

1 **Title:** Restrictions in ankle dorsiflexion range of motion alter landing kinematics but not
2 movement strategy when fatigued

3

4 **ABSTRACT**

5 **Context:** Ankle dorsiflexion range of motion (DF ROM) has been associated with a number
6 of kinematic and kinetic variables associated with landing performance that increase injury
7 risk. However, whether exercise-induced fatigue exacerbates compensatory strategies has not
8 yet been established.

9 **Objectives:** i) explore differences in landing performance between individuals with restricted
10 and normal ankle DF ROM, and ii) identify the effect of fatigue on compensations in landing
11 strategies for individuals with restricted and normal ankle DF ROM.

12 **Design:** Cross-sectional.

13 **Setting:** University research laboratory.

14 **Patients or Other Participants:** 12 recreational athletes with restricted ankle DF ROM
15 (restricted group) and 12 recreational athletes with normal ankle DF ROM (normal group).

16 **Main Outcome Measure(s):** Participants performed five bilateral drop-landings, before and
17 following a fatiguing protocol. Normalized peak vertical ground reaction force (vGRF), time
18 to peak vGRF and loading rate were calculated, alongside sagittal plane initial contact angles,
19 peak angles and joint displacement for the ankle, knee and hip. Frontal plane projection
20 angles were also calculated.

21 **Results:** At baseline, the restricted group landed with significantly less knee flexion ($P =$
22 0.005 , effect size [ES] = 1.27) at initial contact and reduced peak ankle dorsiflexion ($P <$
23 0.001 , ES = 1.67), knee flexion ($P < 0.001$, ES = 2.18) and hip flexion ($P = 0.033$, ES = 0.93)

24 angles. Sagittal plane joint displacement was also significantly less for the restricted group
25 for the ankle ($P < 0.001$, ES = 1.78), knee ($P < 0.001$, ES = 1.78) and hip ($P = 0.028$, ES =
26 0.96) joints.

27 **Conclusions:** These findings suggest individuals with restricted ankle DF ROM adopt
28 different landing strategies than those with normal ankle DF ROM. This is exacerbated when
29 fatigued, although the functional consequences of fatigue on landing mechanics in individuals
30 with ankle DF ROM restriction are unclear.

31 **Keywords:** joint mechanics, ankle restriction, drop-landings

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44 INTRODUCTION

45 Peak vertical ground reaction forces (vGRF) > 8 times bodyweight have been reported during
46 bilateral landings,¹ which has been identified as a causal factor for lower limb injuries.² To
47 support dissipation of vGRF during landings, simultaneous flexion at the ankle, knee and hip
48 joints following ground contact must occur.^{3,4} Thus, movement strategies that assist in
49 attenuating vGRF and enhancing sufficient load sharing across joint segments are
50 advantageous for reducing injury risk. For example, sagittal plane ankle, knee and hip joint
51 alignment at initial contact⁵⁻⁷ and at peak knee flexion⁴ influence the magnitude of peak
52 vGRF during landings, while greater angular joint displacement for the ankle, knee and hip
53 joint supports the load sharing of peak vGRF across each joint segment.⁸ Adopting a
54 movement strategy which keeps peak vGRF below an injury-provoking threshold reduces
55 acute⁹ and chronic¹⁰ injury risk in the lower extremity.

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57 The knee and hip joints have been identified as primary segments for shock absorption during
58 bilateral drop-landings.³ However, restrictions in ankle dorsiflexion range of motion (DF
59 ROM) can negatively influence the coordination of the proximal segments during landings by
60 imposing a mechanical organismic constraint that can limit an individual's capacity to adopt
61 effective movement strategies.¹¹⁻¹⁴ It is therefore possible that reduced ankle DF ROM
62 contributes to the development of compensatory strategies throughout the lower extremity in
63 an attempt to maintain peak vGRF below an intolerable threshold.¹² Consistent with this
64 suggestion, several studies have reported no relationship between ankle mobility and landing
65 forces.¹²⁻¹⁴ However, ankle DF ROM measured using the weight-bearing lunge test (WBLT),
66 is related to ankle dorsiflexion ($r = -0.31$ to -0.34) and knee flexion ($r = -0.37$ to -0.41) angles
67 at initial contact during bilateral drop-landings from drop heights equating to 100% and

68 150% of countermovement jump (CMJ) height in recreational athletes.¹² In the same
69 investigation, significant relationships were also found between ankle DF ROM and peak
70 ankle dorsiflexion ($r = -0.43$ to -0.44), knee flexion ($r = -0.42$ to -0.52) and frontal plane
71 projections angles (FPPA) ($r = 0.37$) at the moment of peak knee flexion during bilateral
72 drop-landings. These findings suggest restrictions in ankle DF ROM cause a stiffer landing
73 strategy through limiting knee flexion, necessitating compensations at initial ground contact
74 and the moment of peak knee flexion to prevent excessive peak vGRF.

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76 The kinematic and kinetic variables associated with landing performance can also be affected
77 by exercise-induced fatigue (defined as the inability for the neuromuscular system to
78 maintain mechanical work for a given task¹⁵), as it has been shown to increase injury risk.¹⁶
79 This may occur during prolonged activities, such as repetitive jumping, which results in
80 exercise-induced fatigue that reduces lower extremity force production.¹⁷ To attenuate peak
81 vGRF, altered movement strategies are required to compensate for diminished muscular force
82 production. As such, ankle plantar flexion has acutely increased (mean difference = 10.6°)
83 under fatigue whilst knee flexion angles have decreased (mean difference = 7.0°) at initial
84 contact during bilateral drop-landings.¹⁸ These alterations in coordination strategies help to
85 prevent fatigue-induced increases in peak vGRF by increasing angular joint displacement for
86 the ankle and knee joint.⁸ Interestingly, such compensations are similar to those demonstrated
87 at initial contact by individuals with restrictions in ankle DF ROM.¹² It may be that when in a
88 fatigued state, individuals with limited ankle DF ROM are unable to alter joint alignment at
89 initial contact as a strategy to manage peak vGRF due to the mobility restriction already
90 requiring this compensation.

