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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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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.

Previous case reports have shown that excessive inversion and internal rotation at 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., 2019; Mok et al., 2011; Panagiotakis et al., 2017; Remus et al., 2018; Terada & Gribble, 2015), while plantarflexion did not necessarily occur (Fong et al., 2009; Fong et al., 2012; Kristianslund et al., 2011; Mok et al., 2011; Panagiotakis et al., 2017). Thus, lower extremity kinematics would be related to recurrent sprain. In cross-sectional studies, while the CAI population has been reported to exhibit different joint kinematics of the lower extremity during landing compared with healthy and coper groups, the results regarding ankle inversion angle differed even between studies using similar movement tasks, such as a single-leg drop landing (Delahunt et al., 2006; Doherty et al., 2016b) and a single-leg forward jump landing and cutting (Kim et al., 2019; Koshino et al., 2016; Son et al., 2017). Similar discrepancies have been reported for the knee and hip joints, with different studies showing that the CAI group had greater or lesser flexion angles than the non-CAI group, or no difference between groups, even during similar movement tasks (Caulfield & Garrett, 2002; Delahunt et al., 2006; Doherty et al., 2016b; Kim et al., 2019; Koshino et al., 2016; Son et al., 2017; Terada et al., 2016). In terms of the kinematics of lower extremity joints, differences between individuals with and without CAI were suggested to become more pronounced during high-demand tasks (Brown et al., 2008; Koshino et al., 2014). These inconsistent results for joint kinematics may be due to differences in the demands of the movement tasks. In addition, joint kinematics in the sagittal plane affected joint moment, negative joint work, and time to peak vertical ground reaction force during single-leg landing (Devita & Skelly, 1992; Lee et al., 2018). The effect of the demand may therefore extend to joint kinetics.

A case report reported that the contribution of the ankle joint to energy dissipation was increased at the time of injury during double-leg stop jump, suggesting that not only kinematics, but also kinetics may be associated with recurrent LAS in individuals with CAI (Terada & Gribble, 2015). Previous studies have suggested that jump and landing kinetics differ between individuals with and without CAI. During a single-leg forward jump landing and cutting task, the CAI group showed larger extension moment, eccentric joint power, and sagittal-plane joint stiffness at the hip joint and smaller ankle plantarflexion and knee extension moment, eccentric joint power, and sagittal-plane joint stiffness at the ankle and knee joint compared with the control or coper groups (Kim et al., 2018; Son et al., 2017). McCann et al. reported a larger contribution of the hip and proximal (combined the knee and hip) joints to energy dissipation and a smaller contribution of the ankle in the CAI group compared with the coper group during a single-leg forward jump landing (McCann et al., 2018). A hip- or proximal-dominant strategy may result from individuals with CAI attempting to reduce demands on the ankle (Kim et al., 2018; McCann et al., 2018; Dejong et al., 2020). In addition, a recent systematic review suggested that jumping movements with increasing demand may highlight hip adaptations in individuals with CAI (Dejong et al., 2020). Thus, the joint kinetics of the lower extremity in individuals with CAI as well as kinematics may be affected by the 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 may be more marked in individuals with CAI than in healthy individuals; those with CAI may show a hip- or proximal (knee and hip)-dominant movement pattern in conditions of higher mechanical demand, because high-demand landings have shown these characteristics (Kim et al., 2018; McCann et al., 2018). However, no studies have investigated the effect of landing height on landing biomechanics among individuals with CAI. Clarification of the effect of mechanical demand (landing height) on landing biomechanics would provide clinicians with suggestions on the need for evaluation and training at several levels of demand in clinical practice. The purpose of this study was to compare the effects of landing height on landing biomechanics among individuals with 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 contribution of the knee and hip joints would increase among individuals with CAI compared with those without CAI at higher landing height.

Materials and methods

Participants

Before this study, we conducted a pilot study that involved four CAI participants and four control participants, using the same experimental procedure (see below) as in this study. The results showed that the partial η^2 of the interaction on the peak hip extension moment was 0.181. Using the value, we performed an a priori power analysis using G*power 3.1 (University of Dusseldorf, Dusseldorf, Germany). A sample size of 18 participants (9 participants per group) was found to be necessary to achieve a statistical significance level of 0.05 and statistical power of 0.80 for group-by-height interaction on peak hip extension moment. Considering the possibility of missing data, we finally recruited 22 participants (11 CAI participants, 11 control participants) to the study. All participants provided written informed consent before enrolment in the study. This study was approved by the ethics committee of our university.

