


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

Title	Lower extremity coordination and symmetry patterns during a drop vertical jump task following acute ankle sprain
Author(s)	Doherty, Cailbhe; Bleakley, Chris J.; Hertel, Jay; Sweeney, Kevin T.; Caulfield, Brian; Ryan, John; Delahunt, Eamonn
Publication date	2014-12
Publication information	Human Movement Science, 38 : 34-46
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/8438
Publisher's statement	This is the author's version of a work that was accepted for publication in Human Movement Science. 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 Human Movement Science (VOL 38, ISSUE 2014, (2014)) DOI: 10.1016/j.humov.2014.08.002.
Publisher's version (DOI)	http://dx.doi.org/10.1016/j.humov.2014.08.002

Downloaded 2017-10-19T01:48:46Z

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:** Acute ankle sprain alters lower extremity coordination and symmetry patterns during a
2 drop vertical jump task.

3 **Authors:**

4 Cailbhe Doherty¹

5 Chris Bleakley³

6 Jay Hertel⁴

7 Kevin Sweeney¹

8 Brian Caulfield¹

9 John Ryan⁵

10 Eamonn Delahunt^{1,2}

11 1. School of Public Health, Physiotherapy and Population Science, University College
12 Dublin, Dublin, Ireland.

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

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

16 4. Department of Kinesiology, University of Virginia, Charlottesville, VA, United
17 States.

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

19

20 **Address for Correspondence:**

21 Cailbhe Doherty

22 A101

23 School of Public Health, Physiotherapy and Population Science

24 University College Dublin

25 Health Sciences Centre

26 Belfield
27 Dublin 4
28 Ireland
29 Email: cailbhe.doherty@ucdconnect.ie
30 Telephone: 00 353 1 7166671
31 Fax: 00 353 1 716 6501

32

33 **Abstract**

34 **Purpose:** Evaluate the movement patterns associated with acute lateral ankle sprain (LAS)
35 injury using biomechanical analyses.

36 **Methods:** Thirty participants with acute LAS and nineteen control participants performed a
37 drop vertical jump (DVJ) task. 3D kinematics and sagittal plane kinetic profiles were plotted
38 for the hip, knee and ankle joints of both limbs for the drop jump (phase 1) and drop landing
39 (phase 2) phases of the DVJ. Inter-limb symmetry and the rate of force development (RFD)
40 during both phases of the DVJ were also determined.

41 **Results:** The LAS group displayed reduced ankle plantarflexion on their injured limb during
42 phase 2 of the DVJ, with greater associated inter-limb asymmetry for this movement
43 compared to control participants ($p < 0.05$). The LAS group also displayed altered kinetic
44 profiles, with increased inter-limb hip asymmetry, for both phases of the DVJ ($p < 0.05$). This
45 was associated with a decrease in the LAS participants' injured limb RFD during phase 2 of
46 the DVJ compared with that of controls ($8517.52 \pm 3012.41\text{N/sec}$ vs $10368.46 \pm$
47 2584.53N/sec ; $p = 0.04$, $\eta^2 = 0.09$).

48 **Conclusion:** acute ankle sprain injury manifests in potentially aberrant coordination
49 strategies as evidenced by an increased dependence on the non-injured limb.

50 **Key terms:** ankle joint [MEsH]; biomechanics [MEsH]; kinematics [MEsH]; kinetics
51 [MEsH]; Task Performance and Analysis [MEsH].

52

53

54

55

56 **1.0 Introduction.**

57 The use of the inverse dynamics method to predict internal moments of force in the lower
58 extremity from kinematic and force-plate data is widespread in experimental biomechanics
59 (Pandy & Andriacchi, 2010). A variety of screening tests have been developed using lower
60 extremity link-segment modelling and inverse dynamics to determine the movement patterns
61 that develop as a consequence of injury, as well as those which may precede injury. The drop
62 vertical jump (DVJ) is one such test that has been previously employed to quantify
63 anomalous movement patterns predictive (Paterno et al., 2010) and consequent (Delahunt et
64 al., 2012) of lower limb musculoskeletal injury. The DVJ requires a participant to drop off a
65 stationary platform, land on both feet, and immediately execute a maximal vertical jump. The
66 DVJ can be broken into two landing phases: the first phase follows the drop off the raised
67 platform and precedes the maximal vertical jump (drop jump); the second phase follows the
68 maximal vertical jump and completes the task (drop landing) (NA. Bates, KR. Ford, GD.
69 Myer, & TE. Hewett, 2013). The first and second phases of the DVJ elicit dichotomous
70 neuromechanical responses (Ambegaonkar, Shultz, & Perrin, 2011; NA. Bates, KR. Ford,
71 GD. Myer, & TE. Hewett, 2013; NA. Bates et al., 2013).

72 The DVJ recreates the limb-synchronous rebounding mechanics and associated injury
73 mechanisms typical of sports such as volleyball and basketball (KR. Ford, Myer, Schmitt,
74 Uhl, & Hewett, 2011). Ankle sprain injury is a significant injury risk for participants of these

75 sports (Doherty et al., 2014), secondary to the rapid impulse loads imparted bilaterally on
76 each lower extremity during landing manoeuvres. A network of static and dynamic restraints
77 control these impulse loads; the static stabilisers of the ankle joint (the lateral ligamentous
78 complex) ensure joint integrity with limited laxity (otherwise known as “static joint
79 stability”), while preparatory and reactive neuromuscular commands organise the motor
80 apparatus in such a way as to limit the rate of force development (RFD) in its component
81 parts (Wikstrom, Tillman, Chmielewski, & Borsa, 2006). These mechanisms combine as
82 “dynamic joint stability”, defined as the ability to maintain normal movement patterns while
83 performing high-level activities without ‘unwanted’ episodes of giving way (Lewek,
84 Chmielewski, Risberg, & Snyder-Mackler, 2003). Disequilibrium between adequate dynamic
85 joint stability and maximal movement efficiency in advanced skill (KR. Ford, van den
86 Bogert, Myer, Shapiro, & Hewett, 2008) is at the heart of a performance conflict which may
87 manifest in acute injury.

88 Acute injury can alter the sensorimotor system-controlled, dynamic restraining mechanisms
89 of the lower extremity in skilled movement (Wikstrom et al., 2006); dynamic restraining
90 mechanisms are then centred around minimising specific joint loading (Fleischmann,
91 Gehring, Mornieux, & Gollhofer, 2011), thus protecting against further injury. However, in
92 limb-synchronous movement tasks, such as the DVJ, these injury induced mechanisms may
93 distort the inter-limb symmetry necessary for the absorption of the forces associated with
94 explosive rebounding-based skills, therefore potentially placing the contralateral limb at
95 increased risk of trauma (Fousekis, Tsepis, & Vagenas, 2012).

