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

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18 Abstract

19 Inadequate energy dissipation during landing may increase the risk of ankle 20 sprain. Mechanical demands (landing height) in landing tasks may affect the 21 biomechanical differences between individuals with and without chronic ankle 22 instability (CAI). However, energy dissipation strategies during landing from 23 various heights in individuals with CAI are unclear. The purpose of this study was 24 to compare the effect of landing height on lower extremity biomechanics between 25 individuals with and without CAI. Eleven participants in each the CAI and 26 Control group performed a single-leg landing from three heights (30, 40, and 50 27 cm). We calculated the contribution of each joint to total energy dissipation at 50-28 ms intervals during 0-200 ms post-initial contact (IC). Peak joint angles and 29 moments and joint stiffnesses were calculated during 0-200 ms post-IC. Two-way 30 mixed analysis of variance revealed significant group-by-height interactions for hip 31 energy dissipation at 101–150 ms post-IC and peak ankle plantarflexion and hip 32 extension moment. These significant interactions suggested that the effects of 33 landing height on the ankle and hip joints differ between individuals with and 34 without CAI. The effect of mechanical demands on altered landing biomechanics 35 among CAI populations should be considered in biomechanical studies and 36 clinical practice.

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

#### 40 Introduction

41 Lateral ankle sprain (LAS) is one of the most common musculoskeletal injuries during 42 sporting activities (Fong et al., 2007). The incidence of this injury is high in sporting 43 activities characterized by jumping, landing, and cutting, such as football, basketball, soccer, gymnastics, and volleyball (Hootman et al., 2007). The recurrence rate in 44 45 basketball players has been reported as 73% (McKay, 2001). Doherty et al. (2016a) 46 reported that 40% of patients with LAS developed to chronic ankle instability (CAI), 47 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 48 49 cartilage strain in the talocrural joint and contribute to the development of ankle 50 osteoarthritis (Bischof et al., 2010). Patients who had a history of one or more LASs 51 showed a 46% greater rate of progression to ankle osteoarthritis than healthy individuals 52 (Lee et al., 2021). In addition, CAI is associated with decreased health-related quality of 53 life (Houston et al., 2015) and disruption of participation in sports activities (Kofotolis et 54 al., 2007; Waldén et al., 2013). LAS and CAI can thus lead to not only short-term, but 55 also middle- or long-term sequelae. While many studies have reported the effectiveness 56 of rehabilitation for preventing re-injury and improving perceived instability (Bleakley et 57 al., 2019; Tsikopoulos et al., 2018), a recent epidemiological study reported that the 58 incidence of LAS remains high, and the prevalence of CAI in athletes is about 20% 59 (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 60 61 causes of LAS. The present model of CAI is complex, including many factors (Hertel & 62 Corbett, 2019), and further investigation of the relationships between factors may provide 63 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 al., 2012; Gehring et al., 2013; Kosik et al., 2019; Kristianslund et al., 2011; Li et al., 66 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.

A previous study showed that the change in joint work with increasing landing height as a representation of mechanical demand in healthy individuals was greater in the knee and hip joints than in the ankle joint during step-off landing (Zhang et al., 2000). Changes in the ankle, knee, and hip joint work with increasing landing height from 32 cm to 62 cm were all 1.4 times, while changes of 1.7, 1.9, and 2.3 times, respectively, were 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 biomechanics would differ between individuals with and without CAI; and 2) the 123 124 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  $\eta^2$  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

participants provided written informed consent before enrolment in the study. Thisstudy 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  $\leq 25$ 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 ( $\pm$  3 years old), height ( $\pm$  5 cm), weight ( $\pm$  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  $\geq 28$ . 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

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.

