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Balance failure in single limb stance due to ankle sprain injury: An analysis of center of pressure using the fractal dimension method

Cailbhe Doherty [a,*], Chris Bleakley [c], Jay Hertel [d], Brian Caulfield [a], John Ryan [e], Eamonn Delahunt [a,b]

[a] School of Public Health, Physiotherapy and Population Science, University College Dublin, Dublin, Ireland
[b] Institute for Sport and Health, University College Dublin, Dublin, Ireland
[c] Sport and Exercise Sciences Research Institute, Ulster Sports Academy, University of Ulster, Newtownabbey, Co. Antrim, Northern Ireland, United Kingdom
[d] Department of Kinesiology, University of Virginia, Charlottesville, VA, United States
[e] St. Vincent's University Hospital, Dublin, Ireland

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ABSTRACT

Instrumented postural control analysis plays an important role in evaluating the effects of injury on dynamic stability during balance tasks, and is often conveyed with measures based on the displacement of the center-of-pressure (COP) assessed with a force platform. However, the desired outcome of the task is frequently characterized by a loss of dynamic stability, secondary to injury. Typically, these failed trials are discarded during research investigations, with the potential loss of informative data pertaining to task success. The novelty of the present study is that COP characteristics of failed trials in injured participants are compared to successful trial data in another injured group, and a control group of participants, using the fractal dimension (FD) method. Three groups of participants attempted a task of eyes closed single limb stance (SLS): twenty-nine participants with acute ankle sprain successfully completed the task on their non-injured limb (successful injury group); twenty eight participants with acute ankle sprain failed their attempt on their injured limb (failed injury group); sixteen participants with no current injury successfully completed the task on their non-dominant limb (successful non-injured group). Between trial analyses of these groups revealed significant differences in COP trajectory FD (successful injury group: 1.58 ± 0.06; failed injury group: 1.54 ± 0.07; successful non-injured group: 1.64 ± 0.06) with a large effect size (0.27). These findings demonstrate that successful eyes-closed SLS is characterized by a larger FD of the COP path when compared to failed trials, and that injury causes a decrease in COP path FD.

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1. Introduction

Dynamic stability is a component of postural control that requires an ability to regulate the vertical projection of the body's center of gravity around its supporting base [1]. Dynamic stability is ubiquitous to the fulfillment of daily living tasks; changing the parameters of a task challenges the human sensorimotor system to utilize previously redundant movement strategies. For example, in circumstances where sensory afferents (such as vision) are restricted secondary to the requirements of a task, sufficient compensatory information can be provided by the remaining afferents (vestibular and somatosensory) in the maintenance of dynamic stability [2–4]. However, in environments where the sensorimotor system is compromised, perhaps due to an injury constraint, task completion may become impossible with concurrent failure of dynamic stability.

Acute ankle sprain is one of the most frequently encountered injuries in a wide range of activity types [5] and has previously been shown to be a source of sensorimotor compromise manifesting in bilateral balance deficit [6–8]. Although a number of studies have analyzed the deficits attributed to this injury in achieving successful balance during tasks of dynamic stability such as single limb balance [7,8], no research currently exists examining the potential differences between successful and failed tasks. This is primarily due to the tendency for failed trials to be discarded in the research setting, thus minimizing data variation and allowing for better explanations of data-sets [9]. However, it is likely that data from these failed tasks possess the unique movement strategy inadequacies contingent

* Corresponding author at: A101, School of Public Health, Physiotherapy and Population Science, University College Dublin, Health Sciences Centre, Belfield, Dublin 4, Ireland. Tel.: +353 1 716667; fax: +353 1 716 6501.
E-mail address: cailbhe.doherty@ucdconnect.ie (C. Doherty).

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with specific types of constraints impinging on the sensorimotor system, thus providing valuable information relating to the requirements of successful task completion.

Single limb balance is often characterized with measures based on the displacement of the center-of-pressure (COP) measured with a force platform [10,11]. The use of traditional measures of COP excursion (e.g. peak sway velocity and total excursion area) is widespread in biomechanics despite their questionable reliability [12]. The underlying premise of these measures is to provide surrogate evaluation of the role of sensory afferents in providing the neurobiological system with the necessary information for single limb balance maintenance, and elucidate the mechanisms by which the sensorimotor system utilizes available redundancies between these afferents when one fails [10,13,14]. In the context of evaluating failed trials however, the fundamental assumptions required for the calculation of these measures are violated, as consecutive points on the COP path no longer operate within the confines of a finite supporting base. Fractal dimension (FD) is a measure of COP excursion complexity that can be appropriately applied to failed and successful trials of single limb balance alike, as the outcome of the task need not be successful to adhere to the assumptions required for its calculation. In characterizing the complexity of COP excursion path, the FD describes the activity of the sensorimotor system in organizing available afferents [15] and the extent to which a person utilizes the base of support available to them [11]; FD has previously been used to compare the COP excursion path during single limb balance in pathological and non-pathological groups [11,15,16].