Participants were recruited from among competitive collegiate athletes who belong to the sports clubs at our university. We asked the following sports clubs to participate in this study: track and field, badminton, lacrosse, soccer, tennis, ice hockey, field hockey, basketball, volleyball, and gymnastics. A total of 379 athletes (243 males, 136 females) were screened for demographic data (age, height, weight, dominant leg, history of LAS, and previous injury) and the Cumberland Ankle Instability Tool Japanese version (CAIT-J) score. Twenty-five athletes met the following inclusion criteria for the CAI group based on the 2013 position statement of the International Ankle Consortium (Gribble et al., 2013): i) history of at least one LAS with interruption of desired physical activity for at least one day, 12 months or more before enrollment in this study; ii) history of at least two LASs; iii) at least two episodes of the ankle "giving-way" in the 6 months before enrollment in this study; and iv) CAIT-J score ≤ 25 (Kunugi et al., 2017). Of these, 14 athletes declined to participate in this study due to time constraints and were therefore excluded. Finally, 11 athletes who agreed to participate in this study were included in the CAI group. Control participants were matched to CAI participants for age (± 3 years old), height (± 5 cm), weight (± 5 kg), and sex. A total of 11 athletes were included in the Control group from the same athletic population as CAI participants. Inclusion criteria for the Control group comprised: i) no history of LAS; and ii) CAIT-J score ≥ 28. Participants were excluded if they met the following exclusion criteria (Gribble et al., 2013): i) a history of fracture or surgery in the lower limb; or ii) a history of major musculoskeletal injuries in the lower limb (other than a history of LAS in the CAI group) in the 3 months before study enrollment. No participants in either group had any history of neurological or vestibular impairments.

For CAI participants, the tested limb was the affected side. If CAI was present bilaterally, the more affected side (as determined by the CAIT-J score) was tested. The CAI and Control groups were matched for the dominance of the tested limb. The dominant leg was defined as the leg that the participant would use to kick a ball (Sadeghi et al., 2000).

Instrumentation

Twenty-five retroreflective markers were placed on specific anatomical landmarks using double-sided adhesive tape, based on a modified Helen Hayes marker set (Kadaba et al., 1990): at the sacrum, bilaterally on the anterior superior iliac spine, greater trochanters, lateral aspect of the thighs, lateral and medial femoral epicondyles, lateral aspect of the shanks, lateral and medial malleoli, posterior heels, and first, second, and fifth metatarsal heads. Participants were barefoot during data collection. Kinematic data were collected using seven infrared cameras (Hawk cameras; Motion Analysis Corporation, Santa Rosa, CA, USA) at 200 Hz. Ground reaction force (GRF) data were collected using a force plate (Type 9286B; Kistler, Winterthur, Switzerland) at 1000 Hz. Kinematic and GRF data were time-synchronized through Cortex 5.5 (Motion Analysis Corporation).

Procedures

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 from three landing heights (30, 40, and 50 cm), in random order (Weinhandl et al., 2015). Participants stood on the box in front of a force plate with the tested limb. 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.

Data analysis

Three-dimensional marker trajectories were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 12 Hz (Ford et al., 2007). For each trial, a lower limb model (comprising the foot, shank, thigh, and pelvis segments) was created using Visual 3D software (C-motion; Germantown, MD, USA) to calculate ankle, knee, and hip joint angles. Joint coordinate systems were defined using the positive x-axis as forward, the positive y-axis as upward, and the positive z-axis as to the right-hand side. Joint angles were calculated using the z-x-y rotation sequence to be equal to the Cardan sequence, and values during the static trial were set to zero. The ankle joint center was defined as the midpoint between lateral and medial malleoli. The knee joint center was set as the midpoint between the lateral and medial femoral epicondyles. The hip joint center was defined based on the method reported by Davis et al (Davis et al., 1991). Using a fourth-order low-pass Butterworth filter with a cutoff frequency of 12 Hz (Ford et al., 2007), GRF data were filtered and synchronized to kinematics data with down-sampling. GRF data were normalized by dividing by weight of each participant.

