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Reliability of unilateral vertical leg stiffness measures assessed during bilateral hopping

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Running Title: Unilateral stiffness in bilateral hopping

Abstract

The assessment of vertical leg stiffness is an important consideration given its relationship to performance. Vertical stiffness is most commonly assessed during a bilateral hopping task. The current study sought to determine the inter-session reliability, quantified by the coefficient of variation, of vertical stiffness during bilateral hopping when assessed for the left and right limbs independently, this had not been previously investigated. On four separate occasions, ten healthy males performed 30 unshod bilateral hops on a dual force plate system with data recorded independently for the left and right limbs. Vertical stiffness was calculated as the ratio of peak ground reaction force to the peak negative displacement of the centre of mass during each hop and was averaged over the 6-10th hops. For vertical stiffness, average coefficients of variation of 15.3% and 14.3% were observed for the left and right limbs respectively. An average coefficient of variation of 14.7% was observed for bilateral vertical stiffness. The current study reports that calculations of unilateral vertical stiffness demonstrate reliability comparable to bilateral calculations. Determining unilateral vertical stiffness values and relative discrepancies may allow the coach to build a more complete stiffness profile of an individual athlete and better inform the training process.

Keywords: leg-spring behaviour, centre of mass displacement, spring-mass model

Word Count: 3241

Introduction

Vertical leg stiffness describes how the body's centre of mass deforms in response to force during a linear, vertical movement task, such as a vertical hop or jump, and aims to provide a representative measure of musculoskeletal stiffness.[1] Although the role of vertical stiffness in modulating injury risk and athletic performance may be well established,[1, 2] literature investigating bilateral asymmetry in vertical stiffness is limited. A strong relationship between vertical stiffness asymmetry and soft-tissue injury has been reported by Pruyn et al;[3] elite Australian Footballer players who experienced soft-tissue injuries had a greater bilateral difference in vertical stiffness than their non-injured counterparts. Such asymmetry may also be expected to impair athletic performance given a resultant imbalance in the application of force[4] however, the latter hypothesis has not been systematically explored. The measurement and quantification of vertical stiffness is therefore of important practical relevance to athletes and coaches.

Vertical stiffness is most commonly assessed during the performance of a bilateral 'hopping' task.[5, 6] As well as offering the most simple spring-mass model with which to assess vertical stiffness,[7] bilateral hopping is established to be more efficient in energetic consumption in comparison to other types of gait[8] and should therefore provide a strong representation of musculoskeletal stiffness.[7] During hopping tasks, individuals are required to perform a number of repeated bilateral jumps on a force plate whilst measurements of vertical ground reaction force and negative displacement of the centre of mass are recorded. The negative displacement of the centre of mass is deemed representative of how much the leg spring deforms, assuming that both limbs function synchronistically, in response to the ground reaction force.[1] Vertical stiffness is subsequently calculated as the ratio of peak ground reaction force to negative centre of mass displacement.[5, 6]

The reliability of vertical stiffness assessment during variations of bilateral hopping tasks has been specifically evaluated in two investigations.[5, 9] This manuscript will consider the coefficient of variation as the primary tool to assess reliability as this is a relative measure that allows for a direct comparison between investigations, irrespective of differences in participants' stiffness, and can be easily interpreted by the practitioner.[10] McLachlan et al. [9] reported coefficients of variation of between 2.7% and 4.9% for vertical stiffness dependant on the frequency and height of hopping; a frequency of 3.2 Hz demonstrated higher reliability than 2.2 Hz and submaximal hopping demonstrated higher reliability than maximal hopping. Joseph et al.[5] reported a coefficient of variation of 5.5% for a hopping frequency of 2.2 Hz and 10.2% for a self-selected hopping frequency. Moreover, they demonstrated stiff-legged hopping to be a more reliable assessment tool than 'bent-leg' hopping where the hopping kinematics were self-determined by the individual; for example, a coefficient of variation of 6.9% was calculated for bent-leg hopping at 2.2 Hz. Bent-leg hopping resulted in greater angular displacement of the knee and ankle, indicating a greater reliance on active force generation during the task, and may therefore explain why this technique appears to be less reliable; the emphasis on maintaining high stiffness in the lower limbs is likely to be reduced if the active component of muscular contraction is greater.

