-coordinate the available sensory afferents, or to rely on the remaining somatosensory and vestibular afferents when visual ones have been removed (24). It is generally accepted that there is redundancy of these three afferents in maintaining SLS (29), whereby a selective priority is placed based on the availability of reliable information (27). This allows the fully functioning somatosensory system to maintain postural control and stability in the presence of altered afferent signals (24). However, prescribing an eyes-closed constraint during the SLS task imposes somatosensory demands beyond the capacity of even healthy individuals (as evidenced by the fact that 15% of controls were unable to complete our eyes-closed task protocol), impairing their ability to exploit available redundancies in the maintenance of static postural control (7). This impairment is seemingly magnified in individuals with musculoskeletal injury on the basis of the current findings, and in light of the evidence previously outlined of participants with a recent history of ankle sprain (7, 9). Thus, a decay in somatosensory afferents, as may occur with acute LAS injury and which is considered to contribute to instability persistence (14), combined with loss of visual input, challenged the ability of the central nervous system to re-coordinate the available information with an appropriated postural control response (13, 27) in individuals with CAI. This then manifested in a deterioration of eyes-closed unilateral standing postural control and stability in the CAI group, with less effective utilisation of the supporting base on the involved limb (7). It is also plausible that the somatosensory deterioration associated with CAI development manifested in a 'hip-dominant' compensatory strategy as evidenced by the significantly greater ankle-hip coupling compared to both "copers" and controls in the eyes-open condition, and compared to controls in the eyes-closed condition. Whereas the ankle strategy of human postural control is more suited to subtle corrections, the hip strategy is considered ideal for substantial disturbances of equilibrium (24). Tropp (32) previously utilised kinematic measures of sway amplitude at the ankle, hip and trunk to confirm the existence of these strategies. He also identified the impaired postural control capacity of individuals with ankle instability in utilising their ankle strategies for SLS, based on an increased number of postural corrections at the trunk required by this group (32). In another kinematic analysis of participants with a history of ankle sprain during an SLS task, Huurnink et al.(21) failed to identify differences in kinematic outcome measures (ankle and hip angular velocities) between participants with and without a history of ankle sprain. We believe the use of the ACMD statistic in the current study to have specifically identified an increased reliance on the more proximal hip strategy in the CAI group, on the basis of the greater waveform similarity between these joints. During normal control of SLS, the foot's narrow base of support makes it necessary to employ the hip strategy in controlling substantial medio-lateral disturbances of postural stability, while ankle movements may only achieve fine-tuning of medio-lateral sway (2). The basis of CAI may be belied by an impaired capacity to fulfil this medio-lateral fine-tuning, with subsequent transition to the more proximal hip. Herein lies a significant limitation of the current analysis; these and any other hypotheses regarding the neuromechanical predictors of CAI still unclear, although the current study is part of a project designed to investigate this issue. Another significant limitation of this analysis is that we were unable to experimentally control whether LAS participants sought additional rehabilitation for their injury. However, to do so would have been unethical, and no treatment data 'clusters' were evident during data management and analysis.

The clinical implications of this study are two-fold: first, in light of the evidence presented on these individuals during their 'recovery', it would seem that the capacity to perform static postural control tasks will challenge the individual to perform subtle corrections with ankle movements. A SLS task and derivations of such may therefore possess value in being part of a rehabilitation programme. Based on previous evidence, we would recommend though that the patient only progresses to such tasks when they are sufficiently able to complete them (6).

Second, the use of eyes-closed SLS as a clinical test to quantify disability and functional capacity should be considered. There is further potential for future research to confirm this. In conclusion, the results of the current study suggest that participants with CAI are separated by ankle sprain copers and non-injured controls in their exhibition of a hip-dominant balance strategy during a task of eyes-open and eyes-closed unilateral stance.

Acknowledgements

This study was supported by the Health Research Board (HRA_POR/2011/46) as follows: PI – Eamonn Delahunt; Co-investigators – Chris Bleakley and Jay Hertel; PhD student – Cailbhe Doherty). The results of the present study do not constitute endorsement by ACSM.

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

REFERENCES

1. Attenborough A, Hiller C, Smith R, Stuelcken M, Greene A, Sinclair P. Chronic Ankle Instability in Sporting Populations. *Sports Med*. 2014;[Epub ahead of print].

2. Baier M, Hopf T. Ankle orthoses effect on single-limb standing balance in athletes with functional ankle instability. *Arch Phys Med Rehabil*. 1998;79(8):939-44.

3. Błaszczyk J, Klonowski W. Postural stability and fractal dynamics. *Acta Neurobiol Exp (Wars)*. 2001;61(2):105-12.

4. Brown C, Padua C, Marshall D, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech (Bristol, Avon)*. 2008;23(6):822-31.

5. Brown CN, Padua DA, Marshall SW, Guskiewicz KM. Variability of motion in individuals with mechanical or functional ankle instability during a stop jump maneuver. *Clinical Biomechanics*. 2009;24(9):762-8.

