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

Authors and affiliations:

Louis P. Howe[1], Theodoros M. Bampouras[2], Jamie North[3], Mark Waldron[3,4]

[1] Medical and Sport Sciences, University of Cumbria, Lancaster, UK.

[2] Lancaster Medical School, Faculty of Health and Medicine, Lancaster University, UK.

[3]School of Sport, Health and Applied Science, St Mary's University, Twickenham, London, UK.

[4] School of Science and Technology, University of New England, NSW, Australia.

Corresponding author:

Louis Howe

University of Cumbria,

Bowerham road,

Lancaster,

LA1 3JD.

Tel: 01524 590 800 ext: 2960

Email: louis.howe@cumbria.ac.uk

Abstract

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

Key words: ankle dorsiflexion; joint mechanics; landing

Highlights

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

1. Introduction

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

One of the modifiable factors associated with suboptimal landing mechanics is restriction in ankle dorsiflexion range of motion (DF ROM), which is inversely related (r = -0.411) to peak vGRF during a bilateral jump-landing task (Fong, Blackburn, Norcross, McGrath & Padua, 2011). The relationship between ankle DF ROM and peak vGRF is likely to be the result of limitations in ankle DF ROM inhibiting knee flexion motion during the shock absorption phase of landing (Fong, Blackburn, Norcross, McGrath & Padua, 2011). This results in a stiffer landing strategy known to increase peak vGRF (Zhang, Bates & Dufek, 2000) and undesirable load being placed on passive structures of the knee (Yu & Garrett, 2007). This is compounded by restrictions in ankle DF ROM also being negatively correlated (r = -0.27 – -0.36) with frontal- and transverse-plane kinematic compensations throughout the lower extremity during both unilateral (Whitting, Steele, McGhee & Munro, 2011) and bilateral landings (Malloy, Morgan, Meinerz, Geiser, & Kipp, 2015; Sigward, Ota & Power, 2008). For example, Malloy et al. (2015) observed that soccer players who presented with reduced ankle DF ROM performed a bilateral landing task with greater peak knee abduction angles. Given that an increased peak knee abduction angle during landings has been highlighted as a significant risk factor for anterior cruciate ligament injury (ACL) (Hewett et al., 2005), ankle DF ROM is an important injury risk factor for a number of populations. However, there is little evidence of other compensatory strategies that may be adopted to manage vGRF when ankle DF ROM is limited, such as altered lower extremity joint angles at initial contact and hip joint kinematics during landings.

Investigations into the relationship between ankle DF ROM and landing mechanics have used a variety of bilateral landing tasks (Fong et al., 2011; Malloy et al., 2015; Sigward et al., 2008). Drop heights for bilateral landings have ranged from 0.30 m (Fong et al., 2011) to 0.46 m (Sigward et al., 2008). Many jumping activities involve landing from a height that significantly exceeds an individual’s countermovement jump (CMJ) height, such as jumping with an arm swing (Slinde, Suber, Suber, Edwén, & Svantesson, 2008) or where a run-up occurs immediately prior to the jump (Young, Wilson, & Byrne, 1999). As differences in the initial contact velocity directly influences landing mechanics and the coordination strategies adopted (Zhang et al., 2000), research is required to determine how restrictions in ankle DF ROM alter the movement demands of these tasks at varying drop heights. Therefore, the aim of this investigation was to determine the relationship between ankle DF ROM and both kinetic and kinematic variables measured during bilateral drop-landings from a range of heights individualized to CMJ performance. We hypothesized that reduced ankle DF ROM would correlate with greater peak vGRF caused by reduced ankle dorsiflexion and knee flexion being available for energy absorption. Furthermore, limitations in ankle DF ROM would cause compensations in coordination strategies at other time points (i.e. initial contact) and separate joint segments (i.e. the hip). Additionally, we hypothesized that landings from higher drop heights would strengthen the relationship between ankle DF ROM and the compensatory strategies in coordination patterns.