Reliability figures have also been reported in investigations conducted by Moir et al.[11] and by Brauner et al.[12] Moir et al.[11] reported a coefficients of variation of 14.4% using a 2.0 Hz hopping test whilst Brauner et al.[12] reported a coefficients of variation of 8.1% using a 2.2 Hz test. The coefficient of variation observed by Moir et al.[11] appears to be a consequence of variability in negative centre of mass displacement (coefficient of variation: 12.4%), although Brauner et al.[12] did not provide such figures to allow comparison. In addition, the participants sampled by Moir et al.[11] exhibited greater vertical stiffness than those sampled by Brauner et al.[12] (34.45 $kN.m^{-1}$ vs 26.5 $kNm.^{-1}$ respectively).

Moresi et al.[13] evaluated the impact of data reduction methods (how hops are analysed) on reliability. The investigators' reported coefficients of variation ranging from 6.5% to 16.6% depending upon the reduction method used; employing inclusion criteria to sample hops within ± 5% of average contact time appeared to provide the most suitable trade-off between reliability and data exclusion, providing coefficients of variation in the region of 9%. Stricter criteria for sampling were set by McLachlan et al.[9] and Joseph et al.,[5] hops were required to be within ± 2% of the set hopping frequency. Although Moresi et al.[13] found such criteria to infer a marginal reduction in the coefficient of variation (<1%), using this sampling method resulted in the exclusion of a large number of trials and greatly reduced the overall sample size. Whilst the vertical stiffness values reported by Moresi et al.[13] (between 16-21 $kN.m^{-1}$) were much lower than those reported by Joseph et al.[5] (~57 $kN.m^{-1}$), they were similar to those reported by McLachlan et al. [9] for hopping at 2.2 Hz (16-20 $kN.m^{-1}$).

Stiffness measures obtained from bilateral versus unilateral hopping tasks have been compared by Brauner et al.[12] The investigators demonstrated that vertical stiffness values were lower during unilateral versus bilateral hopping although observed no effect of leg dominance during the unilateral task. Inter-limb differences during bilateral hopping were not assessed by Brauner et al.[12] Indeed, to the authors' knowledge, the potential presence of vertical stiffness asymmetry between the left and right limbs during bilateral hopping has not been investigated by the literature. It is important to understand how the individual limbs function during bilateral performance, where matched stiffness properties would be desired, as this may not be represented by how the individual limb functions in isolation during unilateral hopping. For example, Benjanuvatra et al.[14] compared impulses generated by the left and right limbs during bilateral and unilateral jumping, observing that the limb producing the largest impulse during the unilateral task did not always produce largest impulse in the bilateral task.

The purpose of the current study was to assess the inter-session reliability of vertical stiffness during bilateral hopping when assessed for the left and right limbs independently. It was hypothesised that the reliability of independent left and right limb measurements of vertical stiffness would not significantly differ from bilateral measurements given that the lower limbs would be expected to function synchronistically during this type of performance task in line with the proposed spring-mass model.

Methods

The study was a repeated measures experiment designed to assess the inter-session reliability of vertical leg stiffness derived from bilateral hopping. On four separate occasions, separated by between six and ten days, participants performed 30 unshod bilateral hops on a dual force plate system with data recorded independently for the left and right limbs.

Ten healthy males (age: 22 ± 2 years; height: 1.76 ± 0.06 m; body mass: 73.3 ± 8.3 kg) volunteered to participate in the study. Participants were recreationally active (≥2.5 hours of physical activity per week), reported no previous (within the last 12 months) or present lower limb injury and provided informed consent to participate in the study. A minimum sample size of eight participants was determined from an a priori power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon the lowest intra-class correlation values reported in the literature (0.85[5]) and a power of 0.8. Full ethical approval was granted by the Institute of Sport and Physical Activity Research, University of Bedfordshire. All procedures were conducted in accordance with the Declaration of Helsinki.

All trials were conducted at the same time of day for each participant, to alleviate the effects of circadian rhythms, and repeated between six to ten days apart to minimise the risk of the previous testing session carrying any residual effects on vertical stiffness. The testing laboratory was controlled at an ambient temperature of 25°C. Participants were instructed to prepare for testing as they would for training; nutrition, hydration and sleep were not monitored. Participants were asked to refrain from all forms of training for at least 24 hours prior to testing.

Participants completed the same warm-up procedure in each experimental trial (Table 1). The warm-up procedure consisted of 15 dynamic exercises progressing from low to high intensities and from generic to specific movement patterns; the warm-up was designed to replicate a typical athletic warm-up that would be undertaken prior to training or competition.[15] A rest period of 60 seconds was prescribed between each of the exercises from the specific movement preparation phase of the warm-up, all other exercises were not prescribed with rest periods. A rest period of 180 seconds was prescribed between the termination of the warm-up and commencement of the testing protocol.

