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1 **Energy dissipation during single-leg landing from three heights in**

2 **individuals with and without chronic ankle instability**

3

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Energy dissipation during single-leg landing from three heights in individuals with and without chronic ankle instability

Abstract

Inadequate energy dissipation during landing may increase the risk of ankle sprain. Mechanical demands (landing height) in landing tasks may affect the biomechanical differences between individuals with and without chronic ankle instability (CAI). However, energy dissipation strategies during landing from various heights in individuals with CAI are unclear. The purpose of this study was to compare the effect of landing height on lower extremity biomechanics between individuals with and without CAI. Eleven participants in each the CAI and Control group performed a single-leg landing from three heights (30, 40, and 50 cm). We calculated the contribution of each joint to total energy dissipation at 50-ms intervals during 0–200 ms post-initial contact (IC). Peak joint angles and moments and joint stiffnesses were calculated during 0–200 ms post-IC. Two-way mixed analysis of variance revealed significant group-by-height interactions for hip energy dissipation at 101–150 ms post-IC and peak ankle plantarflexion and hip extension moment. These significant interactions suggested that the effects of landing height on the ankle and hip joints differ between individuals with and without CAI. The effect of mechanical demands on altered landing biomechanics among CAI populations should be considered in biomechanical studies and clinical practice.

Keywords: ankle sprain; shock absorption; mechanical demand; kinetics; joint work; joint moment

Introduction

Lateral ankle sprain (LAS) is one of the most common musculoskeletal injuries during sporting activities (Fong et al., 2007). The incidence of this injury is high in sporting activities characterized by jumping, landing, and cutting, such as football, basketball, soccer, gymnastics, and volleyball (Hootman et al., 2007). The recurrence rate in basketball players has been reported as 73% (McKay, 2001). Doherty et al. (2016a) reported that 40% of patients with LAS developed to chronic ankle instability (CAI), defined by episodes of "giving way", recurrent sprain, and feelings of instability (Gribble et al., 2013). Altered kinematics of the talus after lateral ankle ligament injury may alter cartilage strain in the talocrural joint and contribute to the development of ankle osteoarthritis (Bischof et al., 2010). Patients who had a history of one or more LASs showed a 46% greater rate of progression to ankle osteoarthritis than healthy individuals (Lee et al., 2021). In addition, CAI is associated with decreased health-related quality of life (Houston et al., 2015) and disruption of participation in sports activities (Kofotolis et al., 2007; Waldén et al., 2013). LAS and CAI can thus lead to not only short-term, but also middle- or long-term sequelae. While many studies have reported the effectiveness of rehabilitation for preventing re-injury and improving perceived instability (Bleakley et al., 2019; Tsikopoulos et al., 2018), a recent epidemiological study reported that the incidence of LAS remains high, and the prevalence of CAI in athletes is about 20% (Koshino et al., 2020). One of the possible reasons for this issue is that insufficient research has been undertaken into the characteristics of CAI, which is one of the major causes of LAS. The present model of CAI is complex, including many factors (Hertel & Corbett, 2019), and further investigation of the relationships between factors may provide insights that contribute to the development of more effective approaches to rehabilitation.

64   Previous case reports have shown that excessive inversion and internal rotation at

65   the ankle joint occurred when LAS or giving-way occurred (Fong et al., 2009; Fong et

66   al., 2012; Gehring et al., 2013; Kosik et al., 2019; Kristianslund et al., 2011; Li et al.,

67   2019; Mok et al., 2011; Panagiotakis et al., 2017; Remus et al., 2018; Terada & Gribble,

68   2015), while plantarflexion did not necessarily occur (Fong et al., 2009; Fong et al., 2012;

69   Kristianslund et al., 2011; Mok et al., 2011; Panagiotakis et al., 2017). Thus, lower

70   extremity kinematics would be related to recurrent sprain. In cross-sectional studies,

71   while the CAI population has been reported to exhibit different joint kinematics of the

72   lower extremity during landing compared with healthy and coper groups, the results

73   regarding ankle inversion angle differed even between studies using similar movement

74   tasks, such as a single-leg drop landing (Delahunt et al., 2006; Doherty et al., 2016b) and

75   a single-leg forward jump landing and cutting (Kim et al., 2019; Koshino et al., 2016;

76   Son et al., 2017). Similar discrepancies have been reported for the knee and hip joints,

77   with different studies showing that the CAI group had greater or lesser flexion angles than

78   the non-CAI group, or no difference between groups, even during similar movement tasks

79   (Caulfield & Garrett, 2002; Delahunt et al., 2006; Doherty et al., 2016b; Kim et al., 2019;

80   Koshino et al., 2016; Son et al., 2017; Terada et al., 2016). In terms of the kinematics of

81   lower extremity joints, differences between individuals with and without CAI were

82   suggested to become more pronounced during high-demand tasks (Brown et al., 2008;

83   Koshino et al., 2014). These inconsistent results for joint kinematics may be due to

84   differences in the demands of the movement tasks. In addition, joint kinematics in the

85   sagittal plane affected joint moment, negative joint work, and time to peak vertical ground

86   reaction force during single-leg landing (Devita & Skelly, 1992; Lee et al., 2018). The

87   effect of the demand may therefore extend to joint kinetics.

88   A case report reported that the contribution of the ankle joint to energy dissipation

89   was increased at the time of injury during double-leg stop jump, suggesting that not only

90   kinematics, but also kinetics may be associated with recurrent LAS in individuals with

91   CAI (Terada & Gribble, 2015). Previous studies have suggested that jump and landing

92   kinetics differ between individuals with and without CAI. During a single-leg forward

93   jump landing and cutting task, the CAI group showed larger extension moment, eccentric

94   joint power, and sagittal-plane joint stiffness at the hip joint and smaller ankle

95   plantarflexion and knee extension moment, eccentric joint power, and sagittal-plane joint

96   stiffness at the ankle and knee joint compared with the control or coper groups (Kim et

97   al., 2018; Son et al., 2017). McCann et al. reported a larger contribution of the hip and

98   proximal (combined the knee and hip) joints to energy dissipation and a smaller

99   contribution of the ankle in the CAI group compared with the coper group during a single-

100   leg forward jump landing (McCann et al., 2018). A hip- or proximal-dominant strategy

101   may result from individuals with CAI attempting to reduce demands on the ankle (Kim

102   et al., 2018; McCann et al., 2018; Dejong et al., 2020). In addition, a recent systematic

103   review suggested that jumping movements with increasing demand may highlight hip

104   adaptations in individuals with CAI (Dejong et al., 2020). Thus, the joint kinetics of the

105   lower extremity in individuals with CAI as well as kinematics may be affected by the

106   demands of jumping and landing movements and may change as demand increases.

107   A previous study showed that the change in joint work with increasing landing

108   height as a representation of mechanical demand in healthy individuals was greater in the

109   knee and hip joints than in the ankle joint during step-off landing (Zhang et al., 2000).

110   Changes in the ankle, knee, and hip joint work with increasing landing height from 32 cm

111   to 62 cm were all 1.4 times, while changes of 1.7, 1.9, and 2.3 times, respectively, were

112   seen when height increased from 32 cm to 103 cm (Zhang et al., 2000). This tendency

113   may be more marked in individuals with CAI than in healthy individuals; those with CAI

114   may show a hip- or proximal (knee and hip)-dominant movement pattern in conditions of

115   higher mechanical demand, because high-demand landings have shown these

116   characteristics (Kim et al., 2018; McCann et al., 2018). However, no studies have

117   investigated the effect of landing height on landing biomechanics among individuals with

118   CAI. Clarification of the effect of mechanical demand (landing height) on landing

119   biomechanics would provide clinicians with suggestions on the need for evaluation and

120   training at several levels of demand in clinical practice. The purpose of this study was to

121   compare the effects of landing height on landing biomechanics among individuals with

122   and without CAI. Our hypotheses were: 1) the effect of landing height on landing

123   biomechanics would differ between individuals with and without CAI; and 2) the

124   contribution of the knee and hip joints would increase among individuals with CAI

125   compared with those without CAI at higher landing height.

126

127   **Materials and methods**

128   ***Participants***

129   Before this study, we conducted a pilot study that involved four CAI participants and

130   four control participants, using the same experimental procedure (see below) as in this

131   study. The results showed that the partial η^2 of the interaction on the peak hip extension

132   moment was 0.181. Using the value, we performed an a priori power analysis using

133   G*power 3.1 (University of Dusseldorf, Dusseldorf, Germany). A sample size of 18

134   participants (9 participants per group) was found to be necessary to achieve a statistical

135   significance level of 0.05 and statistical power of 0.80 for group-by-height interaction

136   on peak hip extension moment. Considering the possibility of missing data, we finally

137   recruited 22 participants (11 CAI participants, 11 control participants) to the study. All

138 participants provided written informed consent before enrolment in the study. This

139 study was approved by the ethics committee of our university.