Participants were asked to keep the hands on the waist, face forward, and maintain a single-leg stance for 5 s after landing. Trials were excluded from data analysis if the entire foot did not contact the force plate, the hands were off the waist, and/or the participant could not maintain a single-leg stance for 5 s after landing. Three successful trials were collected for each landing height. A 1-min rest period was provided between 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., 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 ANOVA, effect size was presented as  $\eta^2$  and interpreted as:  $0.01 < \text{small} \le 0.06 <$ 236 237 medium  $\leq 0.14 < \text{large}$  (Cohen, 1988). For multiple comparison tests using the

Bonferroni correction, Cohen's *d* with 95% confidence interval (CI) was calculated, and interpreted as:  $0.20 < \text{small} \le 0.50 < \text{medium} \le 0.80 < \text{large}$  (Cohen, 1988). The level of statistical significance was set at *P* < 0.05. Statistical analyses were performed using IBM SPSS Statistics version 22 (IBM, Chicago, IL, USA). After all statistical analyses, we performed a post hoc power analysis for all ANOVAs by calculating statistical power (1- $\beta$ ) using G\*power 3.1 (University of Dusseldorf).

244

#### 245 **Results**

No significant differences were identified in age, height, or weight between the CAI and
the Control groups (Table 1). The CAI group displayed significantly lower CAIT-J
scores and a significantly larger number of LASs than the Control group. In addition, no
significant differences in the number of failed trials were seen between groups under
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

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 interactions for any joint angles (ankle dorsiflexion: P = 0.414,  $\eta^2 = 0.01$ ,  $1-\beta = 0.30$ ; 266 ankle inversion: P = 0.378,  $\eta^2 = 0.01$ ,  $1-\beta = 0.33$ ; knee flexion: P = 0.300,  $\eta^2 = 0.01$ ,  $1-\beta$ 267 = 0.39; hip flexion: P = 0.470,  $\eta^2 = 0.00$ , 1- $\beta = 0.26$ ). A significant main effect of group 268 269 was observed for ankle dorsiflexion and knee flexion angle with large and medium 270 effect sizes, respectively (ankle dorsiflexion: P = 0.010,  $\eta^2 = 0.23$ ,  $1 - \beta = 1.00$ ; ankle inversion: P = 0.164,  $\eta^2 = 0.09$ ,  $1 - \beta = 0.62$ ; knee flexion: P = 0.032,  $\eta^2 = 0.14$ ,  $1 - \beta = 0.032$ 271 0.95; hip flexion: P = 0.396,  $\eta^2 = 0.03$ ,  $1 - \beta = 0.25$ ). A significant main effect of height 272 273 was observed for all parameters except peak ankle inversion angle (ankle dorsiflexion:  $P < 0.001, \eta^2 = 0.09, 1 - \beta = 1.00$ ; ankle inversion:  $P = 0.464, \eta^2 = 0.00, 1 - \beta = 0.27$ ; knee 274 flexion: P < 0.001,  $\eta^2 = 0.27$ ,  $1 - \beta = 1.00$ ; hip flexion: P < 0.001,  $\eta^2 = 0.07$ ,  $1 - \beta = 1.00$ ). 275 276 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

small effect sizes, respectively (ankle: P = 0.005,  $\eta^2 = 0.05$ ,  $1-\beta = 0.98$ ; knee: P = 0.928, 288  $\eta^2 = 0.00, 1 - \beta = 0.08$ ; hip:  $P = 0.008, \eta^2 = 0.05, 1 - \beta = 0.98$ ). A significant main effect of 289 290 group was observed on peak ankle plantarflexion moment with a large effect size (P =0.012,  $\eta^2 = 0.20$ ,  $1-\beta = 0.99$ ), but not on peak knee and hip extension moment (knee: P 291 = 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 292 293 effect of height was found for all joint moments with medium to large effect sizes (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 < 0.001294 0.001,  $\eta^2 = 0.60$ ,  $1-\beta = 1.00$ ). Multiple comparisons revealed that peak ankle 295 296 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).

