



Title	Acute ankle sprain injury alters kinematic and centre of pressure measures of postural control during single limb stance
Authors(s)	Doherty, Cailbhe, Delahun, Eamonn, Bleakley, Chris J., Hertel, Jay, Ryan, John, Caulfield, Brian
Publication date	2014-04-12
Publication information	Doherty, Cailbhe, Eamonn Delahun, Chris J. Bleakley, Jay Hertel, John Ryan, and Brian Caulfield. "Acute Ankle Sprain Injury Alters Kinematic and Centre of Pressure Measures of Postural Control during Single Limb Stance." Vol. 48. BMJ Publishing, 2014.
Publisher	BMJ Publishing
Item record/more information	http://hdl.handle.net/10197/8568
Publisher's version (DOI)	10.1136/bjsports-2014-093494.72

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1 **Title:** Acute ankle sprain alters postural control strategies during single limb stance.

2 **Running title:** The effect of acute ankle sprain on balance

3 **Abstract word count:** 237

4 **Word count:** 3960

5 2 tables

6 2 figures

7 **Authors:**

8 Cailbhe Doherty¹

9 Chris Bleakley³

10 Jay Hertel⁴

11 Brian Caulfield¹

12 John Ryan⁵

13 Eamonn Delahunt^{1,2}

14 1. School of Public Health, Physiotherapy and Population Science, University College
15 Dublin, Dublin, Ireland.

16 2. Institute for Sport and Health, University College Dublin, Dublin, Ireland.

17 3. Sport and Exercise Sciences Research Institute, Ulster Sports Academy, University of
18 Ulster, Newtownabbey, Co. Antrim, Northern Ireland.

19 4. Department of Kinesiology, University of Virginia, Charlottesville, VA, United
20 States.

21 5. St. Vincent's University Hospital, Dublin, Ireland.

22

23 **Address for Correspondence:**

24 Cailbhe Doherty

25 A101
26 School of Public Health, Physiotherapy and Population Science
27 University College Dublin
28 Health Sciences Centre
29 Belfield
30 Dublin 4
31 Ireland
32 Email: cailbhe.doherty@ucdconnect.ie
33 Telephone: 00 353 1 7166671
34 Fax: 00 353 1 716 6501

35

36 Conflicts of Interest and Source of Funding:

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

41 **Running title:** Acute ankle sprain alters postural control strategies during single limb stance.

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48 **ABSTRACT**

49 **Background:** Single-limb stance is maintained via the integration of visual, vestibular and
50 somatosensory afferents. Musculoskeletal injury challenges the somatosensory system to
51 reweight distorted sensory afferents. This investigation supplements kinetic analysis of eyes-
52 open and eyes-closed single-limb stance tasks with a kinematic profile of lower limb postural
53 orientation in an acute ankle sprain group to assess the adaptive capacity of the sensorimotor
54 system to injury.

55 **Methods:** Sixty-six participants with acute ankle sprain completed eyes-open single-limb
56 stance on their injured and non-injured limbs. Twenty-three of these participants successfully
57 completed single-limb stance with their eyes closed. A non-injured control group of nineteen
58 participants completed eyes open single-limb stance, with 16 completing eyes closed single-
59 limb stance. 3-dimensional kinematics of the hip, knee and ankle joints as well as associated
60 fractal dimension of the center-of-pressure path were determined for each limb during these
61 tasks.

62 **Findings:** Between trial analyses revealed significant differences in stance limb kinematics
63 and fractal dimension of the center-of-pressure path for eyes closed single-limb stance. The
64 control group bilaterally assumed a position of greater hip flexion compared to ankle sprain
65 participants on their side-matched “involved” ($7.41 \pm 6.1^\circ$ vs $1.44 \pm 4.8^\circ$; $\eta^2 = .34$) and
66 “uninvolved” ($9.59 \pm 8.5^\circ$ vs $2.16 \pm 5.6^\circ$; $\eta^2 = .31$) limbs, with a greater fractal dimension
67 of the center-of-pressure path (involved limb = $1.39 \pm 0.16^\circ$ vs $1.25 \pm 0.14^\circ$; uninvolved
68 limb = $1.37 \pm 0.21^\circ$ vs $1.23 \pm 0.14^\circ$).