140 Participants were recruited from among competitive collegiate athletes who

141 belong to the sports clubs at our university. We asked the following sports clubs to

142 participate in this study: track and field, badminton, lacrosse, soccer, tennis, ice hockey,

143 field hockey, basketball, volleyball, and gymnastics. A total of 379 athletes (243 males,

144 136 females) were screened for demographic data (age, height, weight, dominant leg,

145 history of LAS, and previous injury) and the Cumberland Ankle Instability Tool

146 Japanese version (CAIT-J) score. Twenty-five athletes met the following inclusion

147 criteria for the CAI group based on the 2013 position statement of the International

148 Ankle Consortium (Gribble et al., 2013): i) history of at least one LAS with interruption

149 of desired physical activity for at least one day, 12 months or more before enrollment in

150 this study; ii) history of at least two LASs; iii) at least two episodes of the ankle

151 "giving-way" in the 6 months before enrollment in this study; and iv) CAIT-J score ≤ 25

152 (Kunugi et al., 2017). Of these, 14 athletes declined to participate in this study due to

153 time constraints and were therefore excluded. Finally, 11 athletes who agreed to

154 participate in this study were included in the CAI group. Control participants were

155 matched to CAI participants for age (± 3 years old), height (± 5 cm), weight (± 5 kg),

156 and sex. A total of 11 athletes were included in the Control group from the same athletic

157 population as CAI participants. Inclusion criteria for the Control group comprised: i) no

158 history of LAS; and ii) CAIT-J score ≥ 28. Participants were excluded if they met the

159 following exclusion criteria (Gribble et al., 2013): i) a history of fracture or surgery in

160 the lower limb; or ii) a history of major musculoskeletal injuries in the lower limb (other

161 than a history of LAS in the CAI group) in the 3 months before study enrollment. No

162 participants in either group had any history of neurological or vestibular impairments.

163   For CAI participants, the tested limb was the affected side. If CAI was present

164   bilaterally, the more affected side (as determined by the CAIT-J score) was tested. The

165   CAI and Control groups were matched for the dominance of the tested limb. The

166   dominant leg was defined as the leg that the participant would use to kick a ball

167   (Sadeghi et al., 2000).

168

169   ***Instrumentation***

170   Twenty-five retroreflective markers were placed on specific anatomical landmarks

171   using double-sided adhesive tape, based on a modified Helen Hayes marker set (Kadaba

172   et al., 1990): at the sacrum, bilaterally on the anterior superior iliac spine, greater

173   trochanters, lateral aspect of the thighs, lateral and medial femoral epicondyles, lateral

174   aspect of the shanks, lateral and medial malleoli, posterior heels, and first, second, and

175   fifth metatarsal heads. Participants were barefoot during data collection. Kinematic data

176   were collected using seven infrared cameras (Hawk cameras; Motion Analysis

177   Corporation, Santa Rosa, CA, USA) at 200 Hz. Ground reaction force (GRF) data were

178   collected using a force plate (Type 9286B; Kistler, Winterthur, Switzerland) at 1000 Hz.

179   Kinematic and GRF data were time-synchronized through Cortex 5.5 (Motion Analysis

180   Corporation).

181

182   ***Procedures***

183   First, the static trial was performed with the participant standing, with feet hip-width

184   apart and arms abducted to 90°. Next, participants performed single-leg landing tasks

185   from three landing heights (30, 40, and 50 cm), in random order (Weinhandl et al.,

186   2015). Participants stood on the box in front of a force plate with the tested limb.

187   Participants dropped from the box and landed on the force plate with the tested limb.

188 Participants were asked to keep the hands on the waist, face forward, and maintain a

189 single-leg stance for 5 s after landing. Trials were excluded from data analysis if the

190 entire foot did not contact the force plate, the hands were off the waist, and/or the

191 participant could not maintain a single-leg stance for 5 s after landing. Three successful

192 trials were collected for each landing height. A 1-min rest period was provided between

193 trials to prevent fatigue.

194

195 ***Data analysis***

196 Three-dimensional marker trajectories were filtered using a fourth-order low-pass

197 Butterworth filter with a cutoff frequency of 12 Hz (Ford et al., 2007). For each trial, a

198 lower limb model (comprising the foot, shank, thigh, and pelvis segments) was created

199 using Visual 3D software (C-motion; Germantown, MD, USA) to calculate ankle, knee,

200 and hip joint angles. Joint coordinate systems were defined using the positive x-axis as

201 forward, the positive y-axis as upward, and the positive z-axis as to the right-hand side.

202 Joint angles were calculated using the z-x-y rotation sequence to be equal to the Cardan

203 sequence, and values during the static trial were set to zero. The ankle joint center was

204 defined as the midpoint between lateral and medial malleoli. The knee joint center was

205 set as the midpoint between the lateral and medial femoral epicondyles. The hip joint

206 center was defined based on the method reported by Davis et al (Davis et al., 1991).

207 Using a fourth-order low-pass Butterworth filter with a cutoff frequency of 12 Hz (Ford

208 et al., 2007), GRF data were filtered and synchronized to kinematics data with down-

209 sampling. GRF data were normalized by dividing by weight of each participant.

210   Internal joint moments of the ankle, knee, and hip in the sagittal plane were

211 calculated using an inverse dynamics method (Winter, 2009) and normalized by the

212 height and weight of each participant. The products of joint moment and joint angle

213   velocity represented joint power. Energy dissipations were calculated by integrating the

214   negative region of the joint power curve. Ankle, knee, and hip energy dissipation were

215   summed to calculate total energy dissipation in the sagittal plane. Lastly, we calculated

216   the percentage of energy dissipation by each joint to total energy dissipation, as the

217   contribution of each joint to energy dissipation. Based on a previous study (McCann et

218   al., 2018), percentages of energy dissipation were calculated during the following four

219   periods: 1–50, 51–100, 101–150, and 151–200 ms post-initial contact (IC). Joint

220   stiffnesses of the ankle, knee, and hip joints in the sagittal plane were calculated by

221   dividing the change in internal joint moment from initial contact to peak ankle

222   dorsiflexion and knee and hip flexion, respectively, by the change in joint angle. For

223   joint angles, joint moments, and vertical GRF, we calculated maximum values from IC

224   to 200 ms post-IC. IC was defined as the first point at which vertical GRF exceeded 10

225   N (Ford et al., 2007). For all variables, the means of three successful trials for each

226   condition were used for statistical analyses.

227

228   ***Statistical analysis***

229   Demographic data (age, height, weight, the number of LASs) and CAIT-J scores were

230   compared between the CAI and Control groups using the unpaired t-test. Two-way

231   mixed analysis of variance (ANOVA) was conducted to test for the main effect of group

232   (CAI and Control) and height (30, 40, and 50 cm) and group-by-height interaction on

233   peak vertical GRF, peak joint angle, peak joint moment, the contribution to total energy

234   dissipation, and joint stiffness of each joint. If a significant main effect or interaction

235   was found, Bonferroni post hoc procedures were performed. For two-way mixed

236   ANOVA, effect size was presented as η^2 and interpreted as: $0.01 < \text{small} \leq 0.06 <$

237   medium $\leq 0.14 < $ large (Cohen, 1988). For multiple comparison tests using the

238   Bonferroni correction, Cohen's *d* with 95% confidence interval (CI) was calculated, and

239   interpreted as: $0.20 < \text{small} \le 0.50 < \text{medium} \le 0.80 < \text{large}$ (Cohen, 1988). The level of

240   statistical significance was set at $P < 0.05$. Statistical analyses were performed using

241   IBM SPSS Statistics version 22 (IBM, Chicago, IL, USA). After all statistical analyses,

242   we performed a post hoc power analysis for all ANOVAs by calculating statistical

243   power ($1-\beta$) using G*power 3.1 (University of Dusseldorf).

244

245   **Results**

246   No significant differences were identified in age, height, or weight between the CAI and

247   the Control groups (Table 1). The CAI group displayed significantly lower CAIT-J

248   scores and a significantly larger number of LASs than the Control group. In addition, no

249   significant differences in the number of failed trials were seen between groups under

250   each condition.

251   Figure 1 shows the energy dissipation of each joint in each interval, and Table 2

252   shows the *P*-values, effect sizes, and statistical power for ANOVA. In addition, Tables

253   3 and 4 show Cohen's *d*, as the effect size in multiple comparisons for each variable. A

254   significant group-by-height interaction was found for hip energy dissipation at 101–150

255   ms post-IC with a small effect size (Table 2). There were no significant main effects of

256   group for all energy dissipation. A significant main effect of height was observed for all

257   parameters with large effect size except as follows: hip energy dissipation at 51–100

258   ms, and ankle, knee, and hip dissipation at 151–200 ms. For the hip energy dissipation

259   at 101–150 ms post-IC, multiple comparisons revealed that the CAI group showed

260   significant differences in all landing heights, while the Control group showed

261   significant differences between the 30- and 50-cm conditions and the 40- and 50-cm

262   condition (Figure 1 and Table 4). There was no group difference in hip energy

263 dissipation at 101–150 ms post-IC in all conditions (30-cm: $P = 0.352$, 40-cm: $P =$

264 0.818, 50-cm: $P = 0.665$).

265   Figure 2 shows peak joint angle of each joint. We observed no group-by-height

266 interactions for any joint angles (ankle dorsiflexion: $P = 0.414$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.30$;

267 ankle inversion: $P = 0.378$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.33$; knee flexion: $P = 0.300$, $\eta^2 = 0.01$, $1\text{-}\beta$

268 $= 0.39$; hip flexion: $P = 0.470$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.26$). A significant main effect of group

269 was observed for ankle dorsiflexion and knee flexion angle with large and medium

270 effect sizes, respectively (ankle dorsiflexion: $P = 0.010$, $\eta^2 = 0.23$, $1\text{-}\beta = 1.00$; ankle

271 inversion: $P = 0.164$, $\eta^2 = 0.09$, $1\text{-}\beta = 0.62$; knee flexion: $P = 0.032$, $\eta^2 = 0.14$, $1\text{-}\beta =$

272 0.95; hip flexion: $P = 0.396$, $\eta^2 = 0.03$, $1\text{-}\beta = 0.25$). A significant main effect of height

273 was observed for all parameters except peak ankle inversion angle (ankle dorsiflexion:

274 $P < 0.001$, $\eta^2 = 0.09$, $1\text{-}\beta = 1.00$; ankle inversion: $P = 0.464$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.27$; knee

275 flexion: $P < 0.001$, $\eta^2 = 0.27$, $1\text{-}\beta = 1.00$; hip flexion: $P < 0.001$, $\eta^2 = 0.07$, $1\text{-}\beta = 1.00$).