91

92 It is also feasible that reduced DF ROM limits degrees of movement freedom across key
93 lower-limb segments at peak knee flexion during landings, which may control peak vGRF in
94 a fatigued state. Madigan and Pidcoe¹⁹ found that when participants were acutely fatigued,
95 peak ankle dorsiflexion (mean difference = 4.5°) and knee flexion angles increased (mean
96 difference = 6.7°) resulting in a 0.45 N·kg⁻¹ reduction in peak vGRF during landings.
97 Similarly, James, Scheuermann and Smith²⁰ detected increased angular joint displacement for
98 the knee (mean difference = 7.9°) and a 22% decrease in peak vGRF during bilateral drop-
99 landings after fatiguing exercise. Collectively, these studies show that when individuals are
100 fatigued, attenuation of peak vGRF is achieved by increasing the vertical displacement of
101 centre of mass. For individuals whose movement is constrained by a restriction in ankle DF
102 ROM, this compensatory strategy may not be fully available and their ability to cope with the
103 addition of fatigue may be compromised.

104

105 Therefore, the aims of this study were: i) to examine differences in landing performance
106 between individuals with restricted and normal ankle DF ROM and ii) identify the effect of
107 fatigue on the compensations in landing strategies for individuals with restrictions in ankle
108 DF ROM. We hypothesized that: i) individuals with limitations in ankle DF ROM will
109 present with detectable differences in landing mechanics, and ii) individuals with restricted
110 ankle DF ROM would fail to adopt vGRF attenuation-related strategies demonstrated by
111 individuals with sufficient ankle DF ROM, during landing in a fatigued state.

112

113 **METHODS**

114 **Design**

115 A mixed study design was employed in which participants were assigned to independent
116 groups (based on ankle DF ROM) who all performed landing tasks in both a non-fatigued and
117 fatigued state. Participants were classified as either having restricted ankle DF ROM
118 (restricted group) or normal ankle DF ROM (normal group) according to performance on the
119 overhead squat and forward arm squat tests.²¹ This method was selected due to its ability to
120 identify individuals with a functional restriction in ankle DF ROM, whilst producing a large
121 disparity in ankle DF ROM values between groups.²¹ Briefly, participants were required to
122 complete the overhead squat test and forward arm squat test for six and three repetitions,
123 respectively. Performance was graded in real-time by the lead investigator against the criteria
124 rating outlined by Rabin and Kozol.²¹ When participants were unable to perform a test using
125 a movement strategy that corresponded with the criteria rating, participants were assigned a
126 ‘fail’ for that test. Conversely, participants who performed a test with a movement strategy
127 that matched the criteria rating, a ‘pass’ result was given for that test. Participants who passed
128 the overhead squat and forward arm squat test, were invited to take part in a testing session
129 and assigned to the normal group. Participants who failed both the overhead squat test and
130 forward arm squat test were invited to participate in a testing session and assigned to the
131 restricted group. Participants who failed the overhead squat test but passed the forward arm
132 squat test were excluded from the investigation and did not attend a subsequent testing
133 session.

134

135 After completing the tests for group allocation, participants attended a single-test session,
136 where ankle DF ROM was measured for both limbs independently using the WBLT.
137 Participants then performed three maximal CMJ to establish drop height for the bilateral
138 drop-landings and the threshold for establishing the onset of fatigue. Five bilateral drop-
139 landings were then completed from a drop height of 150% CMJ height, both before and after

140 the performance of a fatiguing protocol. All participants were informed of the risks associated
141 with the testing prior to completing a pre-exercise questionnaire and providing informed
142 written consent. Ethical approval was provided by the Institutional Research Ethics
143 Committee. All test sessions were conducted between 10:00-13:00 h to control for circadian
144 variation.

145

146 **Participants**

147 Using the effect size of 0.47 presented by James, Scheuermann and Smith²⁰ for differences in
148 knee joint displacement during landings following the performance of a fatigue protocol, we
149 performed a representative analysis using G*power to determine the appropriate sample size.
150 With an alpha of 0.05, calculations indicated that to achieve 80% statistical power, a
151 minimum of eight participants per group were required to determine differences in landing
152 mechanics following the fatigue protocol. All participants were required to meet the
153 following inclusion criteria: (1) between the ages of 18-40 years; (2) no lower-extremity
154 injury six-months prior to testing; (3) no history of lower-extremity surgery; (4) regularly
155 compete/participate 1-3 times per week in sport events involving landings activities, such as
156 court, racquet, or team sports.

157

158 Twenty-eight participants volunteered to take part in the experiment. Following the initial
159 screening session using the criteria previously described, four participants were excluded
160 from the analysis, with 12 participants assigned to the restricted group (6 males, 6 females;
161 age = 21 ± 1 years, height = 173.4 ± 9.7 cm, body mass 72.4 ± 10.7 kg) and 12 participants to
162 the normal group (6 males, 6 females; age = 23 ± 5 years, height = 170.0 ± 6.8 cm, body
163 mass 63.7 ± 8.0 kg).