*** Table 1 ***

During each session, participants performed 30 unshod bilateral hops on a dual force plate system (Kistler 9281, Kistler Instruments, Winterthur, Switzerland) with data recorded independently for the left and right limbs; 30 hop trials were chosen as this would allow for the greatest number of potential methods of data reduction.[13] The plates each measured 0.6 m x 0.4 m, were set flush into the laboratory floor as per manufacturer guidelines and spaced by a distance of 0.05 m. Participants performed two hopping trials (two, 30 hop trials) in each experimental session; these were separated by a recovery period of 180 seconds. The execution of each hopping trial was monitored by a United Kingdom Strength and Conditioning Association and National Strength and Conditioning Association (United States of America) accredited strength and conditioning coach to ensure for consistency of technique. Hops were performed at a self-selected frequency as pilot testing indicated that participants were unable to satisfactorily perform the task at a set hopping frequency of 2.2 Hz. At a frequency of 2.2 Hz, the ground contact time of each hop did not always fall within the ±5% recommendation outlined below.

Five consecutive hops from 6th to the 10th hop were sampled for data collection.[6] For inclusion in the reliability analyses, the ground contact time of each of the 5 hops was required to fall within ±5% of the average ground contact time for the 5 hop sample;[13] this was assessed during the post-test data analysis and all hopping trials met this criteria. Kinetic data was sampled at 1000 Hz and saved with the use of the manufacturer supplied software (BioWare 3.24, Kistler, Winterthur, Switzerland) for later offline analysis.

Instants of initial foot contact, take-off and landing were identified from the vertical ground reaction force trace (Figure 1); this was determined as the time-point at which a clear change in force (≥ 10 N) was observed.[16] Acceleration, velocity and negative displacement of the centre of mass were determined from the vertical force trace using the methods described by Blazevich.[17] Vertical stiffness was then calculated as the ratio of peak vertical ground reaction force relative to the peak negative displacement of the centre of mass during the initial ground contact phase[18]; this was averaged over the five sampled hops. As vertical stiffness is affected by body size, stiffness values were reported relative to body mass.[19] For the calculation of bilateral values for the given variables, the vertical ground reaction forces from each hop were summated. The procedures otherwise outlined above were then applied to the summated force data.

*** Figure 1 ***

Inter-session reliability was calculated using each participant's average values across the two hopping trials they performed within each testing session for vertical ground reaction force, negative centre of mass displacement and vertical stiffness; pilot studies undertaken within the same participant population (n = 8) indicated that inter-session reliability was improved by using average values. Intra-session coefficients of variation for vertical stiffness in the current study were 7.9% (intraclass correlation coefficient (ICC): 0.89) and 6.4% (ICC: 0.95) for the left and right limbs respectively.

Reliability was assessed through determination of single (pair-wise) and average ICCs, and the standard error of measurement;[20] these figures were calculated with 90% confidence intervals (90%CI). Average values were determined across testing sessions 2-4 as it was deemed a familiarisation session (T_1) was necessary to accustom participants to the experimental protocol. The standard error of measurement was reported as a coefficient of variation to allow comparison with the current literature. Descriptive statistics, standard errors of measurement, coefficients of variation and 90%CIs were computed using a pre-formatted spreadsheet in Microsoft Excel 2007,[21] while ICCs were calculated using the Statistical Package for the Social Sciences for Windows (v19.0; SPSS Inc., Chicago, USA).

Results

A familiarisation session was necessary to accustom participants to the experimental protocol. Pronounced differences in all parameters were observed between testing session 1 (T_1) and all other testing sessions (T_2, T_3 and T_4) (Table 2), most notably in hopping frequency. Both unilateral and bilateral vertical stiffness were markedly lower in T_1 than in all other testing sessions (Figure 2) and pair-wise inter-session comparisons revealed coefficients of variation ranging from 16.9% to 25.9% between T_1 and all other testing sessions (Table 3). For this reason, data from T_1 was not described in reliability analyses.

*** Tables 2-3 ***

*** Figure 2 ***

The reliability of unilateral vertical stiffness was similar to bilateral vertical stiffness. The average coefficient of variation for unilateral vertical stiffness across T_2-T_4 was 15.3% (ICC: 0.72) for the left limb and 14.3% (ICC: 0.80) for the right limb; this compared to a coefficient of variation of 14.7% (ICC: 0.76) for bilateral vertical stiffness.