276 Multiple comparisons revealed that the CAI group showed a larger peak ankle

277 dorsiflexion angle than the Control group under all height conditions (30 cm: $P = 0.006$;

278 40 cm: $P = 0.025$; 50 cm: $P = 0.029$, Figure 2A). Peak knee flexion angle was larger in

279 the CAI group than in the Control group in the 50-cm condition ($P = 0.011$, Figure 2C)

280 and tended to be larger in the CAI group than in the Control group in the 30- and 40-cm

281 conditions ($P = 0.059$ and $P = 0.098$, respectively). Significant differences between

282 height conditions were observed for all combinations of conditions except as follows:

283 peak ankle dorsiflexion angle between the 40- vs 50-cm conditions in both groups, peak

284 ankle inversion angle between all conditions in both groups, and peak hip flexion angle

285 between the 30- and 40-cm conditions in the CAI group.

286   Figure 3 shows peak joint moment of each joint. Significant group-by-height

287 interactions were observed for peak joint moment of the ankle and hip with medium and

288   small effect sizes, respectively (ankle: $P = 0.005$, $\eta^2 = 0.05$, 1-$\beta = 0.98$; knee: $P = 0.928$,

289   $\eta^2 = 0.00$, 1-$\beta = 0.08$; hip: $P = 0.008$, $\eta^2 = 0.05$, 1-$\beta = 0.98$). A significant main effect of

290   group was observed on peak ankle plantarflexion moment with a large effect size ($P =$

291   0.012, $\eta^2 = 0.20$, 1-$\beta = 0.99$), but not on peak knee and hip extension moment (knee: P

292   $= 0.129$, $\eta^2 = 0.02$, 1-$\beta = 0.70$; hip: $P = 0.457$, $\eta^2 = 0.01$, 1-$\beta = 0.20$). A significant main

293   effect of height was found for all joint moments with medium to large effect sizes

294   (ankle: $P = 0.001$, $\eta^2 = 0.10$, 1-$\beta = 1.00$; knee: $P < 0.001$, $\eta^2 = 0.72$, 1-$\beta = 1.00$; hip: $P <$

295   0.001, $\eta^2 = 0.60$, 1-$\beta = 1.00$). Multiple comparisons revealed that peak ankle

296   plantarflexion moment was significantly increased in the CAI group as landing height

297   increased, but was unchanged in the Control group (Figure 3A). Furthermore, the CAI

298   group demonstrated significantly greater peak ankle plantarflexion moment than the

299   Control group under the 50-cm condition ($P = 0.005$) and a tendency toward greater

300   peak ankle plantarflexion moment than the Control group under the 30- and 40-cm

301   conditions ($P = 0.055$ and $P = 0.065$, respectively). Peak hip extension moment differed

302   significantly between all landing heights in the CAI group, while no significant

303   difference was identified between 40- and 50-cm conditions in the Control group

304   (Figure 3C). Although no significant differences were found between groups, the CAI

305   group tended to exhibit greater peak hip extension moment compared with the Control

306   group under the 50-cm condition ($P = 0.074$).

307   Figure 4 shows joint stiffness in the sagittal plane of each joint and peak vertical

308   GRF. We observed no significant group-by-height interactions for joint stiffnesses

309   (ankle: $P = 0.250$, $\eta^2 = 0.00$, 1-$\beta = 0.45$; knee: $P = 0.370$, $\eta^2 = 0.00$, 1-$\beta = 0.33$; hip: $P =$

310   0.735, $\eta^2 = 0.00$, 1-$\beta = 0.09$). We did not find any significant main effect of group for

311   stiffness in any joint (ankle: $P = 0.934$, $\eta^2 = 0.00$, 1-$\beta = 0.05$; knee: $P = 0.823$, $\eta^2 = 0.00$,

312   1-$\beta = 0.01$; hip: $P = 0.291$, $\eta^2 = 0.04$, 1-$\beta = 0.37$). A significant main effect of height

313 was found on knee and hip stiffness with a medium effect size (knee: $P < 0.001$, $\eta^2 =$

314 0.10, $1\text{-}\beta = 1.00$; hip: $P < 0.001$, $\eta^2 = 0.12$, $1\text{-}\beta = 1.00$), but not on ankle stiffness (ankle:

315 $P = 0.891$, $\eta^2 = 0.00$, $1\text{-}\beta = 1.00$). No significant interaction or main effect of group was

316 found for peak vertical GRF, but a significant main effect of height was evident

317 (interaction: $P = 0.282$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.41$; main effect of group: $P = 0.909$, $\eta^2 =$

318 0.00, $1\text{-}\beta = 0.05$; main effect of height: $P < 0.001$, $\eta^2 = 0.58$, $1\text{-}\beta = 1.00$). Multiple

319 comparisons showed significant differences between all conditions for peak vertical

320 GRF in both groups ($P < 0.05$, Figure 4D).

321

322 **Discussion and implications**

323 The purpose of this study was to compare changes in energy dissipation strategy with

324 increasing landing height between individuals with and without CAI. The main findings

325 of this study were as follows. First, we observed significant group-by-height

326 interactions for hip energy dissipation at 101–150 ms post-IC and peak joint moment at

327 the ankle and hip. Multiple comparison tests showed a significant difference in hip joint

328 energy dissipation at 101–150 ms post-IC between all conditions in the CAI group with

329 medium-to-large effect sizes, but not between the 30- and 40-cm conditions in the

330 Control group (Figure 1). Peak hip extension moment was similarly significantly

331 different between all conditions in the CAI group, but not between 40- and 50-cm

332 conditions in the Control group (Figure 3C). Although not statistically significant, peak

333 hip extension moment in the CAI group tended to be larger than the Control group

334 under the 50-cm condition, with a large effect size (Figure 2C and Table 3). These

335 findings supported our first hypothesis. On the other hand, peak ankle plantarflexion

336 moment increased progressively in the CAI group as landing height increased, but was

337 unchanged in the Control group and was significantly larger in the CAI group under the

338   50-cm condition (Figure 3A). These results differ from our second hypothesis. Second,

339   significant main effects of group were found for ankle dorsiflexion and knee extension

340   angles and peak ankle plantarflexion moment. In multiple comparison tests, significant

341   differences between groups were observed for peak ankle dorsiflexion angle under all

342   conditions and peak knee flexion angle and peak ankle plantarflexion moment under the

343   50-cm condition (Figure 2 and 3). Finally, significant main effects of height were

344   observed in all variables excluded as follows: hip energy dissipation at 51–100 ms post-

345   IC, all energy dissipation at 151–200 ms, peak ankle inversion angle, and ankle

346   stiffness.

347   The primary finding of this study was that group-by-height interaction in hip

348   energy dissipation was observed at 101–150 ms post-IC (Table 2), and significant

349   differences were observed between all conditions in the CAI group, whereas the

350   difference between 30- and 40-cm conditions in the Control group was not significant

351   (Figure 1). In addition, the effect size in the comparison between height conditions was

352   small to medium in the Control group, but medium to large in the CAI group (Table 4),

353   suggesting medium to large differences between height conditions in the CAI group. As

354   with hip energy dissipation, a group-by-height interaction was observed in peak hip

355   extension moment. In the 50-cm condition, the CAI group tended to show greater peak

356   hip extension moment compared with the Control group (Figure 3C). These interactions

357   mean that the effect of landing height for these variables differed depending on whether

358   CAI was present or absent, providing support for our first hypothesis. However, no

359   significant group differences in hip energy dissipation or hip extension moment were

360   observed, as in previous studies (Kim et al., 2018; McCann et al., 2018; Son et al.,

361   2017). Previous studies have reported that individuals with CAI use a hip-dominant

362   strategy during landing following 50% of the maximum vertical jump height or

363   maximum vertical forward jump for that participant (Kim et al., 2018; McCann et al.,

364   2018; Son et al., 2017). Since no significant difference was seen between groups in the

365   present study, we cannot conclude that CAI participants showed increased reliance on

366   the hip joint as landing height increased. The present results (interactions for hip

367   variables, larger effect size in the CAI group than in the Control group in comparisons

368   between height conditions) can be considered to be part of hip-dominant strategies

369   among individuals with CAI, but it should be noted that the effect sizes of the

370   interactions were small. Next, we observed a tendency for the CAI group to have larger

371   peak hip extension moment than the Control group in the 50-cm condition with large

372   effect size (Table 3). Also, although not statistically significant, some knee variables

373   tended to show group differences with larger effect sizes under the 50-cm condition

374   compared with the 30- and 40-cm conditions (e.g., the knee energy dissipation at 101–

375   150 post-IC, knee flexion angle, and knee extension moment, Table 3). These results

376   suggested that the difference between CAI and Control groups might increase as

377   mechanical demands increase. Although our study investigated the effects of landing

378   height in terms of mechanical demands, other factors such as multi-directional

379   movements, quick movements, and complex neuromuscular control are also considered

380   to be among the demands. Other demands might cause differences in movement

381   patterns for individuals with CAI. Future studies need to examine whether group

382   differences can be detected by increasing demands other than landing height.