Internal joint moments of the ankle, knee, and hip in the sagittal plane were calculated using an inverse dynamics method (Winter, 2009) and normalized by the height and weight of each participant. The products of joint moment and joint angle velocity represented joint power. Energy dissipations were calculated by integrating the negative region of the joint power curve. Ankle, knee, and hip energy dissipation were summed to calculate total energy dissipation in the sagittal plane. Lastly, we calculated the percentage of energy dissipation by each joint to total energy dissipation, as the contribution of each joint to energy dissipation. Based on a previous study (McCann et al., 2018), percentages of energy dissipation were calculated during the following four periods: 1–50, 51–100, 101–150, and 151–200 ms post-initial contact (IC). Joint stiffnesses of the ankle, knee, and hip joints in the sagittal plane were calculated by dividing the change in internal joint moment from initial contact to peak ankle dorsiflexion and knee and hip flexion, respectively, by the change in joint angle. For joint angles, joint moments, and vertical GRF, we calculated maximum values from IC to 200 ms post-IC. IC was defined as the first point at which vertical GRF exceeded 10 N (Ford et al., 2007). For all variables, the means of three successful trials for each condition were used for statistical analyses.

Statistical analysis

Demographic data (age, height, weight, the number of LASs) and CAIT-J scores were compared between the CAI and Control groups using the unpaired t-test. Two-way mixed analysis of variance (ANOVA) was conducted to test for the main effect of group (CAI and Control) and height (30, 40, and 50 cm) and group-by-height interaction on peak vertical GRF, peak joint angle, peak joint moment, the contribution to total energy dissipation, and joint stiffness of each joint. If a significant main effect or interaction was found, Bonferroni post hoc procedures were performed. For two-way mixed ANOVA, effect size was presented as η^2 and interpreted as: $0.01 <$ small $\leq 0.06 <$ medium $\leq 0.14 <$ 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 < small ≤ 0.50 < medium ≤ 0.80 < 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).

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.

Figure 1 shows the energy dissipation of each joint in each interval, and Table 2 shows the *P*-values, effect sizes, and statistical power for ANOVA. In addition, Tables 3 and 4 show Cohen's *d*, as the effect size in multiple comparisons for each variable. A significant group-by-height interaction was found for hip energy dissipation at 101–150 ms post-IC with a small effect size (Table 2). There were no significant main effects of group for all energy dissipation. A significant main effect of height was observed for all parameters with large effect size except as follows: hip energy dissipation at 51–100 ms, and ankle, knee, and hip dissipation at 151–200 ms. For the hip energy dissipation at 101–150 ms post-IC, multiple comparisons revealed that the CAI group showed significant differences in all landing heights, while the Control group showed significant differences between the 30- and 50-cm conditions and the 40- and 50-cm 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: $P = 0.818$, 50-cm: $P = 0.665$).

Figure 2 shows peak joint angle of each joint. We observed no group-by-height interactions for any joint angles (ankle dorsiflexion: $P = 0.414$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.30$; ankle inversion: $P = 0.378$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.33$; knee flexion: $P = 0.300$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.39$; hip flexion: $P = 0.470$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.26$). A significant main effect of group was observed for ankle dorsiflexion and knee flexion angle with large and medium effect sizes, respectively (ankle dorsiflexion: $P = 0.010$, $\eta^2 = 0.23$, $1\text{-}\beta = 1.00$; ankle inversion: $P = 0.164$, $\eta^2 = 0.09$, $1\text{-}\beta = 0.62$; knee flexion: $P = 0.032$, $\eta^2 = 0.14$, $1\text{-}\beta = 0.95$; hip flexion: $P = 0.396$, $\eta^2 = 0.03$, $1\text{-}\beta = 0.25$). A significant main effect of height was observed for all parameters except peak ankle inversion angle (ankle dorsiflexion: $P < 0.001$, $\eta^2 = 0.09$, $1\text{-}\beta = 1.00$; ankle inversion: $P = 0.464$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.27$; knee flexion: $P < 0.001$, $\eta^2 = 0.27$, $1\text{-}\beta = 1.00$; hip flexion: $P < 0.001$, $\eta^2 = 0.07$, $1\text{-}\beta = 1.00$). Multiple comparisons revealed that the CAI group showed a larger peak ankle dorsiflexion angle than the Control group under all height conditions (30 cm: $P = 0.006$; 40 cm: $P = 0.025$; 50 cm: $P = 0.029$, Figure 2A). Peak knee flexion angle was larger in the CAI group than in the Control group in the 50-cm condition ($P = 0.011$, Figure 2C) and tended to be larger in the CAI group than in the Control group in the 30- and 40-cm conditions ($P = 0.059$ and $P = 0.098$, respectively). Significant differences between height conditions were observed for all combinations of conditions except as follows: peak ankle dorsiflexion angle between the 40- vs 50-cm conditions in both groups, peak ankle inversion angle between all conditions in both groups, and peak hip flexion angle between the 30- and 40-cm conditions in the CAI group.