96 The purpose of the current investigation was to evaluate the adaptive, lower-extremity
97 dynamic restraining movement preferences of the sensorimotor system in response to acute
98 lateral ankle sprain (LAS) injury using a 3-dimensional link segment model and the inverse
99 dynamics method. We compared a group with acute LAS to a non-injured control group

100 during the performance of the first and second phases of a DVJ task. Multiple hypotheses
101 were proposed for both the kinematic and kinetic data produced from this dataset: (i) acute
102 LAS would result in significant between group differences for temporal kinematic and kinetic
103 variables; (ii) these kinematic and kinetic variables would be contingent with offloading the
104 injured limb of LAS participants, manifesting in excessive inter-limb asymmetries and
105 potentially placing the non-injured limb at increased risk of injury; (iii) these motor control
106 patterns would be expressed in the RFD during the DVJ task.

107

108 **2.0 Methods**

109 *2.1 Participants*

110 Thirty injured participants (twenty-two males and eight females; age 23.2 ± 5.3 years; body
111 mass 74.1 ± 14.3 kg; height 1.75 ± 0.1 m) were recruited from a university-affiliated hospital
112 emergency department within 2 weeks of sustaining a first-time acute LAS for inclusion in
113 the current study. A group of nineteen control participants (fifteen males and four females;
114 age 22.5 ± 1.7 years; body mass 71.55 ± 11.30 kg; height 1.74 ± 0.1 m) were recruited from
115 the hospital catchment area using posters and flyers.

116 The following inclusion criteria were applied: 1) no previous history of ankle sprain injury
117 (excluding the recent acute episode for the injured group); 2) no other lower extremity injury
118 in the last 6 months; 3) no history of ankle fracture; 4) no previous history of major lower
119 limb surgery; 5) no history of neurological disease, vestibular or visual disturbance or any
120 other pathology that would impair their motor performance.

121

122 *2.2 Protocol*

123 Prior to testing, all participants completed the Cumberland Ankle Instability Tool (CAIT) and
124 the activities of daily living and sports subscales of the Foot and Ankle Ability Measure

125 (FAAMadl and FAAMsport) to assess overall ankle joint function(Hiller, Refshauge, Bundy,
126 Herbert, & Kilbreath, 2006) and patient reported functional ability(Carcia, Martin, & Drouin,
127 2008) respectively.

128 Participants wore athletic shorts and t-shirts and were instrumented with 22 infrared markers
129 as part of the Codamotion (CODA) bilateral lower limb gait set-up (Charnwood Dynamics
130 Ltd, Leicestershire, UK). Following the collection of the anthropometric measures required
131 for the calculation of internal joint centres at the hip, knee and ankle joints, lower limb
132 markers and wands were attached as described by Monaghan et al.(Monaghan, Delahunt, &
133 Caulfield, 2006, 2007). For each subject an initial neutral stance trial was acquired to
134 function as a reference position for kinematic analyses and to align the subject with the
135 laboratory coordinate system as recommended in previously published literature(McLean et
136 al., 2007).

137 The DVJ protocol began with each participant standing on top of a 40 cm platform and
138 instructed to keep their feet positioned ‘shoulder width’ apart with their hands on their hips.
139 Participants were then instructed to drop straight down from the raised platform without any
140 vertical launch and land on both feet simultaneously (phase 1), and immediately execute a
141 maximal vertical jump upon contact with the force plates (phase 2). No specific instructions
142 were provided for the execution of either the first or the second landing. A trial was repeated
143 if participants performed a vertical launch when dropping off the platform, if one or both of
144 their feet did not land on separate force plates, if their hands came off their hips, or if they
145 lost balance during the test(Hewett et al., 2005).

146 These testing procedures were approved by the institution’s ethical review board and
147 informed written consent was obtained from each participant prior to involvement in study
148 protocol.

149

150 *2.3 Data processing and analysis*

151 Kinematic data were acquired at 250 Hz using three Codamotion cx1units (Charnwood
152 Dynamics Ltd, Leicestershire, UK) while the kinetic data was acquired at 1000 Hz using two
153 fully integrated AMTI (Watertown, MA) walkway embedded force-plates for each limb
154 during performance of the DVJ. The CODA mpx1 units were time synchronized with the
155 force-plates. Ground reaction force data were passed through a fourth-order zero phase
156 Butterworth low-pass digital filter with a 5-Hz cut-off frequency.

157 Kinematic and kinetic data for both limbs were analysed using the Codamotion software (x-
158 axis = frontal-plane motion; y-axis = sagittal-plane motion; z-axis = transverse-plane motion)
159 and then converted to Microsoft Excel file format. The number of output samples for
160 temporal kinematic and kinetic data was set at 100 + 1 per DVJ phase in the data-export
161 option of the Codamotion software, which represented 100% of the DVJ phase for averaging
162 and further analysis.

163 Time-averaged profiles were calculated for the hip, knee and ankle joints for each participant,
164 with a subsequent calculation of group mean profiles. All time-averaged profiles were plotted
165 during the period from 200-ms pre-initial contact (IC) to 200-ms post-IC for the first and
166 second phases of the DVJ for each limb. The temporal kinematic variables of interest were 3-
167 dimensional hip, knee and ankle angular displacements. Angular displacement profiles were
168 constructed by comparing the angular orientations of the coordinate systems of adjacent limb
169 segments using the coupling set “Euler angles” to represent clinical rotations in three
170 dimensions. The marker positions were processed within a Cartesian frame into rotation
171 angles using vector algebra and trigonometry (Codamotion User Guide, Charnwood
172 Dynamics Ltd, Leicestershire, UK).

173 The temporal kinetic variables of interest were sagittal plane hip, knee, ankle and net lower
174 extremity supporting moments. The supporting moment, M_s , during landing was calculated
175 as follows: $M_s = M_k - M_a - M_h$, where M_k , M_a and M_h are the sagittal plane moments at the
176 knee, ankle and hip respectively (Winter, 1980). Positive M_s values are associated with
177 extensor moments as they are believed to prevent collapse while negative values are
178 associated with flexor moments as they are believed to facilitate collapse (Kepple, Siegle, &
179 Stanhope, 1997). All moments were reported as external joint moments derived from the
180 GRFs created during contact with the force platforms.

