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4 **Reliability of unilateral vertical leg stiffness measures assessed during bilateral hopping**

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16 **Running Title:** Unilateral stiffness in bilateral hopping

17

## Abstract

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

33

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

35

36 **Word Count:** 3241

37

## Introduction

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

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

61           The reliability of vertical stiffness assessment during variations of bilateral hopping  
62 tasks has been specifically evaluated in two investigations.<sup>5, 9</sup> This manuscript will consider  
63 the coefficient of variation as the primary tool to assess reliability as this is a relative measure  
64 that allows for a direct comparison between investigations, irrespective of differences in  
65 participants' stiffness, and can be easily interpreted by the practitioner.<sup>10</sup> McLachlan et al. <sup>9</sup>  
66 reported coefficients of variation of between 2.7% and 4.9% for vertical stiffness dependant  
67 on the frequency and height of hopping; a frequency of 3.2 Hz demonstrated higher reliability  
68 than 2.2 Hz and submaximal hopping demonstrated higher reliability than maximal hopping.  
69 Joseph et al.<sup>5</sup> reported a coefficient of variation of 5.5% for a hopping frequency of 2.2 Hz  
70 and 10.2% for a self-selected hopping frequency. Moreover, they demonstrated stiff-legged  
71 hopping to be a more reliable assessment tool than 'bent-leg' hopping where the hopping  
72 kinematics were self-determined by the individual; for example, a coefficient of variation of  
73 6.9% was calculated for bent-leg hopping at 2.2 Hz. Bent-leg hopping resulted in greater  
74 angular displacement of the knee and ankle, indicating a greater reliance on active force  
75 generation during the task, and may therefore explain why this technique appears to be less  
76 reliable; the emphasis on maintaining high stiffness in the lower limbs is likely to be reduced  
77 if the active component of muscular contraction is greater.

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

86 Moresi et al.<sup>13</sup> evaluated the impact of data reduction methods (how hops are  
87 analysed) on reliability. The investigators' reported coefficients of variation ranging from  
88 6.5% to 16.6% depending upon the reduction method used; employing inclusion criteria to  
89 sample hops within  $\pm 5\%$  of average contact time appeared to provide the most suitable trade-  
90 off between reliability and data exclusion, providing coefficients of variation in the region of  
91 9%. Stricter criteria for sampling were set by McLachlan et al.<sup>9</sup> and Joseph et al.,<sup>5</sup> hops were  
92 required to be within  $\pm 2\%$  of the set hopping frequency. Although Moresi et al.<sup>13</sup> found such  
93 criteria to infer a marginal reduction in the coefficient of variation ( $<1\%$ ), using this sampling  
94 method resulted in the exclusion of a large number of trials and greatly reduced the overall  
95 sample size. Whilst the vertical stiffness values reported by Moresi et al.<sup>13</sup> (between 16-21  
96  $\text{kN}\cdot\text{m}^{-1}$ ) were much lower than those reported by Joseph et al.<sup>5</sup> ( $\sim 57 \text{ kN}\cdot\text{m}^{-1}$ ), they were  
97 similar to those reported by McLachlan et al.<sup>9</sup> for hopping at 2.2 Hz (16-20  $\text{kN}\cdot\text{m}^{-1}$ ).

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

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

117

## Methods

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

122           Ten healthy males (age:  $22 \pm 2$  years; height:  $1.76 \pm 0.06$  m; body mass:  $73.3 \pm 8.3$   
123 kg) volunteered to participate in the study. Participants were recreationally active ( $\geq 2.5$  hours  
124 of physical activity per week), reported no previous (within the last 12 months) or present  
125 lower limb injury and provided informed consent to participate in the study. A minimum  
126 sample size of eight participants was determined from an a priori power analysis (G\*Power  
127 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon the lowest intra-class  
128 correlation values reported in the literature ( $0.85^5$ ) and a power of 0.8. Full ethical approval  
129 was granted by the Institute of Sport and Physical Activity Research, University of  
130 Bedfordshire. All procedures were conducted in accordance with the Declaration of Helsinki.

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

138           Participants completed the same warm-up procedure in each experimental trial (Table  
139 1). The warm-up procedure consisted of 15 dynamic exercises progressing from low to high  
140 intensities and from generic to specific movement patterns; the warm-up was designed to

141 replicate a typical athletic warm-up that would be undertaken prior to training or  
142 competition.<sup>15</sup> A rest period of 60 seconds was prescribed between each of the exercises from  
143 the specific movement preparation phase of the warm-up, all other exercises were not  
144 prescribed with rest periods. A rest period of 180 seconds was prescribed between the  
145 termination of the warm-up and commencement of the testing protocol.