69 **Interpretation:** Acute ankle sprain causes bilateral impairment in postural control strategies.

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

72 **Introduction**

73 Balance is a generic term describing the dynamics of body posture to prevent falling (Winter,
74 1995). Information about body posture in single-limb stance (SLS) with respect to the force
75 of gravity is provided to the central nervous system by vestibular, visual and somatosensory
76 afferents (McCollum G, 1996). The vestibular system acts to detect linear and angular
77 accelerations, vision is the afferent primarily involved in planning movement while the
78 somatosensory system is composed of a multitude of sensors that detect the position and
79 velocity of all body segments, their contact with external objects, and the orientation of
80 gravity (Winter, 1995). The ability of the structurally different sensory afferents (otherwise
81 known as ‘degeneracies’(Glazier, 2009)) to combine and produce similar efferent motor
82 responses allows the sensorimotor system to simplify a task within a limited number of
83 movement strategies (Nashner, 1979). Selective reweighting of these degeneracies by the
84 central nervous system is then based on the availability of reliable information (McKeon PO,
85 2012). As a result, it is possible for the functioning somatosensory system to produce a
86 motor output contingent with maintaining balance in the presence of altered visual, vestibular
87 and/or somatosensory signals (McCollum G, 1996). Despite this, some deterioration in the
88 efferent response may become evident in simple postural control tasks (Winter, 1995).

89

90 Kinematic (Liu et al., 2012) and centre of pressure (COP) (Prieto, 1996) analyses have been
91 previously used to quantify the motor response associated with distorted sensory
92 environments during single limb stance in a variety of populations. A number of measures are
93 currently available with which to characterise the COP path trajectory. However, traditional

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

110

111 Musculoskeletal injury has the potential to challenge postural stability via a direct
112 disturbance of somatosensory afferents, consequently challenging the system to reweight
113 information to produce a suitable efferent response, and has been shown to manifest in
114 bilateral balance deficits following acute lateral ankle sprain (LAS) (Wikstrom EA, 2010).
115 LAS has previously been shown to be a significant injury risk in a wide variety of activity
116 types (Doherty, 2014) and despite a number of studies presenting COP analyses of
117 participants with acute LAS injury during SLS (Evans T, 2004, Hertel J, 2001, Leanderson et
118 al., 1996, Holme et al., 1999, Fridén T, 1989), no current investigation has supplemented

119 these analyses with a kinematic profile of postural orientation. Furthermore, no previous
120 research has explored the capacity of the somatosensory system to cope in the absence of
121 vision during the same task, in this group.
122 Therefore, the purpose of the current investigation was to assess the effects of acute LAS on
123 balance using kinematic and COP analyses in the presence and absence of visual afferents
124 (i.e. eyes-open and eyes-closed SLS). We hypothesized that acute LAS would result in a
125 reduction in participant self-reported function and would cause bilateral modification of
126 postural kinematic orientation strategies when compared to control subjects, which would be
127 reflected by COP trajectory measures sensitive to eyes-open and eyes-closed SLS. Such an
128 analysis may serve to elucidate the strategies used by a somatosensory system challenged not
129 only in organising distorted somatosensory afferents secondary to injury, but also in coping
130 without previously available visual degeneracies (Overstall PW, 1977).