181 The discrete kinetic variable of interest was the RFD of the vertical GRF for each limb and
182 was calculated as the peak vertical GRF divided by the time from IC to peak vertical GRF
183 (Decker, Torry, Noonan, Riviere, & Sterett, 2002) separately for the first and second phases
184 of the DVJ (N/sec).

185 Symmetry between temporal waveform data (angular displacement and moment profiles) was
186 analysed using an eigenvector approach. The measure of trend symmetry (TS) was calculated
187 to compare the time-normalised data for right and left limbs separately during phase 1 and
188 phase 2 of the DVJ for the LAS and control groups as per previous research (Crenshaw &
189 Richards, 2006). The output of the TS calculation is a percentage value, where 0% indicates
190 perfect symmetry between the two waveforms. TS was performed using a sliding window
191 approach, whereby data samples were analysed for symmetry sequentially in groups of 50
192 samples with a window overlap of 50%. This resulted in three separate TS windows to assess
193 the preparatory (Santello, 2005; Stelmach, 1976) and reactive (Lees, 1977, 1981) activities of
194 each landing event, in addition to IC; window 1 analysed from 200ms pre-IC to IC, window 2
195 analysed from 100ms pre-IC to 100ms post-IC and window 3 analysed from IC to 200ms
196 post IC (figure 1).

197 A symmetry angle (SA) calculation (Zifchock, Davis, Higginson, & Royer, 2008) was
198 utilised to evaluate the inter limb RFD symmetry for each individual subject over each phase
199 of the DVJ, with a subsequent calculation of group means (LAS *vs* control). A SA value of
200 0% between matched data points indicates perfect symmetry, while 100% indicates that the
201 two values are equal and opposite in magnitude (Zifchock et al., 2008).

202

203 *2.4 Statistical analysis*

204 The average of each subjects' three trials for all variables was utilized for further analysis
205 (i.e. LAS *vs* control). For the LAS group, limbs were labelled as “involved” and
206 “uninvolved” based on FAAM and CAIT results. For all outcomes, the mean and standard
207 deviation (SD) scores for the involved and uninvolved limbs in the LAS group, and the left
208 and right limbs in the control group were calculated. In all cases, the involved (injured) limb
209 was compared to side-matched limbs in the control group, such that an equal proportion of
210 right and left limbs were labelled as “involved” and “uninvolved” in each group.

211 Participant characteristics were compared between the LAS and control groups using
212 multivariate analysis of variance. The dependent variables were age, mass, sex and height.
213 The independent variable was group (LAS *vs* control).

214 In order to test the hypothesis that acute LAS would cause between-group kinematic and
215 kinetic differences for each limb, during both the first and second phases of the DVJ, two
216 separate analyses were performed: (i) A series of independent samples t-tests for each data
217 point of the time-averaged group 3 dimensional angular displacement and sagittal plane
218 supporting moment profiles. The significance level for these analyses was set a priori at $p <$
219 0.05. (ii) Independent samples t-tests for group (LAS *vs* control) RFD mean profiles for each
220 phase of the DVJ for each limb. The significance level for this analysis was set a priori at $p <$
221 0.05.

222 In order to test the hypothesis that acute LAS would cause an increase in inter-limb
223 asymmetries in the LAS group compared to the control group, a further two analyses were
224 performed: (i) Independent samples t-tests for group (LAS vs control) TS windows for those
225 temporal kinematic and kinetic data with significant between-group differences. The
226 significance level for these analyses was set a priori at $p < 0.05$. (ii) Independent samples t-
227 tests for group (LAS vs control) RFD SA profiles for each phase of the DVJ for each limb.
228 The significance level for temporal analyses was set a priori at $p < 0.05$. Effect sizes were not
229 calculated for temporal data analyses secondary to the number of separate comparisons for
230 each kinematic and kinetic variable. All data were analyzed using Predictive Analytics
231 Software (Version 18, SPSS Inc., Chicago, IL, USA).

232

233 **3.0 Results**

234 There was no statistically significant difference between the LAS group and the control
235 subject group on the combined dependent variables of age, sex height and body mass: $F(4,$
236 $44) = 0.44$, $p = 0.78$; Wilk's Lambda = 0.96; partial eta squared = 0.04. Questionnaire results
237 and participant characteristics are detailed in table 1.

238

239 *3.1 Kinematic and kinetic analyses*

240 (i) Time-averaged 3-dimensional kinematic profiles revealed that the LAS group displayed
241 no difference in 3D angular displacement for the hip, knee or ankle for phase 1 of the DVJ
242 compared to the control group. During phase 2 of the DVJ, LAS participants displayed
243 reduced plantarflexion on their involved limb compared to control participants (figure 2).
244 Time-averaged sagittal plane kinetic profiles revealed that the LAS group displayed
245 statistically significant differences in hip, knee, ankle and net supporting moment profiles for
246 the first and second phases of the DVJ compared to the control group. Between-group

247 differences in temporal kinetic profiles for phase 1 and phase 2 of the DVJ are presented in
248 figure 3.

249 (ii) There was no significant difference in RFD between LAS and control participants of the
250 DVJ for phase 1: Involved limb; LAS: $8090.38 \pm 3807.43\text{N/sec}$ vs control: $9616.79 \pm$
251 3592.99N/sec ; $t(43) = -1.252$, $p = 0.217$, $\eta^2 = 0.04$, two tailed; Uninvolved limb; LAS:
252 $10676.07 \pm 4284.08\text{N/sec}$ vs control: 9562.72 ± 4770.89 ; $t(43) = 0.79$, $p = 0.45$, $\eta^2 = 0.01$,
253 two tailed; however, during phase 2, LAS participants exhibited a significant reduction in
254 RFD on their involved limb only: Involved limb; LAS: $8517.52 \pm 3012.41\text{N/sec}$ vs control:
255 $10368.46 \pm 2584.53\text{N/sec}$; $t(43) = -2.032$, $p = 0.04$, $\eta^2 = 0.09$, two tailed; uninvolved
256 limb; LAS: $9822.88 \pm 3358.97\text{N/sec}$ vs control: $10732.31 \pm 3055.62\text{N/sec}$; $t(43) = -0.881$, $p =$
257 0.38 , $\eta^2 = 0.02$, two tailed.

258

259 *3.2 Symmetry analyses*

260 (i) TS analyses of kinematic data revealed that the LAS group displayed significantly greater
261 inter-limb asymmetry in the second window (from 100ms pre-IC to 100ms post-IC)
262 compared to the control group for angular displacement of the ankle joint in the sagittal plane
263 in phase 2 of the DVJ. TS analyses of kinetic data revealed that the LAS group displayed
264 significantly greater inter-limb asymmetry in the third window (from IC to 200ms post-IC)
265 compared to the control group for hip moment of force in phases 1 and 2 of the DVJ. TS
266 values for all significantly different temporal kinematic and kinetic data between LAS and
267 control groups are detailed in table 2.

