


Provided by the author(s) and University College Dublin Library in accordance with publisher policies. Please cite the published version when available.

Title	Inter-joint coordination strategies during unilateral stance 6-months following first-time lateral ankle sprain
Author(s)	Doherty, Cailbhe; Bleakley, Chris J.; Hertel, Jay; Ryan, John; Sweeney, Kevin T.; Delahunt, Eamonn
Publication date	2015-02
Publication information	Clinical Biomechanics, 30 (2): 129-135
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/8441
Publisher's statement	This is the author's version of a work that was accepted for publication in Clinical Biomechanics. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Clinical Biomechanics (VOL 30, ISSUE 2, (2015)) DOI: 10.1016/j.clinbiomech.2014.12.011.
Publisher's version (DOI)	http://dx.doi.org/10.1016/j.clinbiomech.2014.12.011

Downloaded 2017-09-25T15:33:16Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa) 

Some rights reserved. For more information, please see the item record link above.



1 **Title:** Inter-joint coordination strategies during unilateral stance 6-months following acute
2 lateral ankle sprain.

3 **Running title:** Inter-joint coordination following ankle sprain

4 **Abstract word count:** 248

5 **Word count:** 3996

6 4 tables

7 1 figure

8 **Authors:**

9 Cailbhe Doherty¹

10 Chris Bleakley³

11 Jay Hertel⁴

12 Brian Caulfield¹

13 John Ryan⁵

14 Kevin Sweeney¹

15 Eamonn Delahunt^{1,2}

16 1. School of Public Health, Physiotherapy and Population Science, University College
17 Dublin, Dublin, Ireland.

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

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

21 4. Department of Kinesiology, University of Virginia, Charlottesville, VA, United
22 States.

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

24 **Address for Correspondence:**

25 Cailbhe Doherty

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

36

37 Conflicts of Interest and Source of Funding:

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

42 **Running title:** Inter-joint coordination following ankle sprain

43

44

45

46

47

48

49

50

51 **ABSTRACT**

52 **Background:** Longitudinal analyses of participants with a history of lateral ankle sprain are
53 lacking. This investigation combined measures of inter-joint coordination and stabilometry to
54 evaluate eyes-open (condition 1) and eyes-closed (condition 2) static unilateral stance
55 performance in a group of participants, 6-months after they sustained an acute first time
56 lateral ankle sprain in comparison to a control group.

57 **Methods:** Sixty-nine participants with a 6-month history of lateral ankle sprain and 20 non-
58 injured controls completed three 20-second stance task trials in conditions 1 and 2. An
59 adjusted coefficient of multiple determination statistic was used to compare stance limb 3-D
60 kinematic data for similarity in the aim of establishing patterns of inter-joint coordination.
61 The fractal dimension of the stance limb center of pressure path was also calculated.

62 **Findings:** Between-group analyses revealed significant differences in stance limb inter-joint
63 coordination strategies for conditions 1 and 2, and in the fractal dimension of the center-of-
64 pressure path for condition 2 only. Injured participants displayed increases in ankle-hip
65 linked coordination compared to controls in condition 1 (sagittal/frontal plane: 0.15 [0.14] vs
66 0.06 [0.04]; $\eta^2 = .43$; sagittal/transverse plane: 0.14 [0.11] vs 0.09 [0.05]; $\eta^2 = 0.38$) and
67 condition 2 (sagittal/frontal plane: 0.15 [0.12] vs 0.08 [0.06]; $\eta^2 = 0.48$), with an associated
68 decrease in the fractal dimension of the center-of-pressure path (injured limb: 1.23 ± 0.13 vs
69 1.36 ± 0.13 ; $\eta^2 = 0.20$).

70 **Interpretation:** Participants with a 6-month history of LAS present with a hip-dominant
71 coordination strategy for static unilateral stance compared to non-injured controls.

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

74

75

76 **1.0 Introduction**

77 The high prevalence of ankle sprain in a wide variety of activity types [1] has motivated a
78 large body of research designed to evaluate the movement patterns which develop as a
79 consequence of this acute injury. These movement patterns are typically assessed by means
80 of laboratory analyses of prescribed tasks such as static unilateral stance, whereby kinematic
81 and stabilometric measures are utilised to quantify the coordination of postural control [2-5].
82 Postural control during unilateral stance emerges from a dynamic interaction between
83 feedback mechanisms and a central motor program [6]. Feedback mechanisms originate as
84 sensory afferents which include visual, vestibular and somatosensory components [6]. A
85 decay in somatosensory afferents, as may occur with acute ankle sprain injury [7], combined
86 with loss of visual input, has previously been shown to challenge the ability of the central
87 nervous system to reweight available information with an appropriated coordination response
88 [4,8]. With respect to acute ankle sprain, it has been reported that this manifests as a
89 deterioration of eyes-closed unilateral standing balance capability, with less effective
90 utilisation of the supporting base and an altered kinematical orientation, on both the injured
91 and non-injured limbs [3].

92 The high potential for patients with a history of ankle sprain to suffer recurrence [9,10] has
93 prompted researchers to theorise that recovery or the onset of chronicity is dependent on the
94 type of coordination strategies adopted in the year following the acute injury [11-13]; patients
95 who subjectively report the continuum of residual symptoms collectively labelled ‘chronic
96 ankle instability’ (CAI) [14], or those ‘copers’ who recover with no relapse [15], have both
97 been shown to adopt unique coordination strategies conducive with their injury outcome
98 [11,13]. However, the research evaluating these coordination strategies at a specific time
99 point occurring in the period between the acute episode (<2 weeks following injury) and the
100 determination of recovery/chronicity (>1year following injury), is sparse.

