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1 **Title:** Ankle dorsiflexion range of motion is associated with kinematic but not kinetic
2 variables related to bilateral drop-landing performance at various drop heights

3

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Abstract

Limited evidence is available concerning ankle dorsiflexion range of motion (DF ROM) and its relationship with landing performance from varying drop heights. The aim of this investigation was to determine the relationship between ankle DF ROM and both kinetic and kinematic variables measured during bilateral drop-landings from 50%, 100% and 150% of countermovement jump height. Thirty-nine participants were measured for their ankle DF ROM using the weight-bearing lunge test, after which five bilateral drop-landings were performed from 50%, 100% and 150% of maximal countermovement jump height. Normalized peak vertical ground reaction force (vGRF), time to peak vGRF and loading rate was calculated for analysis, alongside sagittal-plane initial contact angles, peak angles and joint displacement for the hip, knee and ankle. Frontal-plane projection angles were also calculated. Ankle DF ROM was not related to normalized peak vGRF, time to peak vGRF or loading rate ($P > 0.05$), regardless of the drop height. However, at drop heights of 100% and 150% of countermovement jump height, there were numerous significant ($P < 0.05$) moderate to large correlations between ankle DF ROM and initial contact angles ($r = -0.34 - -0.40$) and peak angles ($r = -0.42 - -0.52$) for the knee and ankle joint. Knee joint displacement ($r = 0.39 - 0.47$) and frontal-plane projection angle ($r = 0.37 - 0.40$) had a positive relationship with ankle DF ROM, which was consistent across all drop heights. Ankle DF ROM influences coordination strategies that allow for the management of vGRF during bilateral drop-landings, with alterations in alignment for the knee and ankle joints at both initial contact and peak angles.

Key words: ankle dorsiflexion; joint mechanics; landing

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49 Highlights

- 50 • Ankle dorsiflexion range of motion (DF ROM) does not influence landing forces.
- 51 • Reduced ankle DF ROM alters coordination patterns during bilateral landings.
- 52 • Strategies to compensate for ankle DF ROM restriction may increase injury risk.

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69 1. Introduction

70 Bilateral landings from a height are performed by athletes in training and competition
71 (Bloomfield, Polman & O'Donoghue, 2007; McClay et al., 1994) and are also part of daily
72 life during leisure activities and occupational tasks (Knapik, Craig, Hauret & Jones, 2003).
73 Successfully executing a bilateral landing is necessary to attenuate the large vertical forces
74 that can equate to multiples of body weight thus preserving the integrity of anatomical
75 structures of the lower-limbs (Hewett et al., 2005). To appropriately manage high vertical
76 forces, the hip, knee and ankle joint must be coordinated to provide a movement strategy that
77 facilitates effective dissipation (Yeow, Lee & Goh, 2011a). In athletic populations, the forces
78 experienced during landings have been identified as a mechanism for both acute (Hewett,
79 Myer & Ford, 2006) and chronic (Dierks, Manal, Hamill & Davis, 2011) lower-extremity
80 injuries. Therefore, landing mechanics should be optimized, such that high forces can be
81 effectively managed whilst minimizing injury risk. When less effective coordination
82 strategies are adopted during landing tasks, greater risk of injury occurs (Herrington, 2014;
83 Hewett et al., 2005). Differences in sagittal-plane initial contact angles (Chappell et al., 2005;
84 Rowley & Richards, 2015), peak flexion angles (Blackburn & Padua, 2009; Yu, Lin &
85 Garrett, 2006) and joint angular displacement (Begalle et al., 2015) at the hip, knee and ankle
86 joints have all been associated with greater peak vertical ground reaction forces (vGRF).
87 Likewise, in the frontal- and transverse-plane, greater peak knee valgus angle during landing
88 tasks have been found to increase injury risk (Hewett et al., 2005).

89

90 One of the modifiable factors associated with suboptimal landing mechanics is restriction in
91 ankle dorsiflexion range of motion (DF ROM), which is inversely related ($r = -0.411$) to peak
92 vGRF during a bilateral jump-landing task (Fong, Blackburn, Norcross, McGrath & Padua,

2011). The relationship between ankle DF ROM and peak vGRF is likely to be the result of limitations in ankle DF ROM inhibiting knee flexion motion during the shock absorption phase of landing (Fong, Blackburn, Norcross, McGrath & Padua, 2011). This results in a stiffer landing strategy known to increase peak vGRF (Zhang, Bates & Dufek, 2000) and undesirable load being placed on passive structures of the knee (Yu & Garrett, 2007). This is compounded by restrictions in ankle DF ROM also being negatively correlated ($r = -0.27 - -0.36$) with frontal- and transverse-plane kinematic compensations throughout the lower extremity during both unilateral (Whitting, Steele, McGhee & Munro, 2011) and bilateral landings (Malloy, Morgan, Meinerz, Geiser, & Kipp, 2015; Sigward, Ota & Power, 2008). For example, Malloy et al. (2015) observed that soccer players who presented with reduced ankle DF ROM performed a bilateral landing task with greater peak knee abduction angles. Given that an increased peak knee abduction angle during landings has been highlighted as a significant risk factor for anterior cruciate ligament injury (ACL) (Hewett et al., 2005), ankle DF ROM is an important injury risk factor for a number of populations. However, there is little evidence of other compensatory strategies that may be adopted to manage vGRF when ankle DF ROM is limited, such as altered lower extremity joint angles at initial contact and hip joint kinematics during landings.