383   Proximal muscles (such as the hip and knee muscles) could dissipate more

384   energy because of the greater cross-sectional areas, longer muscle fibers, and relatively

385   shorter tendons than distal muscles (Winters & Woo, 1990). Therefore, if the ankle

386   function in energy dissipation is reduced or mechanical demands are increased,

387   mechanical demands would be redistributed from distal to proximal joints (Coventry et

388   al., 2006; Devita & Skelly, 1992; McCann et al., 2018; Zhang et al., 2000). Previous

389   research has suggested that individuals with CAI exhibit decreased capabilities for

390   shock attenuation at the ankle during single-leg landing, such as decreases in ankle

391   plantarflexion moment (Kim et al., 2018; Son et al., 2017), ankle stiffness (Kim et al.,

392   2018), and the contribution of the ankle to energy dissipation (McCann et al., 2018). In

393   the present study, no differences in ankle energy dissipations were found between

394   groups. We thus could not conclude that the CAI group showed any ankle dysfunction

395   in energy absorption. However, the CAI group scored lower in CAIT-J score than the

396   Control group, which means that CAI participants experienced subjective ankle

397   instability. The interaction for hip energy dissipation and increasing hip energy

398   dissipation with medium to large effect sizes in the CAI group (Table 4) when

399   mechanical demands increased may represent a coping strategy for subjective ankle

400   instability among CAI participants.

401   The present study found no interaction or main effect of group on ankle and

402   knee energy dissipation or peak knee extension moment. In addition, the CAI group

403   showed greater peak ankle plantarflexion moment than the Control group in the 50-cm

404   condition (Figure 3A), and this result was inconsistent with findings from previous

405   studies (Kim et al., 2018; Son et al., 2017). We should consider the possibility that

406   differences in movement tasks affected ankle biomechanics. Our CAI participants

407   showed a large peak ankle plantarflexion moment (Figure 3A), but no significant

408   difference in ankle energy dissipation or stiffness between groups (Figure 1 and 4A).

409   CAI participants in this study may not have been able to convert large ankle

410   plantarflexion moments into energy dissipation and joint stiffness. In terms of injury

411   risk, increased ankle plantarflexor activity may increase the risk of LAS injury by

412   increasing the lever arm of ankle inversion or ankle inversion torque (Lee & Piazza,

413   2008; Vieira et al., 2013). In the present study, no significant differences in ankle

414   inversion angle were apparent between groups, although the CAI group tended to show

415   a larger angle than the Control group in the 30-cm condition (Figure 2B). The

416   relationship between increased ankle plantarflexion moment and LAS risk needs to be

417   investigated in future studies.

418   This study has some limitations that need consideration. First, landing heights

419   were not set relative to each participant, but instead were absolute for all participants.

420   Mechanical demands would have been affected by the physical characteristics and

421   physical abilities of participants. Differences in demands may have led to difficulty

422   detecting significant differences between groups. In future studies, setting landing

423   height in relative manner for each participant may allow better delineation of

424   differences between groups. Second, we did not record electromyographic activity of

425   lower-extremity muscles during landing. Lower-extremity muscles are the main shock

426   absorbers in landing tasks. Characteristics of individuals with CAI may be clarified by

427   measuring both electromyographic activity and biomechanics of the lower extremity.

428   Third, we should also consider statistical power. An a priori power analysis based on

429   our pilot study showed that a huge sample size would be required to obtain sufficient

430   power for ankle, knee, and hip energy dissipation (at least 846 participants per group);

431   therefore, participants in this study were recruited based on the sample size calculation

432   for peak hip extension moment. The post hoc power analysis showed that the significant

433   results in the present study had sufficient statistical power ($1-\beta > 0.93$). Finally, since

434   this study was cross-sectional in design, the findings cannot be used to indicate whether

435   the altered energy dissipation strategy observed in the CAI group is a cause or effect of

436   CAI. In the future, cohort studies could reveal this direction of causality in this

437   relationship.

438

Clinical implications

The present results suggest that differences between conditions of hip energy dissipation

in the CAI group and differences between the CAI and Control groups in terms of ankle

and hip joint moments might be more pronounced as landing height increases. To better

detect biomechanical changes among CAI populations, more demanding landings might

need to be used. Based on the premise that altered biomechanics are associated with

recurrent LAS in individuals with CAI, the goal of rehabilitation for individuals with

CAI is to obtain landing movements similar to those without CAI (healthy people or

copers). Since the biomechanical changes in the lower extremity joints differed

depending on landing height, obtaining a proper landing movement requires practice

landing not only under high-demand conditions, but also under low-demand conditions.

Conclusions

In the present study, we investigated the effect of the mechanical demands of the

movement task (landing height) on landing biomechanics among individuals with CAI.

Significant group-by-height interactions were observed for peak ankle plantarflexion

moment and hip energy dissipation during single-leg landing, suggesting that the effect

of landing height on landing kinetics varies depending on the presence or absence of

CAI. In the CAI group, the effect size of the difference between conditions was larger

than that in the Control group with hip energy dissipation at 101–150 ms post-IC. Peak

ankle plantarflexion moment increased with increasing landing height in the CAI group,

but remained constant in the Control group regardless of landing height. In addition, the

CAI group showed significantly greater peak ankle plantarflexion moment than the

Control group in the 50-cm condition. The present study suggests that the effects of

463   landing height on the ankle and hip joints differed between individuals with and without

464   CAI. The effect of mechanical demands on landing biomechanics of the ankle and hip

465   joint among CAI populations should be considered in biomechanical studies and clinical

466   practice.

467

470

471   **Declaration of interest statement**

472   The authors declare no conflicts of interest in association with this manuscript.

473

References

474 **References**

475 Bleakley, C. M., Taylor, J. B., Dischiavi, S. L., Doherty, C., & Delahunt, E. (2019).

476   Rehabilitation exercises reduce reinjury post ankle sprain, but the content and

477   parameters of an optimal exercise program have yet to be established: A systematic

478   review and meta-analysis. Archives of Physical Medicine and Rehabilitation,

479   100(7), 1367–1375. https://doi.org/10.1016/j.apmr.2018.10.005

480 Bischof, J. E., Spritzer, C. E., Caputo, A. M., Easley, M. E., DeOrio, J. K., Nunley, J.

481   A., & DeFrate, L. E. (2010). In vivo cartilage contact strains in patients with lateral

482   ankle instability. Journal of Biomechanics, 43(13), 2561–2566.

483   https://doi.org/10.1016/j.jbiomech.2010.05.013

484 Brown, C., Padua, D., Marshall, S. W., & Guskiewicz, K. (2008). Individuals with

485   mechanical ankle instability exhibit different motion patterns than those with

486   functional ankle instability and ankle sprain copers. Clinical Biomechanics, 23(6),

487   822–831. https://doi.org/10.1016/j.clinbiomech.2008.02.013

488 Caulfield, B. M., & Garrett, M. (2002). Functional instability of the ankle: differences

489   in patterns of ankle and knee movement prior to and post landing in a single leg

490   jump. International Journal of Sports Medicine, 23(1), 64–68.

491   https://doi.org/10.1055/s-2002-19272

492 Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* L. Erlbaum

493   Associates. https://doi.org/10.4324/9780203771587

494 Coventry, E., O'Connor, K. M., Hart, B. A., Earl, J. E., & Ebersole, K. T. (2006). The

495   effect of lower extremity fatigue on shock attenuation during single-leg landing.

496   Clinical Biomechanics, 21(10), 1090–1097.

497   https://doi.org/10.1016/j.clinbiomech.2006.07.004

498 Davis, R. B., Õunpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data

499 collection and reduction technique. Human Movement Science, 10(5), 575–587.

500 https://doi.org/10.1016/0167-9457(91)90046-Z

501 Dejong, A. F, Koldenhoven, R. M., & Hertel, J. (2020). Proximal adaptations in chronic

502 ankle instability: Systematic review and meta-analysis. Medicine and science in

503 sports and exercise, 52(7), 1563–1575.

504 https://doi.org/10.1249/MSS.0000000000002282

505 Delahunt, E., Monaghan, K., & Caulfield, B. (2006). Changes in lower limb kinematics,

506 kinetics, and muscle activity in subjects with functional instability of the ankle

507 joint during a single leg drop jump. Journal of Orthopaedic Research: Official

508 Publication of the Orthopaedic Research Society, 24(10), 1991–2000.

509 https://doi.org/10.1002/jor.20235

510 Devita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and

511 energetics in the lower extremity. Medicine and Science in Sports and Exercise,

512 24(1), 108–115.

513 Doherty, C., Bleakley, C., Hertel, J., Caulfield, B., Ryan, J., & Delahunt, E. (2016a).

514 Recovery from a first-time lateral ankle sprain and the predictors of chronic ankle

515 instability. The American Journal of Sports Medicine, 44(4), 995–1003.