2. Methods

2.1 Study design

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

2.2 Participants

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

2.3 Weight-bearing lunge test

Following the recording of height and body mass, ankle DF ROM was measured for both the right and left limb in barefoot using the weight-bearing lunge test (WBLT). The WBLT was chosen to measure ankle DF ROM due to its functional similarities to landings as a closed kinetic chain movement (Whitting, Steele, McGhee & Munro, 2013). To measure tibia angle relative to vertical on the lead leg during the WBLT, the trigonometric calculation method (DF ROM = 90- arctan [ground-knee/heel-wall]) was employed for each attempt using the heel-wall and ground-knee distances (Langarika-Rocafort, Emparanza, Aramendi, Castellano & Calleja-González, 2017). In order to measure the heel-wall distance, a 0.70 m tape measure was fixed to the floor, perpendicular to the wall used for testing. Measurements of ground-knee distance were obtained with a 0.70 m tape measure fixed vertically to the wall and perpendicular to the tape measure on the ground. A longitudinal line was marked down on each of the scales for testing purposes.

Using methods previously described (Langarika-Rocafort et al., 2017), participants began the test by facing a bare wall, with the greater toe of the test leg positioned against the wall. The greater toe and the center of the heel were aligned using the marked line on the ground. Participants were instructed to place the non-test foot behind them, with the heel raised and at a distance that they felt allowed them to maximize their performance on the test. In order to maintain balance, participants were asked to keep both hands firmly against the wall throughout. The participants were then instructed to slowly lunge forward by simultaneously flexing at the ankle, knee and hip on the lead leg in an attempt to make contact between the center of the patella and the vertical marked line on the wall. No attempt was made to control trunk alignment. Subtalar joint position was maintained by keeping the test foot in the standardized position and ensuring the patella contact with the vertical line was accurate (Dill, Begalle, Frank, Zinder and Padua, 2014; Whitting et al., 2011). Upon successful completion of an attempt, where contact between the patella and the wall was made with no change in heel position relative to the ground, participants were instructed to move the test foot further away from the wall by approximately 0.05 m. Although participants were not restricted to the number of attempts they were permitted at a given distance, no more than three attempts were performed by any participant. At the last successful attempt, the distances between the heel and the wall, and the distance between the anterosuperior edge of the patella and the ground were recorded to the nearest 0.1 cm. Mean inter-limb difference for ankle DF ROM were $1.9 \pm 1.3^{\circ}$. This procedure was repeated three times, with the mean value for the right limb from the three attempts used for data analysis. Intra-rater reliability for measurements of WBLT performance was calculated using the three values recorded for heel-to-wall distance, knee-to-ground distance and the WBLT score. Two-way mixed (single measure) intra-class correlation coefficients (ICC) for knee-to-wall distance, heel-to-wall distance and WBLT scores was 0.99, 0.98 and 0.97, respectively. Typical error (TE) for knee-to-wall distance, heel-to-wall distance and WBLT scores was 0.11 cm, 0.13 cm and 0.66˚, respectively.

2.4 Establishing drop height for bilateral drop-landings

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

2.5 Bilateral drop-landings

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

Participants then repeated the standardized warm-up, before being familiarized with the bilateral drop-landings from drop heights of 50%, 100% and 150% of their maximum CMJ height. Bilateral drop-landings were performed with participants standing with their arms folded across their chest on a height-adjustable platform (to the nearest 0.01 m). Participants were then instructed to step off the platform whilst ensuring that they did not modify the height of the center of mass prior to dropping from the platform (Zhang et al., 2000). For a landing to be deemed successful, participants were required to ensure they landed with each foot in complete contact with the respective portable force platform, which was positioned 0.15 m away from the elevated platform. Full contact with the force platform was visually monitored throughout by the investigator, with attempts being disregarded when participants made contact with the surrounding wooden mounts or failed to maintain balance (e.g. either taking a step or placing a hand on the ground to prevent falling) upon landing. Participants were instructed to "*land as softly as possible with both feet contacting the force platforms* *simultaneously and with equal weight distribution before returning to a standing position"* to allow for focus of attention to be controlled between trials (Milner, Fairbrither, Srivatsan & Zhang, 2012). To ensure participants displayed their natural landing strategy, no instructions were provided regarding heel contact with the ground during the landing phase of the movement. No feedback on landing performance was provided at any point during testing. All landings were performed barefoot so to prevent any heel elevation associated with footwear from altering landing mechanics and weakening internal validity (Lindenberg & Carcia, 2013). For each drop height, participants performed five landings for data collection, with 60 s recovery provided between landings. Participants completed each block of five bilateral drop-landings from the same drop height in succession, with drop height order randomized using a counterbalanced design.