Figure 3 shows peak joint moment of each joint. Significant group-by-height interactions were observed for peak joint moment of the ankle and hip with medium and small effect sizes, respectively (ankle: $P = 0.005$, $\eta^2 = 0.05$, $1\text{-}\beta = 0.98$; knee: $P = 0.928$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.08$; hip: $P = 0.008$, $\eta^2 = 0.05$, $1\text{-}\beta = 0.98$). A significant main effect of group was observed on peak ankle plantarflexion moment with a large effect size ($P = 0.012$, $\eta^2 = 0.20$, $1\text{-}\beta = 0.99$), but not on peak knee and hip extension moment (knee: $P = 0.129$, $\eta^2 = 0.02$, $1\text{-}\beta = 0.70$; hip: $P = 0.457$, $\eta^2 = 0.01$, $1\text{-}\beta = 0.20$). A significant main effect of height was found for all joint moments with medium to large effect sizes (ankle: $P = 0.001$, $\eta^2 = 0.10$, $1\text{-}\beta = 1.00$; knee: $P < 0.001$, $\eta^2 = 0.72$, $1\text{-}\beta = 1.00$; hip: $P < 0.001$, $\eta^2 = 0.60$, $1\text{-}\beta = 1.00$). Multiple comparisons revealed that peak ankle plantarflexion moment was significantly increased in the CAI group as landing height increased, but was unchanged in the Control group (Figure 3A). Furthermore, the CAI group demonstrated significantly greater peak ankle plantarflexion moment than the Control group under the 50-cm condition ($P = 0.005$) and a tendency toward greater peak ankle plantarflexion moment than the Control group under the 30- and 40-cm conditions ($P = 0.055$ and $P = 0.065$, respectively). Peak hip extension moment differed significantly between all landing heights in the CAI group, while no significant difference was identified between 40- and 50-cm conditions in the Control group (Figure 3C). Although no significant differences were found between groups, the CAI group tended to exhibit greater peak hip extension moment compared with the Control 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: $P = 0.250$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.45$; knee: $P = 0.370$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.33$; hip: $P = 0.735$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.09$). We did not find any significant main effect of group for stiffness in any joint (ankle: $P = 0.934$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.05$; knee: $P = 0.823$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.01$; hip: $P = 0.291$, $\eta^2 = 0.04$, $1\text{-}\beta = 0.37$). A significant main effect of height was found on knee and hip stiffness with a medium effect size (knee: $P < 0.001$, $\eta^2 = 0.10$, $1\text{-}\beta = 1.00$; hip: $P < 0.001$, $\eta^2 = 0.12$, $1\text{-}\beta = 1.00$), but not on ankle stiffness (ankle: $P = 0.891$, $\eta^2 = 0.00$, $1\text{-}\beta = 1.00$). No significant interaction or main effect of group was found for peak vertical GRF, but a significant main effect of height was evident (interaction: $P = 0.282$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.41$; main effect of group: $P = 0.909$, $\eta^2 = 0.00$, $1\text{-}\beta = 0.05$; main effect of height: $P < 0.001$, $\eta^2 = 0.58$, $1\text{-}\beta = 1.00$). Multiple comparisons showed significant differences between all conditions for peak vertical GRF in both groups ($P < 0.05$, Figure 4D).

Discussion and implications

The purpose of this study was to compare changes in energy dissipation strategy with increasing landing height between individuals with and without CAI. The main findings of this study were as follows. First, we observed significant group-by-height interactions for hip energy dissipation at 101–150 ms post-IC and peak joint moment at the ankle and hip. Multiple comparison tests showed a significant difference in hip joint energy dissipation at 101–150 ms post-IC between all conditions in the CAI group with medium-to-large effect sizes, but not between the 30- and 40-cm conditions in the Control group (Figure 1). Peak hip extension moment was similarly significantly different between all conditions in the CAI group, but not between 40- and 50-cm conditions in the Control group (Figure 3C). Although not statistically significant, peak hip extension moment in the CAI group tended to be larger than the Control group under the 50-cm condition, with a large effect size (Figure 2C and Table 3). These findings supported our first hypothesis. On the other hand, peak ankle plantarflexion moment increased progressively in the CAI group as landing height increased, but was unchanged in the Control group and was significantly larger in the CAI group under the

50-cm condition (Figure 3A). These results differ from our second hypothesis. Second, significant main effects of group were found for ankle dorsiflexion and knee extension angles and peak ankle plantarflexion moment. In multiple comparison tests, significant differences between groups were observed for peak ankle dorsiflexion angle under all conditions and peak knee flexion angle and peak ankle plantarflexion moment under the 50-cm condition (Figure 2 and 3). Finally, significant main effects of height were observed in all variables excluded as follows: hip energy dissipation at 51–100 ms post-IC, all energy dissipation at 151–200 ms, peak ankle inversion angle, and ankle stiffness.