164

165 **Procedures**

166 Following the recording of height and body mass during the test session, participants
167 performed the WBLT. Participants began the test by facing a bare wall, with the greater toe
168 of the test leg positioned against the wall. The greater toe and the centre of the heel were
169 aligned using a marked line on the ground, perpendicular to the wall. Participants were
170 instructed to place the non-test foot behind them, with the heel raised and at a distance that
171 they felt allowed them to maximise their performance on the test. In order to maintain
172 balance, participants were asked to keep both hands firmly against the wall throughout. The
173 participants were then instructed to slowly lunge forward by simultaneously flexing at the
174 ankle, knee and hip on the test leg in an attempt to make contact between the centre of the
175 patella and a vertical marked line on the wall, perpendicular to the line on the ground.
176 Subtalar joint position was maintained by keeping the test foot in the standardized position
177 and ensuring the patella accurately contacted the vertical line.²² Any elevation of the heel
178 during the test was regarded as a failed attempt and feedback was provided to the participants
179 regarding their inability to prevent the heel from rising. Upon successful completion of an
180 attempt, where contact between the patella and the wall was made with no change in heel
181 position relative to the ground, participants were instructed to move the test foot further away
182 from the wall by approximately 0.5 cm. No more than three attempts were allowed at any
183 given distance. At the last successful attempt, the distance between the heel and the wall, and
184 the distance between the base of the patella and the ground were recorded to the nearest 0.1
185 cm. To determine ankle DF ROM, the trigonometric calculation method ($DF\ ROM = 90 -$
186 $\arctan [knee\text{-}ground/heel\text{-}wall]$) was employed for each attempt using the heel-wall and
187 ground-knee distances.²³ This procedure was repeated three times for each limb. Intra-rater
188 reliability for this procedure has previously been reported as excellent (intraclass coefficients

189 (ICC) = 0.98), with a standard error of measurement (SEM) as 0.6° being established.²³ To
190 ascertain that inter-limb differences did not exist, an independent t-test was used to compare
191 the mean of the three trials for left and right WBLT scores. Bland-Altman level of agreement
192 analysis for inter-limb asymmetry were $-0.2 \pm 3.8^\circ$ and $0.6 \pm 4.7^\circ$ for the restricted and
193 normal group, respectively. Mean inter-limb differences were not significant ($P > 0.05$) and
194 the right limb was used for data analysis.

195

196 Following a standardized warm-up, participants were then familiarized with the performance
197 of a CMJ. For the CMJ, participants stood bare feet with a hip-width stance with their hands
198 placed on their hips. Participants were then asked to rapidly descend prior to explosively
199 jumping as high as possible, with no control being placed on the depth or duration of the
200 countermovement. Jump height was measured using photoelectric cells (Optojump System,
201 Microgate, Bolzano, Italy). Three maximal effort CMJs were performed, with 60 s recovery
202 between attempts. The maximum value of the three attempts was used to calculate drop
203 height for the bilateral drop-landings as well as to establish the onset of fatigue during the
204 fatigue protocol.

205

206 Reflective markers were then placed directly onto the participants' skin by the same
207 investigator using the anatomical locations for sagittal plane lower-extremity joint
208 movements and FPPA, as outlined by Dingenen et al.²⁴ and Munro, Herrington and
209 Carolan.²⁵ For sagittal plane views, reflective markers were placed on the right
210 acromioclavicular joint, greater trochanter, lateral femoral condyle, lateral malleolus and 5th
211 metatarsal head.²⁴ To establish FPPA for the knee joints, reflective markers were placed at
212 the centre of the right knee joint (midpoint between the femoral condyles), centre of the right

213 ankle joint (midpoint between the malleoli) and on the proximal thigh (midpoint between the
214 anterior superior iliac spine and the knee marker). Midpoints for the knee and ankle were
215 measured with a standard tape measure (Seca 201, Seca, United Kingdom), as described by
216 Munro, Herrington and Carolan.²⁵

217

218 Participants were then familiarized with the bilateral drop-landings from a drop height of
219 150% of maximum CMJ height. Bilateral drop-landings were performed with participants
220 standing bare foot with their arms folded across their chest on a height-adjustable platform (to
221 the nearest 1 cm). Participants were then instructed to step off the platform, leading with the
222 right leg, before immediately bringing the left leg off and alongside the right leg prior to
223 impact with the ground. During this manoeuvre, participants were instructed to ensure that
224 they did not modify the height of the centre of mass prior to dropping from the platform.⁴ For
225 a landing to be deemed successful, participants were required to ensure they landed with each
226 foot simultaneously and in complete contact with the respective portable force platform,
227 which was positioned 15 cm away from the elevated platform. Each foot landed on a separate
228 portable force platform recording at 1000 Hz (Pasco, Roseville, CA, USA), positioned side-
229 by-side, 5 cm apart and embedded in custom-built wooden mounts that were level with the
230 force platforms and did not allow any extraneous movement. Full contact with the force
231 platform was visually monitored during landings throughout by the lead investigator, with
232 landings being disregarded where participants failed to either make full contact with the
233 platform or maintain balance (e.g. either taking a step or placing a hand on the ground to
234 prevent falling) upon landing. To ensure participants displayed their natural landing strategy,
235 no instructions were provided regarding heel contact with the ground during the landing
236 phase of the movement and no feedback on landing performance was provided at any point
237 during testing. All landings were performed barefoot so as to prevent any heel elevation

238 associated with footwear from altering landing mechanics and weakening internal validity.²⁶
239 For each condition (baseline and post fatigue protocol), participants performed five bilateral-
240 drop landings for data collection. Baseline testing allowed for 60 s recovery between
241 landings, while post fatigue protocol no recovery was provided between landings beyond the
242 time it took to ascend the height-adjustable platform.

243

244 For 2D video analysis, sagittal- and frontal plane joint movements were recorded using three
245 standard digital video cameras sampling at 60 Hz (Panasonic HX-WA30) using the
246 procedures outlined by Payton.²⁷ For sagittal plane joint movements, a camera was positioned
247 3.5 m from the centre of either force platform.²⁸ To record frontal plane kinematics, a camera
248 was placed 3.5 m in front of the centre of the force platforms.²⁸ All cameras were placed on a
249 tripod at a height of 0.6 m from the ground.