268 (ii) There was a significant difference in inter-limb RFD symmetry between LAS and control
269 groups. LAS participants displayed increased RFD asymmetry compared to control
270 participants during the DVJ phase 1 ($15.02 \pm 13.09\%$ vs $5.76 \pm 4.16\%$; $t(38.63) = 3.53$, $p =$

271 0.001, two-tailed), and phase 2 ($10.62 \pm 8.64\%$ vs $4.35 \pm 3.49\%$; $t(41.78) = 3.45$, $p = 0.001$,
272 two-tailed) of the DVJ.

273 The magnitude of the differences in the means was large for both phase 1 (mean difference =
274 9.25, 95% CI: 3.95 to 14.55, eta squared = 0.25) and for phase 2 (mean difference = 6.26,
275 95% CI: 2.60 to 9.93, eta squared = 0.23).

276

277 **4.0 Discussion**

278 Temporal kinematic and kinetic data for the current investigation were acquired in the time
279 period from 200ms pre IC to 200ms post IC in the aim of capturing the important features of
280 landing (Lees, 1981): the preparatory (pre-IC) action of the neuromuscular ‘motor
281 programme’ which commences in the airborne phase of landing and endures IC (Santello,
282 2005; Stelmach, 1976), and the reactive (post-IC) ‘impact absorption’ phase of landing in
283 which acceleration is controlled (Lees, 1977, 1981).

284 The kinetic profiles, specifically those examining the total motor pattern of the lower
285 extremity (i.e. the support moment), are critical to understanding the energetics of the LAS
286 participants’ adapted neuromuscular command strategies (Winter, 1993) in response to the
287 significant functional impairment (based on the FAAM and CAIT questionnaire results).

288 During IC of phase 1, LAS participants displayed a small but significant reduction in the net
289 flexor moment compared to control participants on their involved limb (≈ -0.17 vs ≈ -0.36
290 Nm/kg) from 12 ms pre-IC to 8 ms post-IC. This pattern was repeated during impact
291 absorption phase of landing (from 32 to 52 ms post-IC), where LAS participants again
292 displayed a reduction in the net flexor pattern of the lower extremity compared to control
293 participants on their involved limb (≈ -0.61 vs ≈ -1.06 Nm/kg). These results indicate that
294 acute LAS may have resulted in a smaller ratio of net supporting flexion to extension
295 moments (caused by increased extension dominance compared to control participants) on the

296 involved limb during the drop jump component of the DVJ. Impact absorption at landing for
297 the drop jump component of the DVJ serves two functions: to decelerate the body in a
298 controlled pattern so as to optimise joint loading and to reproduce as much of the potential
299 energy associated with the land in the performance of a maximal vertical jump. While we
300 didn't analyse measures of performance such as DVJ jump height or power, the reduced net
301 flexor pattern of LAS participants in phase 1 of the DVJ could indicate a hesitancy to seek
302 achieving maximal performance during the DVJ in the interest of injury protection.

303 The primary focus of impact absorption at landing for the drop land component of the DVJ is
304 the controlled dissipation of landing forces in the completion of the prescribed movement
305 (DeVita & Skelly, 1992). Reflection of the net extensor pattern for phase 2 of the DVJ may
306 indicate decreased capacity of the LAS group to control dissipation in symmetry due to the
307 higher extensor pattern on the uninvolved limb, potentially indicating a compensatory role of
308 the uninvolved limb in unloading the involved limb.

309 This theory is supported by analysis of specific joint extensor patterns: kinetics at the knee
310 joint revealed significant between-group differences on the involved limb always preceding
311 those of the uninvolved limb, and a contrast in the magnitude of the extensor pattern on the
312 involved limb and the uninvolved limb compared to controls. During phase 1 of the DVJ on
313 the involved limb, the LAS group had a reduction in the knee extensor moment compared to
314 controls (≈ 0.68 vs ≈ 1.17 Nm/kg) from 64 to 92 ms post-IC. This was followed by a pattern
315 of increased extensor moment on the uninvolved limb of LAS participants compared to
316 controls (≈ 1.94 vs ≈ -1.33 Nm/kg), from 188 to 200 ms post-IC. A similar trend was
317 observed during phase 2 of the DVJ, where a reduction in involved limb knee extensor
318 moment in LAS participants compared to control participants (≈ 0.70 vs ≈ 1.70 Nm/kg) from
319 56 to 184 ms post-IC preceded an increase in uninvolved limb knee extensor moment
320 compared to control participants (≈ 1.49 vs ≈ 1.06 Nm/kg) from 164 to 196 ms post-IC. This

321 pattern of re-weighting the motor apparatus from the involved to the uninvolved limb is also
322 evident at the kinetic profile for the ankle joint, where during phase 1 of the DVJ, LAS
323 participants exhibited a reduced extensor moment pattern from 4 ms pre-IC to 108ms post-IC
324 compared to control participants on their involved limb (≈ 0.86 vs ≈ 1.30 Nm/kg) and an
325 increased extensor moment pattern from 24 ms to 92 ms post-IC compared to control
326 participants on their uninvolved limb (≈ 1.62 vs ≈ 1.20 Nm/kg). During phase 2 of the DVJ
327 this pattern was not replicated, as LAS participants only displayed a reduced extensor
328 moment on their involved limb compared to control participants from 36 to 40 ms post-IC (\approx
329 0.13 vs ≈ 0.33 Nm/kg); although LAS participants displayed a preparatory reduction in
330 involved limb ankle plantarflexion (from 200 ms pre-IC to 40 ms post-IC), there was no
331 between-groups difference in uninvolved limb extensor pattern at the ankle for phase 2 of the
332 DVJ. The decrease in ankle plantarflexion positioning observed in the acutely injured group
333 concurs with the movement patterns observed in the same task in groups of participants in the
334 chronic phase of ankle sprain injury (Brown, Padua, Marshall, & Guskiewicz, 2008), and
335 may serve to decrease the risk of re-sprain by increasing bony reliance in place of the static
336 stabilisers of the ankle joint (Brown et al., 2008; Wright, Neptune, van den Bogert, & Nigg,
337 2000). That this observation was only present during phase 2 may be the result of better task
338 sensitivity afforded by the greater impact absorption demands of the second phase of the DVJ
339 compared to those of the first (NA. Bates et al., 2013). Alternatively, as technique
340 instructions focused each participant on the body mechanics during the first landing and the
341 goal of achieving a maximal vertical jump subsequently diverted this attention in the second
342 landing (NA. Bates et al., 2013), it is possible that LAS participants naturally sought to
343 offload their injured limb when concentrating on the mechanics of the second landing
344 component only.