The primary finding of this study was that group-by-height interaction in hip energy dissipation was observed at 101–150 ms post-IC (Table 2), and significant differences were observed between all conditions in the CAI group, whereas the difference between 30- and 40-cm conditions in the Control group was not significant (Figure 1). In addition, the effect size in the comparison between height conditions was small to medium in the Control group, but medium to large in the CAI group (Table 4), suggesting medium to large differences between height conditions in the CAI group. As with hip energy dissipation, a group-by-height interaction was observed in peak hip extension moment. In the 50-cm condition, the CAI group tended to show greater peak hip extension moment compared with the Control group (Figure 3C). These interactions mean that the effect of landing height for these variables differed depending on whether CAI was present or absent, providing support for our first hypothesis. However, no significant group differences in hip energy dissipation or hip extension moment were observed, as in previous studies (Kim et al., 2018; McCann et al., 2018; Son et al., 2017). Previous studies have reported that individuals with CAI use a hip-dominant strategy during landing following 50% of the maximum vertical jump height or maximum vertical forward jump for that participant (Kim et al., 2018; McCann et al., 2018; Son et al., 2017). Since no significant difference was seen between groups in the present study, we cannot conclude that CAI participants showed increased reliance on the hip joint as landing height increased. The present results (interactions for hip variables, larger effect size in the CAI group than in the Control group in comparisons between height conditions) can be considered to be part of hip-dominant strategies among individuals with CAI, but it should be noted that the effect sizes of the interactions were small. Next, we observed a tendency for the CAI group to have larger peak hip extension moment than the Control group in the 50-cm condition with large effect size (Table 3). Also, although not statistically significant, some knee variables tended to show group differences with larger effect sizes under the 50-cm condition compared with the 30- and 40-cm conditions (e.g., the knee energy dissipation at 101–150 post-IC, knee flexion angle, and knee extension moment, Table 3). These results suggested that the difference between CAI and Control groups might increase as mechanical demands increase. Although our study investigated the effects of landing height in terms of mechanical demands, other factors such as multi-directional movements, quick movements, and complex neuromuscular control are also considered to be among the demands. Other demands might cause differences in movement patterns for individuals with CAI. Future studies need to examine whether group differences can be detected by increasing demands other than landing height.

Proximal muscles (such as the hip and knee muscles) could dissipate more energy because of the greater cross-sectional areas, longer muscle fibers, and relatively shorter tendons than distal muscles (Winters & Woo, 1990). Therefore, if the ankle function in energy dissipation is reduced or mechanical demands are increased, mechanical demands would be redistributed from distal to proximal joints (Coventry et al., 2006; Devita & Skelly, 1992; McCann et al., 2018; Zhang et al., 2000). Previous research has suggested that individuals with CAI exhibit decreased capabilities for shock attenuation at the ankle during single-leg landing, such as decreases in ankle plantarflexion moment (Kim et al., 2018; Son et al., 2017), ankle stiffness (Kim et al., 2018), and the contribution of the ankle to energy dissipation (McCann et al., 2018). In the present study, no differences in ankle energy dissipations were found between groups. We thus could not conclude that the CAI group showed any ankle dysfunction in energy absorption. However, the CAI group scored lower in CAIT-J score than the Control group, which means that CAI participants experienced subjective ankle instability. The interaction for hip energy dissipation and increasing hip energy dissipation with medium to large effect sizes in the CAI group (Table 4) when mechanical demands increased may represent a coping strategy for subjective ankle instability among CAI participants.

The present study found no interaction or main effect of group on ankle and knee energy dissipation or peak knee extension moment. In addition, the CAI group showed greater peak ankle plantarflexion moment than the Control group in the 50-cm condition (Figure 3A), and this result was inconsistent with findings from previous studies (Kim et al., 2018; Son et al., 2017). We should consider the possibility that differences in movement tasks affected ankle biomechanics. Our CAI participants showed a large peak ankle plantarflexion moment (Figure 3A), but no significant difference in ankle energy dissipation or stiffness between groups (Figure 1 and 4A). CAI participants in this study may not have been able to convert large ankle plantarflexion moments into energy dissipation and joint stiffness. In terms of injury risk, increased ankle plantarflexor activity may increase the risk of LAS injury by 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.