250

251 The fatiguing protocol consisted of participants performing 30 successive CMJs, while
252 maintaining the same technique as described above. Participants were instructed to keep their
253 hands on their hips and repeatedly jump as high as possible for 30 repetitions, while spending
254 minimal time on the ground between repetitions. Verbal encouragement was provided to
255 ensure participants demonstrated maximal effort throughout. Following the 30th repetition,
256 participants rested 30 s before performing a maximal CMJ for testing purposes. Participants
257 then repeated the protocol until a > 20% decline in CMJ jump height was demonstrated.¹⁸
258 Once participants were unable to reach > 80% of their maximum CMJ height, five bilateral
259 drop-landings were immediately performed using the procedures previously described, with
260 no recovery between landings so as to maintain a fatigued state. The last maximal CMJs were

261 recorded for data analysis, with the percentage of fatigue calculated as CMJ height post
262 fatigue protocol divided by CMJ height pre fatigue protocol, multiplied by 100.¹⁸

263

264 **Data analysis**

265 Raw vGRF data were low-pass filtered using a fourth-order Butterworth filter with a cut-off
266 frequency of 50 Hz.²⁹ Peak vGRF data were calculated for each leg and normalized to body
267 mass ($\text{N}\cdot\text{kg}^{-1}$). An independent *t*-test was performed between mean values of peak vGRF for
268 the right and left leg for each participant, which revealed no difference between limbs ($t_{(46)} =$
269 0.657 , $P = 0.515$). As such, peak vGRF, time to peak vGRF and loading rate were
270 independently calculated for the right leg and used for data collection. Peak vGRF data were
271 normalized to body mass and initial contact velocity ($\text{N}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$). To normalize peak vGRF
272 to drop height, initial contact velocity was calculated using the following equation¹²:

273

$$274 \quad \text{Initial contact velocity (m}\cdot\text{s}^{-1}) = \sqrt{2g \cdot DH}$$

275

276 where g is the gravitational acceleration and DH is drop height. For time to peak vGRF to be
277 determined, initial contact was identified as the point that vGRF exceeded 10 N.³⁰ Time to
278 peak vGRF was then calculated as the time difference between initial contact and the time
279 point where peak vGRF occurred. Loading rate was calculated as peak vGRF normalized to
280 body mass divided by time to peak vGRF. Within-session reliability for kinetic measures
281 associated with bilateral drop-landing performance from a drop height equating 150% of
282 CMJ height has previously been reported as excellent (ICC ranging between 0.91 to 0.94),

283 with normalized peak force, time to peak force and loading rate possessing SEM values of
284 $0.23 \text{ N}\cdot\text{kg}^{-1}$, 0.004 s and $6.7 \text{ N}\cdot\text{s}^{-1}$, respectively.³¹

285

286 All video recordings were analysed with free downloadable software (Kinovea for Windows,
287 Version 0.8.15). For sagittal plane joint movements, hip flexion, knee flexion and ankle
288 dorsiflexion angles were calculated at initial contact and the point of peak knee flexion for
289 the right limb. These angles were then used to calculate joint displacement for each joint by
290 subtracting the peak flexion angle from the initial contact angle. Initial contact was defined as
291 the frame prior to visual impact between the foot and the ground that led to visual
292 deformation of the foot complex. Peak flexion was identified visually and defined as the
293 frame where no more downward motion occurred at the hip, knee or ankle joints.²⁴ Hip
294 flexion angle was calculated as the angle between the line formed between the
295 acromioclavular joint and the greater trochanter and the line between the greater trochanter
296 and the lateral femoral condyle. Knee flexion angle was calculated as the angle between the
297 line formed between the greater trochanter and the lateral femoral condyle and the line
298 between the lateral femoral condyle and the lateral malleolus. Ankle dorsiflexion angle was
299 calculated as the angle between the line formed between the lateral femoral condyle and the
300 lateral malleolus and the line between the lateral malleolus and the 5th metatarsal head. FPPA
301 was determined for both sides at the deepest landing position, defined as the frame
302 corresponding to peak knee flexion.²⁵ FPPA was calculated as the angle between the line
303 formed between the proximal thigh marker and the knee joint marker and the line between
304 the knee joint marker and the ankle joint marker.²⁵ For hip flexion, knee flexion and ankle
305 dorsiflexion, smaller values represented greater flexion and ankle dorsiflexion. For FPPA,
306 values $< 180^\circ$ represented knee valgus and values $> 180^\circ$ representing knee varus. Within-
307 session reliability for kinematic measures of bilateral-drop landings from a drop height

308 equating to 150% of CMJ height have been previously reported as very large to nearly perfect
309 (ICC ranging between 0.87 to 0.94). SEM for lower extremity joint angles at initial contact
310 and at peak flexion have been reported as ranging between 1.1° to 1.3° and 2.3° to 6.6°,
311 respectively.²⁸

312

313 **Statistical Analyses**

314 Descriptive statistics (means \pm standard deviation) were calculated for each kinetic and
315 kinematic variable. Normality was confirmed for all dependent variables using the Shapiro-
316 Wilk test. Independent *t*-tests were employed to determine between group differences for
317 WBLT scores, maximum CMJ height and percentage of fatigue for CMJ height following the
318 fatigue protocol. To test our first hypothesis, between-group differences at baseline for
319 landing performance were examined using an independent *t*-test for kinetic and kinematic
320 measures. Effect sizes (Cohen's *d*) were calculated as the difference between the means
321 divided by the pooled standard deviation for all baseline measures and interpreted using the
322 following criteria: < 0.2, a trivial difference; 0.21–0.5, a small difference; 0.51-0.8, a
323 moderate difference; > 0.81, a large difference.³²

324

325 A one-way analysis of covariance (ANCOVA) was performed to test our second hypothesis
326 for between-group differences for landing performance following the fatigue protocol. This
327 statistical analysis was chosen so as to provide greater statistical power and reduce
328 variability, while accounting for between-group differences at baseline caused by the
329 procedures for group allocation.^{33,34} Values for kinetic and kinematic variables associated
330 with landing performance following the fatigue protocol were used as the dependent variable,
331 with baseline (pre) values used as the covariate. The *a-priori* level of statistical significance

332 was set at $P < 0.05$, with a Bonferroni correction applied *post-hoc* in order to reduce the
333 likelihood of Type I errors. As statistical significance is not a contextual factor and its use as
334 the sole measure of significance has been contested³⁵, we also present 95% confidence
335 intervals and effect sizes for a more complete, quantifiable description of the size of the
336 effect. To that end, partial eta squared (η^2) values were calculated to indicate the magnitude
337 of group differences in landing mechanics following the fatigue protocol using the following
338 criteria: 0.02, a small difference; 0.13, a medium difference; 0.26, a large difference.³² All
339 statistical tests were performed using SPSS® statistical software package (v.24; SPSS Inc.,
340 Chicago, IL, USA).