345 It is significant that the trend of altered motor control patterns presenting on the involved
346 limb prior to the uninvolved limb for the knee and ankle persisted throughout all temporal
347 experimental data for both phases of the DVJ. This may indicate that the joint forces
348 experienced by the involved limb are dampened by sequentially increasing the joint forces on
349 the uninvolved limb. This theory is also consistent with the discrete kinetic symmetry
350 analyses, with LAS participants displaying 15% RFD asymmetry for phase 1 of the DVJ
351 (compared to 6% in controls), and 11% RFD asymmetry for phase 2 of the DVJ (compared to
352 4% in controls). The source of this discrete asymmetry can easily be postulated on inspection
353 of the RFD data, with LAS participants' involved limb displaying a reduction in the RFD
354 relative to their uninvolved limb for both phases, which was significant with a moderate
355 effect size on the involved limb during phase 2. Dissipation of the vertical GRF of landing
356 over a longer time period with an appropriate neuromuscular command resulting in reduced
357 RFD serves to reduce the exposure of the injured limb to excessive landing forces (DeVita &
358 Skelly, 1992). The disadvantage of this asymmetry is that there is increased exposure on the
359 uninvolved limb.

360 Asymmetry is also evident in the third window (from IC to 200 ms post-IC) of the hip
361 moment of force profiles for both phase 1 and phase 2 of the DVJ. The hip joint plays a
362 central role in unloading the injured joints of the lower extremity due to the mechanical
363 advantage of its surrounding musculature (Alexander & Ker, 1990), and has previously been
364 shown to have a primary role in the dissipation of impact forces (DeVita & Skelly, 1992;
365 Dufek & Bates, 1990; Zhang, Bates, & Dufek, 2000). The observed asymmetry may have
366 arisen secondary to a neuromuscular overload with a performance conflict between needing
367 to specifically unload the acutely injured ankle joint, globally dissipate impact forces and
368 maintain control between the lower extremity and the head, arms and trunk (Winter, 1993),
369 thus becoming victim to the attempted mastery of the degrees of freedom coordination

370 problem of the motor apparatus (Bernstein, 1967). This conflict is particularly evident in the
371 involved limb angular displacement and increased trend asymmetry at the ankle joint for LAS
372 participants, and in comparing LAS and control participants' hip kinetics during phase 2 of
373 the DVJ; preparatory action of the involved limb precedes a more reactive strategy of the
374 uninvolved limb and the inter-limb post-IC landing strategy is out of sync for LAS
375 participants.

376 The clinical relevance of these findings is twofold: first, clinicians must be aware that acute
377 ankle sprain injury has the capacity to cause bilateral impairment, and potentially increase the
378 risk of injury to the non-injured limb secondary to the asymmetry created by its
379 compensatory role in protecting the injured joint. Second, acute ankle sprain injury manifests
380 in neuromuscular control strategies with similar features to those noted in populations in the
381 chronic phase of injury. The persistence of these strategies may underlie the onset of
382 chronicity and therefore patients must only be allowed to return to activity having completed
383 rehabilitation exercises to self-reported pre-injury levels.

384

385 **Acknowledgements**

386 This study was supported by the Health Research Board (HRA_POR/2011/46). There were
387 no conflicts of interest to report.

388

389

390

391

392

393

394

395
396
397
398
399
400
401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418

5.0 References

- Alexander, R., & Ker, R. (1990). *The architecture of the muscles*. In: *Multiple Muscle Systems: Biomechanics and Movement Organization* (J. M. W. a. S. L. Woo Ed.). New York: Springer-Verlag.
- Ambegaonkar, J., Shultz, S., & Perrin, D. (2011). A subsequent movement alters lower extremity muscle activity and kinetics in drop jumps vs. drop landings. *J Strength Cond Res*, 25(10), 2781-2788.
- Bates, N., Ford, K., Myer, G., & Hewett, T. (2013). Kinetic and kinematic differences between first and second landings of a drop vertical jump task: Implications for injury risk assessments. *Clinical Biomechanics*.
- Bates, N., Ford, K., Myer, G., & Hewett, T. (2013). Timing differences in the generation of ground reaction forces between the initial and secondary landing phases of the drop vertical jump. *Clin Biomech (Bristol, Avon)*, 28(7), 796-799.
- Bernstein, N. (1967). *The Coordination and Regulation of Movements*. London: Pergamon.
- Brown, C., Padua, C., Marshall, D., & Guskiewicz, K. (2008). Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech (Bristol, Avon)*, 23(6), 822-831. doi: 10.1016/j.clinbiomech.2008.02.013
- Carcia, C., Martin, R., & Drouin, J. (2008). Validity of the Foot and Ankle Ability Measure in athletes with chronic ankle instability. *J Athl Train*, 43(2), 179-183. doi: 10.4085/1062-6050-43.2.179

419 Crenshaw, S., & Richards, J. (2006). A method for analyzing joint symmetry and normalcy,
420 with an application to analyzing gait. *Gait Posture*, 24(4), 515-521.

421 Decker, M., Torry, M., Noonan, T., Riviere, A., & Sterett, W. (2002). Landing adaptations
422 after ACL reconstruction. *Medicine and Science in Sports and Exercise*, 34(9), 1408-
423 1413.

424 Delahunt, E., Sweeney, L., Chawke, M., Kelleher, J., Murphy, K., Patterson, M., &
425 Prendiville, A. (2012). Lower limb kinematic alterations during drop vertical jumps in
426 female athletes who have undergone anterior cruciate ligament reconstruction.
427 *Journal of Orthopaedic Research*, 30(1), 72-78.

428 DeVita, P., & Skelly, W. (1992). Effect of landing stiffness on joint kinetics and energetics in
429 the lower extremity. *Medicine and Science in Sports and Exercise*, 24(1), 108-115.

430 Doherty, C., Delahunt, E., Caulfield, B., Hertel, J., Ryan, J., & Bleakley, C. (2014). The
431 Incidence and Prevalence of Ankle Sprain Injury: A Systematic Review and Meta-
432 Analysis of Prospective Epidemiological Studies. *Sports Med*, 44 (1) 123-140

433 Dufek, J., & Bates, B. (1990). Regression models for predicting impact forces and knee joint
434 moments and power during landings. *Proc. CSB*, 55-56.