This study has some limitations that need consideration. First, landing heights were not set relative to each participant, but instead were absolute for all participants. Mechanical demands would have been affected by the physical characteristics and physical abilities of participants. Differences in demands may have led to difficulty detecting significant differences between groups. In future studies, setting landing height in relative manner for each participant may allow better delineation of differences between groups. Second, we did not record electromyographic activity of lower-extremity muscles during landing. Lower-extremity muscles are the main shock absorbers in landing tasks. Characteristics of individuals with CAI may be clarified by measuring both electromyographic activity and biomechanics of the lower extremity. Third, we should also consider statistical power. An a priori power analysis based on our pilot study showed that a huge sample size would be required to obtain sufficient power for ankle, knee, and hip energy dissipation (at least 846 participants per group); therefore, participants in this study were recruited based on the sample size calculation for peak hip extension moment. The post hoc power analysis showed that the significant results in the present study had sufficient statistical power ($1-\beta > 0.93$). Finally, since this study was cross-sectional in design, the findings cannot be used to indicate whether the altered energy dissipation strategy observed in the CAI group is a cause or effect of CAI. In the future, cohort studies could reveal this direction of causality in this relationship.

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 landing height on the ankle and hip joints differed between individuals with and without CAI. The effect of mechanical demands on landing biomechanics of the ankle and hip joint among CAI populations should be considered in biomechanical studies and clinical practice.

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Declaration of interest statement

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

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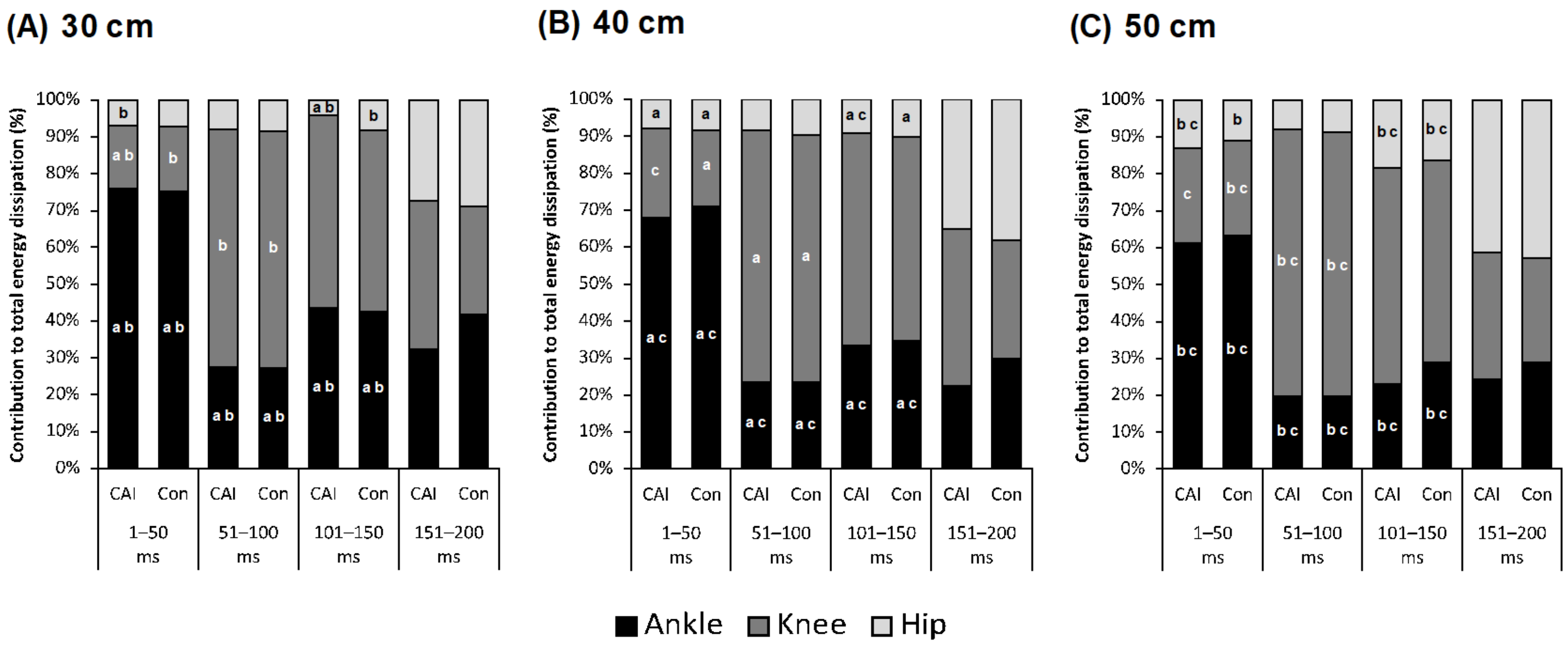

Figure 1. Comparative contributions of each joint to total energy dissipation during each interval between groups and heights in the 30- (A), 40- (B), and 50-cm condition (C).