516 https://doi.org/10.1177/0363546516628870

517 Doherty, C., Bleakley, C., Hertel, J., Caulfield, B., Ryan, J., & Delahunt, E. (2016b).

518 Single-leg drop landing movement strategies in participants with chronic ankle

519 instability compared with lateral ankle sprain 'copers.' Knee Surgery, Sports

520 Traumatology, Arthroscopy, 24(4), 1049–1059. https://doi.org/10.1007/s00167-

521 015-3852-9

522 Fong, D. T. P., Hong, Y., Chan, L. K., Yung, P. S. H., & Chan, K. M. (2007). A

523 systematic review on ankle injury and ankle sprain in sports. Sports Medicine,

524   37(1), 73–94. https://doi.org/10.2165/00007256-200737010-00006

525 Fong, D. T. P., Hong, Y., Yosuke, S., Krosshaug, T., Yung, P. S. H., & Chan, K. M.

526   (2009). Biomechanics of supination ankle sprain: A case report of an accidental

527   injury event in the laboratory. American Journal of Sports Medicine, 37(4), 822–

528   827. https://doi.org/10.1177/0363546508328102

529 Fong, D. T. P., Ha, S. C. W., Mok, K. M., Chan, C. W. L., & Chan, K. M. (2012).

530   Kinematics analysis of ankle inversion ligamentous sprain injuries in sports: Five

531   cases from televised tennis competitions. American Journal of Sports Medicine,

532   40(11), 2627–2632. https://doi.org/10.1177/0363546512458259

533 Ford, K. R., Myer, G. D., & Hewett, T. E. (2007). Reliability of landing 3D motion

534   analysis: Implications for longitudinal analyses. Medicine and Science in Sports

535   and Exercise, 39(11), 2021–2028. https://doi.org/10.1249/mss.0b013e318149332d

536 Gehring, D., Wissler, S., Mornieux, G., & Gollhofer, A. (2013). How to sprain your

537   ankle - a biomechanical case report of an inversion trauma. Journal of

538   Biomechanics, 46(1), 175–178. https://doi.org/10.1016/j.jbiomech.2012.09.016

539 Gribble, P. A., Delahunt, E., Bleakley, C., Caulfield, B., Docherty, C., Fourchet, F.,

540   Fong, D., Hertel, J., Hiller, C., Kaminski, T. W., McKeon, P. O., Refshauge, K.

541   M., Van Der Wees, Vicenzino, B., & Wikstrom, E. (2013). Selection criteria for

542   patients with chronic ankle instability in controlled research: A position statement

543   of the international ankle consortium. Journal of Orthopaedic and Sports Physical

544   Therapy, 43(8), 585–591. https://doi.org/10.2519/jospt.2013.0303

545 Hertel, J. & Corbett, R. O. (2019). An updated model of chronic ankle instability.

546   Journal of Athletic Training, 54(6), 572–588. https://doi.org/10.4085/1062-6050-

547   344-18

548 Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15

549   sports: Summary and recommendations for injury prevention initiatives. Journal of

550   Athletic Training, 42(2), 311–319.

551 Houston, M. N., Hoch, J. M., & Hoch, M. C. (2015). Patient-reported outcome

552   measures in individuals with chronic ankle instability: A systematic review.

553   Journal of Athletic Training, 50(10), 1019–1033. https://doi.org/10.4085/1062-

554   6050-50.9.01

555 Kadaba, M. P., Ramakrishnan, H. K., & Wootten, M. E. (1990). Measurement of lower

556   extremity kinematics during level walking. Journal of Orthopaedic Research, 8(3),

557   383–392. https://doi.org/10.1002/jor.1100080310

558 Kim, H., Son, S. J., Seeley, M. K., & Hopkins, J. T. (2019). Altered movement

559   strategies during jump landing/cutting in patients with chronic ankle instability.

560   Scandinavian Journal of Medicine and Science in Sports, 29(8), 1130–1140.

561   https://doi.org/10.1111/sms.13445

562 Kim, H., Son, S. J., Seeley, M. K., & Hopkins, J. T. (2018). Kinetic compensations due

563   to chronic ankle instability during landing and jumping. Medicine and Science in

564   Sports and Exercise, 50(2), 308–317.

565   https://doi.org/10.1249/MSS.0000000000001442

566 Kofotolis, N. D., Kellis, E., & Vlachopoulos, S. P. (2007). Ankle sprain injuries and

567   risk factors in amateur soccer players during a 2-year period. American Journal of

568   Sports Medicine, 35(3), 458–466. https://doi.org/10.1177/0363546506294857

569 Koshino, Y., Ishida, T., Yamanaka, M., Ezawa, Y., Okunuki, T., Kobayashi, T.,

570   Samukawa, M., Saito, H., & Tohyama, H. (2016). Kinematics and muscle

571   activities of the lower limb during a side-cutting task in subjects with chronic ankle

572   instability. Knee Surgery, Sports Traumatology, Arthroscopy, 24(4), 1071–1080.

573   https://doi.org/10.1007/s00167-015-3745-y

574 Koshino, Y., Samukawa, M., Murata, H., Osuka, S., Kasahara, S., Yamanaka, M., &

575 Tohyama, H. (2020). Prevalence and characteristics of chronic ankle instability and

576 copers identified by the criteria for research and clinical practice in collegiate

577 athletes. Physical Therapy in Sport, 45, 23–29.

578 https://doi.org/10.1016/j.ptsp.2020.05.014

579 Koshino, Y., Yamanaka, M., Ezawa, Y., Ishida, T., Kobayashi, T., Samukawa, M.,

580 Saito, H., & Takeda, N. (2014). Lower limb joint motion during a cross cutting

581 movement differs in individuals with and without chronic ankle instability.

582 Physical Therapy in Sport, 15(4), 242–248.

583 https://doi.org/10.1016/j.ptsp.2013.12.001

584 Kosik, K. B., Hoch, M. C., Heebner, N. R., Hartzell, J., & Gribble, P. A. (2019). A

585 laboratory captured 'giving way' episode during a single-leg landing task in an

586 individual with unilateral chronic ankle instability. Journal of Biomechanics,

587 90(11), 153–158. https://doi.org/10.1016/j.jbiomech.2019.05.009

588 Kristianslund, E., Bahr, R., & Krosshaug, T. (2011). Kinematics and kinetics of an

589 accidental lateral ankle sprain. Journal of Biomechanics, 44(14), 2576–2578.

590 https://doi.org/10.1016/j.jbiomech.2011.07.014

591 Kunugi, S., Masunari, A., Noh, B., Mori, T., Yoshida, N., & Miyakawa, S. (2017).

592 Cross-cultural adaptation, reliability, and validity of the Japanese version of the

593 Cumberland ankle instability tool. Disability and Rehabilitation, 39(1), 50–58.

594 https://doi.org/10.3109/09638288.2016.1138555

595 Lee, J., Song, Y., & Shin, C. S. (2018). Effect of the sagittal ankle angle at initial

596 contact on energy dissipation in the lower extremity joints during a single-leg

597 landing. Gait and Posture, 62, 99–

598 104. https://doi.org/10.1016/j.gaitpost.2018.03.019

599   Lee, S., Song, K., & Lee, S. Y. (2021). Epidemiological study of post-traumatic ankle

600   osteoarthritis after ankle sprain in 195,393 individuals over middle age using the

601   National Health Insurance Database: A retrospective design. Journal of Science

602   and Medicine in Sport (in press). http://doi.org/10.1016/j.jsams.2021.08.018

603   Lee, S. S. M., & Piazza, S. J. (2008). Inversion-eversion moment arms of gastrocnemius

604   and tibialis anterior measured in vivo. Journal of Biomechanics, 41(16), 3366–

605   3370. https://doi.org/10.1016/j.jbiomech.2008.09.029

606   Li, Y., Ko, J., Zhang, S., Brown, C. N., & Simpson, K. J. (2019). Biomechanics of

607   ankle giving way: A case report of accidental ankle giving way during the drop

608   landing test. Journal of Sport and Health Science, 8(5), 494–502.

609   https://doi.org/10.1016/j.jshs.2018.01.002

610   McCann, R. S., Terada, M., Kosik, K. B., & Gribble, P. A. (2018). Energy dissipation

611   differs between females with and without chronic ankle instability. Scandinavian

612   Journal of Medicine and Science in Sports, 28(3), 1227–1234.

613   https://doi.org/10.1111/sms.13004

614   McKay, G. D. (2001). Ankle injuries in basketball: injury rate and risk factors. British

615   Journal of Sports Medicine, 35(2), 103–108. https://doi.org/10.1136/bjsm.35.2.103

616   Mok, K. M., Fong, D. T. P., Krosshaug, T., Engebretsen, L., Hung, A. S. L., Yung, P. S.

617   H., & Chan, K. M. (2011). Kinematics analysis of ankle inversion ligamentous

618   sprain injuries in sports: 2 cases during the 2008 Beijing Olympics. American

619   Journal of Sports Medicine, 39(7), 1548–1552.

620   https://doi.org/10.1177/0363546511399384

621   Panagiotakis, E., Mok, K. M., Fong, D. T. P., & Bull, A. M. J. (2017). Biomechanical

622   analysis of ankle ligamentous sprain injury cases from televised basketball games:

623   Understanding when, how and why ligament failure occurs. Journal of Science and

624   Medicine in Sport, 20(12), 1057–1061. https://doi.org/10.1016/j.jsams.2017.05.006

625   Remus, A., Caulfield, B., Doherty, C., Crowe, C., Severini, G., & Delahunt, E. (2018).

626   A laboratory captured "giving way" episode in an individual with chronic ankle

627   instability. Journal of Biomechanics, 76, 241–246.