435 Fleischmann, J., Gehring, D., Mornieux, G., & Gollhofer, A. (2011). Task-specific initial
436 impact phase adjustments in lateral jumps and lateral landings. *Eur J Appl Physiol.*,
437 111(9), 2327-2337.

438 Ford, K., Myer, G., Schmitt, L., Uhl, T., & Hewett, T. (2011). Preferential quadriceps
439 activation in female athletes with incremental increases in landing intensity. *Journal*
440 *of Applied Biomechanics*, 27(3), 215-222.

441 Ford, K., van den Bogert, J., Myer, G., Shapiro, R., & Hewett, T. (2008). The effects of age
442 and skill level on knee musculature co-contraction during functional activities: a
443 systematic review. *Br J Sports Med.*, 42(7), 561-566.

444 Fousekis, K., Tsepis, E., & Vagenas, G. (2012). Intrinsic Risk Factors of Noncontact Ankle
445 Sprains in Soccer: A Prospective Study on 100 Professional Players. *Am J Sports*
446 *Med.* doi: 10.1177/0363546512449602

447 Hewett, T., Myer, G., Ford, K., Heidt Jr, R., Colosimo, A., McLean, S., . . . Succop, P.
448 (2005). Biomechanical measures of neuromuscular control and valgus loading of the
449 knee predict anterior cruciate ligament injury risk in female athletes: A prospective
450 study. *Am J Sports Med*, 33(4), 492-501.

451 Hiller, C., Refshauge, K., Bundy, A., Herbert, R., & Kilbreath, S. (2006). The Cumberland
452 ankle instability tool: a report of validity and reliability testing. *Arch Phys Med*
453 *Rehabil*, 87(9), 1235-1241. doi: 10.1016/j.apmr.2006.05.022

454 Kepple, T., Siegle, K., & Stanhope, S. (1997). Relative contributions of the lower extremity
455 joint moments to forward progression and support during gait. *Gait Posture*, 6, 1-8.

456 Lees. (1977). *A biomechanical analysis of the movement patterns associated with selected*
457 *static and dynamic balance activities.* . (Doctoral thesis), University of Leeds.

458 Lees. (1981). Methods of impact absorption when landing from a jump. *Eng. Med.*, 10, 204-
459 211.

460 Lewek, M., Chmielewski, T., Risberg, M., & Snyder-Mackler, L. (2003). Dynamic knee
461 stability after anterior cruciate ligament rupture. *Exerc Sport Sci Rev*, 31(4), 195-200.

462 McLean, S., Fellin, R., Suedekum, N., Calabrese, G., Passerallo, A., & Joy, S. (2007). Impact
463 of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc.*, 39(3),
464 502-514.

465 Monaghan, K., Delahunt, E., & Caulfield, B. (2006). Ankle function during gait in patients
466 with chronic ankle instability compared to controls. *Clin Biomech (Bristol, Avon)*,
467 21(2), 168-174. doi: 10.1016/j.clinbiomech.2005.09.004

468 Monaghan, K., Delahunt, E., & Caulfield, B. (2007). Increasing the number of gait trial
469 recordings maximises intra-rater reliability of the CODA motion analysis system.
470 *Gait Posture*, 25(2), 303-315. doi: 10.1016/j.gaitpost.2006.04.011

471 Pandy, M., & Andriacchi, T. (2010). Muscle and joint function in human locomotion. *Annu*
472 *Rev Biomed Eng*, 15(12), 401-433.

473 Paterno, M., Schmitt, L., Ford, K., Rauh, M., Myer, G., Huang, B., & Hewett, T. (2010).
474 Biomechanical measures during landing and postural stability predict second anterior
475 cruciate ligament injury after anterior cruciate ligament reconstruction and return to
476 sport. *Am J Sports Med.*, 38(10), 1968-1978.

477 Santello, M. (2005). Review of motor control mechanisms underlying impact absorption from
478 falls. *Gait and Posture*, 21(1), 85-94.

479 Stelmach, G. (1976). *Motor control: issues and trends*: Academic Press.

480 Wikstrom, E., Tillman, M., Chmielewski, T., & Borsa, P. (2006). Measurement and
481 evaluation of dynamic joint stability of the knee and ankle after injury. *Sports Med*,
482 36(5), 393-410.

483 Winter, D. (1980). Overall principle of lower limb support during stance phase of gait. *J*
484 *Biomech*, 13(11), 923-927.

485 Winter, D. (1993). Knowledge base for diagnostic gait assessments. *Med Prog Technol*,
486 19(2), 61-81.

487 Wright, I., Neptune, R., van den Bogert, A., & Nigg, B. (2000). The influence of foot
488 positioning on ankle sprains. *J Biomech*, 33(5), 513-519.

489 Zhang, S., Bates, B., & Dufek, J. (2000). Contributions of lower extremity joints to energy
490 dissipation during landings. *Medicine and Science in Sports and Exercise*, 32(4), 812-
491 819.

492 Zifchock, R., Davis, I., Higginson, J., & Royer, T. (2008). The symmetry angle: a novel,
493 robust method of quantifying asymmetry. *Gait Posture*, 27(4), 622-627.

494

495

496

497

498

499

500

501

502

503

504

505

506

507

508

509

510

511 Figure legends

512 Figure 1. Illustrative depiction of a link segment model completing window 1 (200ms pre-IC
513 to IC), window 2 (100ms pre-IC to 100ms post-IC) and window 3 (IC to 200ms post-IC) of
514 phase 1 and phase 2 of the DVJ used for the calculation of lower extremity inter-limb trend
515 symmetry. Abbreviations: IC = initial contact; DVJ = drop vertical jump; GRF = ground
516 reaction force.

517

518 Figure 2. Ankle joint plantarflexion-dorsiflexion angle during performance of phase 2 of the
519 DVJ task from 200ms pre-IC to 200ms post-IC for the involved and uninvolved limbs of the
520 LAS and control groups. Dorsiflexion is positive; plantarflexion is negative. Black line with
521 arrow = initial contact. Dashed lines = LAS group; continuous lines = control group; black
522 lines = involved limb; grey lines = uninvolved limb. Bold abscissa axis indicates area of
523 statistically significant greater trend asymmetry for the LAS group. Shaded area enclosed by
524 black line = statistically significant between groups difference for the involved limb.