101 Bernstein described coordination as the process of incorporating redundant motor system
102 degrees of freedom into a controllable unit [16]. Traditionally in laboratory analyses of static
103 unilateral stance, kinematical data from isolated joints (e.g. angular displacement) are
104 presented as a function of time [3,17] to identify the contributing role of each lower-
105 extremity joint to the coordination of postural control. For example, Tropp and Odenrick[18]
106 observed a central role of the ankle joint in postural corrections during single-limb standing,
107 while Doherty et al. [3] identified the important role of the hip in maintaining balance with an
108 increasing number of task constraints (i.e. transition from eyes-open to eyes-closed single-leg
109 stance). However, it has recently been suggested that evaluating inter-joint coordination
110 relationships between segments of the motor apparatus may further advance current
111 understanding of the coordination strategies supporting human postural control in
112 environments of sensory decay [19,20]. Indeed no research currently exists evaluating the
113 inter-joint coordination strategies of a group following first-time, acute lateral ankle sprain
114 (LAS) injury in maintaining postural control during unilateral stance in the presence and
115 absence of visual input, prior to the establishment of CAI or copers status, which can only
116 occur a minimum of 1 year following the initial injury [14,15,21].

117 Therefore, the purpose of this study was to evaluate the coordination of postural control in a
118 group of participants in which recovery or recurrence is yet to be established following first-
119 time, acute LAS. Measures of platform stabilometry and 3-dimensional kinematics of inter-
120 joint coordination were combined to evaluate the coordination of postural control during
121 static unilateral stance in the presence and absence of visual input in a group 6-months after
122 sustaining a first-time, acute LAS, on both their involved and uninvolved limbs. An “adjusted
123 coefficient of multiple determination (ACMD)” statistic [20,22] was used to establish inter-
124 joint coordination between the hip, knee and ankle joints in all planes of motion. ACMD
125 analysis provides a mechanism by which continuous waveform data can be evaluated for

126 similarity [22], thus establishing the relationship between movement patterns at different
127 joints, in different planes of motion. The measure of stabilometry utilised was the fractal
128 dimension (FD) of the centre of pressure (COP) path [23]. FD has previously been used to
129 evaluate unilateral standing balance in participants with acute LAS injury [2,3] and describes
130 the complexity of the COP signal, thus giving an indication of the extent to which a person
131 utilises the base of support available to them [24]. We hypothesised that participants with a
132 recent history of ankle sprain injury would have reduced self-reported function and ability
133 compared to a group with no recent injury history as their recovery would not be complete.
134 Furthermore, it was hypothesized that these participants would display inter-joint
135 coordination patterns contingent with increased reliance on the proximal strategies of the hip
136 joint to maintain unilateral stance stasis (thus compensating for reduced control at the ankle),
137 and that they would display reduced FD of the stance limb COP path (indicating a limited
138 ability to utilise the available base of support).

139

140 **2.0 Methods**

141 **2.1 Participants**

142 A convenience group of sixty-nine participants (forty-four males and twenty-five females;
143 age = 22.78 [4.12] years; height = 1.72 [0.09] m; body mass = 76.6 [13.6] kg) were recruited
144 from a University affiliated hospital Emergency Department within 2-weeks of sustaining a
145 first-time acute LAS injury, to take part in testing procedures for the current investigation,
146 which took place 6 months following recruitment. An additional convenience sample of
147 twenty participants (fifteen males and five females, age = 22.6 [1.7] years; height = 1.73 [0.1]
148 m; body mass = 71.4 [11.29] kg) with no prior history of LAS were recruited from the
149 hospital catchment area population using posters and flyers to act as a control group. All
150 participants signed an informed consent form prior to testing and all testing procedures were

151 approved by the Institutional Review Board where the study was completed. None of the
152 subjects had a history of severe lower extremity injury (excluding the recently sustained LAS
153 for the injured group), vestibular lesions or any other pathology that would impair their motor
154 performance.

155 **2.2 Protocol**

156 All participants were required to complete questionnaires relating to ankle joint function and
157 disability on arrival to the testing laboratory: the activities of daily living and sports subscales
158 of the Foot and Ankle Ability Measure (FAAMadl and FAAMsport) were utilized to quantify
159 self-reported function and participant reported symptoms [25], and the Cumberland Ankle
160 Instability Tool (CAIT) was utilized to evaluate ankle joint function and painful symptoms
161 [26].

162 After completion of the questionnaires, participants were instrumented with the Codamotion
163 bilateral lower limb gait set-up (Charnwood Dynamics Ltd, Leicestershire, UK).

164 Anthropometric measures required for the calculation of internal joint centres of the lower
165 extremity joints were collected for each participant, with subsequent placement of lower limb
166 markers and wands as described by Monaghan et al. [27]. A neutral stance trial was used to
167 align the subject with the laboratory coordinate system and to function as a reference position
168 for subsequent kinematic analysis [28]. Participants then performed three, 20 second trials of
169 quiet unilateral stance barefoot on a force-plate with their eyes open on both limbs, each
170 separated by a 30 second break period. Following another 2 minute rest period, these
171 participants then attempted to complete the unilateral stance task with their eyes closed.