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

2.6 Data analysis

Raw vGRF data for the right leg were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 50 Hz (Roewer, Ford, Myer & Hewett, 2014). Peak vGRF, time to peak vGRF and loading rate was then calculated for the right leg. Peak vGRF data were normalized to body mass and initial contact velocity ($N \cdot kg^{-1} \cdot m \cdot s^{-1}$). To normalize peak vGRF to drop height, initial contact velocity was calculated using the following equation (Niu, Feng, Jiang, & Zhang, 2014):

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

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

All video recordings were analysed with free downloadable software (Kinovea for Windows, Version 0.8.15). For sagittal-plane joint movements, hip flexion, knee flexion and ankle dorsiflexion angles were calculated at initial contact and the maximum flexion point for the right limb. These angles were then used to calculate joint displacement for each joint by subtracting the initial contact angle from the maximum flexion point. Initial contact was defined as the frame prior to visual impact between the foot and the ground that led to deformation of the foot complex. The maximum flexion point was identified visually and defined as the frame where no further downward motion occurred at the hip, knee or ankle joints (Dingenen et al., 2015).

Hip flexion angle was calculated as the angle between a line formed between the acromioclavular joint and the greater trochanter and a line between the greater trochanter and the lateral femoral condyle. Knee flexion angle was calculated as the angle between a line formed between the greater trochanter and the lateral femoral condyle and a line between the femoral condyle and the lateral malleolus. Ankle dorsiflexion angle was calculated as the angle between a line formed between the lateral femoral condyle and the lateral malleolus and a line between the lateral malleolus and the 5^{th} metatarsal head. FPPA was calculated for the right limb at the deepest landing position, defined as the frame corresponding to maximum knee flexion (Munro et al., 2012). This angle was calculated as the angle between the line formed between the proximal thigh marker and the knee joint marker and a line between the knee joint marker and the ankle joint marker (Munro et al., 2012). For hip flexion, knee flexion and ankle dorsiflexion, smaller values represented greater hip flexion, knee flexion and ankle dorsiflexion respectively. For FPPA, values <180° represented knee valgus and values >180° representing knee varus.

For establishing intra-rater reliability of the hip, knee and ankle joint angle at initial contact and at the maximum flexion point, along with FPPA, the first trial from drop heights of 150% of CMJ height was examined. Twenty randomly selected participants (11 males and 9 females) were examined twice by the same investigator, seven days apart. To determine intra-rater reliability for joint angles at initial contact and the maximum flexion point, two-way mixed (single measure) ICC and TE for the same trial was established using a customized spreadsheet (Hopkins, 2016). All 2D kinematic outcome measures showed excellent intra-rater reliability, with ICC for joint angles at initial contact ranging from 0.96 to 0.98 and all TE values <1.2°. Intra-class correlation coefficients for joint angles at the maximum flexion point ranged from 0.95 to 0.99, with all TE values <1.5°.

2.7 Statistical analysis

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

3. Results

Mean ankle DF ROM for the WBLT was 36.3 ± 3.9°. Descriptive statistics for dependant variables associated with bilateral drop-landing performance from drop-heights of 50%, 100% and 150% of CMJ height, along with correlation coefficients and probability statistics, are presented in Table 1, 2 and 3, respectively. Normalized peak vGRF, time to peak vGRF and loading rate for all drop heights was not related to DF ROM, with values ranging from *trivial* to *small* (Table 1, 2 and 3).

