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Authors(s)	Doherty, Cailbhe, Bleakley, Chris J., Hertel, Jay, Caulfield, Brian, Ryan, John, Delahunt, Eamonn
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Authors:

Cailbhe Doherty[1]

Chris Bleakley[3]

Jay Hertel[4]

Brian Caulfield[1]

John Ryan[5]

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

Abstract.

Dynamic stability is ubiquitous to fulfilling daily living activities. Instrumented postural control analysis plays an important role in evaluating the effects of injury on dynamic stability during balance tasks, and is often characterized 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, failed trials of balance tasks are discarded during research investigations. 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. Twenty-nine participants with acute ankle sprain attempted and succeeded a task of eyes closed single limb stance (SLS) on their non-injured limb (successful injury group). A separate group of twenty-eight participants with acute ankle sprain attempted and failed the task on their injured limb (failed injury group). Finally a control group of sixteen participants 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:1.26 ± 0.15; failed injury group:1.17 ± 0.14; successful non-injured group:1.38 ± 0.11) with a large effect size. The present findings demonstrate that successful eyes-closed SLS is characterized by a larger FD of the COP path trajectory when compared to failed trials, and that injury causes a decrease in COP path trajectory FD.

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

1. Introduction

Dynamic stability is a characteristic of postural control that requires the ability to regulate the vertical projection of the body's center of gravity around its base of support [1]. Dynamic stability is ubiquitous to the fulfillment of daily living tasks, and is made possible by efferent sensorimotor system postural responses to constraints impinging on the system [2]. Despite the large number of possible postural responses at the disposal of the sensorimotor system, a number of preferred strategies emerge in the execution of specific tasks. Changing the parameters of the task challenges the human sensorimotor system to utilize previously redundant movement strategies under the influence of higher brain centers and altered peripheral inputs. For example, in circumstances where sensory modalities (such as vision) are restricted secondary to the requirements of a task, sufficient compensatory information can be provided by the remaining modalities (vestibular and somatosensory) in the maintenance of dynamic stability [3-5]. However, the desired outcome is not always possible, and the task outcome may be characterized by failure (loss of dynamic stability).

Research examining the potential differences between successful and failed tasks of dynamic stability is lacking, as failed trials are usually discarded during research investigations to minimize variation and allow better explanations of data sets [6]. However, it is likely that data from a failed task (e.g., eyes closed single limb stance) possesses the unique movement strategy inadequacies contingent with specific types of constraints impinging on the sensorimotor system, thus providing valuable information relating to the requirements of task completion. Injury can be seen as one type of morphological constraint that interacts with others to limit the attempt of a biological system to organize optimally, becoming evident in bilateral deficits in single-limb balance[7,8].

Single limb balance is often characterized with measures based on the displacement of the center-of-pressure (COP) measured with a force platform. However, applying traditional measures of COP displacement to a failed task of single limb balance presents conceptual difficulty. Fractal dimension (FD) is a measure of COP displacement that characterizes the complexity of the COP path, describing the extent to which a person utilizes the base of support available to them [9]. In contrast to the more traditional measures of COP displacement, FD 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 FD calculation. Thus, FD provides a means to evaluate successful and failed trials of the same task, and compare pathological and non-pathological groups [9-11].

Therefore, the aim of the current investigation was to evaluate the COP characteristics of failed, eyes closed, single limb stance trials in patients with an acute injury using the FD method. Acquired successful and failed single limb stance data were analyzed in a group of patients with acute ankle sprain, and a group of control subjects.

2. Methods

Eighty young adults were recruited from a University-affiliated hospital Emergency Department within 2 weeks of sustaining a first-time ankle sprain as part of an investigation into the effects of their injury on single-limb balance 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±13.5kg; height 1.7±0.1m) 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±14.0kg; height 1.7±0.1m), 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, sixteen participants were recruited from the University population (eleven males and five females; age 22.4±1.7 years; mass 71.6±11.6kg; height 1.8±0.1m) to act as a control group for the same investigation.

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.

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)[12]. All participants completed the subscales of the FAAM on arrival to the testing location.

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.

Participants were instructed to stand barefoot, with their stance foot at the center of the force plate and remain as still as possible with their hands on their hips, attempting three 20-second trials of SLS (each separated by a 30 second break) with their eyes closed. 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.