172 Participants were required to complete a minimum of three practice trials on each limb for
173 each condition prior to data acquisition. Participants who were unable to complete a full trial
174 of unilateral stance after five attempts on both limbs were not included in the analysis. The
175 test order between legs was randomized. For both conditions of unilateral stance, subjects

176 were instructed to stand as still as possible with their hands resting on their iliac crests while
177 adopting a postural orientation most natural to them; the position of the non-stance limb was
178 not dictated in the sagittal plane as part of experimental procedures. Trials were deemed
179 invalid if the subject lifted their hands off their iliac crests, placed their non-stance limb on
180 the support surface, moved their non-stance hip into a position > 30 degrees abduction,
181 adducted their non-stance limb against their stance limb for support or lifted their
182 forefoot/heel. In addition a trial was deemed as failed in the eyes closed condition if the
183 subject opened their eyes at any point.

184 **2.3 Kinematic and Kinetic Data Processing**

185 Three Codamotion cx1 units were used to provide information on 3-dimensional angular
186 displacements at the hip, knee and ankle joints for both limbs during the unilateral stance
187 task. Two AMTI (Watertown, MA) walkway embedded force-plates were used to acquire
188 kinetic data. Kinematic and kinetic data acquisition was made at 100 Hz. The Codamotion
189 CX1 units were time synchronized with the force-plates.

190 Kinematic data were calculated by comparing the angular orientations of the coordinate
191 systems of adjacent limb segments using the angular coupling set “Euler angles” to
192 represent clinical rotations in three dimensions. Marker positions within a Cartesian frame
193 were processed into rotation angles using vector algebra and trigonometry.

194 Pairwise comparison of 3-dimensional temporal angular displacement waveforms for the hip,
195 knee and ankle joints of the stance limb were made using the ACMD statistic [22] in the aim
196 of quantifying the similarity of a given pair of waveforms during both conditions of unilateral
197 stance. There were three joint pairs (hip/knee, hip/ankle, and knee/ankle) each operating
198 separately in three dimensions, with twenty-seven resultant ACMD values for each trial of
199 unilateral stance. For example, frontal plane hip motion was compared with frontal, sagittal
200 and transverse plane knee motion, before being compared with the same relative movements

201 at the ankle joint. The mean ACMD from three trials of unilateral stance was used as a
202 representative ACMD for each participant. ACMD values ranged from 0 (no similarity) to 1
203 (two identical curves) [22]. The same data processing procedure was performed for both
204 eyes-open and eyes-closed unilateral stance, on both limbs. See Figure 1 for a representative
205 depiction of an ACMD value between two angular displacement waveforms.

206 Furthermore, mean values of all joint angular ranges (maximum value–minimum value)
207 during testing in each task were computed for comparisons between LAS and control
208 participants.

209 The kinetic data of interest was center of pressure (COP) (the location of the vertical reaction
210 vector on the surface of a force-plate) path for each reach trial. The COP is a bivariate
211 distribution, jointly defined by the antero-posterior (AP) and medio-lateral (ML) coordinates
212 which in a time series define the COP path relative to the origin of the force platform [24].

213 COP data acquired from trials of the unilateral stance were used to compute FD of the
214 combined AP and ML COP path using an algorithm previously published and described by
215 Prieto et al [24]. FD was calculated based on the 20 second interval for each unilateral stance
216 trial, and averaged across the three trials for each participant on each limb. The AP and ML
217 time series were passed through a fourth-order zero phase Butterworth low-pass digital filter
218 with a 5-Hz cut-off frequency[29]. Kinematic and COP data were analysed using the
219 Codamotion software, with the following axis conventions: x axis = frontal-plane motion; y =
220 sagittal-plane motion; z = transverse-plane motion, and then converted to Microsoft Excel file
221 format. Temporal data were set with the number of output samples per trial at 2000 + 1 in the
222 data-export option of the Codamotion software, which represented the complete unilateral
223 stance trial as 100%, for averaging and further analysis.

224 **2.4 Data Analysis and Statistics**

225 For the LAS group, the limb injured at the time of recruitment was labelled as “involved”
226 and the non-injured limb as “uninvolved”. In all cases the limbs in the control group were
227 side matched to the injured group; for each control subject, one limb was assigned as
228 “involved” and one as “uninvolved” so that an equal proportion of right and left limbs were
229 classified as “involved” and “uninvolved” in both the LAS and control groups. For all
230 outcomes, we calculated mean (SD) scores for the involved and uninvolved limbs in the LAS
231 group, and mean (SD) scores for the left and right limbs in the control group.

232 To determine whether the LAS group would demonstrate decreased function compared to the
233 control group a multivariate analysis of variance was undertaken. The independent variable
234 was group (LAS vs. control). The dependent variables were CAIT score, FAAMadl score and
235 FAAMsport score for the involved limb. The significance level for this analysis was set a
236 priori with a bonferonni adjusted alpha level of $p < 0.017$.

237 In order to test our hypothesis that the LAS group would display bilateral changes in inter-
238 joint coordination patterns as determined using the ACMD statistic for pairwise comparison
239 between 3-dimensional joint angular displacement curves, we undertook a series of
240 independent samples t-tests comparing: involved limb vs control, and uninvolved limb vs
241 control for the eyes-open and eyes-closed conditions. Furthermore, the mean joint range of
242 motion in both conditions was computed for all joints in all planes for comparison between
243 LAS and control groups. The significance level for these analyses were adjusted for multiple
244 tests using the Benjamini-Hochberg method for false discovery rate (<5%) [30] in two groups
245 (ACMD and joint ranges) each with two levels (eyes-open and eyes closed).

