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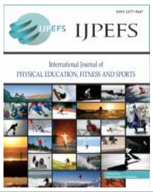


# Reliability of independent kinetic variables and measures of inter-limb asymmetry associated with bilateral drop-landing performance

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**Abstract:** The purpose of this investigation was to establish the within-session reliability for peak vertical ground reaction force (vGRF), time to peak vGRF, and loading rate, both unilaterally and bilaterally, during a drop-landing task as well as the reliability of inter-limb asymmetry in peak vGRF. Twenty-two men (age = 22 ± 4 years; height = 180.4 ± 6.1 cm; mass = 77.9 ± 14.0 kg) and 17 women (age = 20.4 ± 3.6 years; height = 164.6 ± 9.4 cm; mass = 60.3 ± 9.8 kg) volunteered for a single testing session. Participants completed three countermovement jumps (CMJ) to establish maximum jump height before performing five bilateral drop-landings from 50%, 100%, and 150% of their maximum CMJ height. The bilateral drop-landing protocol was then repeated after a 10 min recovery. Systematic bias, intraclass correlation coefficient (ICC), coefficient of variation (CV%) and minimal detectable change (MDC) values for each kinetic measurement was calculated for the left and right leg, as well as bilaterally. There was no systematic bias present between trials ($P > 0.05$). All kinetic measurements showed relative reliability, ranging from *large* to *near perfect* (ICC = 0.57–0.95). Absolute reliability ranged considerably depending on the measure and drop-height, with peak vGRF and time to peak GRF showing the greatest reliability at higher drop heights (CV% = 6.6–9.7%). Loading rate for all drop heights demonstrated CV% ranging 13.0–27.6%. Furthermore, MDC values for inter-limb asymmetries in peak vGRF ranged between 14.5–16.2% for all drop heights. Overall, many of the kinetic measurements evaluated were sufficiently reliable to detect typical changes in bilateral drop-landing performance when greater drop heights were used.

***Key Words:*** within-session reliability, kinetic variables, landings; inter-limb asymmetry

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## Introduction

Bilateral landings are commonly performed in court [1], team sports [2] and gymnastics [3]. When performing such tasks, peak vertical ground reaction forces (vGRF) can increase to multiples of bodyweight [4, 5]. In order to attenuate such high forces, an athlete must adopt a coordinated movement strategy that flexes the ankle, knee and hip joints through the sagittal plane, such that the downward vertical rate of velocity of their centre of mass is progressively decelerated [6]. When coordination strategies to decelerate the centre of mass over a large range of motion are either not accessed as a movement solution [7], the result is a higher peak vGRF. Athletes who are exposed to greater peak vGRF during landings have an increased lower-extremity injury risk [1]. For example, Hewett et al. [8] showed that pre-screened female athletes who subsequently experienced anterior cruciate ligament injuries, produced normalized peak vGRF 20 % higher than non-injured athletes during drop-landing tasks. Additionally, athletes who display higher peak vGRF in the 100 ms following ground contact, place very high load on ligamentous structures located at the tibiofemoral joint [9].

As a result, the loading rate exhibited during landings may provide an insight into the stress being placed on various anatomical structures throughout the kinetic chain [10]. With bilateral drop-landings being commonly used to screen landing competency in athletic populations [11], reliability data that informs practice is required.

During bilateral landing activities, asymmetries in GRF are commonly identified [12, 13]. These asymmetries are an important consideration when working with athletes as they perform a high volume of bilateral landings as part of their physical preparation and competitive movements. Athletes who exhibit a large asymmetry in peak vGRF during bilateral landings may expose their dominant leg to excessive loading, thereby increasing the potential risk for overuse injury [14]. In such instances, reliable identification of bilateral asymmetry and subsequent interventions to reduce the magnitude of the asymmetry might be warranted and thus, in the first instance, it is necessary to investigate the reliability of asymmetries in kinetic variables during bilateral landings.