Figure 4 shows joint stiffness in the sagittal plane of each joint and peak vertical GRF. We observed no significant group-by-height interactions for joint stiffnesses (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 =0.735,  $\eta^2 = 0.00$ ,  $1-\beta = 0.09$ ). We did not find any significant main effect of group for stiffness in any joint (ankle: P = 0.934,  $\eta^2 = 0.00$ ,  $1-\beta = 0.05$ ; knee: P = 0.823,  $\eta^2 = 0.00$ ,  $1-\beta = 0.01$ ; hip: P = 0.291,  $\eta^2 = 0.04$ ,  $1-\beta = 0.37$ ). A significant main effect of height

was found on knee and hip stiffness with a medium effect size (knee: P < 0.001,  $\eta^2 =$ 313 314 0.10,  $1-\beta = 1.00$ ; hip: P < 0.001,  $\eta^2 = 0.12$ ,  $1-\beta = 1.00$ ), but not on ankle stiffness (ankle: P = 0.891,  $\eta^2 = 0.00$ ,  $1 - \beta = 1.00$ ). No significant interaction or main effect of group was 315 316 found for peak vertical GRF, but a significant main effect of height was evident (interaction: P = 0.282,  $\eta^2 = 0.00$ ,  $1 - \beta = 0.41$ ; main effect of group: P = 0.909,  $\eta^2 = 0.909$ 317 0.00,  $1-\beta = 0.05$ ; main effect of height: P < 0.001,  $\eta^2 = 0.58$ ,  $1-\beta = 1.00$ ). Multiple 318 319 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,

2008; Vieira et al., 2013). In the present study, no significant differences in ankle
inversion angle were apparent between groups, although the CAI group tended to show
a larger angle than the Control group in the 30-cm condition (Figure 2B). The
relationship between increased ankle plantarflexion moment and LAS risk needs to be
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

#### 439 *Clinical implications*

440 The present results suggest that differences between conditions of hip energy dissipation 441 in the CAI group and differences between the CAI and Control groups in terms of ankle 442 and hip joint moments might be more pronounced as landing height increases. To better 443 detect biomechanical changes among CAI populations, more demanding landings might 444 need to be used. Based on the premise that altered biomechanics are associated with 445 recurrent LAS in individuals with CAI, the goal of rehabilitation for individuals with 446 CAI is to obtain landing movements similar to those without CAI (healthy people or 447 copers). Since the biomechanical changes in the lower extremity joints differed 448 depending on landing height, obtaining a proper landing movement requires practice 449 landing not only under high-demand conditions, but also under low-demand conditions.

450

#### 451 Conclusions

452 In the present study, we investigated the effect of the mechanical demands of the 453 movement task (landing height) on landing biomechanics among individuals with CAI. 454 Significant group-by-height interactions were observed for peak ankle plantarflexion 455 moment and hip energy dissipation during single-leg landing, suggesting that the effect 456 of landing height on landing kinetics varies depending on the presence or absence of 457 CAI. In the CAI group, the effect size of the difference between conditions was larger 458 than that in the Control group with hip energy dissipation at 101–150 ms post-IC. Peak 459 ankle plantarflexion moment increased with increasing landing height in the CAI group, 460 but remained constant in the Control group regardless of landing height. In addition, the 461 CAI group showed significantly greater peak ankle plantarflexion moment than the 462 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	
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470	
471	Declaration of interest statement
472	The authors declare no conflicts of interest in association with this manuscript.
473	

#### 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
- ankle instability: Systematic review and meta-analysis. Medicine and science in
  sports and exercise, 52(7), 1563–1575.
- 504 https://doi.org/10.1249/MSS.00000000002282
- 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
- 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/10.4085/1062-6050547 344-18
- 548 Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15