110

Investigations into the relationship between ankle DF ROM and landing mechanics have used a variety of bilateral landing tasks (Fong et al., 2011; Malloy et al., 2015; Sigward et al., 2008). Drop heights for bilateral landings have ranged from 0.30 m (Fong et al., 2011) to 0.46 m (Sigward et al., 2008). Many jumping activities involve landing from a height that significantly exceeds an individual's countermovement jump (CMJ) height, such as jumping with an arm swing (Slinde, Suber, Suber, Edwén, & Svantesson, 2008) or where a run-up occurs immediately prior to the jump (Young, Wilson, & Byrne, 1999). As differences in the

118 initial contact velocity directly influences landing mechanics and the coordination strategies
119 adopted (Zhang et al., 2000), research is required to determine how restrictions in ankle DF
120 ROM alter the movement demands of these tasks at varying drop heights. Therefore, the aim
121 of this investigation was to determine the relationship between ankle DF ROM and both
122 kinetic and kinematic variables measured during bilateral drop-landings from a range of
123 heights individualized to CMJ performance. We hypothesized that reduced ankle DF ROM
124 would correlate with greater peak vGRF caused by reduced ankle dorsiflexion and knee
125 flexion being available for energy absorption. Furthermore, limitations in ankle DF ROM
126 would cause compensations in coordination strategies at other time points (i.e. initial contact)
127 and separate joint segments (i.e. the hip). Additionally, we hypothesized that landings from
128 higher drop heights would strengthen the relationship between ankle DF ROM and the
129 compensatory strategies in coordination patterns.

130

131 **2. Methods**

132 *2.1 Study design*

133 Using a cross-sectional design, participants reported for a single test session wearing spandex
134 shorts and vest to evaluate the relationship between ankle DF ROM and the performance of
135 bilateral drop-landings from drop heights of 50%, 100% and 150% of maximum CMJ height.
136 All test sessions were conducted between 10:00 am and 1:00pm to control for circadian
137 variation.

138

139 *2.2 Participants*

140 Using the findings of Fong et al. (2011), we performed a representative analysis to determine
141 the appropriate sample size based on measures of ankle DF ROM and its relationship with
142 peak vGRF ($r = -0.411$). Calculations indicated that to achieve 80% statistical power, a
143 minimum of 32 participants were required to detect a significant ($P < 0.05$) correlation
144 between ankle DF ROM and peak vGRF. Thirty-nine recreational athletes (22 men, 17
145 women, age = 22 ± 4 years, height = 1.74 ± 0.15 m, body mass 70.2 ± 15.1 kg) volunteered to
146 participate in this study. Recreational athletes were defined as a person who regularly
147 competes 1-3 times per week in sport events involving landings activities, such as court,
148 racquet or team sports (Chappell, Yu, Kirkendall & Garrett, 2002). Any participant with a
149 history of lower-extremity surgery or had lower-extremity injury six-months prior to testing
150 were excluded. All participants were informed of the risks associated with the testing, prior to
151 completing a pre-exercise questionnaire and providing informed written consent. Ethical
152 approval was provided by the Institutional Research Ethics Panel.

153

154 *2.3 Weight-bearing lunge test*

155 Following the recording of height and body mass, ankle DF ROM was measured for both the
156 right and left limb in barefoot using the weight-bearing lunge test (WBLT). The WBLT was
157 chosen to measure ankle DF ROM due to its functional similarities to landings as a closed
158 kinetic chain movement (Whitting, Steele, McGhee & Munro, 2013). To measure tibia angle
159 relative to vertical on the lead leg during the WBLT, the trigonometric calculation method
160 ($\text{DF ROM} = 90 - \arctan [\text{ground-knee/heel-wall}]$) was employed for each attempt using the
161 heel-wall and ground-knee distances (Langarika-Rocafort, Emparanza, Aramendi, Castellano
162 & Calleja-González, 2017). In order to measure the heel-wall distance, a 0.70 m tape
163 measure was fixed to the floor, perpendicular to the wall used for testing. Measurements of

164 ground-knee distance were obtained with a 0.70 m tape measure fixed vertically to the wall
165 and perpendicular to the tape measure on the ground. A longitudinal line was marked down
166 on each of the scales for testing purposes.

167

168 Using methods previously described (Langarika-Rocafort et al., 2017), participants began the
169 test by facing a bare wall, with the greater toe of the test leg positioned against the wall. The
170 greater toe and the center of the heel were aligned using the marked line on the ground.