525 Abbreviations: IC = initial contact; DVJ = drop vertical jump; LAS = lateral ankle sprain.

526

527 Figure 3. Sagittal plane joint moment-of-force profiles for the hip, knee and ankle during
528 performance of phase 1 and phase 2 of the DVJ task from 200ms pre-IC to 200ms post-IC for
529 the involved and uninvolved limbs of the LAS and control groups. Extension moments are
530 positive; flexion moments are negative. Black line with arrow = initial contact. Dashed lines
531 = LAS group; continuous lines = control group; black lines = involved limb; grey lines =
532 uninvolved limb. Bold abscissa axis indicates area of statistically significant greater trend
533 asymmetry for the LAS group. Shaded area enclosed by black line = area of statistically
534 significant between groups difference for the involved limb. Shaded area enclosed by grey
535 line = area of statistically significant between groups difference for the uninvolved limb.

536 Abbreviations: Mh = Hip moment; Mk = Knee Moment; Ma = Ankle moment; Ms = Support
537 moment (Mk-Mh-Ma); IC = initial contact; DVJ = drop vertical jump; LAS = lateral ankle
538 sprain.

539

540

541

Figure 1

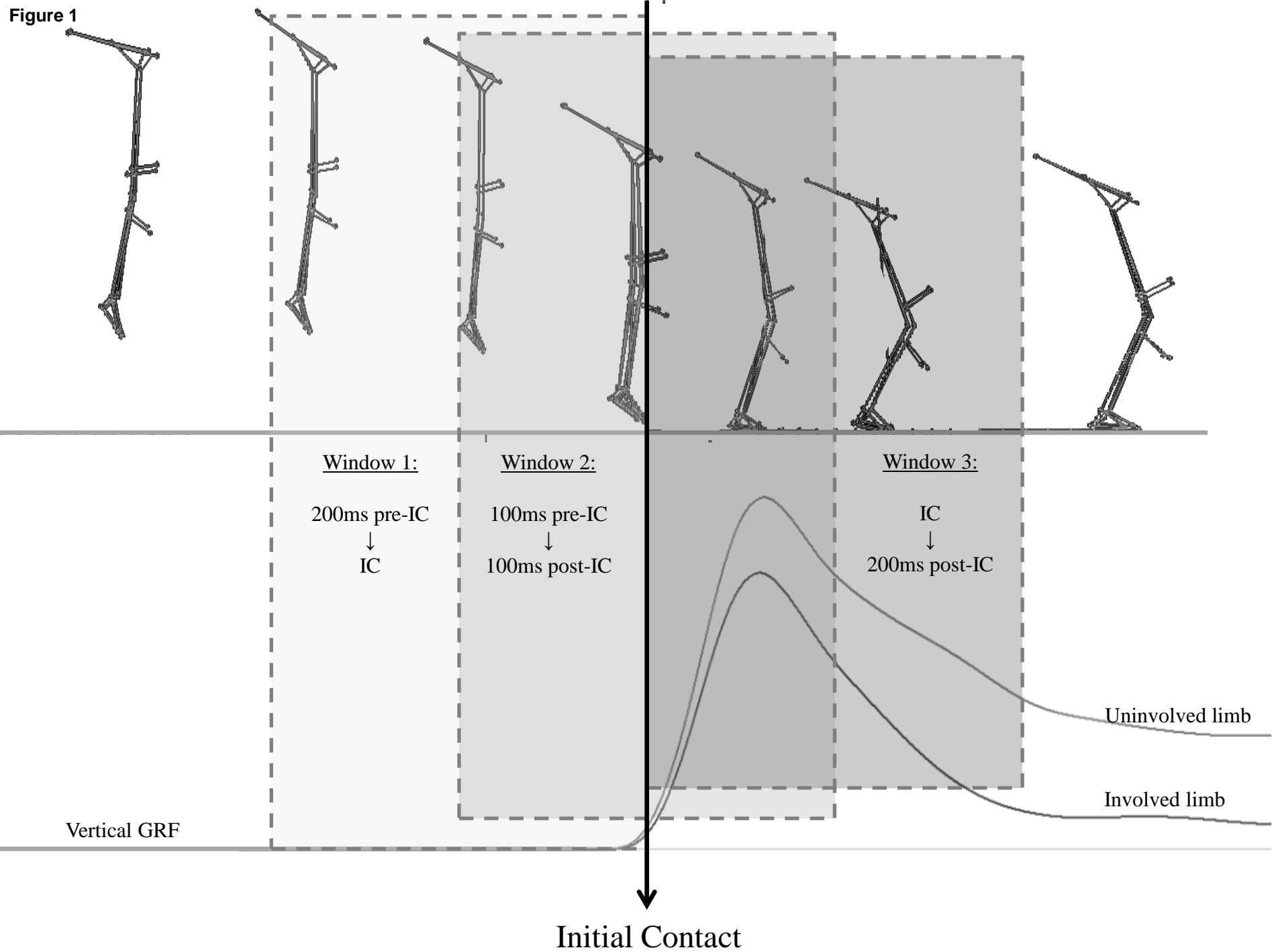


Figure 2

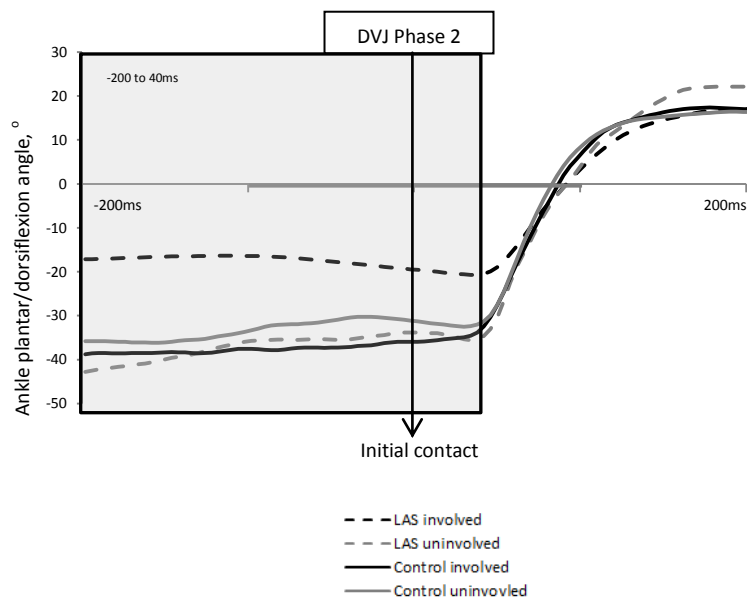


Figure 3

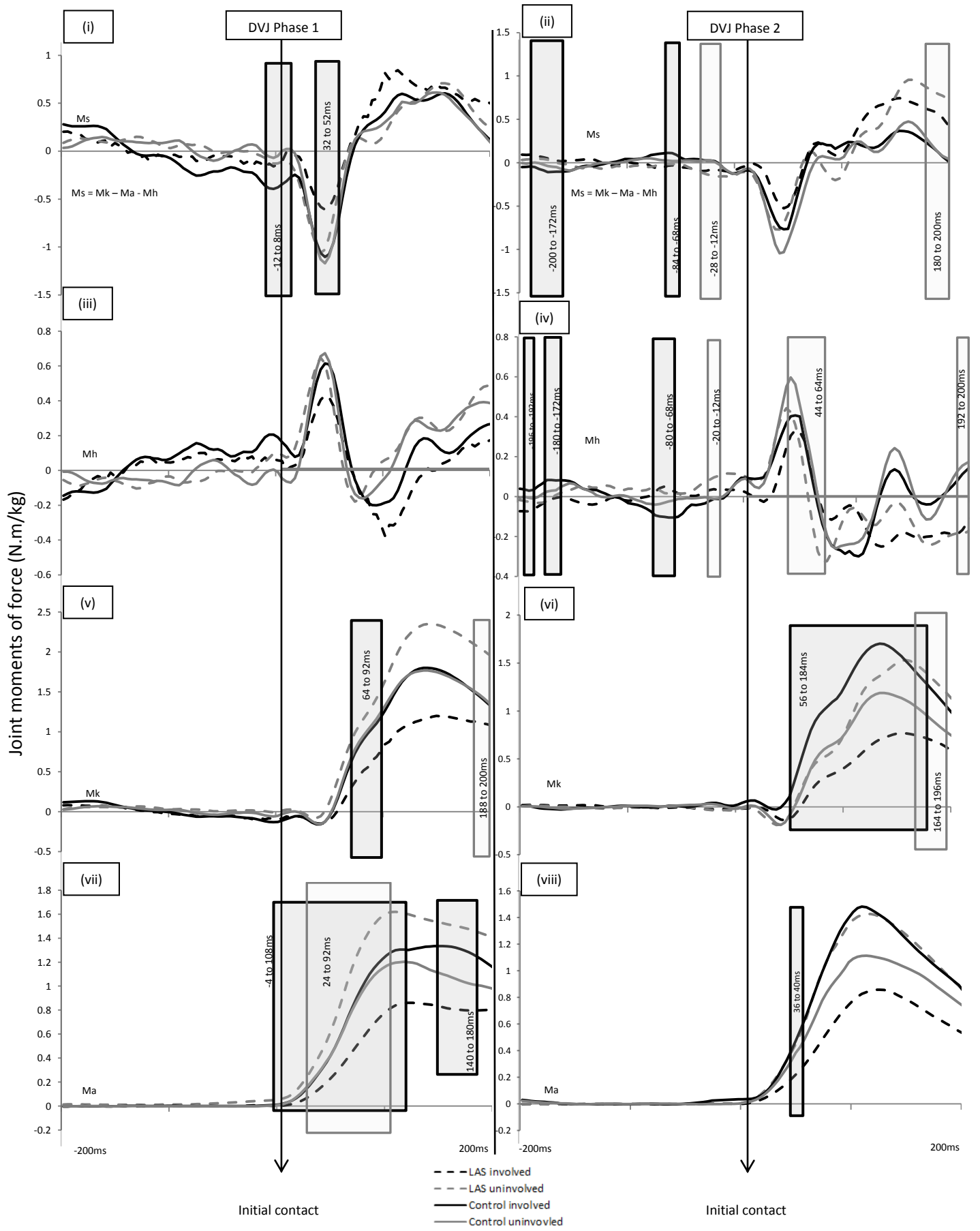


Table 1. Participant characteristics and questionnaire scores (mean \pm SD with 95% CIs) for the LAS and control groups. LAS = ankle sprain

	Age (years)	Mass (kg)	Height (m)	CAIT	FAAMadl	FAAMsport