628   https://doi.org/10.1016/j.jbiomech.2018.05.015

629   Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000). Symmetry and limb dominance

630   in able-bodied gait: A review. Gait and Posture, 12(1), 34–45.

631   https://doi.org/10.1016/S0966-6362(00)00070-9

632   Son, S. J., Kim, H., Seeley, M. K., & Hopkins, J. T. (2017). Movement strategies

633   among groups of chronic ankle instability, coper, and control. Medicine and

634   Science in Sports and Exercise, 49(8), 1649–1661.

635   https://doi.org/10.1249/MSS.0000000000001255

636   Terada, M., Ball, L. M., Pietrosimone, B. G., & Gribble, P. A. (2016). Altered visual

637   focus on sensorimotor control in people with chronic ankle instability. Journal of

638   Sports Sciences, 34(2), 171–180. https://doi.org/10.1080/02640414.2015.1043324

639   Terada, M., & Gribble, P. A. (2015). Jump landing biomechanics during a laboratory

640   recorded recurrent ankle sprain. Foot and Ankle International, 36(7), 842–848.

641   https://doi.org/10.1177/1071100715576517

642   Tsikopoulos, K., Mavridis, D., Georgiannos, D., & Vasiliadis, H. S. (2018). Does

643   multimodal rehabilitation for ankle instability improve patients' self-assessed

644   functional outcomes? A network meta-analysis. Clinical Orthopaedics & Related

645   Research, 476(6), 1295–1310.

646   https://doi.org/10.1097/01.blo.0000534691.24149.a2

647   Vieira, T. M. M., Minetto, M. A., Hodson-Tole, E. F., & Botter, A. (2013). How much

648   does the human medial gastrocnemius muscle contribute to ankle torques outside

649 the sagittal plane? Human Movement Science, 32(4), 753–767.

650 https://doi.org/10.1016/j.humov.2013.03.003

651 Waldén, M., Hägglund, M., & Ekstrand, J. (2013). Time-trends and circumstances

652 surrounding ankle injuries in men's professional football: An 11-year follow-up of

653 the UEFA Champions League injury study. British Journal of Sports Medicine,

654 47(12), 748–753. https://doi.org/10.1136/bjsports-2013-092223

655 Weinhandl, J. T., Irmischer, B. S., & Sievert, Z. A. (2015). Sex differences in unilateral

656 landing mechanics from absolute and relative heights. Knee, 22(4), 298–303.

657 https://doi.org/10.1016/j.knee.2015.03.012

658 Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement: 4th*

659 *Edition.* John Wiley & Sons, Inc.

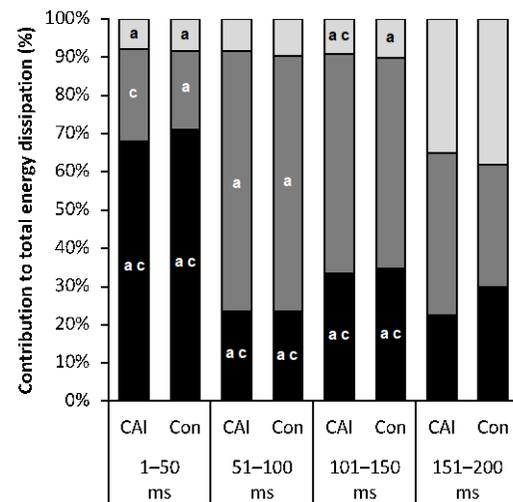660 Winters, J. M., & Woo, S. L. Y. (1990). *Multiple muscle systems: biomechanics and*

661 *movement organization.* Springer-Verlag New York.

662 Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity

663 joints to energy dissipation during landings. Medicine and Science in Sports and

664 Exercise, 32(4), 812–819. https://doi.org/10.1097/00005768-200004000-00014

665
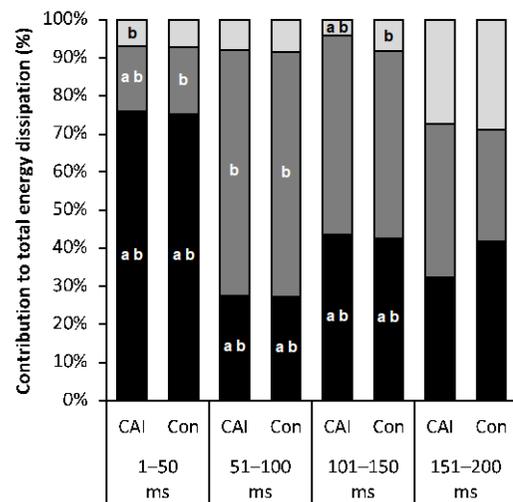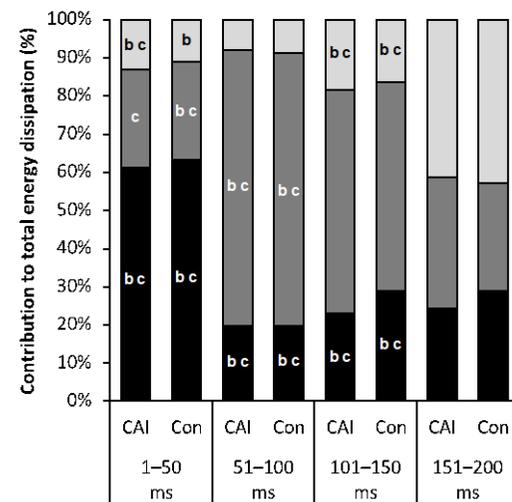
Figure 1. Comparative contributions of each joint to total energy dissipation during each interval between groups and heights in the 30- (A), 40-

(B), and 50-cm condition (C).

a Significant difference from the 50-cm condition in the same group ($P < 0.05$).

b Significant difference from the 40-cm condition in the same group ($P < 0.05$).

c Significant difference from the 30-cm condition in the same group ($P < 0.05$).

Abbreviations: CAI, chronic ankle instability; Con, control.

(A) Ankle dorsiflexion **(B) Ankle inversion** **(C) Knee flexion** **(D) Hip flexion**
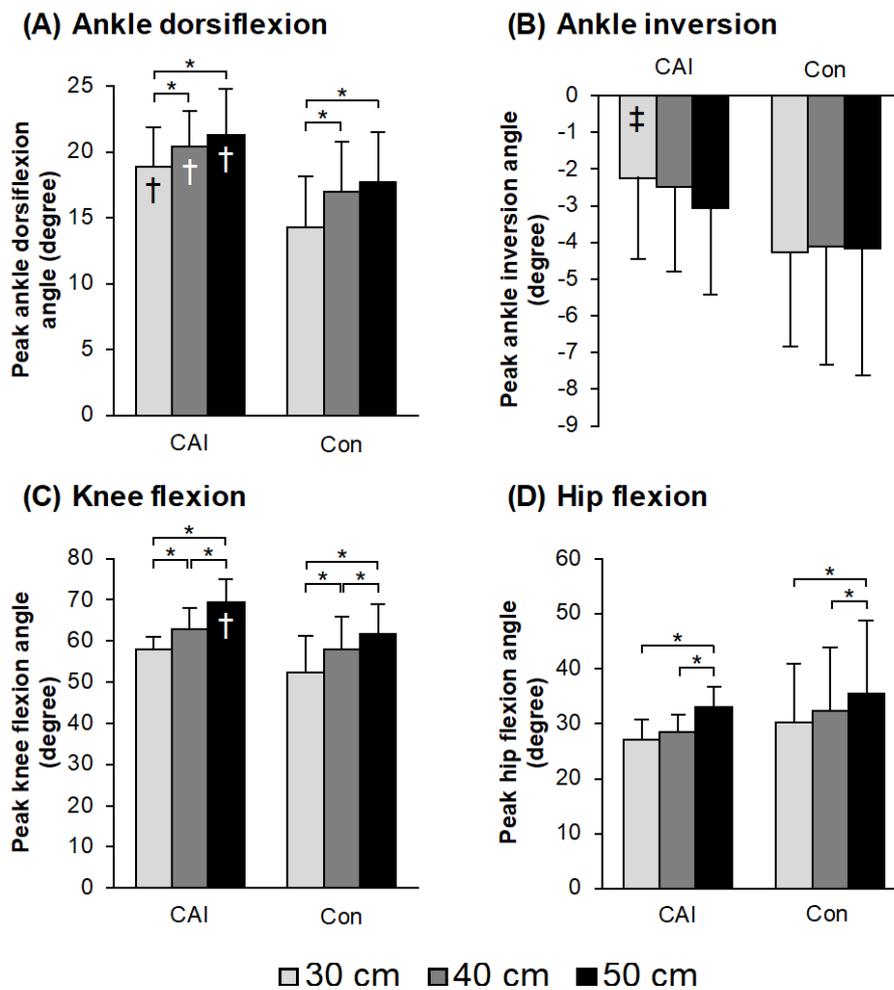
□ 30 cm ■ 40 cm ■ 50 cm

Figure 2. Comparative peak joint angle of ankle dorsiflexion (A), ankle inversion (B),

knee flexion (C), and hip flexion (D) between groups and heights.

* Significant difference between heights in the same group ($P < 0.05$).

† Significant difference compared with the Control group at the same height ($P < 0.05$).

‡ A tendency to be larger in the CAI group compared with the Control group at the same

height ($P < 0.10$).

Abbreviations: CAI, chronic ankle instability; Con, control.