171 Participants were instructed to place the non-test foot behind them, with the heel raised and at
172 a distance that they felt allowed them to maximize their performance on the test. In order to
173 maintain balance, participants were asked to keep both hands firmly against the wall

174 throughout. The participants were then instructed to slowly lunge forward by simultaneously
175 flexing at the ankle, knee and hip on the lead leg in an attempt to make contact between the
176 center of the patella and the vertical marked line on the wall. No attempt was made to control

177 trunk alignment. Subtalar joint position was maintained by keeping the test foot in the

178 standardized position and ensuring the patella contact with the vertical line was accurate

179 (Dill, Begalle, Frank, Zinder and Padua, 2014; Whitting et al., 2011). Upon successful

180 completion of an attempt, where contact between the patella and the wall was made with no

181 change in heel position relative to the ground, participants were instructed to move the test

182 foot further away from the wall by approximately 0.05 m. Although participants were not

183 restricted to the number of attempts they were permitted at a given distance, no more than

184 three attempts were performed by any participant. At the last successful attempt, the distances

185 between the heel and the wall, and the distance between the anterosuperior edge of the patella

186 and the ground were recorded to the nearest 0.1 cm. Mean inter-limb difference for ankle DF

187 ROM were $1.9 \pm 1.3^\circ$. This procedure was repeated three times, with the mean value for the

188 right limb from the three attempts used for data analysis. Intra-rater reliability for

189 measurements of WBLT performance was calculated using the three values recorded for
190 heel-to-wall distance, knee-to-ground distance and the WBLT score. Two-way mixed (single
191 measure) intra-class correlation coefficients (ICC) for knee-to-wall distance, heel-to-wall
192 distance and WBLT scores was 0.99, 0.98 and 0.97, respectively. Typical error (TE) for
193 knee-to-wall distance, heel-to-wall distance and WBLT scores was 0.11 cm, 0.13 cm and
194 0.66°, respectively.

195

196 *2.4 Establishing drop height for bilateral drop-landings*

197 Following a standardized warm-up, participants were familiarized with the CMJ. For the
198 CMJ, participants stood bare feet with a hip-width stance and each foot placed on a separate
199 portable force platform recording at 1000 Hz (Pasco, Roseville, CA, USA). The force plates
200 were positioned side-by-side, 0.05 m apart and embedded in custom-built wooden mounts
201 that were level with the force platforms and did not allow any extraneous movement during
202 the landing. Participants' hands were placed on their hips and remained in this position
203 throughout the jump to isolate the contribution from the lower-extremity. Participants were
204 then asked to rapidly descend prior to explosively jumping as high as possible, with no
205 control being placed on the depth or duration of the countermovement. For data collection,
206 three maximal effort CMJs were performed, with 60 s recovery between attempts. Using a
207 custom-made Microsoft Excel spreadsheet, the force-time data was analysed using the time in
208 the air method to calculate vertical jump height to the nearest 0.01 m (Moir, 2008). The
209 maximum value of the three attempts was then used to calculate box height for the bilateral
210 drop-landings.

211

212 *2.5 Bilateral drop-landings*

213 Following the performance of the CMJ, reflective markers were placed on each participant by
214 the same investigator using the anatomical locations for sagittal-plane lower-extremity joint
215 movements and frontal-plane projection angle (FPPA) outlined by Dingenen et al. (2015) and
216 Munro, Herrington and Carolan (2012), respectively. For sagittal-plane views, reflective
217 markers were placed on the right acromioclavicular joint, greater trochanter, lateral femoral
218 condyle, lateral malleolus and 5th metatarsal head (Dingenen et al., 2015). To establish FPPA
219 for the right knee joint, reflective markers were placed at the center of the knee joint
220 (midpoint between the femoral condyles), center of the ankle joint (midpoint between the
221 malleoli) and on the proximal thigh (midpoint between the anterior superior iliac spine and
222 the knee marker). Midpoints for the knee and ankle were measured with a standard tape
223 measure (Seca 201, Seca, United Kingdom), as outlined by Munro et al. (2012).

224

225 Participants then repeated the standardized warm-up, before being familiarized with the
226 bilateral drop-landings from drop heights of 50%, 100% and 150% of their maximum CMJ
227 height. Bilateral drop-landings were performed with participants standing with their arms
228 folded across their chest on a height-adjustable platform (to the nearest 0.01 m). Participants
229 were then instructed to step off the platform whilst ensuring that they did not modify the
230 height of the center of mass prior to dropping from the platform (Zhang et al., 2000). For a
231 landing to be deemed successful, participants were required to ensure they landed with each
232 foot in complete contact with the respective portable force platform, which was positioned
233 0.15 m away from the elevated platform. Full contact with the force platform was visually
234 monitored throughout by the investigator, with attempts being disregarded when participants
235 made contact with the surrounding wooden mounts or failed to maintain balance (e.g. either
236 taking a step or placing a hand on the ground to prevent falling) upon landing. Participants
237 were instructed to “*land as softly as possible with both feet contacting the force platforms*