131

132 **Methods**

133 **Participants**

134 Sixty-six participants (forty-three males and twenty-three females; age 23.2 +/- 5 years; body
135 mass 75.8 +/- 14.5 kg; height 1.73 +/- 0.1 m) were recruited from a University-affiliated
136 hospital Emergency Department within 2 weeks of sustaining a first-time LAS for the current
137 investigation. The following inclusion criteria were applied to all potential participants: (1)
138 no previous history of ankle sprain injury (excluding the recent acute episode for the injured
139 group); (2) no other lower extremity injury in the last 6 months; (3) no history of ankle
140 fracture; (4) no previous history of major lower limb surgery; (5) no history of neurological
141 disease, vestibular or visual disturbance or any other pathology that would impair their motor
142 performance. An additional group of nineteen uninjured participants (fifteen males and four
143 females; age 22.5 +/- 1.7 years; body mass 71.55 +/- 11.3 kg; height 1.74 +/- 0.1 m) with no

144 prior history of LAS were recruited from the hospital catchment area population using posters
145 and flyers to act as a control group. Participants were required to sign an informed consent
146 form approved by the University Human Research Ethics Committee on arrival to the
147 University biomechanics laboratory.

148

149 **Questionnaires**

150 Self-reported function, patient reported symptoms and functional ability as measures of LAS
151 severity were assessed using the activities of daily living and sports subscales of the Foot and
152 Ankle Ability Measure (FAAMadl and FAAMsport) (Carcia, 2008). Overall ankle joint
153 function and symptoms were evaluated using the Cumberland Ankle Instability Tool (CAIT)
154 (Hiller, 2006).

155

156 **Procedures**

157 Prior to completion of the SLS task, participants were instrumented with the Codamotion
158 bilateral lower limb gait set-up (Charnwood Dynamics Ltd, Leicestershire, UK). Following
159 collection of specific anthropometric measures required for the calculation of internal joint
160 centres at the hip, knee and ankle joints, lower limb markers and wands were attached, as
161 described by Monaghan et al. (Monaghan, 2006, Monaghan, 2007). A neutral stance trial was
162 used to align the subject with the laboratory coordinate system and to function as a reference
163 position for subsequent kinematic analysis as recommended in previously published literature
164 (McLean, 2007). Kinematic data acquisition was made at 1000 Hz using 3 Codamtion CX1
165 units and kinetic data at 100 Hz using 2 AMTI (Watertown, MA) walkway embedded force-
166 plates. The Codamotion CX1 units were time synchronized with the force-plates.

167

168

169 **Single-leg stance trials**

170 Participants performed three, 20 second trials of quiet SLS barefoot on a force- plate with
171 their eyes open on both limbs, each separated by a 30 second break period. Following another
172 2 minute rest period, these participants then attempted to complete the SLS task with their
173 eyes closed. Participants were required to complete a minimum of three practice trials on
174 each limb for each condition prior to data acquisition. Participants who were unable to
175 complete a full trial of SLS in the eyes closed condition after five attempts on both limbs
176 were not included in this part of the analysis. The test order between legs was randomized.
177 For both conditions of SLS, subjects were instructed to stand as still as possible with their
178 hands resting on their iliac crests while adopting a postural orientation most natural to them;
179 the position of the non-stance limb was not dictated as part of experimental procedures. Trials
180 were deemed invalid if the subject lifted their hands off their iliac crests, placed their non-
181 stance limb on the support surface, moved their non-stance hip into a position > 30 degrees
182 abduction or lifted their forefoot/heel. A trial was deemed as failed in the eyes closed
183 condition if the subject opened their eyes at any point.

184

185 **Data Processing of Kinematics and COP measures**

186 Kinematic data were calculated by comparing the angular orientations of the coordinate
187 systems of adjacent limb segments using the angular coupling set “Euler angles” to
188 represent clinical rotations in three dimensions. Marker positions within a Cartesian frame
189 were processed into rotation angles using vector algebra and trigonometry. Discrete whole-
190 trial averaged joint angular position values were calculated for the hip, knee and ankle joints
191 in the sagittal, transverse and frontal planes of motion, producing nine ‘joint position’
192 dependent variables of interest for each limb.