Coefficients of variation for vertical ground reaction force were lower than for negative centre of mass displacement. The average coefficient of variation for vertical ground reaction force across T_2-T_4 was 2.8% (ICC: 0.98), 3.3% (ICC: 0.97) and 3.0% (ICC: 0.98) for the left, right and both limbs respectively., whilst the average coefficient of variation for negative centre of mass displacement across T_2-T_4 was 13.0% (ICC: 0.88), 12.1% (ICC: 0.92) and 12.4% (ICC: 0.90) for the left, right and both limbs respectively.

Discussion

The current study reports coefficients of variation for unilateral vertical leg stiffness of 15.3% and 14.3%, for the left and right limbs respectively, and a coefficient of variation of 14.7% for bilateral vertical stiffness across three testing sessions. It may therefore be concluded that unilateral vertical stiffness can be determined during bilateral hopping without detracting from the reliability of the method. The independent determination of vertical stiffness for the left and right limbs during a bilateral task is a technique that had not been previously applied by the literature. Determining unilateral vertical stiffness values may allow the coach to build a more complete profile of an individual's stiffness profile, identifying any potential asymmetries between the left and right limbs which may be associated with an increased injury risk[3] or impaired performance.[4] This knowledge should better inform the training process.

The current study reports notable differences in all measured parameters between the first testing session and all other testing sessions, particularly for hopping frequency. It may therefore be concluded that one familiarisation session was necessary to accustom participants to the bilateral hopping protocol; this should be of consideration to future investigations employing this method of vertical stiffness assessment. No obvious benefit of undertaking more than one familiarisation session was apparent in the population sampled.

The coefficient of variation of 14.7% reported for bilateral vertical stiffness in the current study is comparable to the figure of 14.4% reported by Moir et al.,[11] however, is greater than other figures previously reported of 2.7%[9], 5.5%[5], 8.1%[11] and 9.8%[13] where a set hopping frequency has been determined. Joseph et al.[7] indicates that reliability is improved by hopping at a set versus a self-selected hopping frequency; the investigators reported a coefficient of variation of 10.2% for hopping at a self-selected frequency. However, pilot testing (n = 8) conducted prior to the current study indicated that a representative group of participants unable to hop consistently at the frequency of 2.2 Hz recommended by Joseph et al.[5] and would not have been able to fulfil the necessary sampling criteria for analysis of the hops (each hop within ± 5% of the average ground contact time). Whilst the representative participant group sampled in the pilot study were all physically active individuals, few were regularly engaging in plyometric activities and demonstrated the ability to successfully deviate from a self-selected hopping frequency when asked to do so. The current study observed that participants were able to hop at a repeatable frequency following a single familiarisation session (coefficient of variation: 1.9%), although large range of frequencies (1.96 - 3.28 Hz) was observed between participants. It is established that increased hopping frequency results in a reduction in negative centre of mass displacement and resultant increase in vertical stiffness,[7, 22] the observed discrepancy in hopping frequency may therefore explain the large inter-participant variance in vertical stiffness observed in the current study. Future investigations should seek to maintain a set, pre-determined frequency where possible as this is likely to reduce inter-participant variation and improve the reliability of the method.

Given that low coefficients of variation for vertical ground reaction force were reported in the current study (2.8 - 3.3%), the observed variability of vertical stiffness measures in the current study is a consequence of variability in negative centre of mass displacement. The current study observed coefficients of variation of 12 - 13% for centre of mass displacement, suggesting that individuals were demonstrating inconsistent hopping strategies between trials despite maintaining a steady hopping frequency. As a linear decrease in negative centre of mass displacement was observed over the four trials (Table 2), it may be concluded that either individuals were experiencing either a learning effect or a training effect over the testing period (undertaken over approximately 28 days) which affected their execution of the hopping task.