238 *simultaneously and with equal weight distribution before returning to a standing position”* to
239 allow for focus of attention to be controlled between trials (Milner, Fairbrither, Srivatsan &
240 Zhang, 2012). To ensure participants displayed their natural landing strategy, no instructions
241 were provided regarding heel contact with the ground during the landing phase of the
242 movement. No feedback on landing performance was provided at any point during testing.
243 All landings were performed barefoot so to prevent any heel elevation associated with
244 footwear from altering landing mechanics and weakening internal validity (Lindenberg &
245 Carcia, 2013). For each drop height, participants performed five landings for data collection,
246 with 60 s recovery provided between landings. Participants completed each block of five
247 bilateral drop-landings from the same drop height in succession, with drop height order
248 randomized using a counterbalanced design.

249

250 For 2D video analysis, right lower extremity sagittal- and frontal-plane joint movements were
251 recorded using three standard digital video cameras sampling at 60 Hz (Panasonic HX-
252 WA30). Both cameras were set up using the procedures outlined by Payton (2007). For
253 sagittal- and frontal-plane joint movements, a camera was positioned 3.5 m from the right
254 side and front of the force platforms, respectively (Dingenen et al., 2015; Dingenen, Malfait,
255 Vanrenterghem, Verschueren, SM & Staes, 2014). All cameras were placed on a tripod at a
256 height of 0.60 m from the ground (Dingenen et al., 2014; Dingenen et al., 2015).

257

258 *2.6 Data analysis*

259 Raw vGRF data for the right leg were low-pass filtered using a fourth-order Butterworth filter
260 with a cut-off frequency of 50 Hz (Roewer, Ford, Myer & Hewett, 2014). Peak vGRF, time
261 to peak vGRF and loading rate was then calculated for the right leg. Peak vGRF data were

262 normalized to body mass and initial contact velocity ($\text{N}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$). To normalize peak
263 vGRF to drop height, initial contact velocity was calculated using the following equation
264 (Niu, Feng, Jiang, & Zhang, 2014):

$$265 \quad \text{Initial contact velocity (m}\cdot\text{s}^{-1}) = \sqrt{2g \cdot DH}$$

266 where g is the gravitational acceleration and DH is drop height. For time to peak vGRF to be
267 determined, initial contact was identified as the point that vGRF exceeded 10 N for the right
268 limb. Time to peak vGRF was then calculated as the time difference between initial contact
269 and the time point where peak vGRF occurred. Loading rate was calculated as normalized
270 peak vGRF to body mass divided by time to peak vGRF. Within-session reliability for kinetic
271 measures of bilateral drop-landing performance for the step-off limb from drop heights
272 equalling 50%, 100% and 150% of CMJ height have previously been reported (Howe, North,
273 Waldron & Bampouras, 2018), with normalized peak vGRF, time to peak vGRF and loading
274 rate possessing ICC ranging from 0.87-0.92, 0.75-0.91 and 0.88-0.94, respectively. For
275 normalized peak vGRF, time to peak vGRF and loading rate, TE ranged from 0.20-0.22
276 $\text{N}\cdot\text{kg}^{-1}$, 0.007-0.034 s and 4.85-5.61 $\text{N}\cdot\text{s}^{-1}$, respectively across drop heights (Howe et al.,
277 2018).

278

279 All video recordings were analysed with free downloadable software (Kinovea for Windows,
280 Version 0.8.15). For sagittal-plane joint movements, hip flexion, knee flexion and ankle
281 dorsiflexion angles were calculated at initial contact and the maximum flexion point for the
282 right limb. These angles were then used to calculate joint displacement for each joint by
283 subtracting the initial contact angle from the maximum flexion point. Initial contact was
284 defined as the frame prior to visual impact between the foot and the ground that led to
285 deformation of the foot complex. The maximum flexion point was identified visually and

286 defined as the frame where no further downward motion occurred at the hip, knee or ankle
287 joints (Dingenen et al., 2015).

288

289 Hip flexion angle was calculated as the angle between a line formed between the
290 acromioclavular joint and the greater trochanter and a line between the greater trochanter and
291 the lateral femoral condyle. Knee flexion angle was calculated as the angle between a line
292 formed between the greater trochanter and the lateral femoral condyle and a line between the
293 femoral condyle and the lateral malleolus. Ankle dorsiflexion angle was calculated as the
294 angle between a line formed between the lateral femoral condyle and the lateral malleolus
295 and a line between the lateral malleolus and the 5th metatarsal head. FPPA was calculated for
296 the right limb at the deepest landing position, defined as the frame corresponding to
297 maximum knee flexion (Munro et al., 2012). This angle was calculated as the angle between
298 the line formed between the proximal thigh marker and the knee joint marker and a line
299 between the knee joint marker and the ankle joint marker (Munro et al., 2012). For hip
300 flexion, knee flexion and ankle dorsiflexion, smaller values represented greater hip flexion,
301 knee flexion and ankle dorsiflexion respectively. For FPPA, values $<180^\circ$ represented knee
302 valgus and values $>180^\circ$ representing knee varus.