193

194 Kinetic data acquired from the trials of SLS were used to compute the FD of the COP path.
195 The COP is a bivariate distribution, jointly defined by the antero-posterior (AP) and medio-
196 lateral (ML) coordinates which in a time series define its path relative to the origin of the
197 force platform (Prieto, 1996). The AP and ML time series were passed through a fourth-order
198 zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency. We have
199 adopted an algorithm previously published and described in the seminal paper by Prieto et al
200 (Prieto, 1996) to calculate FD of the combined AP and ML COP paths. FD was calculated
201 based on the 20 second interval for each SLS trial, and averaged across the three trials for
202 each participant on each limb.

203

204 **Data Analysis and Statistics**

205 For the LAS group, limbs were labelled as “involved” and “uninvolved” based on FAAM
206 and CAIT results. For all outcomes, we calculated mean (SD) scores for the involved and
207 uninvolved limbs in the LAS group, and mean (SD) scores for the left and right limbs in the
208 control group. Participant characteristics were compared between the LAS and control groups
209 using multivariate analysis of variance. The dependent variables were age, mass, sex and
210 height. The independent variable was status (injured vs non-injured).

211

212 In order to test our hypothesis that acute LAS would cause bilateral changes in COP and
213 kinematic measures of postural orientation, we undertook a series of independent samples t-
214 tests for each outcome comparing: involved limb vs control, and uninvolved limb vs control.
215 In all cases the limbs in the control group were side matched to the injured group. The
216 significance level for analyses were adjusted for multiple tests using the Benjamini-Hochberg
217 method for false discovery rate (<5%) (Benjamini, 1995). All data were analyzed using
218 Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA).

219

220 **Results**

221 Regarding participant characteristics there was no statistically significant difference between
222 the LAS and control groups on the combined dependent variables, $F(4, 80) = 1.75$, $p = 0.14$;
223 Wilk's Lambda = 0.91; partial eta squared = 0.08. Regarding function the CAIT score for the
224 ankle sprain group was 11.85 ± 7.91 . The FAAMadl score for the ankle sprain group was
225 $68.50 \pm 18.65\%$. The FAAMsport score for the ankle sprain group was $32.11 \pm 23.85\%$.
226 Participant characteristics and questionnaire score are detailed in Table 1.

227

228 All participants completed the eyes-open SLS task on both limbs. Of the sixty-six participants
229 in the LAS group, twenty-three completed the SLS task with their eyes-closed on both their
230 involved and uninvolved limbs. Of the nineteen participants in the control group, sixteen
231 completed the SLS task with their eyes-closed on both limbs.

232

233 There was no significant difference in eyes-open SLS kinematics between the LAS and
234 control groups for the involved and uninvolved limbs. There was no significant difference in
235 eyes-open SLS FD scores for the LAS and control groups involved and uninvolved limbs.

236

237 There was a significant difference in eyes-closed SLS kinematics between the LAS and
238 control groups for the involved and uninvolved limbs. Multiple testing with a false discovery
239 rate of less than 5% revealed that control group exhibited increased hip flexion compared to
240 LAS group on both the involved (control group: $7.41 \pm 6.1^\circ$, LAS group: $1.44 \pm 4.8^\circ$; $t(1, 38) = -3.42$, $p = 0.001$, two tailed) and uninvolved (control group: $9.59 \pm 8.5^\circ$, ankle sprain
241 group: $2.16 \pm 5.6^\circ$; $t(1, 38) = -3.30$, $p = 0.002$, two tailed) limbs. The magnitude of the
242 differences in the means for the involved limb was -5.96° (95% CI: -9.49 to -2.43°) and -7.4°
243

244 (95% CI: -11.98 to -2.87°) for the uninvolved limb. Means +/-SD for each joint in each plane
245 of motion, with corresponding t-test statistics are detailed in Table 2. Between-groups
246 comparisons of the kinematic profile for the involved and uninvolved limbs are detailed in
247 Figures 1 and 2 ('k-flake graph').