341

342 **RESULTS**

343 **Between-group differences at baseline**

344 There were a between-group difference for WBLT scores, with the normal group
345 demonstrating greater ankle DF ROM ($t_{(22)} = -10.19$, $P < 0.001$). However, there were no
346 between-group differences at baseline in CMJ height ($t_{(22)} = -1.96$, $P = 0.062$). Table 1 presents
347 both groups' landing performance scores at baseline for WBLT performance, CMJ height,
348 kinetic and kinematic measures, including effect sizes and associated 95% confidence intervals.
349 There were no between-group differences for any kinetic measures associated with landings
350 between groups at baseline.

351

352 At initial contact, the restricted group landed with less knee flexion ($t_{(22)} = 3.12$, $P = 0.005$)
353 and greater ankle plantarflexion ($t_{(22)} = 1.64$, $P = 0.116$). At the moment of peak knee flexion
354 for all joints in the sagittal plane, the restricted group displayed less ankle dorsiflexion ($t_{(22)} =$
355 4.10 , $P < 0.001$), knee flexion ($t_{(22)} = 5.34$, $P < 0.001$) and hip flexion ($t_{(22)} = 2.28$, $P =$

356 0.033). Joint displacement for the ankle ($t_{(22)} = -4.35, P < 0.001$), knee ($t_{(22)} = -4.35, P <$
357 0.001) and hip ($t_{(22)} = -2.35, P = 0.028$) were also significantly less for the restricted group.
358 Other between-group differences were small to trivial.

359

360 ***INSERT TABLE 1 HERE***

361

362 **Effects of fatigue**

363 Figure 1 presents between-group differences for post-test kinematic measures of bilateral
364 drop-landing performance. All participants achieved a $> 20\%$ reduction in CMJ height
365 following the performance of the fatigue protocol (restricted group = $68.2 \pm 9.8\%$; normal
366 group = $71.0 \pm 6.9\%$), with no difference between groups for scores of percentage of fatigue
367 ($t_{(22)} = -0.99, P = 0.333$). There were no main effects of group on post-test normalized peak
368 vGRF ($F_{(1,21)} = 0.59, P = 0.451, \eta^2 = 0.03$), time to peak vGRF ($F_{(1,21)} = 1.17, P = 0.291, \eta^2 =$
369 0.05) and loading rate ($F_{(1,21)} = 0.42, P = 0.523, \eta^2 = 0.02$). Furthermore, the ANCOVA
370 revealed no effect of group on post-test ankle plantar flexion angle ($F_{(1,21)} = 0.03, P = 0.868,$
371 $\eta^2 = 0.00$), knee flexion angle ($F_{(1,21)} = 0.00, P = 0.965, \eta^2 = 0.00$) or hip flexion angle ($F_{(1,21)}$
372 $= 2.12, P = 0.160, \eta^2 = 0.09$) at initial contact. There was a main effect of group on peak
373 flexion for ankle dorsiflexion ($F_{(1,21)} = 5.80, P = 0.025, \eta^2 = 0.22$). Changes from baseline
374 showed that the restricted group displayed less ankle dorsiflexion (mean difference = 0.3°)
375 than the normal group (mean difference = 2.7°) following the fatiguing protocol. There were
376 no main effects of group on peak knee flexion angle ($F_{(1,21)} = 0.60, P = 0.809, \eta^2 = 0.00$),
377 peak hip flexion angle ($F_{(1,21)} = 0.20, P = 0.661, \eta^2 = 0.01$) and FPPA ($F_{(1,21)} = 1.92, P =$
378 $0.180, \eta^2 = 0.08$). There was a main effect of group on ankle joint displacement following the
379 fatiguing protocol ($F_{(1,21)} = 7.88, P = 0.011, \eta^2 = 0.27$). Pairwise comparisons revealed

380 greater ankle joint displacement for the normal group (mean difference = 2.4°) relative to the
381 restricted group (mean difference = 0.1°). There was no main effect of group on knee joint
382 displacement ($F_{(1,21)} = 0.66$, $P = 0.427$, $\eta^2 = 0.03$) and hip joint displacement ($F_{(1,21)} = 0.37$, P
383 = 0.557, $\eta^2 = 0.02$) post-test.

384

385 ***INSERT FIGURE 1 HERE***

386

387 **DISCUSSION**

388 This study had two main aims; first we examined the kinetic and kinematic characteristics of
389 landing technique among recreational athletes with either functional restrictions or no
390 restrictions in ankle DF ROM. Secondly, we assessed the effects of acute fatigue on landing
391 technique between these two groups. We hypothesized that the restricted group would show
392 different landing strategies to the normal group. Further, we hypothesized that this would
393 affect their ability to compensate for reduced force production capability whilst fatigued,
394 resulting in greater disparities in landing mechanics between groups. Consistent with our first
395 hypothesis, the results revealed that individuals with limited ankle DF ROM land with less
396 knee flexion at initial contact and reduced ankle, knee and hip flexion at the moment of knee
397 peak knee flexion. This resulted in the restricted group displaying significantly less ankle,
398 knee and hip joint displacement relative to the normal group. However, despite these
399 disparities in kinematic patterns, there were no differences in kinetic variables during landing.
400 Furthermore, our findings show that recreational athletes with limited ankle DF ROM were
401 incapable of utilizing greater ankle joint motion when landing in an exercise induced fatigued
402 state, which was in contrast to the normal group. However, this movement compensation did

403 not result in differences between groups for any other kinematic or kinetic variable analysed,
404 meaning that the functional relevance of this finding is uncertain.