303

304 For establishing intra-rater reliability of the hip, knee and ankle joint angle at initial contact
305 and at the maximum flexion point, along with FPPA, the first trial from drop heights of 150%
306 of CMJ height was examined. Twenty randomly selected participants (11 males and 9
307 females) were examined twice by the same investigator, seven days apart. To determine intra-
308 rater reliability for joint angles at initial contact and the maximum flexion point, two-way
309 mixed (single measure) ICC and TE for the same trial was established using a customized

310 spreadsheet (Hopkins, 2016). All 2D kinematic outcome measures showed excellent intra-
311 rater reliability, with ICC for joint angles at initial contact ranging from 0.96 to 0.98 and all
312 TE values $<1.2^\circ$. Intra-class correlation coefficients for joint angles at the maximum flexion
313 point ranged from 0.95 to 0.99, with all TE values $<1.5^\circ$.

314

315 2.7 Statistical analysis

316 Descriptive statistics (means \pm standard deviation) were calculated for all dependent
317 variables. The assumption of normality was checked using the Shapiro-Wilk test. Pearson
318 bivariate correlation analysis were used to establish the relationship between ankle DF ROM
319 and kinetic and kinematic dependant variables associated with bilateral drop-landing
320 performance from drop heights of 50%, 100% and 150% of maximum CMJ height. Pearson
321 bivariate correlations were interpreted as *trivial* (0.0-0.1), *small* (0.1-0.3), *moderate* (0.3-0.5),
322 *large* (0.5-0.7), *very large* (0.7-0.9), *nearly perfect* (0.9-1) and *perfect* (1) (Hopkins, 2016).
323 95% confidence intervals were calculated for all bivariate correlations to determine the
324 influence of drop height on the relationship between ankle DF ROM and landing mechanics.
325 The *alpha-priori* level of significance was set at $P < .05$. All statistical tests were performed using
326 SPSS® statistical software package (v.24; SPSS Inc., Chicago, IL, USA).

327

328 3. Results

329 Mean ankle DF ROM for the WBLT was $36.3 \pm 3.9^\circ$. Descriptive statistics for dependant
330 variables associated with bilateral drop-landing performance from drop-heights of 50%,
331 100% and 150% of CMJ height, along with correlation coefficients and probability statistics,
332 are presented in Table 1, 2 and 3, respectively. Normalized peak vGRF, time to peak vGRF

333 and loading rate for all drop heights was not related to DF ROM, with values ranging from
334 *trivial* to *small* (Table 1, 2 and 3).

335

336 From a drop height of 50% (0.15 ± 0.04 m) of maximum CMJ height, significant *moderate*
337 relationships were found between ankle DF ROM and peak knee flexion angle, FPPA and
338 sagittal-plane knee joint displacement (Table 1). From drop heights of 100% (0.30 ± 0.08 m)
339 and 150% (0.44 ± 0.12 m) of maximum CMJ height, ankle DF ROM was related (*moderate*
340 to *large*) to knee flexion angle at initial contact, peak ankle dorsiflexion and peak knee
341 flexion angle, FPPA and sagittal-plane knee joint displacement (Table 2 and 3). Ankle DF
342 ROM was *moderately* related to initial contact angles at the ankle at 100% of maximum CMJ
343 height (Table 2). 95% confidence intervals for all bivariate correlations demonstrated overlap
344 across all drop heights. All other relationships were not significant.

345

346 ***INSERT TABLES 1-3 HERE***

347

348 **4. Discussion**

349 The aim of this study was to evaluate the relationship between ankle DF ROM, measured via
350 the WBLT, and the kinetic and kinematic variables associated with bilateral drop-landing
351 performance. We hypothesized that limitations in ankle DF ROM would result in greater
352 peak vGRF and altered coordination strategies. However, we partially reject this hypothesis,
353 as only relationships between ankle DF ROM and kinematic variables were found during
354 bilateral drop-landings, without changes in kinetic variables associated with vGRF across all
355 drop heights. Ankle DF ROM was mostly *moderately* related to a number of kinematic

356 variables at the knee and ankle joints, indicating a large amount of unexplained variance in
357 the relationship between ankle DF ROM and kinematic variables associated with landing
358 performance. In addition, the relationship between ankle DF ROM and some kinematic
359 variables were only apparent at drop heights of 100% and 150% of CMJ height, indicating
360 greater mechanical loads may exaggerate the demands for compensatory strategies in
361 coordination during landings. However, there was no association between ankle DF ROM
362 and hip joint kinematics during landings. Therefore, ankle DF ROM is related only to
363 kinematic variables of the ankle and knee during drop-landings, with some relationships
364 becoming significant only at higher drop-landing heights.