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.

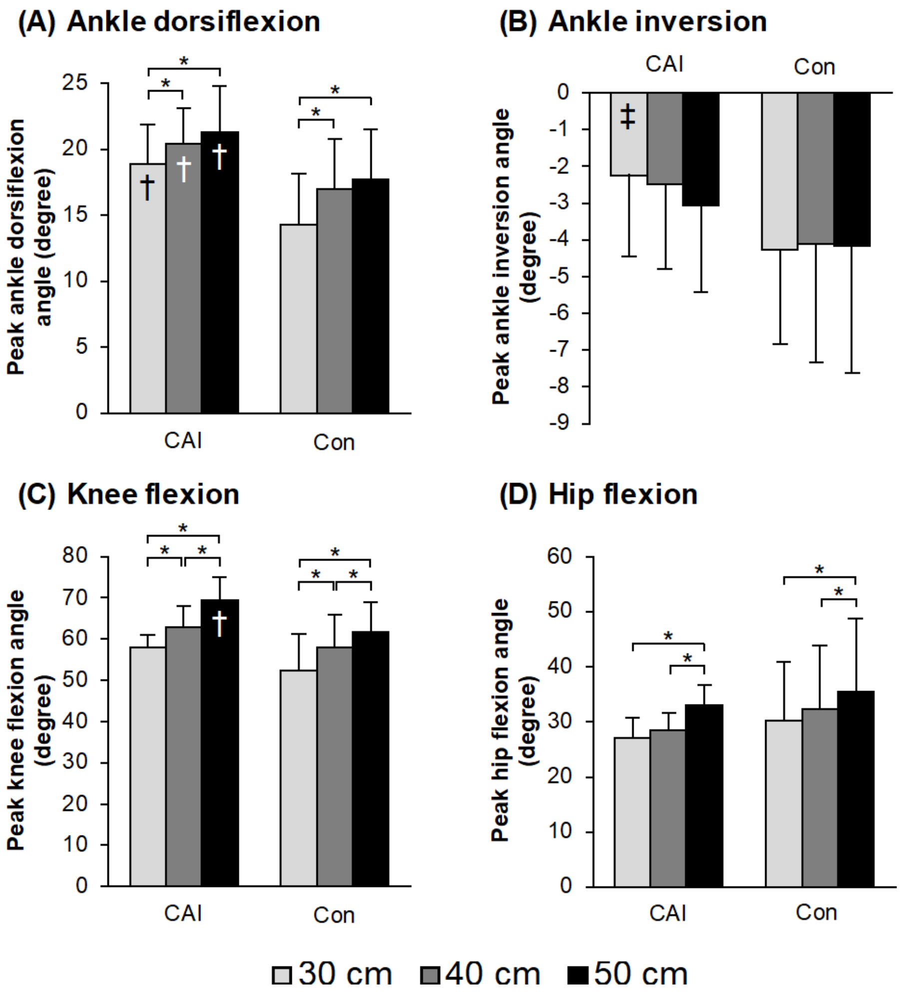

Figure 2. Comparative peak joint angle of ankle dorsiflexion (A), ankle inversion (B), knee flexion (C), and hip flexion (D) between groups and heights.

* 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.