The current investigation developed in corollary to a longitudinal analysis of acute ankle sprain injury. It was noted that participants with acute ankle sprain were regularly unable to complete the prescribed task of eyes-closed single-limb balance. However, a number of individuals were able to complete this task on their non-injured limb. The aim of the current investigation was to compare the COP excursion path FD of failed and successful trials of eyes closed, single limb stance in a group with acute ankle sprain, and to compare the COP excursion path FD of successful trials of the same task between the ankle sprain group and a non-injured control group. We hypothesized that failed trials of single limb balance would be characterized by a lower COP path excursion FD compared to successful trials, indicating that injured participants are less able to utilize the base of support available to them, and that participants with acute ankle sprain would display bilateral deficits following injury, as evidenced by a lower COP path excursion on their non-injured limb FD compared to control participants.

2. Methods

2.1. Participants

Eighty young adults were recruited from a University-affiliated Hospital Emergency Department within 2 weeks of sustaining a first-time ankle sprain between the 6th of June 2012 and the 1st of August 2013. Fifty-two of these participants were unable to weight-bear on their injured limb as part of the task requirements, with the remaining twenty-eight (seventeen males and eleven females; age 23.2 ± 4.3 years; mass 74.5 ± 13.5 kg; height 1.7 ± 0.1 m) failing attempts at the task on their injured limb. A sub-group of the original eighty participants (eighteen males and eleven females; age 21.5 ± 3.32 years; mass 74.8 ± 14.0 kg; height 1.7 ± 0.1 m), separate to those who attempted and failed the task on their injured limb, were able to complete the task on their non-injured limb. Furthermore, a convenience sample of sixteen participants were recruited from the University population (eleven males and five females; age 22.4 ± 1.7 years; mass 71.6 ± 11.6 kg; height 1.8 ± 0.1 m) to act as a control group for the same investigation (Fig. 1).

All participants signed an informed consent form approved by the University Human Research Ethics Committee. Inclusion criteria were as follows: (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; (5) no history of neurological disease, vestibular or visual disturbance or any other pathology that would impair their motor performance.

2.2. Questionnaires

Self-reported function, patient reported symptoms and functional ability as measures of ankle sprain severity were assessed using the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) [17]. All participants completed the subscales of the FAAM on arrival to the testing location.

2.3. Instrumentation

All experimental procedures were completed in the University biomechanics laboratory. Kinetic data were sampled at 100 Hz using 2 fully integrated AMTI (Watertown, MA, USA) walkway embedded force-plates. The kinetic data time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency.

2.4. Testing procedures

Participants were required to stand barefoot facing forward, with the center-point of their stance foot over the center of the force plate. The test instructions were as follows: "you are required to stand on one leg and remain as still as possible with your hands on your hips and your eyes closed for twenty seconds. If you are unable to maintain this position without falling, you may place your non-stance limb on the ground, regain your balance as quickly as possible and continue the balance trial". Participants were required to attempt three 20-s trials of SLS (each separated by a

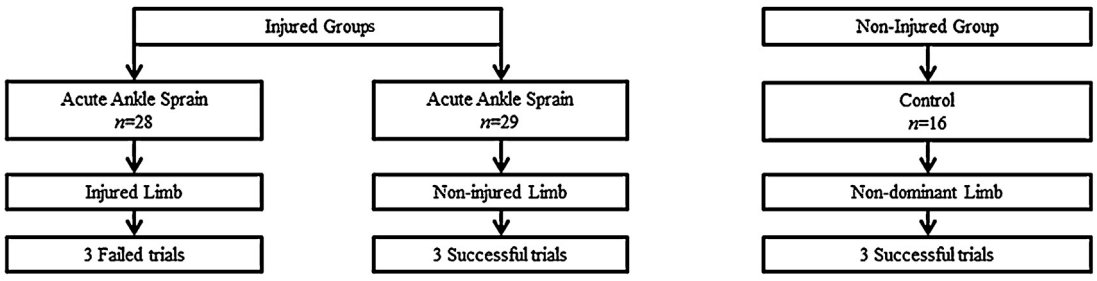

Fig. 1. Consort diagram depicting the number of participants recruited into the study and the trials completed specific to limb and type (success or failure).

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30 s break). The center point of the foot was determined as the intersection of two lines drawn perpendicularly from the sagittal plane midpoint of the foot (from the posterior part of the calcaneus to the end of the first toe) to the frontal plane midpoint of the foot (from the head of the first meta-tarsal). Participants were required to complete a minimum of five practice trials on each limb (injury conditional) prior to data acquisition, with an obligatory two-minute rest following this practice. The test order between legs was randomized. In situations where participants were unable to support full bodyweight on their injured limb, the non-injured limb was tested in isolation. A failed trial was defined by a loss of balance forcing the participant to use the non-stance limb on the support surface to regain or prevent loss of stability. Subjects were not informed that failed trial data were being saved to ensure an honest effort for each trial.