246 In order to test our hypothesis that the LAS group would display altered COP path trajectory
247 FD during unilateral stance, an independent samples, two-sided t-test was undertaken for
248 each limb (involved and uninvolved) in each condition. The significance level for this
249 analysis was set a priori with a Bonferroni adjusted alpha level of 0.025.

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

252

253 **3.0 Results**

254 Regarding self-reported function and disability, a statistically significant main effect was
255 observed for the combined dependent variables, $F(3, 72) = 14.81, p < 0.01$, Wilks' Lambda =
256 0.61, partial eta squared = 0.38. Questionnaire scores with details of relevant statistical
257 analyses for the LAS and control groups are detailed in Table 1.

258 All participants completed the eyes-open SLS task on both limbs. Of the sixty-nine
259 participants in the LAS group, thirty-eight (23 males & 15 females) completed the SLS task
260 with their eyes-closed on both their involved and uninvolved limbs. Of the twenty
261 participants in the control group, seventeen (12 males & 5 females) completed the SLS task
262 with their eyes-closed on both limbs.

263 Regarding inter-joint coordination, the LAS group displayed significantly increased
264 similarities in joint angular motions based on ACMD values between sagittal plane hip
265 motion and both frontal and transverse plane ankle motion on their involved limb compared
266 to control participants in the eyes open condition (Table 2). Similarly in the eyes-closed
267 condition, the LAS group displayed significantly increased similarities in joint angular
268 motion based on ACMD values between sagittal plane hip motion and frontal plane ankle
269 motion on their involved limb compared to control participants (Table 3). LAS participants
270 also displayed significantly greater transverse plane range of ankle motion compared to
271 controls in the eyes-open condition, and significantly greater sagittal plane range of hip
272 motion compared to controls in the eyes-closed condition. Joint motion ranges for both
273 conditions of unilateral stance are detailed in Table 4.

274 Regarding the kinetic variables of interest, LAS participants displayed reduced stance limb
275 FD compared to control participants on their involved limb in the eyes closed condition only
276 (1.23 ± 0.13 vs 1.36 ± 0.13 ; $t(56) = -0.66$, $p = 0.001$, two-tailed). The magnitude of the
277 differences in the mean (mean difference = -0.13 , 95% CI: -0.21 to -0.05) was large (eta
278 squared = 0.20). There was no significant difference between LAS and control participants'
279 stance limb FD in the eyes open condition for the involved (1.15 ± 0.20 vs 1.23 ± 0.12 ; $t(86)$
280 = -1.69 , $p = 0.09$, two tailed) or uninvolved (1.12 ± 0.25 vs 1.03 ± 0.28 ; $t(86) = 1.26$, $p =$
281 0.21 , two tailed) limbs. There was no significant difference between LAS and control
282 participants' stance limb FD in the eyes closed condition for the uninvolved limb (1.21 ± 0.25
283 vs 1.26 ± 0.19 ; $t(56) = -0.66$, $p = 0.51$, two tailed).

284

285 **4.0 Discussion**

286 The findings of the current investigation illustrate that participants with a 6-month history of
287 LAS display increased ankle-hip linked joint coordination during unilateral stance in both the
288 presence and absence of vision. Nashner and McCollum were the first to propose the
289 existence of two coordination strategies that can be used either independently or in
290 conjunction by the central motor program based on the feedback received from sensory
291 afferents in order to achieve adaptable control of the COP within the supporting base [31]:
292 the synchronous exploitation of torques around the ankle joint that constitutes the 'ankle
293 strategy' is appropriate for subtle changes in postural control while a 'hip strategy', which
294 generates shear forces around the hip joint, compensates for more substantial disturbances in
295 equilibrium [31,32]. It is plausible that a decay of sensory afferents (as may occur with injury
296 [6,8]), forces the adoption of strategies more appropriate for safely maintaining balance,
297 although this may still manifest in an alteration, and deterioration, in standing postural
298 control [33]. The results of the current study can be seen to conform to the propositions first

299 made by Nashner and McCollum, and as such we believe it appropriate to evaluate these
300 coordination strategies within the context of their theoretical framework.

301 The use of the ACMD statistic to establish normative similarities in 3-dimensional inter-joint
302 movement patterns for the lower extremity during eyes-open and eyes-closed unilateral
303 stance using the control group in the current study has allowed for the determination of a
304 number of injury-affiliated alterations present in the group with a 6-month history of LAS
305 [20]. This group with a history of LAS, who reported significantly decreased function on
306 their previously injured (involved) limb, displayed increased hip-ankle inter-joint
307 coordination patterns compared to the control group in both conditions of unilateral stance.
308 Specifically, there was greater ‘coupling’ of sagittal plane hip motion and both frontal and
309 transverse plane ankle motion in the eyes-open condition. Similarly, in the eyes-closed
310 condition, there was greater coupling of sagittal plane hip motion and frontal plane ankle
311 motion. These results may indicate the utilisation of a more hip-dominant balance strategy in
312 the LAS group, perhaps due to the local somatosensory compromise associated with reduced
313 ankle joint function, which was further confounded (and subsequently compensated for), by
314 removal of visual afferents. These theories are supported on inspection of the joint range
315 values, where the LAS group displayed significantly greater transverse plane ankle motion in
316 the eyes-open condition, and significantly greater sagittal plane hip motion in the eyes-closed
317 condition.