365

366 The principal finding for this investigation was that ankle DF ROM did not correlate to peak
367 vGRF, time to peak vGRF or loading rate during landings for all drop heights. Among some
368 studies, inverse relationships between ankle DF ROM and peak vGRF in both healthy (Fong
369 et al., 2011) and previously injured (Hoch, Farwel, Gaven & Weinhandl, 2015) participants
370 has been reported during landing tasks. However, consistent with our results, investigations
371 by Whitting et al. (2011) and Malloy et al. (2015) have found no relationship between ankle
372 DF ROM and peak vGRF during landing tasks. Although differences in study design may
373 explain these conflicting findings, one possible reason may be the different compensatory
374 movement patterns observed between studies. For example, participants with limited ankle
375 DF ROM have been shown to compensate in the frontal-plane, with increased peak rearfoot
376 eversion (Whittling et al., 2013) and knee abduction angles (Malloy et al., 2015). However,
377 no such relationship was reported by Fong et al. (2011). It has been suggested that during
378 landing tasks, frontal- and transverse-plane compensations in the lower-extremity caused by
379 restrictions in ankle DF ROM, may enable individuals to access a movement strategy that
380 allows for the continued lowering of the center of mass to attenuate peak vGRF (Mason-

381 Mackay et al., 2017). The disadvantage to this strategy would be the potential for excessive
382 loading on the passive structures supporting the knee joint as valgus alignment increases (Yu
383 & Garrett, 2007), resulting in a greater injury risk. Thus, in the current study, the weak
384 relationships between vGRF and ankle DF ROM are likely to be explained by an altered
385 kinematic profile during landing.

386

387 We also hypothesized that the hip joint would contribute to the attenuation of vertical forces
388 during landing tasks. This was based upon previous findings showing the rate of hip flexion
389 is highest at the time of peak vGRF (Yeow et al., 2011a), indicating that the hip joint has a
390 primary role in the dissipation of vGRF during landings. Others have also demonstrated that
391 the eccentric work performed by the hip joint musculature increases proportionally with
392 landing from larger drop heights and when “softer” landings are cued in order to reduce peak
393 vGRF (Zhang et al., 2000). Relative to a single-leg landing from the same drop height,
394 double-leg landings have been shown to result in greater hip joint displacement (Yeow, Lee
395 & Goh, 2011b). Collectively, this evidence indicates that the hip joint is a major contributor
396 to the dissipation of forces during bilateral landing tasks. However, if this were the case for
397 our study, a relationship should have been found between ankle DF ROM and sagittal-plane
398 hip kinematics, which wasn't the case. This is a major finding of the current study. It is
399 possible that not all of the current participants with limitations in ankle DF ROM employed a
400 ‘hip joint compensation’ strategy, thus modifying the relationship between ankle DF ROM
401 and either sagittal-plane hip kinematic or peak vGRF. Indeed, the type of compensation
402 strategy adopted among those with ankle DF ROM restrictions is inconsistent between
403 individuals during multi-joint closed kinetic chain activities (Beach, Frost, Clark, Maly &
404 Callaghan, 2014). Furthermore, gender differences in landing strategy have previously been
405 shown during bilateral drop-landings (Decker, Torry, Wyland, Sterett & Steadman, 2003) and

406 therefore, may also account for variation in the compensation strategies observed. Future
407 research should seek to identify whether gender influences the relationship between ankle DF
408 ROM and landing performance.

409

410 An alternative explanation for our findings may be the inverse relationships found between
411 ankle DF ROM and initial contact angles at the ankle ($r = -0.31 - -0.34, P < 0.05$) and knee (r
412 $= -0.37 - -0.40, P < 0.05$) joint. These relationship indicates that individuals with reduced
413 ankle DF ROM compensate during landing tasks by altering their posture at initial contact,
414 with greater ankle plantar flexion and reduced knee flexion. Altering initial contact angles at
415 the lower-extremity have previously been highlighted as a strategy for force dissipation
416 (Blackburn & Padua, 2009; Rowley & Richards, 2015), with greater ankle plantar flexion and
417 reduced knee flexion at initial contact resulting in lower peak vGRF and loading rates during
418 landings (Rowley & Richards, 2015). Landing with greater ankle plantar flexion at initial
419 contact potentially offsets deficits in dorsiflexion at the maximum flexion point to maintain
420 total sagittal-plane joint displacement. This strategy offers individuals with reduced ankle DF
421 ROM a solution to maintaining peak vGRF at a manageable level. To support this suggestion,
422 we did not observe any relationship between ankle DF ROM and initial contact angles at drop
423 heights of 50% of maximum CMJ height, where peak vGRF were notably lower. However,
424 landing with greater ankle plantarflexion at initial contact has been shown to result in greater
425 risk for ankle ligament injury (Wright, Neptune, van den Bogert & Nigg, 2000). Therefore,
426 our findings support the suggestion that deficits in ankle DF ROM potentially result in
427 coordination compensations at initial contact during landings that may result in increased
428 injury risk (Delahunt, Cusack, Wilson & Doherty, 2013).