The current study observed an average negative displacement of the centre of mass of 0.10 m. It is important to note that the negative centre of mass displacement observed in the population sampled by Joseph et al.[5] was substantially lower, despite hopping at a greater frequency; Joseph et al.[5] reported an average negative centre of mass displacement of 0.05 m during 2.2 Hz hopping. Moir et al.[11] and Brauner et al.[12] are the only other investigators to present figures for negative centre of mass displacement, reporting values of 0.12 m and 0.11 m respectively. The similarity of these investigators' figures to those of the current study may explain why their coefficients of variation for vertical stiffness are also more comparable than those of Joseph et al.[5] Demonstrating less negative displacement during the ground contact phase of hopping is likely to be indicative of participants with a greater capability to utilise the stretch-shortening cycle and who may be classified as more 'skilled' performers in plyometric activities; for example, Hobara et al.[23] has reported greater negative centre of mass displacement in untrained individuals in comparison to trained endurance runners (0.11 vs. 0.08 m; $P < .001$). The sampling of individuals with experience of plyometric training would be expected to mitigate potential learning or training effects as it may be anticipated that more skilled performers would exhibit more consistent hopping kinematics than less skilled performers, a likely consequent of greater familiarity with these types of activity[24] and a greater capacity to utilise the stretch-shortening cycle.[23] Sampling plyometric-trained participants is therefore likely to improve the reliability of the method and is recommended in future investigations.

In conclusion, the current study demonstrated that values of unilateral vertical stiffness may be determined during bilateral hopping without impacting the reliability of the method. The determination of unilateral vertical stiffness values may allow the coach to build a more complete profile of an individual’s stiffness properties and identify asymmetries which may relate to performance and/or injury risk.

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Tables

Table 1 The experimental warm-up protocol completed by the participants in each experimental trial.

Warm-up phase	***Exercise***	***Prescription (sets x reps)***
Generic movement preparation	Inchworm	1x6
	Quadruped thoracic rotation	1x6each
	Push up to 'T'	1x6each
	Supine glute bridge with abduction	1x12
	Mountain climber	1x6each
	Squat thrust to squat	1x6
	Squat to Stand	1x6
	Single leg, stiff-legged deadlift to reverse lunge	1x6each
Plyometric / stiffness preparation	Lateral step down	1x8each
	Single leg calf raise	1x8each
	Alternate leg ankling drill	1x8each
	Vertical countermovement jump	1x4
Specific movement preparation	Bilateral hopping	1x10
	Bilateral drop jump (from 0.18 m)	1x2
	Unilateral drop jump (from 0.18 m)	1x2each

Table 2 Mean (± standard deviation) values for vertical ground reaction force, negative centre of mass displacement, vertical leg stiffness and hopping frequency for the left, right and both limbs across four bilateral hopping testing sessions (T_1-T_4).

Variable	**Limb**	**T_1**	**T_2**	**T_3**	**T_4**
Vertical ground reaction force (N)	Left	1438 ± 227	1406 ± 206	1384 ± 222	1341 ± 210
	Right	1495 ± 208	1437 ± 203	1424 ± 238	1378 ± 221
	Both	2933 ± 420	2843 ± 408	2808 ± 458	2718 ± 429
Negative centre of mass displacement (m)	Left	0.129 ± 0.055	0.101 ± 0.032	0.100 ± 0.029	0.091 ± 0.031
	Right	0.129 ± 0.061	0.104 ± 0.035	0.100 ± 0.032	0.093 ± 0.034
	Both	0.129 ± 0.058	0.102 ± 0.034	0.100 ± 0.031	0.092 ± 0.032
Vertical leg stiffness ($\text{N.m}^{-1}\text{.kg}^{-1}$)	Left	176 ± 55	217 ± 62	198 ± 43	217 ± 52
	Right	186 ± 62	220 ± 65	208 ± 55	224 ± 56
	Both	362 ± 114	437 ± 126	406 ± 98	441 ± 105
Hopping frequency (Hz)	Both	2.60 ± 0.27	2.79 ± 0.30	2.83 ± 0.32	2.84 ± 0.35

Table 3: Inter-session reliability comparisons for vertical leg stiffness, vertical ground reaction force and negative centre of mass displacement for the left, right and both limbs across four bilateral hopping sessions (T_1-T_4). Values are reported as the coefficient of variation (CV ± 90% confidence intervals) and intra-class correlation coefficient (ICC ± 90% confidence intervals).