248

249 There was a significant difference in eyes-closed SLS FD scores between the LAS and
250 control groups for the involved and uninvolved limbs. Multiple testing with a false discovery
251 rate of less than 5% revealed that the LAS group displayed reduced FD of the COP path
252 trajectory compared to the control group on both their involved (LAS group: 1.25 +/-0.14,
253 control group: 1.39 +/-0.16; $t(1, 38) = -3.09$, $p = 0.00$, two tailed) and uninvolved limbs (LAS
254 group: 1.23 +/-0.14, control group: 1.37 +/-0.21; $t(1,38) = -2.53$, $p = 0.01$, two tailed).

255

256 **Discussion**

257 Our results demonstrate a significant difference between the postural orientation utilized by
258 participants with acute LAS compared to non-injured controls, during eyes-closed SLS.
259 Specifically, these injured participants, who reported significant functional impairment,
260 assumed a position of reduced hip flexion compared to non-injured participants with no
261 functional impairment. This difference was observed bilaterally and the effect size was large
262 for both limbs. The position of reduced hip flexion was associated with reduced complexity
263 of the COP path, as illustrated by the smaller FD of the LAS group on both their involved and
264 uninvolved limbs. There was no difference between postural orientation as depicted by the
265 kinematic variables and associated complexity of the COP path trajectory of the LAS group
266 compared to the control group in the eyes-open condition.

267

268 This is the first analysis to combine stabilometric and kinematic measures of angular
269 displacement during SLS in a group with acute LAS, and the first to present an evaluation of
270 the eyes-closed condition for this task in this group. Measurement of discrete characteristics
271 of the COP path such as its length, area and velocity is a branch of stabilometry that has
272 previously been used to explore the effects of acute ankle sprain on single-limb balance with
273 relatively consistent findings: acute ankle sprain injury causes an increase in COP velocity,
274 and by extension, a greater displacement of the COP in a specified time interval (Evans T,
275 2004, Hertel J, 2001, Holme et al., 1999, Fridén T, 1989). However, the statistical approach
276 to analysis of the dependent variables applied in some of the aforementioned investigations is
277 a source of concern, bringing the observed consistency of these measures in this population
278 into question. Indeed, the absence of parametric analysis (Holme et al., 1999), and a lack of
279 control for multiplicity of dependent variables (Evans T, 2004, Hertel et al., 2001, Fridén T,
280 1989) with adjusted alpha levels, thus increasing the probability of family-wise error, is cause
281 for concern. Furthermore, the reliability of the traditional measures of COP used in these
282 investigations has been shown to be questionable (Doyle TL, 2005), with contradictory
283 findings having been previously reported in the literature (McKeon and Hertel, 2006b).
284 Hence, we have chosen to utilise FD as a measure of COP analysis, and have adopted a
285 Benjamini-Hochberg method for false discovery rate correction for multiple testing in the
286 current investigation (<5%) for all variables in the avoidance of increasing family-wise error.
287
288 FD represents a reliable method of analyzing COP path trajectory (Doyle TL, 2005,
289 Myklebust JB, 1995), whereby a change in FD may indicate a change in the postural control
290 strategies for maintaining quiet stance (Doyle TL, 2005). Furthermore, FD has been shown to
291 be a suitable means to characterise quiet stance COP under a number of conditions as
292 compared to more traditional measures (Doyle TL, 2005). Błaszczyk et al. (Błaszczyk, 2001)