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

INSERT TABLES 1-3 HERE

4. Discussion

The aim of this study was to evaluate the relationship between ankle DF ROM, measured via the WBLT, and the kinetic and kinematic variables associated with bilateral drop-landing performance. We hypothesized that limitations in ankle DF ROM would result in greater peak vGRF and altered coordination strategies. However, we partially reject this hypothesis, as only relationships between ankle DF ROM and kinematic variables were found during bilateral drop-landings, without changes in kinetic variables associated with vGRF across all drop heights. Ankle DF ROM was mostly *moderately* related to a number of kinematic variables at the knee and ankle joints, indicating a large amount of unexplained variance in the relationship between ankle DF ROM and kinematic variables associated with landing performance. In addition, the relationship between ankle DF ROM and some kinematic variables were only apparent at drop heights of 100% and 150% of CMJ height, indicating greater mechanical loads may exaggerate the demands for compensatory strategies in coordination during landings. However, there was no association between ankle DF ROM and hip joint kinematics during landings. Therefore, ankle DF ROM is related only to kinematic variables of the ankle and knee during drop-landings, with some relationships becoming significant only at higher drop-landing heights.

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

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

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

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

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

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

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

It is important to acknowledge some potential limitations with the study. Firstly, we investigated the relationship between ankle DF ROM and landing mechanics using a participant sample with both male and female recreational athletes. Landing mechanics have been shown to differ between genders, with less peak knee flexion and greater knee valgus moments being demonstrated by females during landings (Chappell et al., 2002). Nevertheless, our results are similar to studies who identified a relationship between ankle DF ROM and landing mechanics in female (Malloy et al., 2015; Sigward et al., 2008) and male populations (Whitting et al., 2011), as well as investigations using a mixed sample (Fong et al., 2011). Therefore, our results can likely be generalized to both genders. However, the degree to which ankle DF ROM impacts landing mechanics for each gender is currently unknown and warrants further investigation. Another limitation was that our investigation did not consider menstrual cycle status for female participants, which has been shown to influence tendon stiffness and joint laxity (Cesar et al., 2011). It is possible, therefore, that the association found in our investigation between ankle DF ROM and landing performance may be influenced by the menstrual cycle, which researchers may wish to examine in future research.

5. Conclusions

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

Acknowledgements: none.

Declarations of interest: none.

Funding: this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interests: none.

References

1. Beach, T. A., Frost, D. M., Clark, J. M., Maly, M. R., & Callaghan, J. P. (2014). Unilateral ankle immobilization alters the kinematics and kinetics of lifting. *Work, 47*, 221-234.
2. Begalle, R. L., Walsh, M. C., McGrath, M. L., Boling, M. C., Blackburn, J. T., & Padua, D. A. (2015). Ankle dorsiflexion displacement during landing is associated with initial contact kinematics but not joint displacement. *Journal of Applied Biomechanics*, *31*, 205-210.
3. Blackburn, J. T., & Padua, D. A. (2009). Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *Journal of Athletic Training*, 44, 174-179.
4. Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science and Medicine*, *6*, 63-70.
5. Cesar, G. M., Pereira, V. S., Santiago, P. R. P., Benze, B. G., da Costa, P. H. L., Amorim, C. F., & Serrão, F. V. (2011). Variations in dynamic knee valgus and gluteus medius onset timing in non-athletic females related to hormonal changes during the menstrual cycle. *The Knee*, *18*, 224-230.
6. Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., & Yu, B. (2005). Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *The American Journal of Sports Medicine*, *33*, 1022-1029.
7. Chappell, J. D., Yu, B., Kirkendall, D. T., & Garrett, W. E. (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *The American Journal of Sports Medicine*, *30*, 261-267.

8. Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics, 18,* 662-669.

9. Delahunt, E., Cusack, K., Wilson, L., & Doherty, C. (2013). Joint mobilization acutely improves landing kinematics in chronic ankle instability. *Medicine and Science in Sports and Exercise*, *45*, 514-519.

10. Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. (2011). Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Medicine and Science in Sports and Exercise*, *43*, 693–700.