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 [9]. 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 and described in the seminal paper by Prieto et al [9] to calculate FD. 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 [13]. The complexity of the COP path gives an indication of the stability achieved by the postural control system [10]. FD was calculated based on the 20s interval for each individual successful SLS trial, and averaged across the three attempts. For failed trials, FD was calculated for each individual attempt using the data available 3 seconds prior to touchdown of the non-stance limb, and averaged across three trials. In situations where multiple intervals of 3second fails could be chosen for analysis from one of the three SLS trials, the 3second interval prior to touchdown of the non-stance limb within the longest duration window of eyes-closed SLS was chosen.

A 10 newton cut-off was utilized to determine the point of touchdown of the non-stance limb on the supporting force plate. The length of interval (3s) 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).

A one-way between-groups analysis of variance was conducted to explore the effect of failure (injured limb) or success (non-injured limb, control limb) 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). The significance level for this analysis was set a priori at $p < 0.05$.

A one-way between-groups MANOVA was also 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. The significance level for this analysis was set a priori at $p < 0.025$. All data were analyzed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA). Tukey HSD post hoc comparisons were undertaken when a significant main effect for the one-way ANOVA and/or between groups MANOVA was observed.

3. **Results**.

There was a statistically significant difference in questionnaire results between groups on the combined dependent variables: $F(2,70) = 15.84$, $p < 0.025$; Pillai's Trace = 0.63; partial eta squared = 0.32. Differences between groups with post-hoc comparisons using the Tukey HSD test are presented in table 1.Clinically meaningful changes in 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%) [14].

There was a statistically significant difference at the level of $p < 0.05$ in fractal dimension scores for the three groups: $F (2, 70) = 11.61$, $p < 0.05$ (Table 2). The effect size calculated using eta squared was 0.33, thus indicating a large effect size. Results from post-hoc comparisons using the Tukey HSD test are presented in table 2.

4. Discussion

The results of the current investigation indicate that successful eyes-closed SLS is characterized by larger FD of the COP path trajectory when compared to failed eyes-closed SLS trials in participants with acute ankle sprain. In addition, the decrease in successful trial COP path trajectory FD on the non-injured limb of ankle sprain participants when compared to that of control participants is in agreement with previous research that acute ankle sprain can cause bilateral deficits in postural control [15]. The calculated effect size for the one-way between groups ANOVA was large, suggesting that the success or failure of the task was dependent on the FD of the COP trajectory, and that injury causes a decrease in FD on the non-injured limb. 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 clinically meaningful deficits in self-reported functional outcome for the injured groups [14], as measured using the FAAM in both ankle injury subgroups, and that there were no differences in perceived functional outcome between the two injured groups.

An essential part of any biomechanical analysis is the characterization of the complex patterns produced in the biological realm [13], such as COP in quiet stance. A large body of research into balance as assessed using measures of COP has evolved [9,16]. Although traditional measures of COP such as peak sway velocity and total excursion area are used extensively, their reliability is questionable [17], as evidenced by contradictory findings in synonymous patient groups [18]. A newly developed measure of COP excursion called time-to-boundary (TTB) has shown promise in a number of studies[19-23], but is based conceptually on the premise that the task position is maintained successfully, and is therefore inappropriate for use in the current investigation. TTB and the traditional measures of COP aim to assess the role of afferent information relayed from each of the three (visual, vestibular and somatosensory) sensory systems in providing the neurobiological system with the necessary information for balance maintenance, and to determine how redundancies between these systems can assist when one fails [16,20,24]. Despite this, no current research is available which evaluates the COP variables associated with these failures, when the participants are actually unable to complete the prescribed task.

Evaluating a fall with measures of COP presents computational and conceptual difficulties. The reduction in dimensionality that occurs with all repetitive coordinated movement [25] allowing for representative kinematic analyses is violated in instances of task failure, where unique compensatory reactions must emerge specific to this violation to prevent falling; the uniqueness of any given balance failure will produce COP path trajectories that are inconsistent and highly variable. Therefore, the COP path trajectory of a failed SLS trial is difficult to characterize; traditional COP measures stand to mask the unique qualities of a fail using procedures of aggregation and averaging, and the assumptions of new measures such as TTB are violated in assessing a task that is failed.