Given that variables such as peak vGRF (N), time to peak vGRF (s), and loading rate ($N \bullet s^{-1}$) are commonly reported in the literature as being associated with injury risk [8, 10, 15], coaches should be aware of the inherent error associated with testing procedures. This includes error on behalf of the athlete while performing a given protocol (biological error) and that of the equipment (technical error) [16]. Although previous investigations have reported the reliability for outcome measures relating to the propulsive phase of bilateral jumping tasks in various populations [17-20], there is limited information on the kinetic factors associated with bilateral drop-landings [21], especially in regards to the presence of inter-limb asymmetries. The aim of this investigation was, therefore, to assess the reliability of peak vGRF, time to peak vGRF and loading rate, both bilaterally and unilaterally, during bilateral drop-landings from various landing heights, and to also establish the reliability for inter-limb asymmetries in peak vGRF during these landing tasks.

## Methods

A within-session repeated measures design was used to establish the reliability for all kinetic variables related to bilateral drop-landings. Participants were required to report to the university laboratory for a single testing session. After familiarization, participants performed three countermovement jumps (CMJ) to establish maximum jump height for the landing task. Subsequently, participants performed five bilateral drop-landings from three heights: 50% of their maximum CMJ 100% of their maximum CMJ and 150% of their maximum CMJ. The participants then repeated the bilateral drop-landings from each height following a 10 min recovery.

### Participants

Thirty-nine men (*n* = 22; age = 22 ± 4 years; height = 180.4 ± 6.1 cm; mass = 77.9 ± 14.0 kg) and women (*n* = 17; age = 20.4 ± 3.6 years; height = 164.6 ± 9.4 cm; mass = 60.3 ± 9.8 kg) volunteered for this study. All reported to be physically active, defined as regularly performing a minimum of 30 minutes of moderate intensity exercise three times per week for at least six-months prior to testing [22]. Participants were excluded if they had a history of lower-extremity surgery or had lower-extremity injury six-months prior to testing. 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 of the lead author.

### Procedures

The participants performed a 5 minute standardized warm-up and three familiarization CMJ attempts. Countermovement jumps were performed from a standing position with each foot placed on a portable force platform recording at 1000 Hz (Pasco, Roseville, CA, USA). The force platforms were positioned side-by-side and embedded in custom built wooden mounts that were level with the force platforms, preventing any extraneous movement that could influence the force trace recorded. In bare feet, participants were informed to stand with their feet hip-width apart and with hands on their hips to eliminate the contribution of the arm swing. 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 [23]. Upon landing, participants were required to ensure that full contact was made between each foot and the respective force platforms, with trials excluded if either foot made contact with the wooden mounts or neighbouring force platform. Following familarization, participants performed three CMJ for data analysis with a 60 second recovery between trials. 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 cm [24]. The maximum value of the three attempts was then used to calculate box height for the bilateral drop-landings.

Participants were given 10 minutes' recovery prior to repeating the standardized warm-up and performing three familiarization trials of bilateral drop-landings from each height. For the bilateral drop-landings, participants stood bare foot with their arms folded across their chest on a height-adjustable platform (to the nearest 1 cm) positioned 15 cm away from the two force platforms. Participants then stepped off the height-adjustable platform, leading with the right leg, before immediately bringing the left leg off and alongside the right leg prior to ground contact. Participants were instructed to ensure they did not alter the vertical displacement of their centre of mass in this process so as to control for drop height [25]. Participants were asked 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*". This instruction was used in order to control for participants' focus of attention during the landing task between trials [26]. Full contact with the force platform was visually monitored throughout, with attempts disregarded if participants failed to either make full contact with the platform or maintain balance upon landing. No feedback was provided regarding the performance of the landing task. For data collection, participants performed five landings from drop heights of 50%, 100% and 150% of their maximum CMJ height with a counterbalanced design employed to control for an order effect. Following each landing, 60 second recovery was provided before commencing the next trial. After a 10 minute recovery and standardized warm-up, participants repeated the bilateral drop-landing protocol, with drop height randomized for both trials 1 and 2.

## Data analysis

Raw vGRF data were low-pass filtered using a fourth-order Butterworth filter with a cut-off frequency of 50 Hz [27]. Peak vGRF, time to peak vGRF, and loading rate was then calculated unilaterally for the right and left leg, as well as bilaterally. For bilateral measures, both the left and right force data were summed prior to analysis. Peak vGRF data was normalized to body mass ($N \bullet kg^{-1}$). For time to peak vGRF to be determined, initial contact was identified as the point that vGRF exceeded 10 N both for each limb and bilaterally [28]. 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 divided by time to peak vGRF [29]. To calculate inter-limb asymmetries in peak vGRF, the asymmetry index equation was performed for each landing as outlined by Jordan et al. [30]:

$$\text{Asymmetry Index} = (\text{Right peak vGRF} - \text{Left peak vGRF}) * 100 / (\text{Right peak vGRF} + \text{Left peak vGRF})$$

where a positive value was arbitrarily assigned to right leg dominance, while a negative number indicated left leg dominance. All force-time measures were averaged across the five landings for each trial.