318 Despite the stasis sought as part of the constraints of the unilateral stance tasks used in the
319 current study, an unremitting synchrony of postural adjustments is required to maintain
320 equilibrium throughout their course. An impaired ability to correct any disequilibrium created
321 by these postural adjustments using the ankle strategy secondary to inadequate ankle function
322 may require the motor apparatus to adopt another strategy, one which can more suitably
323 compensate for the increased joint ranges presenting at distal parts of the kinetic chain (which

324 have the capacity to be magnified proximally [34]), and which possesses a greater availability
325 of non-distorted somatosensory afferents; specifically, we refer to the strategy of the hip.
326 Tropp and Odenrick [18] previously established the importance of ankle joint function in
327 maintaining unilateral stance. This ankle strategy is limited by the foot's ability to exert
328 torque in contact with the supporting surface [18]. Perhaps the initial balance deficits
329 associated with pain and swelling that presented in the acute phase of LAS injury [3],
330 persisted into the weeks and months following; an acute distortion of somatosensory afferents
331 [35] manifested in an immediate impairment in ankle joint function [3,36], potentially
332 forcing the adoption of the more proximal hip strategy [3,18], and this may have persisted 6-
333 months following the injury, as evidenced by the current findings. That the LAS group
334 displayed increased inter-joint coupling in 79% of all cases for both the involved limb in both
335 the eyes-open and eyes-closed conditions suggests a reduced ability for separate components
336 of the kinetic chain to function independently following the initial injury.

337 The reduction in involved limb FD that presented in LAS participants with their eyes closed
338 during unilateral stance suggests that they were unable to sufficiently utilise the available
339 base of support in this condition when confined to a hip-dominant postural control strategy
340 [3,24]. However, in consideration of the absence of between-group differences for the eyes-
341 open condition despite the utilisation of a similar hip-dominant strategy, it is clear that there
342 is no linear relationship between stance limb FD and postural control ability; too large an FD
343 has previously been attributed to an inability to synergistically modulate sensory afferents in
344 producing an efferent response [37] while too small a FD has previously been linked with
345 insufficient utilisation of the available base of support [24]. COP analyses are merely
346 surrogate measures of postural control, and often mask the complex coordination strategies
347 that precede them, particularly in instances of unilateral stance [20]. Furthermore, FD has
348 previously failed to distinguish between an acute LAS and control groups in the eyes open

349 condition [3], but has made distinctions between these groups when visual afferents have
350 been removed [2,3]. In the current situation we would consider that the ineffective ankle
351 strategy of LAS participants limited their ability to utilise the available base of support; one
352 manifestation of this was a reduction in FD, which coincided with greater range of movement
353 at the hip. Another potential manifestation of this would have been a normal value of FD,
354 maybe due in part to the increase in rotational movements at the ankle (as is evident in the
355 eyes open condition). That both of these conditions were characterised by a hip-dominant
356 strategy as determined using the ACMD analyses suggests that the specific movements at
357 each joint played an important role in the trajectory of the stance limb FD, a theory confirmed
358 by consideration of the joint range values. In summary we theorise that reduced control at
359 the ankle was compensated for in the eyes-closed condition by greater movements at the hip
360 joint with a coinciding hip-dominant strategy and a reduced FD, while in the eyes-open
361 condition, the same lack of control at the ankle manifested in greater local rotational
362 movement (directly affecting the complexity of COP patterns), and despite a similar hip-
363 dominant balance strategy, an FD within normal ranges.

364 The presence of bilateral postural control impairments in subjects with acute LAS during
365 similar tasks of unilateral stance [3,4], and the absence of such deficits in the current sample
366 suggests that acute LAS has the capacity to cause spinal-level inhibition through gamma
367 motor neuron loop dysfunction [38], but that this does not always persist in the months
368 following the acute episode [39]. Alternatively, it may be that a persistence of peripheral
369 impairment with/without central impairment is sufficient to limit an individual's capacity to
370 maintain successful balance. Whether these deficits preceded or occurred as a result of injury,
371 and contribute to chronicity or recovery, is unknown due to the design of the current study.

372 Herein lies a significant limitation of the current study: future analyses would benefit from

373 following participants after testing procedures are completed to determine the movement
374 patterns most likely to contribute to the onset of CAI, or recovery.
375 The primary implication of the current findings for clinicians is that coordination strategies
376 continue to be altered 6-months following acute ankle sprain injury, with the hip seemingly
377 playing a significant compensatory role for the injured ankle. As the hip is more suited to
378 synchronising the global movements of the head, arms and trunk with the lower extremities,
379 reweighted dominance on hip joint strategies may have a local ‘detraining’ effect at the ankle.
380 If the ankle is then unable to fulfil its primary in completing the local movement subtleties
381 required for normal unperturbed standing balance [31], this may contribute to instability.
382 Thus, clinicians must devise rehabilitation protocols with these issues in mind.