(A) Ankle plantarflexion **(B) Knee extension** **(C) Hip extension**

□ 30 cm ■ 40 cm ■ 50 cm
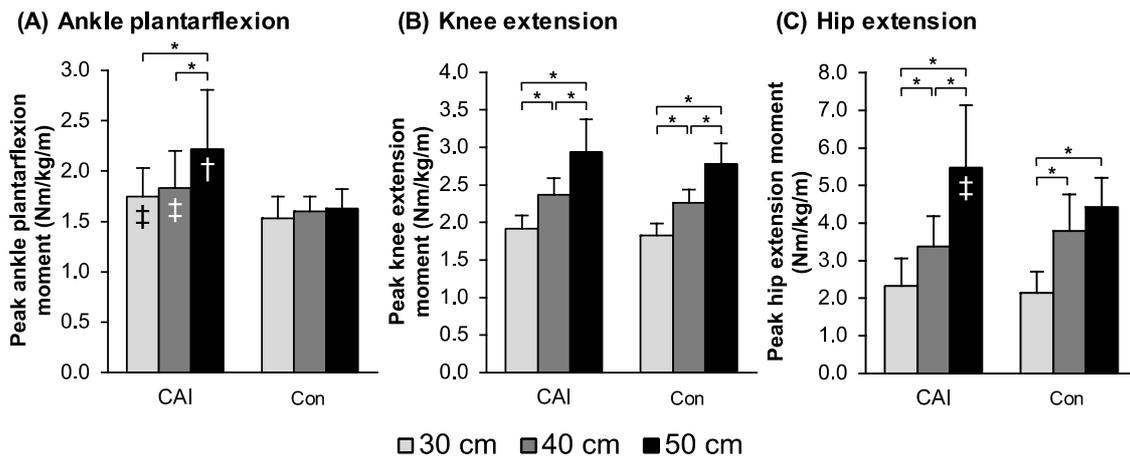
Figure 3. Comparative peak joint moment of ankle plantarflexion (A), knee extension

(B), and hip extension (C) between groups and heights.

* Significant difference between heights in the same group ($P < 0.05$).

† Significant difference compared with the Control group at the same height ($P < 0.05$).

‡ A tendency to be larger in the CAI group compared with the Control group at the same

height ($P < 0.10$).

Abbreviations: CAI, chronic ankle instability; Con, control.

(A) Ankle stiffness

(B) Knee stiffness

(C) Hip stiffness

(D) Peak vGRF

□ 30 cm ■ 40 cm ■ 50 cm
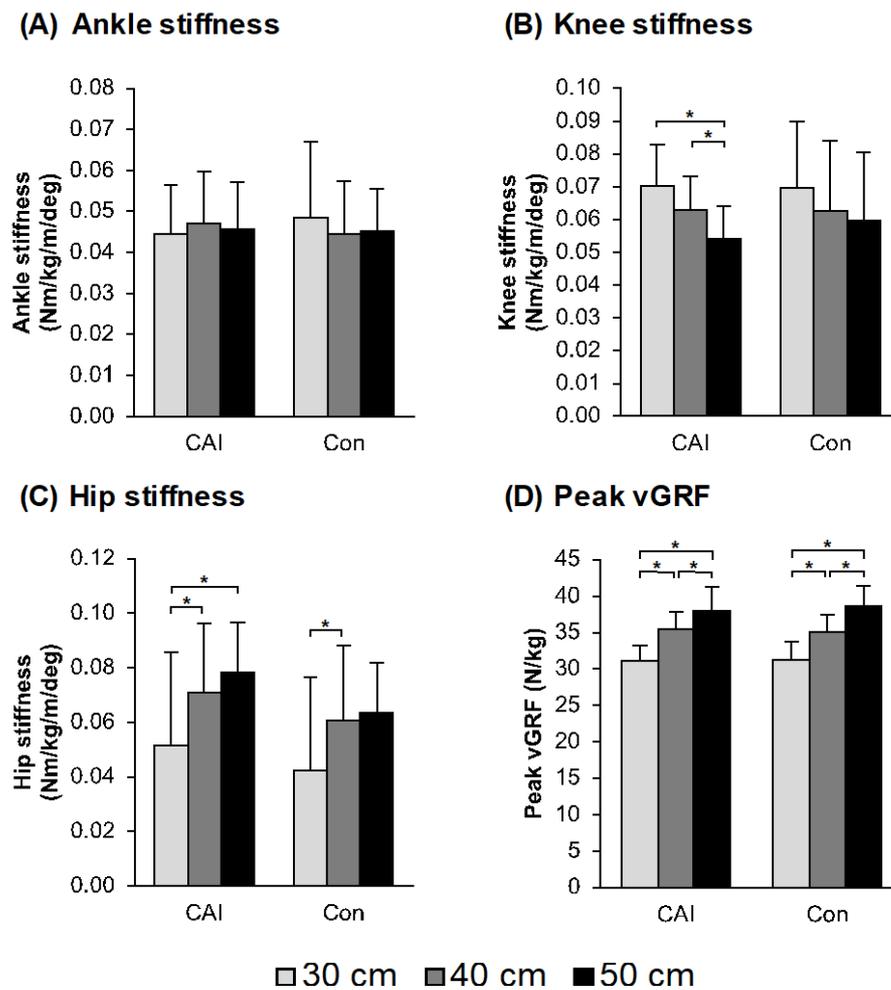
Figure 4. Comparative joint stiffness in the sagittal plane of ankle (A), knee (B), and hip (C) and peak vertical ground reaction force (D) between groups and heights.

* Significant difference between heights in the same group ($P < 0.05$).

Abbreviations: CAI, chronic ankle instability; Con, control; vGRF, vertical ground reaction force.

697 **Table 1.** Comparative participants' characteristics and the number of failed trials in each landing height between the CAI and the Control group.

	CAI	Con	Cohen's d	P-value
Sex	7 males, 4 females	7 males, 4 females	—	—
Age (years)	21.6 ± 1.6	20.6 ± 2.1	0.54 (-0.33, 1.36)	0.184
Height (m)	1.67 ± 0.07	1.68 ± 0.09	-0.12 (-0.96, 0.72)	0.786
Weight (kg)	57.1 ± 6.3	59.3 ± 10.1	-0.26 (-1.09, 0.59)	0.542
CAIT-J score	20.7 ± 4.8	29.6 ± 0.7	-2.59 (-3.61, -1.38)	< 0.001
Number of LASs (n)	4.4 ± 3.0	0	2.07 (0.97, 3.02)	< 0.001
	(range, 2–10)			
Time since initial LAS (years)	7.4 ± 5.1	—	—	—
Failed trials (n)				
30 cm	1.5 ± 0.5	1.6 ± 3.7	-0.04 (-0.87, 0.80)	0.800
40 cm	1.5 ± 0.9	1.8 ± 5.0	-0.08 (-0.92, 0.76)	0.623
50 cm	1.9 ± 0.7	1.8 ± 1.4	0.09 (-0.75, 0.92)	0.836

698   Data are presented as mean ± standard deviation.

699   Effect sizes were presented as Cohen's d (lower limit of the 95% confidence interval, upper limit of the 95% confidence interval).

700   Abbreviations: CAI, chronic ankle instability; Con, control; CAIT-J, Cumberland Ankle Instability Tool Japanese version; LAS, lateral ankle

701   sprain.

702 **Table 2.** Main effect of group and height and group-by-height interaction on the contribution of each joint to total energy dissipation during each

703 interval post-initial contact.

	1–50 ms			51–100 ms			101–150 ms			151–200 ms		
	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip
P-value												
Interaction	0.316	0.193	0.405	0.981	0.905	0.805	0.222	0.864	**0.013**	0.877	0.832	0.991
Group	0.514	0.488	0.805	0.914	0.667	0.591	0.457	0.346	0.828	0.338	0.242	0.795
Height	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.357	**< 0.001**	**0.033**	**< 0.001**	0.070	0.503	0.094
η^2												
Interaction	0.01	0.03	0.01	0.00	0.00	0.00	0.01	0.01	**0.01**	0.00	0.01	0.00
Group	0.01	0.01	0.00	0.00	0.01	0.01	0.02	0.06	0.06	0.02	0.02	0.00
Height	**0.46**	**0.36**	**0.23**	**0.40**	**0.27**	0.01	**0.44**	**0.12**	**0.16**	0.04	0.00	0.06
1-β												
Interaction	0.38	0.52	0.28	0.05	0.07	0.09	0.05	0.06	**0.94**	0.08	0.09	0.05
Group	0.17	0.18	0.06	0.05	0.09	0.13	0.20	0.30	0.06	0.32	0.46	0.06

| Height | **1.00** | **1.00** | **1.00** | **1.00** | **1.00** | 0.34 | **0.93** | **1.00** | **1.00** | 0.75 | 0.24 | 0.70 |

704 Values in bold are statistically significant.

705

706   **Table 3.** Cohen's *d* and its 95% confidence interval for each variable in multiple comparison between groups.