Limb	**Value**	**T_1-T_2**	**T_1-T_3**	**T_1-T_4**	**T_2-T_3**	**T_2-T_4**	**T_3-T_4**
Vertical leg stiffness							
Left	CV	25.9% (18.9-42.6)	17.1% (12.5-28.2)	21.0% (15.3-34.6)	15.3% (11.2-25.2)	15.9% (11.6-26.2)	16.5% (12.0-27.1)
	ICC	0.32 (-0.25 - 0.72)	0.61 (0.14 - 0.86)	0.48 (-0.06 - 0.80)	0.75 (0.37 - 0.91)	0.76 (0.40 - 0.92)	0.61 (0.13 - 0.86)
Right	CV	23.0% (16.8-37.9)	17.5% (12.8-28.8)	19.4% (14.1-31.9)	15.4% (11.2-25.3)	14.3% (10.5-23.6)	14.2% (10.4-23.4)
	ICC	0.53 (0.02 - 0.83)	0.70 (0.28 - 0.90)	0.63 (0.16 - 0.87)	0.79 (0.46 - 0.93)	0.82 (0.53 - 0.94)	0.79 (0.45 - 0.93)
Both	CV	24.2% (17.6-39.8)	16.9 (12.3-27.7)	19.6% (14.3-32.2)	15.3% (11.1-25.1)	14.9% (10.9-24.5)	15.3% (11.2-25.2)
	ICC	0.43 (-0.11 - 0.78)	0.67 (0.23 - 0.88)	0.57 (0.07 - 0.84)	0.77 (0.42 - 0.92)	0.80 (0.47 - 0.93)	0.63 (0.35 - 0.85)
Vertical ground reaction force							
Left	CV	3.8% (2.7 - 6.2)	5.1% (3.7 - 8.4)	5.5% (4.0 - 9.0)	2.9% (2.1 - 4.7)	4.2% (3.0 - 6.8%)	2.7% (1.9 - 4.4)
	ICC	0.96 (0.88 - 0.99)	0.93 (0.80 - 0.98)	0.92 (0.76 - 0.97)	0.98 (0.93 - 0.99)	0.95 (0.84 - 0.98)	0.98 (0.94 - 0.99)
Right	CV	5.1% (3.7 - 8.4)	7.8% (5.7 - 12.8)	8.0% (5.9 - 13.2)	3.6% (2.6 - 5.9)	3.9% (2.9 - 6.5)	2.9% (2.1 - 4.7)
	ICC	0.91 (0.75 - 0.97)	0.82 (0.52 - 0.94)	0.79 (0.46 - 0.93)	0.96 (0.89 - 0.99)	0.95 (0.86 - 0.99)	0.98 (0.93 - 0.99)
Both	CV	3.7% (2.7 - 6.1)	6.0% (4.3 - 9.8)	6.3% (4.6 - 10.4)	3.2% (2.3 - 5.3)	4.0% (2.9 - 6.6)	2.7% (2.0 - 4.5)
	ICC	0.96 (0.87 - 0.99)	0.90 (0.71 - 0.97)	0.88 (0.65 - 0.96)	0.97 (0.91 - 0.99)	0.95 (0.85 - 0.98)	0.98 (0.94 - 0.99)
Negative centre of mass displacement							
Left	CV	29.3% (21.8-48.4)	27.5% (19.9-45.6)	26.6% (19.0-20.9)	12.8% (9.5 - 20.9)	6.6% (4.7 - 11.4)	11.1% (8.5 - 18.0)
	ICC	0.63 (0.17 - 0.87)	0.66 (0.20 - 0.88)	0.70 (0.28 - 0.89)	0.86 (0.63 - 0.96)	0.97 (0.90 - 0.99)	0.90 (0.70 - 0.97)
Right	CV	29.5% (21.6-48.0)	29.2% (21.6-48.0)	28.2% (20.7-46.1)	12.3% (9.4 - 19.8)	6.6% (4.7 - 10.3)	10.0% (7.5 - 16.9)
	ICC	0.70 (0.28 - 0.89)	0.69 (0.27 - 0.89)	0.73 (0.34 - 0.91)	0.90 (0.71 - 0.97)	0.98 (0.91 - 0.99)	0.93 (0.79 - 0.98)
Both	CV	29.2% (21.7-48.2)	28.4% (20.8-47.3)	27.4% (19.8-44.4)	12.4% (9.5 - 20.8)	5.7% (4.7 - 10.4)	10.5% (7.6 - 17.0)
	ICC	0.67 (0.23 - 0.88)	0.68 (0.24 - 0.89)	0.72 (0.31 - 0.90)	0.88 (0.67 - 0.96)	0.97 (0.92 - 0.99)	0.91 (0.75 - 0.97)

Figure Captions

Figure 1 - An example of the vertical force trace associated with bilateral hopping and the identification of instants of initial foot contact, take-off and separation of individual hops.

Figure 2 - Vertical leg stiffness for the left, right and both limbs across each of the four testing sessions