11. Dill, K. E., Begalle, R. L., Frank, B. S., Zinder, S. M., & Padua, D. A. (2014). Altered knee and ankle kinematics during squatting in those with limited weight-bearing–lunge ankle-dorsiflexion range of motion. *Journal of Athletic Training, 49*, 723-732.

12. Dingenen, B., Malfait, B., Vanrenterghem, J., Verschueren, S. M., & Staes, F. F. (2014). The reliability and validity of the measurement of lateral trunk motion in two-dimensional video analysis during unipodal functional screening tests in elite female athletes. *Physical Therapy in Sport, 15*, 117-123.

13. Dingenen, B., Malfait, B., Vanrenterghem, J., Robinson, M. A., Verschueren, S. M., & Staes, F. F. (2015). Can two-dimensional measured peak sagittal plane excursions during drop vertical jumps help identify three-dimensional measured joint moments? *The Knee, 22*, 73-79.

14. Fong, C. M., Blackburn, J. T., Nocross, M. F., McGrath, M., & Padua, D. A. (2011). Ankle-dorsiflexion range of motion and landing biomechanics. *Journal of Athletic Training*, *46*, 5-10.

15. Herrington, L. (2014). Knee valgus angle during single leg squat and landing in patellofemoral pain patients and controls. *The Knee, 21*, 514-517.

16. Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, Jr R. S., Colosimo, A. J., McLean, S. G., Van den Bogert, A. J., Paterno, M. V., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *The American Journal of Sports Medicine*, *33*, 492-501.

17. Hewett, T. E., Myer, G. D., & Ford, K. R. (2006). Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *The American Journal of Sports Medicine*, *34*, 299-311.

18. Hoch, M. C., Farwell, K. E., Gaven, S. L., & Weinhandl, J. T. (2015). Weight-bearing dorsiflexion range of motion and landing biomechanics in individuals with chronic ankle instability. *Journal of Athletic Training*, *50*, 833-839.

19. Hopkins, W. G. Precision of measurement. (2016). http://sportsci.org/resource/stats. Accessed June 20 2018.

20. Howe, L., North, J., Waldron, M., & Bampouras, T. (2018). Reliability of independent kinetic variables and measures of inter-limb asymmetry associated with bilateral drop-landing performance. *International Journal of Physical Education, Fitness and Sports*, *7*, 32-47.

21. Knapik, J. J., Craig, S. C., Hauret, K. G., & Jones, B. H. (2003). Risk factors for injuries during military parachuting. *Aviation, Space, and Environmental Medicine, 74*, 768-774.

22. Langarika-Rocafort, A., Emparanza, J. I., Aramendi, J. F., Castellano, J., & Calleja-González, J. (2017). Intra-rater reliability and agreement of various methods of measurement to assess dorsiflexion in the Weight Bearing Dorsiflexion Lunge Test (WBLT) among female athletes. *Physical Therapy in Sport*, *23*, 37-44.

23. Lima, Y. L., de Paula Lima, P. O., Bezerra, M. A., de Oliveira, R. R., & Almeida, G. P. L. (2018). The association of ankle dorsiflexion range of motion and dynamic knee valgus: A systematic review with meta-analysis. *Physical Therapy in Sport, 29,* 61-69.

24. Lindenberg, K. M., & Carcia, C. R. (2013). The influence of heel height on vertical ground reaction force during landing tasks in recreationally active and athletic collegiate females. *International Journal of Sports Physical Therapy*, *8*, 1-8.

25. Malloy, P., Morgan, A., Meinerz, C., Geiser, C., & Kipp, K. (2015). The association of dorsiflexion flexibility on knee kinematics and kinetics during a drop vertical jump in healthy female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy, 23,* 3550-3555.

26. Mason-Mackay, A. R., Whatman, C., & Reid, D. (2017). The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: A systematic review. *Journal of Science and Medicine Sport, 20*, 451-458.