6. 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;40(1):172-6.

7. 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;29(6):643-9.

8. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Single-leg drop landing motor control strategies following acute ankle sprain injury. *Scand J Med Sci Sports*. 2014.

9. Doherty C, Bleakley C, Hertel J, et al. Inter-joint coordination strategies during unilateral stance 6-months following acute lateral ankle sprain. *Clin Biomech*. 2015.

10. Doherty C, Bleakley C, Hertel J, et al. Lower extremity coordination and symmetry patterns during a drop vertical jump task following acute ankle sprain. *Hum Mov Sci*. 2014;38C:34-46.

11. 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.

12. Doyle T, Newton R, Burnett A. Reliability of traditional and fractal dimension measures of quiet stance center of pressure in young, healthy people. *Arch Phys Med Rehabil* 2005;86(10):2034-40.

13. Evans T, Hertel J, Sebastianelli W. Bilateral deficits in postural control following lateral ankle sprain. *Foot Ankle Int*. 2004;25(11):833-9.

14. Freeman MA. Instability of the foot after injuries to the lateral ligament of the ankle. *J Bone Joint Surg Br*. 1965;47(4):669-77.

15. Gribble P, Delahunt E, Bleakley C, 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(8):585-91.

16. Gribble PA, Delahunt E, Bleakley C, et al. Selection criteria for patients with chronic ankle instability in controlled research: A position statement of the International Ankle Consortium. *British journal of sports medicine*. 2014;48(13):1014-8.

17. Gribble PA, Delahunt E, Bleakley CM, et al. Selection criteria for patients with chronic ankle instability in controlled research: A position statement of the international ankle consortium. *Journal of Athletic Training*. 2014;49(1):121-7.

18. Hertel J, Olmsted-Kramer LC. Deficits in time-to-boundary measures of postural control with chronic ankle instability. *Gait Posture*. 2007;25(1):33-9.

19. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3-13.

20. Huberty C, Morris J. Multivariate analysis versus multiple univariate analyses. *Psychological Bulletin*. 1989;105(2):302-8.

21. 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(2):183-8.

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;7:849:60.

23. Katz MJ, George EB. Fractals and the analysis of growth paths. *Bull Math Bio*. 1985;47(2):273-86.

24. McCollum G, Shupert C, Nashner L. Organizing sensory information for postural control in altered sensory environments. *J Theor Biol*. 1996;180(3):257-70.

25. McKeon PO, Hertel J. Chronic ankle instability affects time-to-boundary measures of postural control in females but not males. *The Journal of orthopaedic and sports physical therapy*. 2006;36(11):A-24.

26. McKeon PO, Hertel J. The dynamical-systems approach to studying athletic injury. *Athletic Therapy Today*. 2006;11(1):31-3.

27. 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):1-6.

28. Nashner L, McCollum G. The organization of human postural movements: a formal basis and experimental synthesis. *Behav Brain Sci*. 1985;8:135-72.

29. Nashner LM. Organization and programming of motor activity during posture control. *Progress in Brain Research*. 1979;50:177-84.

30. 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(9):956-66.

31. Shields C, Needle A, Rose W, Swanik C, Kaminski T. Effect of elastic taping on postural control deficits in subjects with healthy ankles, copers, and individuals with functional ankle instability. *Foot Ankle Int*. 2013;34(10):1427-35.

32. Tropp H, Odenrick P. Postural control in single-limb stance. *J Orthop Res*. 1988;6(6):833-9.

33. Wikstrom E, Brown C. Minimum Reporting Standards for Copers in Chronic Ankle Instability Research. *Sports Med*. 2014;44(2):251-68.

34. Wikstrom E, Hubbard-Turner T, McKeon P. Understanding and treating lateral ankle sprains and their consequences: a constraints-based approach. *Sports Med*. 2013;43(6):385-93.

35. Wikstrom EA, Bishop MD, Inamdar AD, Hass CJ. Gait termination control strategies are altered in chronic ankle instability subjects. *Med Sci Sports Exerc*. 2010;42(1):197-205.

36. Wikstrom EA, Fournier KA, McKeon PO. Postural control differs between those with and without chronic ankle instability. *Gait Posture*. 2010;32(1):82-6.

37. Wikstrom EA, Hass CJ. Gait termination strategies differ between those with and without ankle instability. *Clin Biomech (Bristol, Avon)*. 2012;27(6):619-24.

38. Winter D. Biomechanics and motor control of human movement. 4th ed. Hoboken, NJ: *John Wiley and Sons*; 2009. p. 14-45.

39. Wright C, Arnold B, Ross S, Linens S. Recalibration and Validation of the Cumberland Ankle Instability Tool Cutoff Score for Individuals With Chronic Ankle Instability. *Arch Phys Med Rehabil*. 2014;[Epub ahead of print].

40. Wu G, Siegler S, Allard P, 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(4):543-8.