383

384 **5.0 Conclusions**

385 In conclusion, the results of the current study suggest that participants with a 6-month history
386 of LAS report reduced ankle joint function and increased disability compared to uninjured
387 controls, and that this manifests in a hip-dominant balance strategy during tasks of eyes-open
388 and eyes-closed unilateral stance.

389

390 **Acknowledgements**

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

394

395 **References**

- 396 [1] Doherty C, Delahunt E, Caulfield B, Hertel J, Ryan J, Bleakley C. The Incidence and
397 Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-Analysis of
398 Prospective Epidemiological Studies. *Sports Med* 2014;44 (1) 123-140
- 399 [2] Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Balance failure in
400 single limb stance due to ankle sprain injury: an analysis of center of pressure using
401 the fractal dimension method. *Gait & Posture* 2014.
- 402 [3] Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Postural control
403 strategies during single limb stance following acute lateral ankle sprain. *Clinical*
404 *Biomechanics* 2014.
- 405 [4] Evans T, Hertel J, Sebastianelli W. Bilateral deficits in postural control following
406 lateral ankle sprain. *Foot Ankle Int* 2004;25:833-839.
- 407 [5] Hertel J, Buckley W, Denegar C. Serial testing of postural control after acute lateral
408 ankle sprain. *J Athl Train* 2001;36:363-368.
- 409 [6] McCollum G, Shupert C, Nashner L. Organizing sensory information for postural
410 control in altered sensory environments. *J Theor Biol* 1996;180:257-270.
- 411 [7] Freeman MA. Instability of the foot after injuries to the lateral ligament of the ankle. *J*
412 *Bone Joint Surg Br* 1965;47:669-677.
- 413 [8] McKeon PO, Stein AJ, Ingersoll CD, Hertel J. Altered plantar-receptor stimulation
414 impairs postural control in those with chronic ankle instability. *J Sport Rehabil*
415 2012;21:1-6.
- 416 [9] Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries.
417 *British journal of sports medicine* 2005;39:e14; discussion e14.
- 418 [10] Konradsen L, Bech L, Ehrenbjerg M, Nickelsen T. Seven years follow-up after ankle
419 inversion trauma. *Scand J Med Sci Sports* 2002;12:129-135.

- 420 [11] Wikstrom EA, Fournier KA, McKeon PO. Postural control differs between those with
421 and without chronic ankle instability. *Gait Posture* 2010;32:82-86.
- 422 [12] Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA.
423 Discriminating between copers and people with chronic ankle instability. *J Athl Train*
424 2012;47:136-142.
- 425 [13] Brown CN, Padua DA, Marshall SW, Guskiewicz KM. Hip kinematics during a stop-
426 jump task in patients with chronic ankle instability. *J Athl Train* 2011;46:461-467.
- 427 [14] Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion
428 criteria when investigating insufficiencies in chronic ankle instability. *Med Sci Sports*
429 *Exerc* 2010;42:2106-2121.
- 430 [15] Wikstrom EA, Brown C. Minimum Reporting Standards for Copers in Chronic Ankle
431 Instability Research. *Sports Med* 2014;44:251-268.
- 432 [16] Bernstein N. *The Coordination and Regulation of Movements*. London: Pergamon;
433 1967.
- 434 [17] Huurnink A, Fransz D, Kingma I, Verhagen E, van Dieën J. Postural stability and
435 ankle sprain history in athletes compared to uninjured controls. *Clin Biomech*
436 (Bristol, Avon) 2014;29:183-188.
- 437 [18] Tropp H, Odenrick P. Postural control in single-limb stance. *J Orthop Res*
438 1988;6:833-839.
- 439 [19] Wheat J, Glazier P. *Movement system variability: Human kinetics*; 2005.
- 440 [20] Liu W, Santos MJ, McIntire K, Loudon J, Goist-Foley H, Horton G. Patterns of inter-
441 joint coordination during a single-limb standing. *Gait and Posture* 2012;36:614-618.
- 442 [21] Gribble P, Delahunt E, Bleakley C, Caulfield B, Docherty C, Fourchet F, et al.
443 Selection criteria for patients with chronic ankle instability in controlled research: a

- 444 position statement of the International Ankle Consortium. *The Journal of orthopaedic*
445 *and sports physical therapy* 2013;43:585-591.
- 446 [22] Kadaba M, Ramakrishnan H, Wootten M, Gainey J, Gorton G, Cochran G.
447 Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J*
448 *Orthop Res* 1989;7:849:860.
- 449 [23] Katz MJ, George EB. Fractals and the analysis of growth paths. *Bull Math Bio*
450 1985;47:273-286.
- 451 [24] Prieto T, Myklebust J, Hoffmann R, Lovett E, Myklebust B. Measures of postural
452 steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed*
453 *Eng* 1996;43:956-966.
- 454 [25] Carcia C, Martin R, Drouin J. Validity of the Foot and Ankle Ability Measure in
455 athletes with chronic ankle instability. *J Athl Train* 2008;43:179-183.
- 456 [26] Hiller C, Refshauge K, Bundy A, Herbert R, Kilbreath S. The Cumberland ankle
457 instability tool: a report of validity and reliability testing. *Arch Phys Med Rehabil*
458 2006;87:1235-1241.
- 459 [27] Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients with
460 chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon)*
461 2006;21:168-174.
- 462 [28] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB
463 recommendation on definitions of joint coordinate system of various joints for the
464 reporting of human joint motion—part I: ankle, hip, and spine. *Journal of*
465 *Biomechanics* 2002;35:543-548.
- 466 [29] Winter D. *Biomechanics and motor control of human movement*. 4th ed. Hoboken,
467 NJ: John Wiley and Sons; 2009.