	CAI vs Con		
	30 cm	40 cm	50 cm
Energy dissipation			
1–50 ms			
Ankle	0.10 (-0.73, 0.94)	-0.47 (-1.32, 0.38)	-0.7 (-1.54, 0.19)
Knee	-0.08 (-0.92, 0.76)	0.76 (-0.11, 1.63)	0.07 (-0.77, 0.90)
Hip	-0.08 (-0.92, 0.76)	-0.12 (-0.96, 0.72)	0.83 (-0.05, 1.71)
51–100 ms			
Ankle	0.07 (-0.77, 0.90)	0.01 (-0.83, 0.84)	0.05 (-0.79, 0.89)
Knee	0.06 (-0.78, 0.89)	0.26 (-0.60, 1.09)	0.36 (-0.49, 1.20)
Hip	-0.15 (-0.99, 0.68)	-0.30 (-1.15, 0.54)	-0.39 (-1.23, 0.46)
101–150 ms			
Ankle	0.10 (-0.74, 0.93)	-0.13 (-0.97, 0.71)	-2.01 (-3.06, -0.97)
Knee	0.33 (-0.51, 1.17)	0.24 (-0.60, 1.08)	0.77 (-0.10, 1.64)

Hip	-0.43 (-1.28, 0.42)	-0.10 (-0.94, 0.74)	0.38 (-0.47, 1.22)
151–200 ms			
Ankle	-0.35 (-1.19, 0.49)	-0.41 (-1.25, 0.44)	-0.48 (-1.33, 0.37)
Knee	0.42 (-0.43, 1.27)	0.49 (-0.36, 1.34)	0.70 (-0.17, 1.56)
Hip	-0.06 (-0.90, 0.78)	-0.13 (-0.97, 0.71)	-0.13 (-0.96, 0.71)

Peak joint angle

Ankle dorsiflexion	1.32 (0.39, 2.25)	1.03 (0.14, 1.93)	2.01 (0.96, 3.05)
Ankle inversion	0.85 (-0.02, 1.73)	0.58 (-0.28, 1.43)	0.76 (-0.11, 1.63)
Knee flexion	0.85 (-0.02, 1.73)	0.74 (-0.13, 1.61)	2.38 (1.27, 3.50)
Hip flexion	-0.41 (-1.25, 0.44)	-0.41 (-1.25, 0.44)	-0.46 (-1.31, 0.39)

Peak joint moment

Ankle plantarflexion	0.87 (-0.01, 1.75)	0.83 (-0.04, 1.71)	2.68 (1.50, 3.86)
Knee extension	0.57 (-0.29, 1.42)	0.56 (-0.29, 1.42)	0.88 (0.00, 1.76)
Hip extension	0.26 (-0.58, 1.10)	-0.48 (-1.32, 0.37)	1.61 (0.64, 2.58)

Joint stiffness

Ankle	-0.26 (-1.10, 0.58)	0.20 (-0.64, 1.04)	0.05 (-0.78, 0.89)
Knee	0.05 (-0.79, 0.88)	0.02 (-0.82, 085)	-0.67 (-1.53, 0.19)
Hip	0.27 (-0.57, 1.11)	0.39 (-0.46, 1.23)	1.31 (0.38, 2.24)

Peak vGRF

	-0.04 (-0.88, 0.79)	0.17 (-0.67, 1.01)	-0.41 (-1.26, 0.44)

707   Data are presented as Cohen's *d* (lower limit of *d*, upper limit of *d*).

708   Abbreviations: CAI, chronic ankle instability; Con, control; vGRF, vertical ground reaction force.

709

710   **Table 4.** Cohen's *d* and its 95% confidence interval for each variable in multiple comparison between heights.

	CAI			Con		
	40 vs 30 cm	50 vs 30 cm	50 vs 40 cm	40 vs 30 cm	50 vs 30 cm	50 vs 40 cm
Energy dissipation						
1–50 ms						
Ankle	-1.30	-2.26	-1.05	-0.68	-2.30	-1.44
	(-1.81, -0.79)	(-3.26, -1.27)	(-1.80, -0.30)	(-1.18, -0.18)	(-3.16, -1.44)	(-2.04, -0.83)
Knee	1.54	1.56	0.33	0.80	2.00	0.99
	(0.84, 2.25)	(0.78, 2.35)	(-0.53, 1.19)	(0.10, 1.50)	(1.11, 2.89)	(0.52, 1.46)
Hip	0.28	1.55	1.25	0.26	0.94	0.70
	(-0.37, 0.93)	(0.65, 2.46)	(0.57, 1.94)	(-0.30, 0.81)	(0.03, 1.86)	(0.19, 1.21)
51–100 ms						
Ankle	-0.82	-1.64	-0.96	-1.09	-2.15	-0.82
	(-1.39, -0.26)	(-2.41, -0.88)	(-1.67, -0.24)	(-1.89, -0.29)	(-3.04, -1.26)	(-1.39, -0.26)
Knee	0.67	1.70	0.81	0.50	1.25	0.91

	(-0.13, 1.47)	(0.81, 2.58)	(0.24, 1.38)	(0.07, 0.92)	(0.61, 1.90)	(0.41, 1.40)
Hip	0.12	0.01	-0.12	0.24	0.04	-0.19
	(-0.33, 0.57)	(-0.51, 0.52)	(-0.47, 0.24)	(-0.07, 0.54)	(-0.31, 0.39)	(-0.46, 0.08)
101–150 ms						
Ankle	-1.29	-3.44	-1.56	-0.75	-1.35	-0.72
	(-2.33, -0.25)	(-4.86, -2.02)	(-2.28, -0.85)	(-1.37, -0.14)	(-2.09, -0.62)	(-1.06, -0.39)
Knee	0.54	0.65	0.12	0.65	0.59	-0.04
	(-0.23, 1.31)	(-0.04, 1.34)	(-0.22, 0.45)	(-0.15, 1.44)	(-0.24, 1.41)	(-0.36, 0.24)
Hip	0.60	1.76	0.93	0.15	0.61	0.45
	(0.25, 0.870)	(1.13, 2.39)	(0.54, 1.33)	(-0.03, 0.34)	(0.35, 0.87)	(0.20, 0.70)
151–200 ms						
Ankle	-0.49	-0.38	0.12	-0.44	-0.48	-0.05
	(-1.16, 0.18)	(-1.09, 0.32)	(-0.74, 0.99)	(-0.79, -0.08)	(-1.12, 0.16)	(-0.76, 0.65)
Knee	0.07	-0.30	-0.40	0.10	-0.04	-0.18
	(-0.68, 0.81)	(-0.88, 0.28)	(-0.99, 0.19)	(-0.19, 0.33)	(-0.73, 0.65)	(-0.71, 0.35)

Hip	0.32	0.52	0.28	0.33	0.55	0.19
	(-0.60, 1.24)	(-0.28, 1.32)	(-0.32, 0.87)	(-0.01, 0.68)	(-0.16, 1.25)	(-0.52, 0.90)
Peak joint angle						
Ankle dorsiflexion	0.52	0.74	0.30	0.71	0.89	0.18
	(0.06, 0.98)	(0.35, 1.14)	(-0.20, 0.80)	(0.43, 1.00)	(0.36, 1.42)	(-0.21, 0.57)
Ankle inversion	-0.11	-0.36	-0.25	0.06	0.03	-0.03
	(-0.46, 0.25)	(-0.71, -0.02)	(-0.56, 0.06)	(-0.30, 0.43)	(-0.37, 0.43)	(-0.19, 0.14)
Knee flexion	1.16	2.56	1.24	0.64	1.18	0.52
	(0.54, 1.78)	(1.60, 3.51)	(0.58, 1.90)	(0.40, 0.88)	(0.72, 1.65)	(0.18, 0.86)
Hip flexion	0.39	1.68	1.43	0.18	0.44	0.26
	(-0.05, 0.83)	(0.87, 2.48)	(0.71, 2.15)	(0.08, 0.28)	(0.26, 0.62)	(0.15, 0.37)
Peak joint moment						
Ankle plantarflexion	0.25	1.02	0.79	0.36	0.49	0.20
	(-0.12, 0.63)	(0.43, 1.61)	(0.35, 1.22)	(-0.15, 0.86)	(-0.09, 1.07)	(-0.11, 0.52)
Knee extension	2.29	3.09	1.67	2.55	4.35	2.33

	(1.26, 3.31)	(1.85, 4.34)	(0.85, 2.49)	(1.47, 3.63)	(2.77, 5.93)	(1.46, 3.20)
Hip extension	1.34	2.44	1.60	2.07	3.33	0.72
	(0.67, 2.01)	(1.47, 3.42)	(0.98, 2.23)	(1.19, 2.95)	(2.10, 4.56)	(0.34, 1.11)
Joint stiffness						
Ankle	0.22	0.11	-0.12	-0.25	-0.21	0.07
	(-0.24, 0.68)	(-0.43, 0.64)	(-0.53, 0.29)	(-0.44, -0.06)	(-0.58, 0.16)	(-0.26, 0.40)
Knee	-0.64	-1.43	-0.86	-0.33	-0.48	-0.14
	(-1.26, -0.02)	(-2.16, -0.70)	(-1.59, -0.14)	(-0.71, 0.05)	(-0.90, -0.05)	(-0.32, 0.04)
Hip	0.64	0.98	0.34	0.59	0.69	0.11
	(0.25, 1.03)	(0.23 1.73)	(-0.19, 0.86)	(0.18, 1.01)	(0.14, 1.24)	(-0.22, 0.43)
Peak vGRF						
	1.93	2.49	0.88	1.54	2.81	1.38
	(1.24, 2.62)	(1.59, 3.40)	(0.47, 1.30)	(1.01, 2.06)	(1.89, 3.74)	(0.89, 1.88)

711 Data are presented as Cohen's *d* (lower limit of *d*, upper limit of *d*).

712 Abbreviations: CAI, chronic ankle instability; Con, control; vGRF, vertical ground reaction force.