293 compared the COP path trajectory FD in healthy elderly participants in eyes-open bilateral
294 stance to that of eyes-closed bilateral stance. The increase in FD that occurred with
295 elimination of visual afferents led the authors to attribute a change in FD to a change in
296 balance and postural stability. In pathological conditions, FD has been shown to be useful in
297 evaluating postural instability in Parkinson and ataxia patients in bilateral stance in eyes open
298 and eyes closed conditions (Manabe et al., 2001). Results from the research of Manabe et al.
299 (Manabe et al., 2001) elucidated that the transition to eyes-closed stance corresponded with
300 an increase in FD in pathological and control groups, with an associated higher FD in the
301 pathological group. This was proportional to the severity of the condition in the pathological
302 group. Cimolin et al. (Cimolin, 2011) observed an increase in FD in participants with Prader-
303 Willi Syndrome compared to healthy controls during bilateral stance with their eyes-open.
304 They theorized that higher FD values may be interpreted as an inability of pathological
305 patients to synergistically modulate the three sources of afferent information (i.e., the visual,
306 vestibular and somatosensory systems) involved in maintaining balance.

307

308 In contrast to the findings reported in these analyses, we have observed a decrease in FD
309 associated with pathology (acute LAS), which was present in the eyes-closed condition only,
310 for both the involved and uninvolved limbs of injured participants. We offer two explanations
311 for the contrasting results: differences in subject sample and task type separate the current
312 investigation from those previously discussed. Specifically, we have assessed participants
313 with acute LAS injury (as opposed to participants with longstanding neurological
314 impairment) during a task of single limb stance (in contrast to the bilateral stance task utilized
315 in the investigations by Cimolin et al. (Cimolin, 2011) and Manabe et al. (Manabe et al.,
316 2001). With regards to the results observed in the current analysis, we theorize that a linear
317 relationship between COP path trajectory and its associated FD does not exist; there may be

318 an ideal FD which is specific to the constraints of the task and those limiting the individual,
319 but it does not place on a scale where more or less is better or worse. In losing some of the
320 available degeneracies via the distortion of somatosensory afferents, the postural control
321 system of the injured participants has fewer available strategies with which to complete the
322 prescribed task. While an increase in FD has previously been associated with the loss of
323 visual afferents (Błaszczyk, 2001, Doyle TL, 2005), the lower FD within the constraints of
324 this condition in the injured group compared to the non-injured group in the current
325 investigation may reflect a postural control system with fewer available strategies with which
326 to complete the task. In essence the injured participants were less able to utilize the base of
327 support available to them, as evidenced by a reduced FD. That there was no difference in the
328 eyes-open condition between LAS and control participants reflects that the presence of visual
329 afferents sufficed to allow the postural control system of this injured group to optimally
330 organize the network of constraints and degeneracies in a manner similar to that of the
331 control group; several investigations have demonstrated that in circumstances where one or
332 two sensory afferents are deficient, sufficient compensatory information can be provided by
333 remaining sources for equilibrium to be maintained (Horak et al., 1990, Nashner, 1971). The
334 non-significance of the between-group findings for the eyes-open condition is however in
335 contrast with previous research (Evans T, 2004, Hertel J, 2001, Leanderson et al., 1996,
336 Holme et al., 1999, Fridén T, 1989) and may be due to these studies' previously discussed
337 methodological differences.

338

339 Although the SLS balance task is intended to be static in nature, every participant displayed
340 varying amounts of movement despite being asked to stand as still as possible. Consequently,
341 the time series represent an internally generated perturbation, as well as the organization of a
342 postural control system in which the resultant ground reaction forces differ to the