FD is a measure that has been shown to be reliable and provides an indication of the complexity of a signal by analyzing the signal in its entirety and describing its shape [13,17]. We chose to determine the FD of successful and failed SLS trials of twenty seconds and three seconds duration respectively. Characterizing the complexity of the COP path is better achieved with trials of longer duration, and as such, we chose to analyze the full duration of successful trials as it enabled superior characterization of the COP path FD. We are confident however that the interval of three seconds for characterizing failed trials was adequate as it allowed us to include a larger sample of failed trials (we rarely encountered intervals of maintained eyes-closed SLS greater than three seconds in length for this groups' analysis). Furthermore, FD is a relative measure of COP displacement, whereby the COP path is evaluated in reference to itself, which justifies the comparison of trials of different length.

Blaszczyk and Klonowski [10] characterized the COP path trajectories in healthy elderly people in quiet stance with their eyes open and closed using FD. Their findings associated an increase in FD in the eyes closed condition, which is in agreement with the findings of Prieto et al. [9]. Successful trials of SLS in these studies were dependent on the capacity of the sensorimotor system to reweight afferent sensory information according to its availability, exploiting available redundancies from the vestibular and somatosensory systems in the absence of vision [26]. 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 [15], the available redundancies on which the sensorimotor system could rely on for maintenance of balance in the current investigation were eradicated. This coincided with a decrease in FD during eyes-closed SLS on the contralateral side to injury in participants when compared to a control group. A decrease in FD was also associated with task failure. We hypothesize that the FD reflects the activity of the postural control system, a theory supported by the findings of Blaszczyk [10] and Prieto [9], which show an increased FD with task difficulty (eyes open to eyes closed conditions) 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 trajectory 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 is as a result of a significantly lower FD. Thus, to succeed at eyes-closed SLS, one must utilize the available base of support in an effective manner, which is reflected in the larger FD of successful trials. 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 [11]. As such, superior postural steadiness may display a COP path trajectory 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 [27-30]. Furthermore, the findings of the current investigation imply that while these 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 resulting in COP path trajectories of low FD. A task that surpasses the capabilities of the injured individual may not be beneficial, as there is no exploration of the available neuromotor landscape in instances of repeated failure, as evidenced by the reduced FD during failed tasks.

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. Furthermore, prospectively following the acute ankle sprain group using the same measures at numerous time-points following injury would have allowed the determination of whether FD values return to normal with recovery. Future research must establish how COP trajectories re-stabilize following injury with/without rehabilitation, and whether certain patterns are associated with the onset of chronicity.

Conclusion

In this study we investigated the COP path trajectory characteristics of failed trials of eyes-closed SLS using the FD approach in a group of individuals with ankle sprain, by comparing them to successful trials on their non-injured limb, and those of control participants.

Our data demonstrated that a failed trial was associated with a lower FD, which may have been a corollary to injury, as evidenced by a decrease in FD during successful trials on the non-injured limb compared to control participants. 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.

Conflict of Interest statement

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

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Table 1

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]
Non-injured control group	100 ± 0[a,c]	100 ± 0[a,c]

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

[c] significantly different from successful injured group;

[a] significantly different from failed injured group;

[b] significantly different from non-injured control group.

Table 2

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	Lower bound
Successful injured	vs.	Failed injured	0.028	.0080860	.1750913
FD:1.26±0.15		Successful non-injured	0.008	-.2245073	-.0282082
Successful non-injured	vs.	Successful injured	0.008	.0282082	.2245073
FD:1.38±0.11		Failed injured	0.000	.1191757	.3167172
Failed injured	vs.	Successful non-injured	0.000	-.3167172	-.1191757
FD:1.16±0.12		Successful injured	0.028	-.1750913	-.0080860

***Research Highligts**

Research highlights

1. We assess the effect of ankle sprain on single limb balance.
2. We quantify the center of pressure (COP) characteristics of a failed trial.
3. Balance failure is associated with reduced complexity of the COP path.
4. Acute ankle sprain results in bilateral balance deficit
5. Balance rehabilitation exercises must be completed successfully to be beneficial.