## Statistical analysis

Descriptive statistics (means ± standard deviation) were calculated for all variables. The assumption of normality was confirmed using the Shapiro-Wilk test. To examine for heteroscedastic errors, the relationship between the mean values between tests and the difference between repeat tests was evaluated using Pearson's coefficient. The within-session reliability for peak vGRF, time to peak vGRF, and loading rate for each limb (left and right) and bilaterally, along with asymmetries in peak vGRF between limbs, was initially assessed using a paired samples *t*-test to calculate systematic bias between trial 1 and 2 from each box height [16]. The *α-priori* level of significance was set at $P < 0.05$, with a Bonferroni correction applied *post-hoc* to the α-level for the ten variables pairwise between-comparisons (i.e. $0.05/10 = P = 0.005$) from each box height in order to reduce the risk of type I errors [31]. Relative reliability was determined using an intra-class correlation coefficient (ICC) as suggested by Atkinson and Nevill [16] and reported with 95% confidence intervals, with ICCs interpreted as follows: 0.01-0.3 *poor*, 0.3-0.5 *moderate*, 0.5-0.7 *large*, 0.7-0.9 *very large*, and >0.9 *nearly perfect* [32]. Absolute reliability was calculated using the coefficient of variation (CV%), the 95% limits of agreement, standard error of measurement (SEM; $SEM = SD\sqrt{1-ICC}$) [16] and minimal detectable change (MDC; $MDC = SEM*1.96*\sqrt{2}$) [33]. Due to the peak vGRF asymmetry being interval data, CV% was not calculated for this variable. ICC and CV% were calculated using customised Microsoft Excel spreadsheet available online [34]. The CV% was used as the primary measure of absolute reliability but we have reported a variety of statistical interpretations to facilitate wider applications or different preferences of researchers or practitioners. All statistical tests were performed using SPSS® statistical software package (v.24; SPSS Inc., Chicago, IL, USA).

## Results

The group mean for CMJ height was 29.8 ± 8.1 cm. Mean and standard deviations for all variables are presented in Tables 1-4. There was no systematic bias or heteroscedasticity found between trials 1 and 2 for any variable for each drop height. For measures of peak vGRF, relative reliability was *nearly perfect* (ICC ≥0.90) for all variables except peak vGRF on the right extremity from the 50% CMJ drop height, which had *very large* relative reliability (ICC = 0.87). Measures of absolute reliability for peak vGRF are reported in Table 1, with CV% ranging from 7.1–13.0% for all variables. Time to peak vGRF demonstrated relative reliability of *large* to *near perfect* across all drop heights (ICC = 0.57–0.92). However, absolute reliability was greater for drop heights of 150% CMJ height (CV% = 6.6–9.5%) when compared to drop heights of 100% CMJ height (CV% = 10.5 – 13.1%) and 50% CMJ height (CV% = 14.9–27.6%) for time to peak vGRF (Table 2). Loading rate possessed *very large* to *near perfect* relative reliability (ICC = 0.86 – 0.95) across all drop heights, and absolute reliability establishing CV% ranging between 13.0–27.6% (Table 3). Measures of reliability for asymmetries in peak vGRF are shown in Table 4, with relative reliability shown to be *very large* (ICC = 0.72–0.74).

## Discussion

The primary purpose of this study was to establish the within-session reliability for force-time measures of the bilateral drop-landing from drop heights of 50%, 100% and 150% of maximum CMJ height. Our data shows that kinetic measures of bilateral drop-landing performance have relative reliability ranging from *large* to *near perfect*, with absolute reliability (represented by CV%) ranging from 6.6–27.6%. Therefore, the bilateral drop-landing can be reliably used as a screening tool for athlete populations, although the variability in error will be strongly influenced by the force-time measurement analysed and the magnitude of change being detected [16].