146

147 \*\*\* Table 1 \*\*\*

148

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

163         Five consecutive hops from 6<sup>th</sup> to the 10<sup>th</sup> hop were sampled for data collection.<sup>6</sup> For  
164 inclusion in the reliability analyses, the ground contact time of each of the 5 hops was

165 required to fall within  $\pm 5\%$  of the average ground contact time for the 5 hop sample;<sup>13</sup> this  
166 was assessed during the post-test data analysis and all hopping trials met this criteria. Kinetic  
167 data was sampled at 1000 Hz and saved with the use of the manufacturer supplied software  
168 (BioWare 3.24, Kistler, Winterthur, Switzerland) for later offline analysis.

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

180

181 \*\*\* Figure 1 \*\*\*

182

183         Inter-session reliability was calculated using each participant's average values across  
184 the two hopping trials they performed within each testing session for vertical ground reaction  
185 force, negative centre of mass displacement and vertical stiffness; pilot studies undertaken  
186 within the same participant population ( $n = 8$ ) indicated that inter-session reliability was  
187 improved by using average values. Intra-session coefficients of variation for vertical stiffness

188 in the current study were 7.9% (intraclass correlation coefficient (ICC): 0.89) and 6.4% (ICC:  
189 0.95) for the left and right limbs respectively.

190 Reliability was assessed through determination of single (pair-wise) and average  
191 ICCs, and the standard error of measurement;<sup>20</sup> these figures were calculated with 90%  
192 confidence intervals (90%CI). Average values were determined across testing sessions 2-4 as  
193 it was deemed a familiarisation session (T<sub>1</sub>) was necessary to accustom participants to the  
194 experimental protocol. The standard error of measurement was reported as a coefficient of  
195 variation to allow comparison with the current literature. Descriptive statistics, standard  
196 errors of measurement, coefficients of variation and 90%CIs were computed using a pre-  
197 formatted spreadsheet in Microsoft Excel 2007,<sup>21</sup> while ICCs were calculated using the  
198 Statistical Package for the Social Sciences for Windows (v19.0; SPSS Inc., Chicago, USA).

199

## Results

200 A familiarisation session was necessary to accustom participants to the experimental  
201 protocol. Pronounced differences in all parameters were observed between testing session 1  
202 (T<sub>1</sub>) and all other testing sessions (T<sub>2</sub>, T<sub>3</sub> and T<sub>4</sub>) (Table 2), most notably in hopping  
203 frequency. Both unilateral and bilateral vertical stiffness were markedly lower in T<sub>1</sub> than in  
204 all other testing sessions (Figure 2) and pair-wise inter-session comparisons revealed  
205 coefficients of variation ranging from 16.9% to 25.9% between T<sub>1</sub> and all other testing  
206 sessions (Table 3). For this reason, data from T<sub>1</sub> was not described in reliability analyses.

207

208 \*\*\* Tables 2-3 \*\*\*

209 \*\*\* Figure 2 \*\*\*

210

211 The reliability of unilateral vertical stiffness was similar to bilateral vertical stiffness.  
212 The average coefficient of variation for unilateral vertical stiffness across T<sub>2</sub>-T<sub>4</sub> was 15.3%  
213 (ICC: 0.72) for the left limb and 14.3% (ICC: 0.80) for the right limb; this compared to a  
214 coefficient of variation of 14.7% (ICC: 0.76) for bilateral vertical stiffness.

215 Coefficients of variation for vertical ground reaction force were lower than for  
216 negative centre of mass displacement. The average coefficient of variation for vertical ground  
217 reaction force across T<sub>2</sub>-T<sub>4</sub> was 2.8% (ICC: 0.98), 3.3% (ICC: 0.97) and 3.0% (ICC: 0.98) for  
218 the left, right and both limbs respectively., whilst the average coefficient of variation for  
219 negative centre of mass displacement across T<sub>2</sub>-T<sub>4</sub> was 13.0% (ICC: 0.88), 12.1% (ICC: 0.92)  
220 and 12.4% (ICC: 0.90) for the left, right and both limbs respectively.