- 468 [30] Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and
469 powerful approach to multiple testing. *Journal of the Royal Statistical Society*
470 1995;51:289–300.
- 471 [31] Nashner L, McCollum G. The organization of human postural movements: a formal
472 basis and experimental synthesis. *Behav. Brain Sci* 1985;8:135-172.
- 473 [32] Hwang S Fau - Tae K, Tae K Fau - Sohn R, Sohn R Fau - Kim J, Kim J Fau - Son J,
474 Son J Fau - Kim Y, Kim Y. The balance recovery mechanisms against unexpected
475 forward perturbation. *Ann Biomed Eng* 2009 37:1629-1637.
- 476 [33] Winter DA. Human balance and posture control during standing and walking. *Gait*
477 *and Posture* 1995;3:193-214.
- 478 [34] Fong CM, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion
479 range of motion and landing biomechanics. *J Athl Train* 2011;46:5-10.
- 480 [35] Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional
481 instability of the foot. *J Bone Joint Surg Br* 1965;47:678-685.
- 482 [36] Djupsjöbacka M. *Fundamentals of Musculoskeletal Pain*.2008.
- 483 [37] Cimolin V, Galli M, Rigoldi C, Grugni G, Vismara L, Mainardi L, et al. Fractal
484 dimension approach in postural control of subjects with Prader-Willi Syndrome. *J*
485 *Neuroeng Rehabil* 2011;20:8-45.
- 486 [38] Khin-Myo-Hla, Ishii T, Sakane M, Hayashi K. Effect of anesthesia of the sinus tarsi
487 on peroneal reaction time in patients with functional instability of the ankle. *Foot*
488 *Ankle Int* 1999;20:554-559.
- 489 [39] Wikstrom E, Naik S, Lodha N, Cauraugh J. Bilateral balance impairments after lateral
490 ankle trauma: a systematic review and meta-analysis. *Gait Posture* 2010;31:407-414.

491

492

493 Figure legends

494 Figure 1: Frontal plane ankle and hip motion recorded during unilateral stance with eyes
495 open. Eversion and adduction are positive; inversion and abduction are negative. Two curves
496 showed similar changes in the same direction (ACMD = 0.74).

497

Table 1

Table 1. Participant self-reported function and disability questionnaire scores [mean \pm SD] for the involved limb of LAS and control groups.

Group	CAIT (/30)	FAAMadl (%)	FAAMsport (%)
LAS	21.60 \pm 5.79 ^a	95.80 \pm 5.83 ^a	87.05 \pm 17.73 ^a
Control	30 \pm 0.00	100 \pm 0.00	100 \pm 0.00

LAS = lateral ankle sprain; FAAMadl = activities of daily living subscale of the Foot and Ankle Ability Measure; FAAMsport = sport subscale of the Foot and Ankle Ability Measure.

^a significantly different from control group;

Table 2

Table 2. Mean ACMD values with associated SDs and p-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open condition.

Joint pair		Eyes open														
		Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control		P-value	LAS		Control		P-value	LAS		Control		P-value
Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Involved	F/F	.22	.15	.15	.12	0.043	.21	.18	.14	.12	0.152	.20	.17	.15	.14	0.285
	F/S	.19	.15	.16	.12	0.390	.25	.22	.25	.23	0.984	.20	.17	.18	.14	0.601
	F/T	.26	.17	.21	.17	0.224	.21	.17	.16	.11	0.240	.18	.15	.12	.10	0.154
	S/F	.15	.14	.06	.04	0.000*	.21	.18	.12	.11	0.050	.20	.17	.15	.08	0.102
	S/S	.22	.17	.18	.14	0.311	.57	.23	.60	.22	0.590	.32	.22	.27	.16	0.338
	S/T	.14	.11	.09	.05	0.001*	.18	.14	.11	.10	0.058	.17	.14	.11	.08	0.085
	T/F	.33	.22	.33	.21	0.943	.24	.20	.28	.17	0.412	.24	.18	.26	.15	0.610
	T/S	.18	.13	.17	.13	0.691	.23	.18	.16	.13	0.091	.23	.17	.17	.15	0.151
	T/T	.42	.23	.41	.22	0.901	.39	.24	.41	.21	0.792	.28	.21	.27	.17	0.970
Uninvolved	F/F	.20	.13	.19	.15	0.664	.21	.21	.15	.13	0.209	.23	.16	.16	.13	0.093
	F/S	.18	.14	.25	.20	0.133	.23	.18	.22	.16	0.866	.16	.13	.20	.14	0.342
	F/T	.26	.18	.24	.17	0.652	.18	.15	.17	.13	0.793	.19	.14	.13	.09	0.076
	S/F	.15	.12	.11	.08	0.203	.15	.15	.19	.15	0.254	.19	.14	.20	.14	0.652
	S/S	.20	.15	.23	.12	0.460	.54	.23	.57	.23	0.699	.31	.20	.25	.16	0.204
	S/T	.15	.12	.13	.15	0.415	.11	.11	.16	.09	0.089	.20	.14	.14	.09	0.058
	T/F	.31	.22	.26	.16	0.218	.24	.19	.17	.14	0.119	.22	.17	.20	.20	0.606
	T/S	.15	.11	.16	.11	0.742	.19	.15	.23	.16	0.287	.13	.10	.16	.11	0.369
	T/T	.41	.22	.32	.23	0.105	.34	.22	.38	.29	0.598	.30	.21	.23	.19	0.140

*Denotes statistically significant between-groups difference; '/' denotes comparison between two joints/planes of motion. Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

Table 3

Table 3. Mean ACMD values with associated SDs and p-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-closed condition.