27. McClay, I. S., Robinson, J. R., Andriacchi, T. P., Frederic, E. C., Gross, T., Marin, P., Valiant, G., Williams, K. R., & Cavanagh, P. R. (1994). A profile of ground reaction forces in professional basketball. *Journal of Applied Biomechanics, 10*, 222-236.

28. Milner, C.E., Fairbrother, J. T., Srivatsan, A., & Zhang, S. (2012). Simple verbal instruction improves knee biomechanics during landing in female athletes. *The Knee, 19,* 399-403.

29. Moir, G. L. (2008). Three different methods of calculating vertical jump height from force platform data in men and women. *Measurement in Physical Education and Exercise Science, 12,* 207-218.

30. Munro, A., Herrington, L., & Carolan, M. (2012). Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *Journal of Sport Rehabilitation, 21,* 7-11.

31. Niu, W., Feng, T., Jiang, C., & Zhang, M. (2014). Peak vertical ground reaction force during two-leg landing: A systematic review and mathematical modeling. *Biomed Research International, 2014*.

32. Payton, C. J. (2007). Motion analysis using video. In C. J. Payton, & R. M. Bartlett (Eds.), *Biomechanical evaluation of movement in sport and exercise* (pp. 8-32). New York: Routledge.

33. Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics, 25*, 142-146.

34. Renstrom, P., Ljungqvist, A., Arendt, E., Beynnon, B., Fukubayashi, T., Garrett, W., Georgoulis, T., Hewett, T. E., Johnson, R., Krosshaug, T., & Mandelbaum, B. (2008). Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *British Journal of Sports Medicine, 42*, 394-412.

35. Roewer, B. D., Ford, K. R., Myer, G. D., & Hewett, T. E. (2014). The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: artefact or 'artifiction'? *British Journal of Sports Medicine*, *48*, 464–468.

36. Rowley, K. M., & Richards, J. G. (2015). Increasing plantarflexion angle during landing reduces vertical ground reaction forces, loading rates and the hip's contribution to support moment within participants. *Journal of Sports Sciences, 33*, 1922-1931.

37. Sigward, S. M., Ota, S., & Powers, C. M. (2008). Predictors of frontal plane knee excursion during a drop land in young female soccer players. *Journal of Orthopaedic and Sports Physical Therapy*, *38*, 661-667.

38. Slinde, F., Suber, C., Suber, L., Edwén, C.E., & Svantesson, U. (2008). Test-retest reliability of three different countermovement jumping tests. *The Journal of Strength & Conditioning Research*, 22, 640-644.

39. Whitting, J. W., Steele, J. R., McGhee, D. E., & Munro, B. J. (2011). Dorsiflexion capacity affects Achilles tendon loading during drop landings. *Medicine and Science in Sports and Exercise, 4*, 706–713.

40. Whitting, J. W., Steele, J. R., McGhee, D. E., & Munro, B. J. (2013). Passive dorsiflexion stiffness is poorly correlated with passive dorsiflexion range of motion. *Journal of Science and Medicine in Sport*, *16*, 157–161.

41. Wright, I. C., Neptune, R. R., van den Bogert, A. J., & Nigg, B. M. (2000). The influence of foot positioning on ankle sprains. *Journal of Biomechanics, 33*, 513–9.

42. Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2011a). Non-linear flexion relationships of the knee with the hip and ankle, and their relative postures during landing. *The Knee, 18*, 323-328.

43. Yeow, C.H., Lee, P.V.S., & Goh, J.C.H. (2011b). An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Human Movement Science, 30*, 624-635.

44. Young, W., Wilson, G., & Byne, C. (1999). Relationship between strength qualities and performance in standing and run-up vertical jumps. *Journal of Sports Medicine and Physical Fitness, 29*, 285-293.

45. Yu, B., Lin, C. F., & Garrett, W. E. (2006). Lower extremity biomechanics during the landing of a stop-jump task. *Clinical Biomechanics, 21,* 297-305.

46. Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. B *British Journal of Sports Medicine, 41*, 47-51.

47. Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise,* 32, 812-819.

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

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

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

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

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

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

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

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

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