405

406 A primary finding of the current study was that participants with ankle DF ROM restriction
407 modified their landing mechanics at initial contact and at peak flexion. This occurred
408 throughout the lower extremity, resulting in significant differences for angular joint
409 displacement at the ankle, knee and hip joints. Specifically, at initial contact, participants
410 with restricted ankle DF ROM landed with 5.5° less knee flexion. This is consistent with the
411 findings of others,^{12,36} where relationships between ankle DF ROM and knee flexion angles at
412 initial contact during single-leg ($r = 0.33$) and double-leg landings ($r = -0.31$) were reported.
413 Collectively, these results suggest that individuals compensate for restrictions in ankle DF
414 ROM (as measured using the WBLT) by landing with greater knee extension prior to
415 contacting the ground. It is likely that this movement strategy occurs in an attempt to
416 maintain knee joint displacement, as peak knee flexion angles are significantly reduced by
417 restrictions in ankle DF ROM.^{12,36} The majority of acute non-contact knee injuries occur
418 close to the point of initial contact during landings.³⁷ Landing with greater knee extension at
419 initial contact has been associated with increased tibia anterior shear forces;⁶ a known
420 mechanism for anterior cruciate ligament injury.³⁸ Therefore, reduced ankle DF ROM may
421 expose the knee to greater shear forces during landings, with the potential to increase injury
422 risk.

423

424 Compensations at initial contact for restricted ankle DF ROM did not occur at the ankle joint
425 itself. This was an unexpected finding, given that moderate negative relationships have been
426 reported between ankle DF ROM and ankle plantar flexion angles at initial contact ($r = -0.34$)

427 during bilateral drop-landings from 100% of CMJ height.¹² Increasing ankle plantar flexion at
428 initial contact provides a functional strategy for managing vGRF,⁷ resulting in preservation of
429 ankle joint displacement.⁸ However, the relationship between ankle DF ROM and ankle
430 plantar flexion angle at initial contact is not always consistent. Dowling, McPherson and
431 Paci³⁶ found no such relationship during single-leg drop landings, while Howe et al.¹²
432 reported a non-significant relationship during bilateral drop-landings from drop heights
433 equalling 150% of CMJ height. As the present investigation found no difference in ankle
434 plantar flexion angles at initial contact between groups, we suggest that the ankle does not
435 provide a means of movement compensation at this stage of the landings for those with
436 restrictions in ankle DF ROM.

437

438 In the current study, ankle DF ROM restriction significantly reduced baseline measures of
439 peak flexion angles and joint displacement for the ankle, knee and hip joints, with large effect
440 sizes found between groups. This is consistent with previous studies, where ankle
441 dorsiflexion and knee flexion angles at peak flexion, along with joint displacement for these
442 segments, have each been related to WBLT performance among both healthy^{12,36} and
443 injured³⁰ populations. The current finding is, therefore, in keeping with the sagittal plane
444 coupling observed between the ankle and knee joints, whereby dorsiflexion at the ankle
445 complex facilitates flexion at the knee joint during landings.³ This coordination pattern
446 allows for greater shock absorption,³ supporting the management of vGRF when loading is
447 greater due to task constraints. Manipulating the demand of a bilateral drop-landing by
448 increasing drop height from 0.32 m to 1.03 m was reported to increase ankle and knee joint
449 displacement by 4.2° and 11.6°, respectively.⁴ Reduced peak knee flexion has been shown to
450 increase peak vGRF,⁴ quadriceps muscle activity⁵ and frontal plane knee abduction
451 moments.³⁹ Each of these variables has been associated with increased anterior cruciate

452 ligament injury risk.⁴⁰ Therefore, limitations in ankle DF ROM may cause individuals to
453 adopt landing strategies that could potentially cause knee ligament injury.

454

455 This is the first investigation, to our knowledge, that has shown restrictions in ankle DF ROM
456 significantly reduces hip flexion angles at peak flexion and hip flexion joint displacement
457 during bilateral landings in a healthy and athletic population. During both unilateral³⁶ and
458 bilateral landings,¹² ankle DF ROM has a small relationship with hip flexion angles at the
459 moment of peak flexion ($r = -0.23$ to -0.28). In the current study, we found that the restricted
460 group had lower peak hip flexion angles, with a mean difference of 16.3° compared to the
461 normal group. Furthermore, mean hip joint displacement was 14.7° less for the restricted
462 group. The hip joint has been shown to provide an important contribution to the dissipation of
463 forces during landing tasks,³ with a vital role for managing vGRF when landing from higher
464 drop heights.⁴ As a result, restrictions in ankle DF ROM potentially limits the hip joint's
465 capacity to contribute to vGRF attenuation during landings, particularly from greater drop
466 heights.

467

468 We found no difference for kinetic measures of landing performance between the restricted
469 and normal group. Studies exploring the relationship between ankle DF ROM and kinetic
470 variables have been inconclusive. A number of studies have found no significant relationship
471 for ankle DF ROM and peak vGRF, time to peak vGRF and loading rate.¹²⁻¹⁴ However, Fong
472 et al.¹¹ did identify a moderate negative relationship between ankle DF ROM and peak vGRF
473 during a jump-landing task. It has been proposed that the frontal plane compensations in the
474 lower extremity reported by Whitting et al.¹⁴ and Malloy et al.¹³ may provide a strategy that
475 assists in preserving the descent of the centre of mass to allow for vGRF attenuation.¹²

476 However, the data reported here challenges this suggestion, with FPPA for both groups
477 showing no significant difference. The present findings indicate kinetic variables associated
478 with landing performance are unlikely to be regulated exclusively by angular joint
479 displacement or postures at specific time points (i.e. peak flexion) in lower extremity. Peak
480 vGRF has been negatively correlated with angular velocity for the knee ($r = -0.60$) and hip
481 joint ($r = -0.45$) at initial contact during a stop-jump task.⁴¹ Similarly, increased eccentric
482 work performed by the knee and hip extensors⁴ and increased muscular activity prior to initial
483 contact⁴² also contributes to energy dissipation and aids in the attenuation of peak vGRF.
484 Therefore, variables such as knee and hip angular velocity at initial contact and the eccentric
485 work performed by the knee extensors may compensate for the reduced lower extremity joint
486 displacement caused by restrictions in ankle DF ROM, resulting in the management of peak
487 vGRF during landings. These findings indicate that ankle DF ROM may alter the
488 requirements during landings for lower extremity strength qualities, due to a limited capacity
489 to flex the knee and hip joints following ground contact. However, this suggestion is
490 speculative, with research required to establish whether restricted ankle DF ROM demands
491 greater rates of force development to effectively manage peak vGRF during landings.