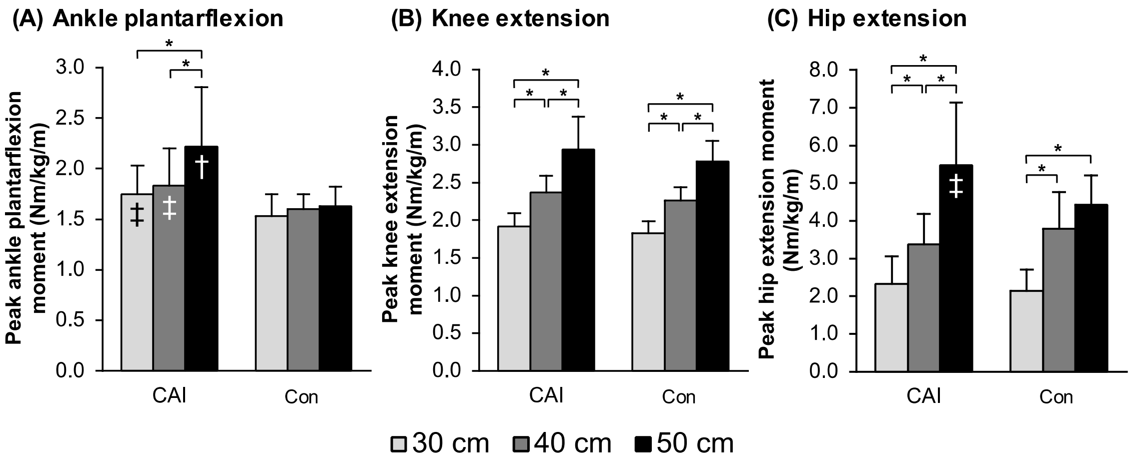

Figure 3. Comparative peak joint moment of ankle plantarflexion (A), knee extension (B), and hip extension (C) between groups and heights.

* 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.

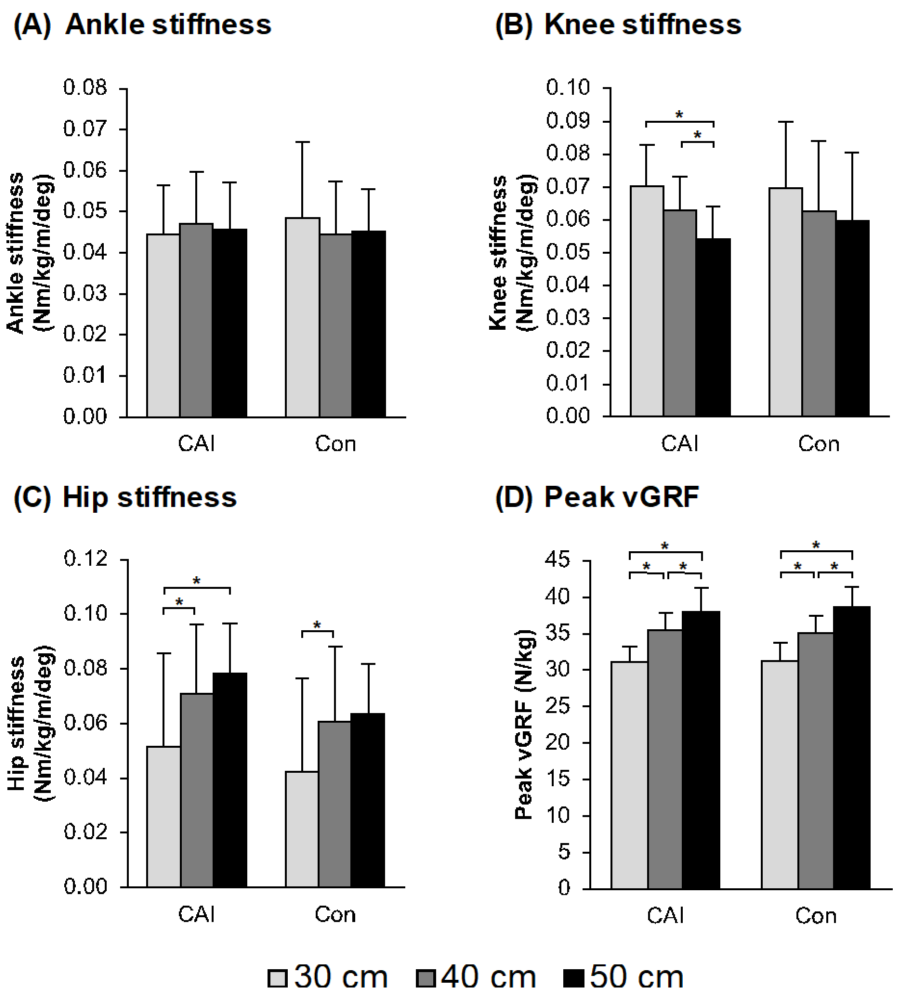

Figure 4. Comparative joint stiffness in the sagittal plane of ankle (A), knee (B), and hip (C) and peak vertical ground reaction force (D) between groups and heights.

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

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

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 (range, 2–10)	0	2.07 (0.97, 3.02)	< 0.001
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

Data are presented as mean ± standard deviation.

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

Abbreviations: CAI, chronic ankle instability; Con, control; CAIT-J, Cumberland Ankle Instability Tool Japanese version; LAS, lateral ankle 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			101–150 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

Values in bold are statistically significant.

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)

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

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

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)

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

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