429

430 Ankle DF ROM was negatively associated with peak flexion angles for the ankle and knee
431 joint at all drop heights. Restrictions in ankle DF ROM have been associated with reduced
432 peak ankle dorsiflexion (Hoch et al., 2015) and knee flexion (Fong et al., 2011; Hoch et al.,
433 2015; Malloy et al., 2015) during various landing tasks. The relationship between ankle DF
434 ROM and peak knee flexion angle during landings is particularly relevant during
435 rehabilitation, or for management of injury risk among athletic populations, who regularly
436 perform landing activities. Limited peak knee flexion during landings has been shown to
437 result in greater peak vGRF (Zhang et al., 2000), quadriceps activity (Blackburn & Padua,
438 2009) and frontal-plane knee abduction moments (Pollard, Sigward & Powers, 2010). The
439 combined increase in these variables is associated with increased risk of ACL injury
440 (Renstrom et al., 2008). As such, limitations in ankle DF ROM may be a modifiable risk
441 factor for ACL injuries.

442

443 We report a positive relationship between ankle DF ROM and FPPA during bilateral drop
444 landings at all drop heights, suggesting that participants with reduced ankle DF ROM had
445 greater knee valgus at the maximum flexion point. This important finding supports previous
446 evidence that limited ankle DF ROM is associated with medial knee displacement during a
447 number of functional closed kinetic chain activities (Lima, de Paula Lima, Bezerra, de
448 Oliveira & Almeida, 2018). It has been suggested that this compensation occurs in order to
449 allow the proximal tibia to continue its forward rotation over the foot via a pronation strategy
450 at the foot complex (Dill et al., 2014). This strategy for managing vGRF during landings is
451 related to increased lower-extremity injury risk (Renstrom et al., 2008) and might be
452 avoidable with increased ROM of the ankle.

453

454 We hypothesized that relationships between ankle DF ROM and landing mechanics would
455 increase at greater drop heights. This was based on previous findings revealing landings from
456 greater drop heights increased peak angles for ankle dorsiflexion (Zhang et al., 2000).
457 Therefore, we hypothesized that participants with reduced ankle DF ROM would utilize less
458 ankle ROM when dropping from greater heights, displaying exaggerated compensations in
459 their coordination strategies in order to dissipate vGRF. While the significant relationships
460 found were descriptively different between drop heights, there was considerable overlap of
461 95% CIs, thereby inferring no statistical differences. As overlap was present in all
462 relationships, our investigation did not identify a clear influence for drop height on the
463 association between ankle DF ROM and landing strategy.

464

465 It is important to acknowledge some potential limitations with the study. Firstly, we
466 investigated the relationship between ankle DF ROM and landing mechanics using a
467 participant sample with both male and female recreational athletes. Landing mechanics have
468 been shown to differ between genders, with less peak knee flexion and greater knee valgus
469 moments being demonstrated by females during landings (Chappell et al., 2002).

470 Nevertheless, our results are similar to studies who identified a relationship between ankle
471 DF ROM and landing mechanics in female (Malloy et al., 2015; Sigward et al., 2008) and
472 male populations (Whitting et al., 2011), as well as investigations using a mixed sample
473 (Fong et al., 2011). Therefore, our results can likely be generalized to both genders.

474 However, the degree to which ankle DF ROM impacts landing mechanics for each gender is
475 currently unknown and warrants further investigation. Another limitation was that our
476 investigation did not consider menstrual cycle status for female participants, which has been
477 shown to influence tendon stiffness and joint laxity (Cesar et al., 2011). It is possible,
478 therefore, that the association found in our investigation between ankle DF ROM and landing

479 performance may be influenced by the menstrual cycle, which researchers may wish to
480 examine in future research.

481

482 **5. Conclusions**

483 Ankle DF ROM did not relate to peak vGRF during bilateral drop-landings. This appears to
484 have occurred due to the compensations in coordination strategies developed by individuals
485 with reduced ankle DF ROM. In particular, our findings indicate that individuals with limited
486 ankle DF ROM may land with greater ankle plantar flexion and knee extension at initial
487 contact, alongside reduced ankle dorsiflexion and knee flexion at the maximum flexion point
488 in order to support the attenuation of GRF. As the relationships established in our
489 investigation were predominantly moderate, factors beyond ankle DF ROM likely influence
490 the landing strategy adopted by an individual. Furthermore, frontal-plane compensations were
491 also observed, with ankle DF ROM also being related with FPPA. Although these alterations
492 in movement strategies allow individuals to manage the vertical forces experience during
493 landings, they may also lead to a greater injury risk during landing activities.

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684 **Table 1.** Descriptive and correlational statistics for the relationship between ankle DF ROM and
 685 kinetic and kinematic variables from drop heights of 50% of maximum countermovement jump
 686 height.