Importantly, no systematic bias was detected between trials using the within-session design, indicating that no learning effect, participant bias, or acute adaptations were present between trials [16]. These findings suggest that the procedures used for this investigation were appropriate for diminishing the effects of systematic error. Practitioners, however, should remain aware of such considerations when designing procedures for testing an athlete's landing capabilities in order to reduce error and allow for better interpretation of their data [33].

Similar findings have previously been identified, with James et al. [21] reporting relative reliability as *very large* for bilateral measures of peak vGRF (ICC = 0.77) and loading rate (ICC = 0.87) for bilateral drop-landings from a 61 cm box. Similarly, using a within-session design, Walsh et al. [35] reported *near perfect* reliability for peak vGRF and time to peak vGRF (ICC = 0.98 and 0.92, respectively) following a bilateral drop-landing from a 31 cm box. Collectively, our findings support previous investigations; however, we have extended our interpretation of measurement error by quantifying absolute reliability (i.e. agreement) for all variables, across varying box heights for both unilateral and bilateral measures.

The ICC's for bilateral and unilateral measures of peak vGRF across each drop height ranged from 0.87–0.95, with CV% between 7.1–13.0% (Table 1). Although the ICC values suggested peak vGRF during bilateral landings to be arbitrarily reliable, it has been suggested that < 10% for CV% is the acceptable threshold for a test measure to be deemed reliable [36].

**Table 1** Within-session reliability for normalized peak vGRF for bilateral drop-landing from all drop height.

| | Trial 1 Mean ± SD | Trial 2 Mean ± SD | Change in mean | 95% LOA | ICC (95% CI) | CV (%) | SEM | MDC |
|---|---|---|---|---|---|---|---|---|
| Drop height 50% of maximum CMJ height | | | | | | | | |
| Total peak vGRF ($N\bullet kg^{-1}$) | 2.74 ± 0.91 | 2.71 ± 0.91 | -0.03 | 0.03 ± 0.79 | 0.90 (0.84 – 0.94) | 9.4 | 0.28 | 0.78 |
| Right peak vGRF ($N\bullet kg^{-1}$) | 1.76 ± 0.64 | 1.70 ± 0.54 | -0.06 | 0.06 ± 0.61 | 0.87 (0.78 – 0.92) | 13.0 | 0.21 | 0.60 |
| Left peak vGRF ($N\bullet kg^{-1}$) | 1.23 ± 0.41 | 1.22 ± 0.44 | 0.01 | 0.01 ± 0.33 | 0.92 (0.87 – 0.96) | 10.0 | 0.12 | 0.32 |
| Drop height 100% of maximum CMJ height | | | | | | | | |
| Total peak vGRF ($N\bullet kg^{-1}$) | 3.41 ± 1.17 | 3.21 ± 0.95 | -0.20 | 0.20 ± 0.85 | 0.92 (0.87 – 0.95) | 8.8 | 0.30 | 0.83 |
| Right peak vGRF ($N\bullet kg^{-1}$) | 2.02 ± 0.75 | 1.93 ± 0.63 | -0.10 | 0.10 ± 0.56 | 0.92 (0.86 – 0.95) | 10.1 | 0.20 | 0.55 |
| Left peak vGRF ($N\bullet kg^{-1}$) | 1.62 ± 0.58 | 1.54 ± 0.51 | -0.09 | 0.09 ± 0.46 | 0.91 (0.86 – 0.95) | 11.2 | 0.16 | 0.45 |
| Drop height 150% of maximum CMJ height | | | | | | | | |
| Total peak vGRF ($N\bullet kg^{-1}$) | 4.18 ± 1.27 | 3.99 ± 1.28 | -0.18 | 0.18 ± 0.77 | 0.95 (0.92 – 0.97) | 7.1 | 0.27 | 0.75 |
| Right peak vGRF ($N\bullet kg^{-1}$) | 2.43 ± 0.80 | 2.32 ± 0.78 | -0.11 | 0.11 ± 0.65 | 0.92 (0.86 – 0.95) | 9.6 | 0.23 | 0.63 |
| Left peak vGRF ($N\bullet kg^{-1}$) | 2.11 ± 0.75 | 2.06 ± 0.76 | -0.06 | 0.06 ± 0.49 | 0.95 (0.91 – 0.97) | 9.7 | 0.17 | 0.47 |

*Notes:* vGRF = Vertical ground reaction forces; LOA = Limits of agreement; ICC = Intraclass correlation coefficient; CV = Coefficient of variation; CI = Confidence interval; SEM = Standard error of measurement; MDC = Minimal detectable change. * = Significant difference between trial 1 and 2.