343 displacement of the segments of the kinetic chain to which they are coupled (Winter, 1995,
344 Myklebust JB, 1995). The current research tackles this issue by supplementing measures of
345 the COP path trajectory with an averaged 3-dimensional kinematic profile of lower limb
346 alignment to discern the differences in joint position that accompany COP FD. Furthermore,
347 conceptualization of the postural orientation that produced the observed FD makes the current
348 findings more accessible to clinicians. The kinematic profiles can be seen to reflect the FD of
349 the COP path: similar to the FD in the eyes-open condition, there were no differences in the
350 average position assumed by LAS participants at the hip, knee or ankle in the sagittal, frontal
351 or transverse planes of motion compared to control participants for either the involved or
352 uninvolved limbs. However, in the eyes-closed condition, the reduced FD of LAS
353 participants compared to control participants on both the involved and uninvolved limbs was
354 linked to a bilateral decrease in hip flexion. The presence of bilateral impairments in subjects
355 with acute LAS is well documented in the literature (Wikstrom EA, 2010), supporting the
356 hypothesis that LAS has the capacity to cause spinal-level inhibition through gamma motor
357 neuron loop dysfunction resulting in postural control impairment (Khin-Myo-Hla, 1999). The
358 conscious perception of swelling and pain associated with the acute ankle sprain in the
359 current sample during the full weight-bearing SLS task had the capacity to cause this
360 supraspinal inhibition, thus impairing postural control strategies when potential degeneracies
361 became unavailable (i.e. in the eyes-closed condition). This is reflected in the bilaterally
362 observed decrease in hip flexion and COP path trajectory FD in the injured group (with
363 significant self-reported functional impairment) compared to the non-injured group (with no
364 self-reported functional impairment).

365

366 The ankle joint has a central role for maintaining equilibrium in SLS. The elimination of
367 visual afferents disrupts this equilibrium, and corrections in healthy populations are then

368 made at the hip (Tropp and Odenrick, 1988). We hypothesize that the natural transition from
369 an inverted pendulum model (where the ankle has a central role in postural corrections) to a
370 multi-segmental chain model (where the hip has a central role in postural corrections) on
371 removal of visual afferents did not occur in the injured group secondary to a change in the
372 sensory environment due to injury (McCollum G, 1996). In the eyes-open task for both
373 groups, the sensorimotor system had the ability to shift reliance away from the affected area
374 toward other available receptors, hence no between-group differences were observed.

375

376 The consequences of these bilaterally observed impairments in postural control are of
377 significant importance considering their role in increasing the risk of re-spraining the injured
378 ankle (McGuine TA, 2000, Tropp et al., 1984), and particularly in view of the equality of the
379 observed effects on the involved and uninvolved limbs; it has been estimated that at least 1
380 out of 3 individuals who incur an ankle sprain will go on to have recurrent issues (Gerber et
381 al., 1998), indicating that current care and decisions for return to activity may be inadequate
382 for ankle sprains (Medina McKeon JM, 2013). We encourage caution in returning athletes to
383 play too quickly following acute LAS, and the completion of rehabilitation protocols
384 bilaterally. The potential worth of a task of eyes-closed SLS as a simple yet challenging
385 early-stage rehabilitation exercise should also be noted.

386 It is however important to note that the simplicity of the kinematic analysis technique used in
387 the current investigation must be considered a potential limitation. We chose to quantify a
388 surrogate of the motor output using COP and averaged kinematic measures to provide a
389 simple and immediately accessible conceptualisation of the sensorimotor response to
390 distorted sensory afferents. Future research may benefit from more advanced analyses of
391 movement variability and between-joint coupling during SLS to further advance current
392 understanding. Furthermore, future investigations would benefit from a follow-up period

393 whereby participants with acute LAS are evaluated longitudinally in the determination of
394 outcome; recovery or the onset of chronicity. Finally, static postural control testing may not
395 be sensitive enough to identify all functional deficits associate with acute ankle sprain injury.
396 Dynamic balance tests, such as the Star Excursion Balance Test may serve as a means to
397 functionally assess patients with acute LAS. This test may be more sensitive in detecting
398 functional deficits in the entire lower extremity during dynamic activities (Gribble et al.,
399 2012). Further profiling of kinematic and kinetic variables in this area is warranted.