492

493 The second major aim of this study was to investigate the effect of exercise-induced fatigue
494 on landing mechanics in individuals with restricted ankle DF ROM. In this regard, another
495 primary finding was the difference found between groups in ankle joint coordination during
496 landings after an acute bout of exercise-induced fatigue. We found moderate and large effects
497 for post-intervention ankle joint angle at peak flexion and ankle joint displacement
498 respectively. These findings suggest that the restricted group was unable to access additional
499 ankle dorsiflexion when performing landings in a fatigued state (Figure 1). This was in
500 contrast to the normal group, who increased peak ankle dorsiflexion by 2.7° and ankle joint

501 displacement by 2.4° when acutely fatigued. However, no differences were found when
502 comparing groups and the effect of fatigue for the knee or hip joints for any kinematic
503 measure associated with landing performance. Furthermore, no differences between groups
504 were identified for any kinetic variable analysed following the fatigue protocol. Whether such
505 small differences in peak flexion angles and joint displacement at the ankle are functionally
506 relevant is unknown. As both groups were still able to access greater joint displacement at the
507 knee and hip during landings it seems that the additional ankle DF ROM used by the normal
508 group played no role in facilitating motion at the proximal segments.

509

510 Another consideration is whether 2D video analysis is able to detect such differences in
511 landing strategy. Howe et al.²⁸ investigated the reliability of using 2D video analysis for
512 bilateral drop-landings from drop heights equating to 150% of maximum CMJ height and
513 reported minimal detectable change values for ankle dorsiflexion angle at peak flexion and
514 ankle joint displacement were 6.8° and 6.0°, respectively. As differences for the normal group
515 following fatigue protocol did not exceed these thresholds it may be that the change in joint
516 kinematics for this group can be defined as ‘real’. Therefore, individuals with restrictions in
517 ankle DF ROM are no more constrained in their ability to adjust their landing strategy when
518 fatigued, than individuals with normal ankle mobility. These findings suggest the presence of
519 ankle DF ROM hypomobility does not exponentially increase injury risk when performing
520 landings in a fatigued state.

521

522 This study is not without potential limitations. Firstly, this investigation used 2D video
523 analysis to measure kinematic variables at distinct time points during bilateral-landings.
524 While three-dimensional motion capture is considered the gold standard, many practitioners

525 do not have access to such equipment in practical environments. The technologies used in
526 this study are readily accessible in clinical settings and, consequently, provide clear practical
527 application. Additionally, all kinematic measures presented in this investigation have shown
528 acceptable within-session reliability, with CV% ranging between 1.1–11.4%.²⁸ Intra-rater
529 reliability has also been reported, with typical error values <1.5° for all measures.¹² Another
530 limitation was that our investigation did not control for menstrual cycle status for female
531 participants, which has been shown to affect joint laxity⁴³ and landing mechanics.⁴⁴ As a
532 result, it is possible that the differences found in our investigation may have been influenced
533 by the menstrual cycle, which should be controlled for in future research.

534

535 **CONCLUSION**

536 Individuals who have restricted ankle DF ROM based on their performance of closed-chain
537 activities adopt different landing strategies compared to non-restricted controls. In particular,
538 individuals with functional limitations in ankle DF ROM use less ankle motion relative to
539 controls during bilateral drop-landing landings. This is further exaggerated with the addition
540 of fatigue, although these differences must be interpreted with caution due to the sensitivity
541 of 2D video analysis for detecting changes in landing kinematics. At the knee, individuals
542 compensate for reduced peak knee flexion angles by landing in a more extended posture at
543 initial contact, in an attempt to maintain knee angular joint displacement and limit peak
544 vGRF to a manageable level. This is also the first investigation to demonstrate that
545 restrictions in ankle DF ROM affect sagittal plane hip kinematics during bilateral landings,
546 with reduced peak flexion angles and angular joint displacement at the hip. As restrictions in
547 ankle DF ROM appear to promote landing strategies that are more extended and stiffer in

548 nature, injury risk may be increased during landing tasks for individuals with limited ankle