LAS	23.2 \pm 5.26; [95% CI: 22.34 to 25.16]	74.12 \pm 14.29; [95% CI: 68.78 to 79.45]	1.75 \pm 0.10; [95% CI: 1.71 to 1.78]	15.00 \pm 6.62; [95% CI: 12.43 to 17.57]	70.26 \pm 27.44%; [95% CI: 59.41 to 81.12]	60.13 \pm 35.70%; [95% CI: 46.01 to 74.25]
Control	22.53 \pm 1.68; [95% CI: 21.72 to 23.34]	71.55 \pm 11.31; [95% CI: 66.01 to 77.01]	1.75 \pm 0.08; [95% CI: 1.71 to 1.78]	30 \pm 0; [95% CI: 30 to 30]	100 \pm 0%; [95% CI: 100 to 100]	100 \pm 0%; [95% CI: 100 to 100]

Table 2

Table 2. Trend symmetry data between involved and uninvolved limbs for LAS and control participants during phases 1 and 2 of the drop vertical jump task. Window 1 = 200ms pre-IC to IC; Window 2 = 100ms pre-IC to 100ms post-IC; Window 3 = IC to 200ms post-IC.

Variable		Trend symmetry (%)						P value		
		LAS			Control			LAS vs Control		
Sagittal plane	DVJ phase	Window 1	Window 2	Window 3	Window 1	Window 2	Window 3	Window 1	Window 2	Window 3
Net support moment of force	1	14.62	31.72	26.22	16.13	20.15	13.04	0.78	0.18	0.15
Hip moment of force	1	20.16	29.28	27.60	18.80	23.43	14.65	0.77	0.46	0.04 ^a
Knee moment of force	1	10.95	10.15	2.84	5.21	3.15	1.88	0.09	0.07	0.60
Ankle moment of force	1	18.27	1.59	5.04	21.25	0.20	3.49	0.68	0.25	0.70
Ankle angular displacement	2	12.66	8.75	1.24	13.11	1.11	1.49	0.93	0.00 ^a	0.72
Net support moment of force	2	22.59	41.68	25.54	11.11	22.22	10.59	0.24	0.42	0.14
Hip moment of force	2	21.69	23.75	26.60	21.86	15.03	11.81	0.98	0.11	0.01 ^a
Knee moment of force	2	21.95	15.69	3.25	13.66	5.77	1.98	0.17	0.12	0.27
Ankle moment of force	2	27.50	0.63	3.15	25.35	0.34	1.39	0.88	0.45	0.30

^aDenotes statistically significant between groups difference. Abbreviations: LAS = lateral ankle sprain; IC = initial contact.