221

## Discussion

222           The current study reports coefficients of variation for unilateral vertical leg stiffness  
223 of 15.3% and 14.3%, for the left and right limbs respectively, and a coefficient of variation of  
224 14.7% for bilateral vertical stiffness across three testing sessions. It may therefore be  
225 concluded that unilateral vertical stiffness can be determined during bilateral hopping without  
226 detracting from the reliability of the method. The independent determination of vertical  
227 stiffness for the left and right limbs during a bilateral task is a technique that had not been  
228 previously applied by the literature. Determining unilateral vertical stiffness values may  
229 allow the coach to build a more complete profile of an individual's stiffness profile,  
230 identifying any potential asymmetries between the left and right limbs which may be  
231 associated with an increased injury risk<sup>3</sup> or impaired performance.<sup>4</sup> This knowledge should  
232 better inform the training process.

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

239           The coefficient of variation of 14.7% reported for bilateral vertical stiffness in the  
240 current study is comparable to the figure of 14.4% reported by Moir et al.,<sup>11</sup> however, is  
241 greater than other figures previously reported of 2.7%<sup>9</sup>, 5.5%<sup>5</sup>, 8.1%<sup>11</sup> and 9.8%<sup>13</sup> where a set  
242 hopping frequency has been determined. Joseph et al.<sup>7</sup> indicates that reliability is improved  
243 by hopping at a set versus a self-selected hopping frequency; the investigators reported a  
244 coefficient of variation of 10.2% for hopping at a self-selected frequency. However, pilot

245 testing ( $n = 8$ ) conducted prior to the current study indicated that a representative group of  
246 participants unable to hop consistently at the frequency of 2.2 Hz recommended by Joseph et  
247 al.<sup>5</sup> and would not have been able to fulfil the necessary sampling criteria for analysis of the  
248 hops (each hop within  $\pm 5\%$  of the average ground contact time). Whilst the representative  
249 participant group sampled in the pilot study were all physically active individuals, few were  
250 regularly engaging in plyometric activities and demonstrated the ability to successfully  
251 deviate from a self-selected hopping frequency when asked to do so. The current study  
252 observed that participants were able to hop at a repeatable frequency following a single  
253 familiarisation session (coefficient of variation: 1.9%), although large range of frequencies  
254 (1.96 - 3.28 Hz) was observed between participants. It is established that increased hopping  
255 frequency results in a reduction in negative centre of mass displacement and resultant  
256 increase in vertical stiffness,<sup>7, 22</sup> the observed discrepancy in hopping frequency may  
257 therefore explain the large inter-participant variance in vertical stiffness observed in the  
258 current study. Future investigations should seek to maintain a set, pre-determined frequency  
259 where possible as this is likely to reduce inter-participant variation and improve the reliability  
260 of the method.

261 Given that low coefficients of variation for vertical ground reaction force were reported in the  
262 current study (2.8 - 3.3%), the observed variability of vertical stiffness measures in the  
263 current study is a consequence of variability in negative centre of mass displacement. The  
264 current study observed coefficients of variation of 12 - 13% for centre of mass displacement,  
265 suggesting that individuals were demonstrating inconsistent hopping strategies between trials  
266 despite maintaining a steady hopping frequency. As a linear decrease in negative centre of  
267 mass displacement was observed over the four trials (Table 2), it may be concluded that  
268 either individuals were experiencing either a learning effect or a training effect over the

269 testing period (undertaken over approximately 28 days) which affected their execution of the  
270 hopping task.

271         The current study observed an average negative displacement of the centre of mass of  
272 0.10 m. It is important to note that the negative centre of mass displacement observed in the  
273 population sampled by Joseph et al.<sup>5</sup> was substantially lower, despite hopping at a greater  
274 frequency; Joseph et al.<sup>5</sup> reported an average negative centre of mass displacement of 0.05 m  
275 during 2.2 Hz hopping. Moir et al.<sup>11</sup> and Brauner et al.<sup>12</sup> are the only other investigators to  
276 present figures for negative centre of mass displacement, reporting values of 0.12 m and 0.11  
277 m respectively. The similarity of these investigators' figures to those of the current study may  
278 explain why their coefficients of variation for vertical stiffness are also more comparable than  
279 those of Joseph et al.<sup>5</sup> Demonstrating less negative displacement during the ground contact  
280 phase of hopping is likely to be indicative of participants with a greater capability to utilise  
281 the stretch-shortening cycle and who may be classified as more 'skilled' performers in  
282 plyometric activities; for example, Hobara et al.<sup>23</sup> has reported greater negative centre of  
283 mass displacement in untrained individuals in comparison to trained endurance runners (0.11  
284 vs. 0.08 m;  $P < .001$ ). The sampling of individuals with experience of plyometric training  
285 would be expected to mitigate potential learning or training effects as it may be anticipated  
286 that more skilled performers would exhibit more consistent hopping kinematics than less  
287 skilled performers, a likely consequent of greater familiarity with these types of activity<sup>24</sup> and  
288 a greater capacity to utilise the stretch-shortening cycle.<sup>23</sup> Sampling plyometric-trained  
289 participants is therefore likely to improve the reliability of the method and is recommended in  
290 future investigations.