549 DF ROM.

550

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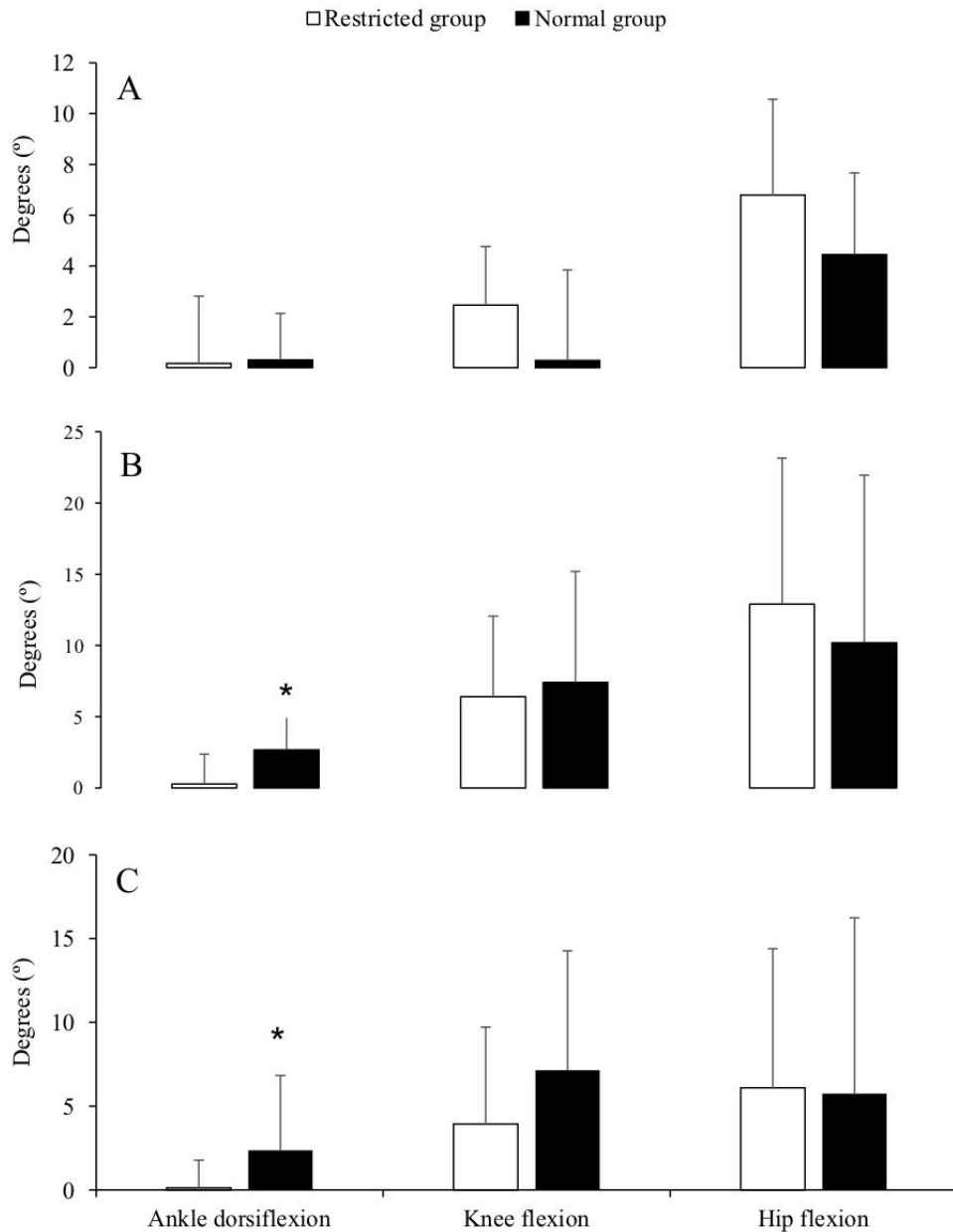
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671

672 **Figure 1.** Group differences for kinematic measures of bilateral drop-landing performance
 673 following the fatigue protocol A) initial contact, B) peak flexion and C) sagittal plane joint
 674 displacement. Values represent differences from baseline testing. Means \pm SD. * Between-
 675 group difference ($P < 0.05$).

676

677

678 **Table 1.** Between-group differences at baseline for kinetic and kinematic measures
 679 associated with landing performance.

	Restricted (n=12)	Normal (n=12)	Mean difference (95% Confidence interval)	Effect size (95% Confidence interval)
	Mean ± SD	Mean ± SD		
Weight-bearing lunge test (°)	32.0 ± 3.3	44.6 ± 2.7	-12.6 (-15.1 – -10.0)*	4.2 (3.8 – 4.6)
Countermovement jump height (m)	0.30 ± 0.08	0.37 ± 0.10	-0.07 (-0.14 – 0.00)	0.8 (0.6 – 1.1)
<i>Kinetic variables</i>				
Peak force (N·kg ⁻¹ · m·s ⁻¹)	0.068 ± 0.021	0.064 ± 0.011	0.004 (-0.010 – 0.018)	0.2 (0.0 – 0.5)
Time to peak force (s)	0.058 ± 0.011	0.055 ± 0.010	0.003 (-0.005 – 0.012)	0.3 (0.1 – 0.5)
Loading rate (N·s ⁻¹)	38.7 ± 21.3	38.0 ± 11.3	0.7 (-13.7 – 15.2)	0.0 (-0.2 – 0.4)
<i>Initial contact angles</i>				
Ankle (°)	153.1 ± 3.7	150.4 ± 4.8	2.9 (-0.8 – 6.5)	0.7 (0.4 – 0.9)
Knee (°)	170.2 ± 3.1	164.7 ± 5.3	5.5 (1.9 – 9.3)*	1.3 (1.0 – 1.5)
Hip (°)	161.8 ± 4.9	160.3 ± 5.8	1.6 (-3.0 – 6.1)	0.3 (0.1 – 0.5)
<i>Peak flexion angles</i>				
Ankle (°)	110.8 ± 7.6	96.8 ± 9.0	14.0 (6.9 – 21.1)*	1.7 (1.4 – 2.0)
Knee (°)	102.1 ± 6.4	79.2 ± 13.4	22.8 (13.8 – 31.9)*	2.2 (1.9 – 2.5)
Hip (°)	95.0 ± 17.1	78.7 ± 17.9	16.3 (1.5 – 31.1)*	0.9 (0.7 – 1.2)
Frontal plane projection angles (°)	200.0 ± 20.8	207.1 ± 19.2	-7.1 (-24.1 – 9.8)	0.4 (0.1 – 0.6)
<i>Joint displacement</i>				
Ankle dorsiflexion (°)	42.5 ± 5.9	53.6 ± 6.6	-11.1 (-16.4 – -5.8)*	1.8 (1.5 – 2.1)
Knee flexion (°)	68.2 ± 5.9	85.5 ± 12.8	-17.3 (-25.5 – -9.1)*	1.8 (1.5 – 2.1)
Hip flexion (°)	66.9 ± 14.0	81.6 ± 16.5	-14.7 (-27.7 – -1.7)*	1.0 (0.7 – 1.2)

680 * different between groups at the $P < 0.05$ level.

681