Variable	Mean \pm SD	<i>r</i>	Upper and lower 95% confidence intervals	<i>P</i> value
Peak vGRF, N·kg ⁻¹ ·m·s ⁻¹	1.06 \pm 0.39	-0.28	0.04, -0.55	0.08
Time to peak vGRF, s	0.077 \pm 0.022	-0.12	0.20, -0.42	0.47
Loading rate, N·s ⁻¹	28.1 \pm 18.01	0.01	-0.31, 0.32	0.95
<i>Initial contact angle, °</i>				
Ankle plantar flexion	148.6 \pm 6.9	-0.18	0.14, -0.47	0.28
Knee flexion	169.4 \pm 5.0	-0.15	0.17, -0.44	0.37
Hip flexion	161.6 \pm 7.0	-0.06	0.26, -0.37	0.73
<i>Peak angle, °</i>				
Ankle dorsiflexion	105.5 \pm 9.7	-0.27	0.05, -0.54	0.10
Knee flexion	117.6 \pm 17.3	-0.37	-0.06, -0.61	0.02*
Hip flexion	127.1 \pm 24.0	-0.23	0.09, -0.51	0.16
Frontal plane projection	184.4 \pm 10.7	0.40	0.10, 0.64	0.01*
<i>Sagittal-plane joint displacement, °</i>				
Ankle	43.1 \pm 7.5	0.18	-0.14, 0.47	0.26
Knee	51.8 \pm 14.2	0.39	0.08, 0.63	0.01*
Hip	34.4 \pm 19.6	0.26	-0.06, 0.53	0.11

687 * Significant correlation between ankle dorsiflexion range of motion and variable.

688

689 **Table 2.** Descriptive and correlational statistics for the relationship between ankle DF ROM and
 690 kinetic and kinematic variables from drop heights of 100% of maximum countermovement jump
 691 height.

Variable	Mean \pm SD	<i>r</i>	Upper and lower 95% confidence intervals	<i>P</i> value
Peak vGRF, N \cdot kg ⁻¹ ·m \cdot s ⁻¹	0.85 \pm 0.30	-0.15	0.17, -0.44	0.36
Time to peak vGRF, s	0.065 \pm 0.021	-0.18	0.14, -0.47	0.27
Loading rate, N \cdot s ⁻¹	38.0 \pm 24.0	0.10	-0.22, 0.40	0.55
<i>Initial contact angle, °</i>				
Ankle plantar flexion	149.3 \pm 7.6	-0.34	-0.03, -0.59	0.03*
Knee flexion	167.6 \pm 4.8	-0.37	-0.06, -0.61	0.02*
Hip flexion	161.5 \pm 6.9	-0.07	0.25, -0.38	0.69
<i>Peak angle, °</i>				
Ankle dorsiflexion	104.7 \pm 9.1	-0.44	-0.14, -0.66	0.01*
Knee flexion	107.5 \pm 17.6	-0.42	-0.12, -0.65	0.01*
Hip flexion	114.4 \pm 26.6	-0.26	0.06, -0.53	0.10
Frontal plane projection	186.7 \pm 14.0	0.37	0.06, 0.61	0.02*
<i>Sagittal-plane joint displacement, °</i>				
Ankle	44.5 \pm 7.1	0.19	-0.13, 0.48	0.24
Knee	60.1 \pm 14.9	0.39	0.08, 0.63	0.02*
Hip	47.1 \pm 22.2	0.30	-0.02, 0.56	0.07

692 * Significant correlation between ankle dorsiflexion range of motion and variable.

693

694 **Table 3.** Descriptive and correlational statistics for the relationship between ankle DF ROM and
 695 kinetic and kinematic variables from drop heights of 150% of maximum countermovement jump
 696 height.

Variable	Mean \pm SD	<i>r</i>	Upper and lower 95% confidence intervals	<i>P</i> value
Peak vGRF, N·kg ⁻¹ ·m·s ⁻¹	0.83 \pm 0.24	-0.11	0.21, -0.41	0.53
Time to peak vGRF, s	0.053 \pm 0.012	-0.21	0.11, -0.49	0.19
Loading rate, N·s ⁻¹	52.0 \pm 27.4	0.15	-0.17, 0.44	0.36
<i>Initial contact angle, °</i>				
Ankle plantar flexion	149.6 \pm 7.0	-0.31	0.01, -0.57	0.06
Knee flexion	165.6 \pm 4.5	-0.40	-0.10, -0.64	0.01*
Hip flexion	160.4 \pm 6.9	-0.07	0.25, -0.38	0.67
<i>Peak angle, °</i>				
Ankle dorsiflexion	104.6 \pm 8.4	-0.43	-0.13, -0.66	0.01*
Knee flexion	101.7 \pm 14.6	-0.52	-0.24, -0.72	0.001*
Hip flexion	104.6 \pm 26.4	-0.28	0.04, -0.55	0.08
Frontal plane projection	187.5 \pm 14.3	0.37	0.06, 0.61	0.02*
<i>Sagittal-plane joint displacement, °</i>				
Ankle	45.0 \pm 6.4	0.22	-0.10, 0.50	0.17
Knee	63.6 \pm 12.5	0.47	0.18, 0.68	0.003*
Hip	55.7 \pm 22.2	0.32	0.00, 0.58	0.05

697 * Significant correlation between ankle dorsiflexion range of motion and variable.

698