**Table 2.** Within-session reliability for time to peak vGRF for bilateral drop-landing from all drop heights.

| | Trial 1 Mean ± SD | Trial 2 Mean ± SD | Change in mean | 95% LOA | ICC (95% CI) | CV (%) | SEM | MDC |
|---|---|---|---|---|---|---|---|---|
| Drop height 50% of maximum CMJ height | | | | | | | | |
| Total time to peak vGRF (s) | 0.088 ± 0.031 | 0.092 ± 0.035 | 0.004 | -0.004 ± 0.038 | 0.84 (0.74 – 0.90) | 15.9 | 0.013 | 0.037 |
| Right time to peak vGRF (s) | 0.077 ± 0.022 | 0.081 ± 0.025 | 0.005 | -0.005 ± 0.033 | 0.75 (0.61 – 0.85) | 14.9 | 0.012 | 0.033 |
| Left time to peak vGRF (s) | 0.114 ± 0.057 | 0.108 ± 0.045 | -0.006 | 0.006 ± 0.094 | 0.57 (0.37 – 0.73) | 27.6 | 0.034 | 0.093 |
| Drop height 100% of maximum CMJ height | | | | | | | | |
| Total time to peak vGRF (s) | 0.068 ± 0.023 | 0.068 ± 0.022 | 0.000 | -0.004 ± 0.034 | 0.91 (0.84 – 0.94) | 10.7 | 0.007 | 0.019 |
| Right time to peak vGRF (s) | 0.065 ± 0.021 | 0.064 ± 0.015 | -0.001 | 0.001 ± 0.021 | 0.84 (0.74 – 0.90) | 10.5 | 0.007 | 0.020 |
| Left time to peak vGRF (s) | 0.080 ± 0.035 | 0.080 ± 0.035 | 0.000 | 0.000 ± 0.033 | 0.89 (0.82 – 0.94) | 13.1 | 0.011 | 0.032 |
| Drop height 150% of maximum CMJ height | | | | | | | | |
| Total time to peak vGRF (s) | 0.055 ± 0.014 | 0.056 ± 0.014 | 0.001 | -0.001 ± 0.017 | 0.82 (0.72 – 0.89) | 9.5 | 0.006 | 0.016 |
| Right time to peak vGRF (s) | 0.053 ± 0.012 | 0.054 ± 0.012 | 0.001 | -0.001 ± 0.010 | 0.91 (0.85 – 0.95) | 6.6 | 0.004 | 0.010 |
| Left time to peak vGRF (s) | 0.063 ± 0.027 | 0.063 ± 0.023 | 0.000 | 0.000 ± 0.021 | 0.92 (0.86 – 0.95) | 8.7 | 0.007 | 0.020 |

*Notes:* vGRF = Vertical ground reaction forces; LOA = Limits of agreement; ICC = Intraclass correlation coefficient; CV = Coefficient of variation; CI = Confidence interval; SEM = Standard error of measurement; MDC = Minimal detectable change. * = Significant difference between trial 1 and 2.