400

401 **Conclusions**

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

407

408 **Acknowledgements**

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

412

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523 Figure legends

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

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

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Table 1

Table 1. Participant characteristics and questionnaire scores (mean +/- SD with 95% CIs) for the LAS and control groups. LAS = ankle sprain

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

LAS = ankle sprain

Table 2

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

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

Figure 1

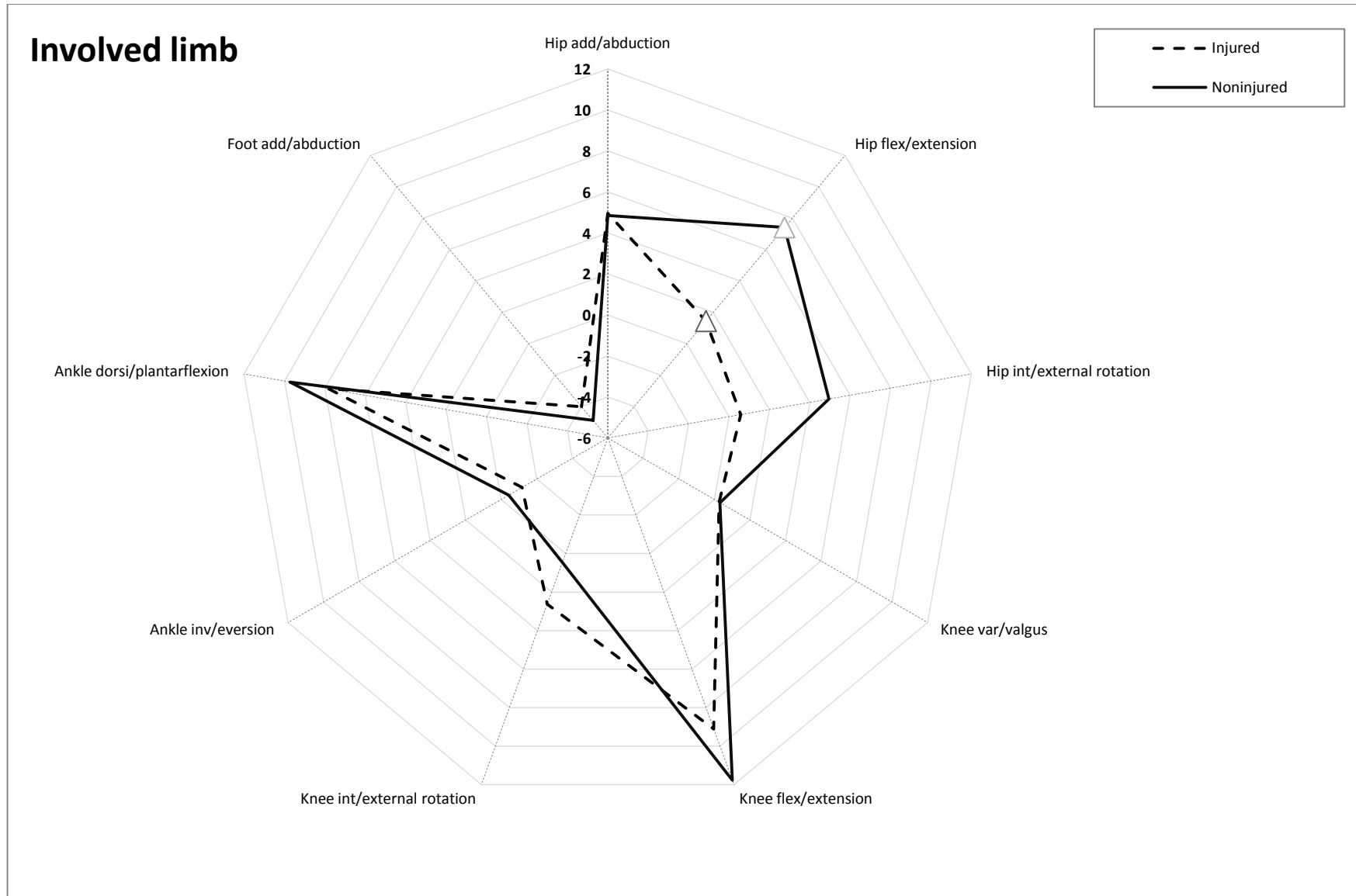


Figure 2