Joint pair		Eyes closed														
		Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control		P-value	LAS		Control		P-value	LAS		Control		P-value
Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Involved	F/F	.26	.19	.18	.12	0.135	.25	.22	.22	.22	0.657	.22	.21	.20	.15	0.750
	F/S	.23	.21	.12	.12	0.051	.25	.23	.19	.13	0.178	.18	.12	.13	.10	0.200
	F/T	.33	.18	.23	.12	0.067	.23	.17	.24	.24	0.853	.17	.15	.15	.13	0.676
	S/F	.15	.12	.08	.06	0.000*	.13	.12	.11	.09	0.557	.21	.21	.22	.19	0.856
	S/S	.26	.23	.24	.19	0.857	.56	.25	.45	.20	0.149	.39	.26	.33	.20	0.410
	S/T	.11	.12	.11	.08	0.970	.14	.16	.11	.12	0.437	.13	.17	.16	.09	0.521
	T/F	.43	.24	.36	.27	0.330	.29	.22	.25	.25	0.526	.24	.20	.36	.26	0.087
	T/S	.18	.18	.11	.10	0.094	.20	.20	.20	.12	0.881	.16	.18	.15	.15	0.797
	T/T	.45	.26	.42	.33	0.717	.39	.28	.36	.27	0.709	.33	.24	.31	.32	0.840
Uninvolved	F/F	.25	.17	.26	.19	0.798	.18	.17	.11	.13	0.089	.23	.22	.24	.18	0.946
	F/S	.20	.16	.16	.13	0.369	.25	.21	.18	.15	0.238	.20	.17	.19	.13	0.830
	F/T	.35	.17	.29	.16	0.190	.16	.15	.15	.15	0.700	.16	.13	.12	.10	0.200
	S/F	.09	.09	.08	.06	0.560	.14	.14	.11	.09	0.394	.20	.17	.19	.16	0.751
	S/S	.23	.20	.19	.19	0.495	.58	.24	.52	.22	0.373	.37	.26	.28	.22	0.199
	S/T	.15	.13	.09	.07	0.066	.14	.15	.08	.07	0.038	.15	.15	.11	.07	0.182
	T/F	.40	.28	.37	.23	0.672	.28	.21	.18	.16	0.102	.20	.18	.29	.20	0.092
	T/S	.14	.15	.16	.11	0.543	.17	.15	.16	.14	0.821	.14	.15	.14	.11	0.858
	T/T	.52	.24	.43	.25	0.245	.35	.21	.38	.25	0.707	.39	.24	.27	.20	0.075

*Denotes statistically significant between-groups difference; ‘/’ denotes comparison between two joints/planes of motion. Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.

Table 4

Table 4. Mean joint angular range values with associated SDs and p-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open and eyes-closed conditions. Values are reported in degrees.

		Eyes open														
		Hip					Knee					Ankle				
		LAS		Control		P-value	LAS		Control		P-value	LAS		Control		P-value
Mean	SD	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Involved	F	4.82	4.39	3.86	3.70	0.378	2.85	5.91	2.03	1.82	0.546	12.40	19.96	5.70	2.35	0.009
	S	5.01	5.15	3.27	2.69	0.150	7.41	9.55	5.27	3.01	0.327	5.57	6.95	4.17	2.66	0.384
	T	6.71	4.73	5.80	3.97	0.437	6.09	8.54	4.27	3.26	0.354	8.64	4.45	6.04	1.84	0.000*
Uninvolved	F	11.12	8.93	9.51	6.08	0.502	4.14	7.13	4.22	4.27	0.964	16.39	12.84	11.22	5.64	0.120
	S	9.32	7.42	10.13	9.36	0.732	11.25	8.75	9.69	6.28	0.513	8.13	4.57	6.63	3.36	0.232
	T	12.40	6.10	14.16	8.37	0.389	8.34	6.53	7.58	5.81	0.686	15.47	7.32	12.51	4.95	0.138
		Eyes closed														
Involved	F	5.07	4.37	3.24	1.64	0.007	2.51	3.18	2.11	1.77	0.594	16.63	45.30	8.70	11.73	0.442
	S	5.33	5.21	3.19	1.06	0.003*	8.44	11.18	5.93	2.88	0.104	11.28	44.56	4.30	2.43	0.487
	T	6.32	3.26	5.14	2.89	0.150	5.31	5.38	6.58	4.84	0.349	11.33	19.99	7.77	4.31	0.433
Uninvolved	F	10.49	8.80	10.98	12.82	0.871	3.73	4.28	3.35	3.61	0.762	25.45	56.52	21.01	21.10	0.770
	S	8.40	4.96	8.69	6.75	0.861	11.32	7.15	8.06	5.65	0.120	7.95	4.66	11.93	16.31	0.367
	T	11.27	5.25	11.95	7.19	0.702	6.80	3.76	14.13	20.42	0.188	14.50	7.16	18.44	14.13	0.318

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

Figure 1