**Table 3.** Within-session reliability for loading rate for bilateral drop-landing from all drop heights.

| | Trial 1<br>Mean ± SD | Trial 2<br>Mean ± SD | Change in mean | 95% LOA | ICC (95% CI) | CV (%) | SEM | MDC |
|---|---|---|---|---|---|---|---|---|
| Drop height 50% of maximum CMJ height | | | | | | | | |
| Total loading rate (N/s) | 40.3 ± 25.3 | 38.7 ± 27.9 | -1.6 | 1.60 ± 26.33 | 0.88 (0.80 – 0.93) | 20.9 | 9.3 | 25.7 |
| Right loading rate (N/s) | 28.1 ± 18.0 | 25.8 ± 16.2 | -2.3 | 2.30 ± 16.80 | 0.88 (0.80 – 0.93) | 23.4 | 5.9 | 16.4 |
| Left loading rate (N/s) | 16.2 ± 11.6 | 16.2 ± 13.7 | 0.0 | 0.02 ± 13.44 | 0.86 (0.77 – 0.92) | 27.6 | 4.7 | 13.2 |
| Drop height 100% of maximum CMJ height | | | | | | | | |
| Total loading rate (N/s) | 61.5 ± 37.9 | 54.8 ± 27.3 | -6.7 | 6.70 ± 30.91 | 0.89 (0.82 – 0.94) | 16.1 | 10.9 | 30.2 |
| Right loading rate (N/s) | 38.0 ± 24.0 | 35.0 ± 19.3 | -3.0 | 3.03 ± 17.26 | 0.92 (0.87 – 0.95) | 16.7 | 6.1 | 16.8 |
| Left loading rate (N/s) | 27.1 ± 18.9 | 24.0 ± 14.0 | -3.1 | 3.08 ± 15.55 | 0.89 (0.82 – 0.94) | 22.8 | 5.5 | 15.2 |
| Drop height 150% of maximum CMJ height | | | | | | | | |
| Total loading rate (N/s) | 86.6 ± 42.5 | 81.1 ± 41.7 | -5.5 | 5.47 ± 26.70 | 0.95 (0.92 – 0.97) | 13.0 | 9.4 | 26.0 |
| Right loading rate (N/s) | 52.0 ± 27.4 | 49.3 ± 27.4 | -2.7 | 2.74 ± 19.14 | 0.94 (0.90 – 0.96) | 14.0 | 6.7 | 18.7 |
| Left loading rate (N/s) | 41.3 ± 24.1 | 40.1 ± 24.5 | -1.3 | 1.27 ± 15.05 | 0.95 (0.92 – 0.97) | 17.0 | 5.3 | 14.7 |

*Notes:* LOA = Limits of agreement; ICC = Intraclass correlation coefficient; CV = Coefficient of variation; CI = Confidence interval; SEM = Standard error of measurement; MDC = Minimal detectable change. * = Significant difference between trial 1 and 2.

**Table 4.** Within-session reliability for peak vGRF asymmetry for bilateral drop-landing from all drop heights.

| | Trial 1<br>Mean ± SD | Trial 2<br>Mean ± SD | Change in mean | 95% LOA | ICC (95% CI) | SEM | MDC |
|---|---|---|---|---|---|---|---|
| Peak vGRF asymmetry at 50% CMJ (%) | 17.4 ± 10.6 | 16.5 ± 11.6 | -0.9 | 0.89 ± 16.50 | 0.72 (0.57 – 0.83) | 5.9 | 16.2 |
| Peak vGRF asymmetry at 100% CMJ (%) | 10.9 ± 9.8 | 11.3 ± 10.9 | 0.4 | -0.41 ± 14.82 | 0.74 (0.60 – 0.84) | 5.3 | 14.6 |
| Peak vGRF asymmetry at 150% CMJ (%) | 7.7 ± 9.8 | 6.7 ± 10.8 | -0.9 | 0.91 ± 15.28 | 0.73 (0.57 – 0.83) | 5.4 | 15.0 |

*Notes:* CMJ = Countermovement jump height; vGRF = Vertical ground reaction forces; LOA = Limits of agreement; ICC = Intraclass correlation coefficient; CI = Confidence interval; SEM = Standard error of measurement; MDC = Minimal detectable change. * = Significant difference between trial 1 and 2.