2.5. Data reduction

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 [11]. The local COP origin for the stance limb was defined by the arithmetic means of the AP and ML time series [11]. FD is a discrete unit-less measure of the degree to which a curve fills the metric space which it encompasses. We have adopted an algorithm previously published by Katz [18] and described in the seminal paper by Prieto et al. [11] to calculate FD:

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

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. Higher FD values are associated with greater complexity of the COP path, with lower FD values indicative of a less complex (or 'straighter') COP path [18]. FD was calculated based on the 20 s interval for each individual successful SLS trial. For failed trials, FD was calculated for each individual attempt using the data available 3 s prior to touchdown of the non-stance limb. FD was determined using a sliding window approach, whereby the FD of COP path excursion was determined in groups of 200 (N) data samples (or 2 s), with a window overlap of 50%. Therefore, the FD of a successful trial was determined as the average FD of twenty 2-s windows, each overlapping by 1 s and the FD of a failed trial was determined as the average FD of two 2-s windows with an overlap of 1 s. Trial FDs were then averaged across the three attempts of SLS.

A 10N cut-off was utilized to determine the point of touchdown of the non-stance limb on the supporting force plate. The length of interval (3 s) was decided by author consensus, whereby on review of data this was the most commonly available, longest duration window of SLS data for failed trials (as there were usually multiple fails in each individual SLS trial).

Table 1
Self-reported outcome scores for the FAAM (injured leg [successful injured group], non-injured leg [failed injured group] and non-dominant leg [successful non-injured group]).

Group	FAAMadl (%)	FAAMsport (%)
Successful injured group	67.01 ± 26.36[b]	26.81 ± 29.29[b]
Failed injured group	66.67 ± 19.33[b]	37.27 ± 23.23[b]
Successful non-injured group	100 ± 0[a,c]	100 ± 0[a,c]

[a] Significantly different from failed injured group.
[b] Significantly different from successful non-injured group.
[c] Significantly different from successful injured group.

2.6. Data analysis and statistics

2.6.1. Questionnaires

A one-way between-groups MANOVA was conducted to explore differences in questionnaire scores between groups. Two dependent variables were used: percentage scores for the FAAMadl and FAAMsport. The independent variable was group. 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. The significance level for this analysis was set a priori at $p < 0.025$. Tukey HSD post hoc comparisons were undertaken when a significant main effect for the one-way ANOVA and/or between groups MANOVA was observed. Associated effect sizes (η^2) were calculated using the formula as described in Pallant [19] with 0.01 = small effect size, 0.06 = medium effect size and 0.14 = large effect size [20].

2.6.2. Fractal dimension

A one-way between-groups ANOVA was conducted to explore the effect of failure (injured limb trials) or success (non-injured limb and control limb trials) on the FD of the COP path. Participants were divided into three discrete groups according to their completed trial type (successful injury group: non-injured limb succeed; failed injury group: injured limb fail; successful non-injured group: non-dominant limb succeed). Preliminary assumption testing was conducted to check for univariate outliers, normality and homogeneity of variance–covariance matrices, with no serious violations noted. The significance level for this analysis was set a priori at $p < 0.05$.

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

3. Results

3.1. Questionnaires

There was a statistically significant difference in questionnaire results between groups on the combined dependent variables: F (2, 70) = 15.84, p = 0.00; Wilks' lambda = 0.064; partial eta squared = 0.32. Post hoc comparisons using the Tukey HSD test revealed decreased function in the injured groups compared to the non-injured group, and are presented in Table 1. Clinically meaningful changes in

Table 2
Fractal dimension scores for the three groups during eyes closed single-limb stance following post hoc analysis.

Group			p value	95% confidence interval	
				Lower bound	Upper bound
Successful injured	vs.	Failed injured	0.028	.004	.084
FD: 1.58 ± 0.06		Successful non-injured	0.016	−.100	−.009
Successful non-injured	vs.	Successful injured	0.016	.009	.100
FD: 1.64 ± 0.06		Failed injured	0.000	.052	.145
Failed injured	vs.	Successful non-injured	0.028	−.084	−.004
FD: 1.54 ± 0.07		Successful injured	0.000	−.145	−.052

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outcome scores for the FAAMadl and FAAMsport subscales were determined for both injured groups based on previous research (MCD for FAAMadl = ±5.70%; MCD for the FAAMsport = ±12.30%) [21].