291         In conclusion, the current study demonstrated that values of unilateral vertical  
292 stiffness may be determined during bilateral hopping without impacting the reliability of the  
293 method. The determination of unilateral vertical stiffness values may allow the coach to build

294 a more complete profile of an individual's stiffness properties and identify asymmetries  
295 which may relate to performance and/or injury risk.

296

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- 366
- 367

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

<i>Warm-up phase</i>	<i>Exercise</i>	<i>Prescription (sets x reps)</i>
<i>Generic movement preparation</i>	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
<i>Plyometric / stiffness preparation</i>	Lateral step down	1x8each
	Single leg calf raise	1x8each
	Alternate leg ankling drill	1x8each
	Vertical countermovement jump	1x4
<i>Specific movement preparation</i>	Bilateral hopping	1x10
	Bilateral drop jump (from 0.18 m)	1x2
	Unilateral drop jump (from 0.18 m)	1x2each

372 **Table 2** Mean ( $\pm$  standard deviation) values for vertical ground reaction force, negative  
 373 centre of mass displacement, vertical leg stiffness and hopping frequency for the left, right  
 374 and both limbs across four bilateral hopping testing sessions (T<sub>1</sub>-T<sub>4</sub>).

<b>Variable</b>	<b>Limb</b>	<b>T<sub>1</sub></b>	<b>T<sub>2</sub></b>	<b>T<sub>3</sub></b>	<b>T<sub>4</sub></b>
<b>Vertical ground reaction force (N)</b>	Left	1438 $\pm$ 227	1406 $\pm$ 206	1384 $\pm$ 222	1341 $\pm$ 210
	Right	1495 $\pm$ 208	1437 $\pm$ 203	1424 $\pm$ 238	1378 $\pm$ 221
	Both	2933 $\pm$ 420	2843 $\pm$ 408	2808 $\pm$ 458	2718 $\pm$ 429
<b>Negative centre of mass displacement (m)</b>	Left	0.129 $\pm$ 0.055	0.101 $\pm$ 0.032	0.100 $\pm$ 0.029	0.091 $\pm$ 0.031
	Right	0.129 $\pm$ 0.061	0.104 $\pm$ 0.035	0.100 $\pm$ 0.032	0.093 $\pm$ 0.034
	Both	0.129 $\pm$ 0.058	0.102 $\pm$ 0.034	0.100 $\pm$ 0.031	0.092 $\pm$ 0.032
<b>Vertical leg stiffness (N.m<sup>-1</sup>.kg<sup>-1</sup>)</b>	Left	176 $\pm$ 55	217 $\pm$ 62	198 $\pm$ 43	217 $\pm$ 52
	Right	186 $\pm$ 62	220 $\pm$ 65	208 $\pm$ 55	224 $\pm$ 56
	Both	362 $\pm$ 114	437 $\pm$ 126	406 $\pm$ 98	441 $\pm$ 105
<b>Hopping frequency (Hz)</b>	Both	2.60 $\pm$ 0.27	2.79 $\pm$ 0.30	2.83 $\pm$ 0.32	2.84 $\pm$ 0.35

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377 **Table 3:** Inter-session reliability comparisons for vertical leg stiffness, vertical ground reaction force and negative centre of mass displacement  
 378 for the left, right and both limbs across four bilateral hopping sessions (T<sub>1</sub>-T<sub>4</sub>). Values are reported as the coefficient of variation (CV ± 90%  
 379 confidence intervals) and intra-class correlation coefficient (ICC ± 90% confidence intervals).

Limb	Value	T <sub>1</sub> -T <sub>2</sub>	T <sub>1</sub> -T <sub>3</sub>	T <sub>1</sub> -T <sub>4</sub>	T <sub>2</sub> -T <sub>3</sub>	T <sub>2</sub> -T <sub>4</sub>	T <sub>3</sub> -T <sub>4</sub>
<b>Vertical leg stiffness</b>							
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)
<b>Vertical ground reaction force</b>							
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)
<b>Negative centre of mass displacement</b>							
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)

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### Figure Captions

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

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

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