This practice for determining absolute reliability would indicate that unilateral measures of peak vGRF during the bilateral drop-landing from heights of 50% and 100% of an individual's CMJ height should be considered to lack the necessary reliability (Table 1). Similarly, time to peak vGRF CV% ranged from 10.5–27.6% for bilateral drop-landings at 50% and 100% of CMJ height, both bilaterally and unilaterally (Table 2), resulting in the same arbitrary outcome of unacceptable reliability. However, the use of this arbitrary cut-off point has been contested on the basis that that it is not based on a well-defined analytical goal [16]. Therefore, as part of our investigation, we purposely chose not to apply an arbitrary 10% threshold for CV% to determine reliability. Instead, practitioners should appreciate that measurements of peak vGRF and time to peak vGRF during bilateral drop-landings, are likely to be more variable at lower drop heights and evaluate this in conjunction with the anticipated or likely signal changes. For example, Vu et al. [37] previously showed that firefighters performing bilateral drop-landings from a 41 cm drop height wearing restrictive firefighting boots were exposed to 10.8% greater peak vGRF bilaterally, when compared to landings in athletic footwear. Based on our data, the increase in peak vGRF associated with wearing firefighting boots would be defined as real from any drop-height between the individuals' 50–150% CMJ height. However, in a study by Milner et al. [26] investigating the effects of verbal instruction on a bilateral landing task, an instructional cue to land *with knees over your toes* led to a 9.0% mean reduction in bilateral peak vGRF across their cohort. Had this landing been performed from a drop height equalling 50% of each individual's maximum CMJ height, this reduction in peak vGRF would reside within the boundaries of measurement error and could not be defined as real change. As changes in landing mechanics have been shown to invoke an increase in peak vGRF of up to 29.6% bilaterally [38], we suggest that CV% reported in our investigation for peak vGRF may still be low enough to identify changes in an athlete's capacity to successfully attenuate forces across all drop heights. Similarly, differences in time to peak vGRF have been previously shown to differ by approximately 12.3% bilaterally between gymnasts and recreational athletes from a drop landing of 30 cm [39]. If this drop height equated to the participants 100% CMJ height, this difference in time to peak vGRF would exceed the CV% of 10.7% established in our investigation, and therefore present as a meaningful difference between cohorts. Therefore, we recommend that practitioners appreciate the measurement error established in our investigation for kinetic measures associated with bilateral landings to interpret an athlete's competency to dissipate forces. This interpretation must be made relative to the athlete's maximum CMJ height, as lower drop heights produce greater variability in measurement error.

Loading rate has previously been suggested to be an important mechanical variable to consider during landing activities, as it relates to injury risk [40]. The mean loading rates increased proportionally with box height. However, the CV% for loading rate observed was among the largest, particularly at lower drop-heights. Yet, loading rate measured bilaterally during drop-landings from 61 cm, have been shown to acutely decrease by 23% following a fatigue protocol [41]. Furthermore, significant reductions in ankle plantar flexion angles at initial contact have been shown to increase loading rate bilaterally by 711%, rising from 47.99 N/s to 341.16 N/s [13]. When compared to our data, such changes would be regarded as meaningful across all drop heights relative to the CV% reported in Table 3. With such large changes acutely observed, it is likely that differences in loading rate can be detected, although the magnitude of change will need to be relatively large depending on drop height.

The change reported herein between box height and the reliability of landing kinetics supports the findings of recent investigations [42], where the variability (CV%) in lower-limb joint moments were reduced as a function of drop height, which ranged from 20% to 180% of CMJ height. It was suggested that the reduced variability in joint moments observed with increased landing heights indicated a more consistent, yet potentially harmful, reliance on selected joint structures during more demanding tasks, which may increase injury risk [42]. Here, we expand upon these findings by reporting the reduced variability of kinetic drop-landing profiles at greater box heights. More specifically, our data indicate that the relative variability for peak vGRF, time to peak vGRF, and loading rate measured both bilaterally and unilaterally, all decreased with greater drop heights.

For practical purposes, we established the MDC values for all force-time variables. These values allow for practitioners to identify whether an intervention has resulted in 'meaningful' change [33]. An example of this could be a reduction in the peak vGRF an individual is exposed to during bilateral drop-landings. An athlete performing a bilateral drop-landing from a drop height of 50% CMJ height with the bilateral peak vGRF of 2.5 N•kg$^{-1}$, would need to reduce peak vGRF by >0.78 N•kg$^{-1}$ for the change to be defined as meaningful. Likewise, if the same athlete were to present with bilateral peak vGRF of 4.8 N•kg$^{-1}$ from a drop height of 150% CMJ height, a reduction of >0.75 N•kg$^{-1}$, would be required for the intervention to be deemed successful. These MDC values represent changes in peak vGRF of 31% and 16% from drop heights equating to 50% and 150% of CMJ height, respectively. This example further illustrates the need to identify drop heights for screening landing mechanics relative to the athletes CMJ height when interpreting force-time data. However, practitioners should be aware that the use of MDC values to define a change as meaningful for an individual remains somewhat arbitrary and is based on a number of assumptions, such as data being distributed normally [16]. It may be that analytical goals for identifying real change following an intervention be based on practical outcomes that are driven by the literature relevant to the kinetic measurement being assessed relative to the demographic profile of the population.