- sports: Summary and recommendations for injury prevention initiatives. Journal of
  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
- Kadaba, M. P., Ramakrishnan, H. K., & Wootten, M. E. (1990). Measurement of lower
  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
- to chronic ankle instability during landing and jumping. Medicine and Science in
  Sports and Exercise, 50(2), 308–317.
- 565 https://doi.org/10.1249/MSS.00000000001442
- 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
- laboratory captured 'giving way' episode during a single-leg landing task in an
  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
- 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
- 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
- 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
- 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
- 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.00000000001255
- 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
- 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
- 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.
- Winters, J. M., & Woo, S. L. Y. (1990). *Multiple muscle systems: biomechanics and 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

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

- 667 (B), and 50-cm condition (C).
- 668 **a** Significant difference from the 50-cm condition in the same group (P < 0.05).
- 669 **b** Significant difference from the 40-cm condition in the same group (P < 0.05).
- 670 **c** Significant difference from the 30-cm condition in the same group (P < 0.05).
- 671 Abbreviations: CAI, chronic ankle instability; Con, control.





□ 30 cm ■ 40 cm ■ 50 cm



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

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

676 <sup>†</sup> Significant difference compared with the Control group at the same height (P < 0.05).

<sup>677</sup> <sup>‡</sup> A tendency to be larger in the CAI group compared with the Control group at the same



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

680



682 **Figure 3.** Comparative peak joint moment of ankle plantarflexion (A), knee extension

- 683 (B), and hip extension (C) between groups and heights.
- 684 \* Significant difference between heights in the same group (P < 0.05).

<sup>685</sup> <sup>†</sup> Significant difference compared with the Control group at the same height (P < 0.05).

- <sup>4</sup> A tendency to be larger in the CAI group compared with the Control group at the same
- 687 height (P < 0.10).
- 688 Abbreviations: CAI, chronic ankle instability; Con, control.
- 689





□ 30 cm ■ 40 cm ■ 50 cm

691 Figure 4. Comparative joint stiffness in the sagittal plane of ankle (A), knee (B), and

692 hip (C) and peak vertical ground reaction force (D) between groups and heights.

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

694 Abbreviations: CAI, chronic ankle instability; Con, control; vGRF, vertical ground

695 reaction force.

696

	CAI	Con	Cohen's d	P-value
Sex	7 males, 4 females	7 males, 4 females		
Age (years)	$21.6\pm1.6$	$20.6\pm2.1$	0.54 (-0.33, 1.36)	0.184
Height (m)	$1.67\pm0.07$	$1.68\pm0.09$	-0.12 (-0.96, 0.72)	0.786
Weight (kg)	$57.1\pm6.3$	$59.3\pm10.1$	-0.26 (-1.09, 0.59)	0.542
CAIT-J score	$20.7\pm4.8$	$29.6\pm0.7$	-2.59 (-3.61, -1.38)	< 0.001
Number of LASs (n)	$4.4\pm3.0$	0	2.07 (0.97, 3.02)	< 0.001
	(range, 2–10)			
Time since initial LAS (years)	$7.4\pm5.1$	_	_	_
Failed trials (n)				
30 cm	$1.5\pm0.5$	$1.6 \pm 3.7$	-0.04 (-0.87, 0.80)	0.800
40 cm	$1.5\pm0.9$	$1.8\pm5.0$	-0.08 (-0.92, 0.76)	0.623
50 cm	$1.9\pm0.7$	$1.8 \pm 1.4$	0.09 (-0.75, 0.92)	0.836

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

- 698 Data are presented as mean  $\pm$  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.

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
 interval post-initial contact.

	1–50 ms		51–100 ms 101–15		50 ms		151–200 ms					
	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip
<i>P</i> -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
$\eta^2$												
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 <i>-β</i>												
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

	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)				

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

	Hip	-0.43 (-1.28, 0.42)	-0.10 (-0.94, 0.74)	0.38 (-0.47, 1.22)
1	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)
Pea	ak 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)
Pea	ak 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

	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	

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

		(-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)
1(	01–150 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)
1:	51–200 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.