3.2. Fractal dimension

There was a statistically significant difference in fractal dimension scores for the three groups: $F(2, 70) = 12.96$, $p = 0.00$. The effect size calculated using eta squared was 0.27. Results from post hoc comparisons using the Tukey HSD test revealed that successful eyes-closed SLS was characterized by a larger FD of the COP path when compared to failed trials of the same task in participants with acute ankle sprain, and that successful trials of eyes-closed SLS on the non-injured limb of participants with acute ankle sprain was significantly reduced compared to that of non-injured participants, indicating bilateral deficits associated with this unilateral injury. These results are presented in Table 2.

4. Discussion

This is the first analysis to utilize stabilometric measures to quantify the COP path patterns of failed unilateral standing balance. The results of the current investigation confirm our hypotheses that successful trials of eyes closed SLS would be characterized by larger FD of the COP path and that acute ankle sprain injury manifests in bilateral deficits in postural control (which is in agreement with previous research) [6].

The calculated effect size for the one-way between groups ANOVA was large suggesting that the success or failure of the task was expressed in the FD of the COP trajectory and that injury manifests in bilateral deficit during eyes closed SLS. Furthermore, with regard to the significant findings between groups on the post hoc tests, the 95% confidence intervals did not cross zero, thus affirming the aforementioned point. Questionnaire results showed that differences in task performance between the injured and non-injured groups may have been due to significant and clinically meaningful [21] self-reported functional deficit caused by the acute ankle sprain injury. The non-significance in self-reported function between the two injured groups affirms the pertinence for inter-trial comparison.

The FD evaluation of COP excursion provides a mechanism by which the complex patterns of failed SLS trials can be characterized. Previous research using FD as a tool has quantified the changing patterns of COP that occurs with removal of visual afferents [11,16], and with pathology [15,22]. These researchers collectively concluded that FD provides a means by which changes in postural stability [16], severity of pathology [22], and sensorimotor system activity during balance [15] can be quantified. Successful trials of stance in these studies were dependent on the capacity of the sensorimotor system to re-weight afferent sensory information according to its availability by exploiting available redundancies from the vestibular and somatosensory systems in the absence of vision [23]. With regards to the current investigation, by constraining the sensorimotor system to a task of eyes-closed SLS, combined with the somatosensory damage of ankle sprain injury and coinciding centrally mediated changes in postural control mechanisms [6], the available redundancies on which the sensorimotor system of injured participants could rely on for maintenance of balance were limited. This coincided with a decrease in FD during eyes-closed SLS on the contralateral side to injury in injured participants when compared to a control group. A decrease in FD was also associated with task failure. We theorize that the FD of the COP path reflects the activity of the postural control system, a theory supported by the findings of Błaszczyk [16] and Prieto [11], who have shown a larger FD with task difficulty in healthy participants. We offer that with the introduction of an organismic constraint in the form of an acute ankle sprain injury, the resultant reduced COP path FD during eyes-closed SLS reflects a postural control system less able to fulfill the demands of the task. By extension, when this postural control system is unable to complete the task, it manifests in a significantly lower FD of the COP path. Thus, to succeed at eyes-closed SLS, one must utilize the available base of support in an effective manner via a sensorimotor system which effectively balances afferent input with efferent response. We believe this to be reflected in the larger FD of successful trials in the current study. It is important to note however that we do not associate there to be a linear relationship between FD and postural stability. Excessively high FD values have previously been shown to be demonstrative of an inability of pathological patients to synergistically modulate the three sensory systems involved in maintaining posture [15]. As such, superior postural steadiness may display a COP path FD specific to the task and the individual, lying on a spectrum where too much or too little has negative connotations.

Our findings supplement the plethora of research demonstrating the importance of balance training for recovery following musculoskeletal injuries such as ankle sprain [24–28]. The main clinical implication of the current research is that, in evaluating successful trials of SLS in comparison to failed trials, there is an inference that while rehabilitation tasks, if administered, should be challenging enough to encourage the exploration of the available base of support with a coinciding large FD, they must not be too difficult as to result in consistent failure, thus manifesting in COP path trajectories of low FD. We recommend that clinicians administer tasks of sufficient difficulty to challenge the sensorimotor system to organize the network of constraints impinging on the system through an appropriated weighting of afferent input with suitable efferent response. Should the patient be unable to sufficiently maintain balance, the difficulty of the task should be regressed. For example, if the patient is unable to complete SLS with their eyes closed, then perhaps it may be more suitable to assume a position of bilateral stance, encouraging weighted dominance on the injured limb, or to attempt the SLS task with their eyes open.

The primary limitation of this study includes the lack of more grouping variables; specifically, it would have been beneficial to be able to compare successful trials of eyes-closed SLS on an injured limb to those of the uninjured limb. However, the severity of the injuries prevented the acquisition of a sufficient number of successful SLS trials on injured limbs for analysis.

5. Conclusion

The FD method appears to provide a suitable means to characterize stance task failures, and provides an informative description of COP path trajectories between independent groups.

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Conflict of interest statement

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

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