Asymmetries during athletic activities have been suggested to impair performance outcomes [43] and increase injury risk [14, 44]. Our investigation showed that a large amount of variability in peak vGRF asymmetry existed during the bilateral drop-landings, with MDC values larger than, or approaching, the mean asymmetry observed in our population across all drop heights (Table 4). This is similar to previous findings [14], with the asymmetries in vGRF during bilateral landings appearing to vary greatly between trials. Inter-limb asymmetries in force profiles during bilateral landings are particularly important metrics among post-rehabilitation athletes. For example, Paterno et al. [29] found that a group of female athletes, who had returned to sport two years after anterior cruciate ligament reconstructive surgery, demonstrated side-to-side vGRF asymmetries during a drop vertical jump. These asymmetries were in favour of the uninvolved limb and resulted in a mean difference of 0.5 x bodyweight in peak vGRF, representing a mean asymmetry index score of 14.3% [29]. If this magnitude of asymmetry was found during the performance of a bilateral drop-landing task, based on the MDC values presented in Table 4, this asymmetry value would not present as meaningful, regardless of drop height. Therefore when screening for asymmetries during bilateral drop-landings, our investigation suggests that peak vGRF should be analyzed with caution due to the error associated with this outcome variable. Although a number of possibilities exist for why such high levels of variability in asymmetry for peak vGRF were present, the training background of the participants included in our investigation may have prompted the high level of variability observed between trials. Recently it has been shown that athletes who are highly familiar with performing specific landing tasks exhibit less variability in inter-limb asymmetries relative to novice athletes [46]. Novice athletes who are less familiar with landing tasks may demonstrate greater inter-limb variability in their movement strategies between trials while they explore adaptive behaviours in search of coordination solutions to the movement problem [45]. Therefore, our findings may not be applicable to individuals well-trained in bilateral landing tasks. Future research should look to establish the variability for asymmetries in athletes regularly performing bilateral landing tasks as part of their competitive sport and training.

The findings presented in this investigation should not be used for different landing tasks of a similar nature. As all of the kinetic variables measured in our investigation have been shown to differ between vertical CMJ, forward jumps, single leg landings and bilateral drop-landings [12, 47], our findings should not be directly applied to other landing tasks. This has led to the functionality of the bilateral drop-landing being questioned as it presents with differing task constraints from that of landing tasks that are preceded with a propulsive action (i.e. jumping) [47]. However, in contrast to screening landings from a CMJ, the bilateral drop-landing allows for practitioners to easily control the downward velocity at impact with the ground [48]. In this sense, the bilateral drop-landing may allow for an athlete's landing mechanics to be screened in a controlled manner, whilst being able to identify potential risk factors for injury. Although it has not currently been shown that reducing modifiable risk factors for injury within the bilateral drop-landing may alter landing mechanics in other landing tasks, it is likely that the skills required are transferable.

## Practical applications

With such high force demands being placed on an athlete's musculoskeletal system during bilateral landing tasks, injury risk is clearly a primary consideration for practitioners. With portable force platforms being affordable and accessible to coaches, the reliability of kinetic variables related to landing performance has been presented in this study. Our investigation showed that peak vGRF, time to peak vGRF, loading rate and asymmetry in peak vGRF possessed relative reliability values ranging from *large* to *near perfect*. However, the signal to noise values suggest that drop height will likely influence the variability observed in force-time measures from bilateral landing. Specifically, CV% measured for both legs and for a single-limb during bilateral drop-landings decreased for peak vGRF, time to peak vGRF, and loading rate with greater drop heights. This is an important consideration for practitioners, with measurement error for kinetic variables being influenced by drop height in relation to an individual's CMJ performance. In instances where the performance of a landing task is assessed without an appreciation for drop height relative to an individual's maximum CMJ height, there is potential for error in interpreting force-time variables between athletes. Based on our data, we suggest drop heights of 150% of an individuals maximum CMJ height be used so to provide greater reliability for assessing drop-landing kinetics.

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## Competing Interests

The authors declare that they have no competing interests.

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