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# Do the peak and mean force methods of assessing vertical jump force asymmetry agree?

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1 **Title:** Do the peak and mean force methods of assessing vertical jump force  
2 asymmetry agree?

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5

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17

18

19 **Abstract**

20 The aim of this study was to assess agreement between peak and mean force  
21 methods of quantifying force asymmetry during the countermovement jump (CMJ).

22 Forty-five men performed four CMJ with each foot on one of two force plates recording  
23 at 1000 Hz. Peak and mean were obtained from both sides during the braking and  
24 propulsion phases. The dominant side was obtained for the braking and propulsion  
25 phase as the side with the largest peak or mean force and agreement was assessed  
26 using percentage agreement and the kappa coefficient. Braking phase peak and mean  
27 force methods demonstrated a percentage agreement of 84% and a kappa value of  
28 0.67 (95% confidence limits: 0.45 to 0.90), indicating substantial agreement.  
29 Propulsion phase peak and mean force methods demonstrated a percentage  
30 agreement of 87% and a kappa value of 0.72 (95% confidence limits: 0.51 to 0.93),  
31 indicating substantial agreement. While agreement was substantial, side-to-side  
32 differences were not reflected equally when peak and mean force methods of  
33 assessing CMJ asymmetry were used. These methods should not be used  
34 interchangeably, but rather a combined approach should be used where practitioners  
35 consider both peak and mean force to obtain the fullest picture of athlete asymmetry.

36

37 **Keywords:** Countermovement jump, movement symmetry, kinetics, method  
38 comparison

39

40

## 41 ***Introduction***

42 The vertical jump provides practitioners with a way of assessing their athletes' capacity  
43 to accelerate their body mass within a relatively controllable methodological  
44 framework (Aragon, 2000; Balsalobre-Fernandez, Glaister, & Lockey, 2015; Bosco,  
45 Luhtanen, & Komi, 1983; Hatze, 1998; Impellizzeri, Rampinini, Maffiuletti, & Marcora,  
46 2007; Mundy, Smith, Lauder, & Lake, 2017). Jumping on a force plate can provide  
47 practitioners with information regarding the forces that accelerate their whole body  
48 centre of gravity (CoG) and how long these forces are applied for (Hatze, 1998; Lake,  
49 Mundy, & Comfort, 2014; Mundy et al., 2017; Street, McMillan, Board, Rasmussen, &  
50 Heneghan, 2001). Multiplying the average force applied over the propulsion phase of  
51 vertical jumping by the duration of this phase yields impulse, and, if determined  
52 accurately, this impulse is proportional to take-off velocity (Hatze, 1998). This in turn  
53 dictates jump height. However, the last decade has seen an increase in research  
54 interest in using the vertical jump to assess lower-body asymmetry by studying the  
55 distribution of forces between the left and right sides (Bailey, Sato, Burnett, & Stone,  
56 2015; Bell, Sanfilippo, Binkley, & Heiderscheit, 2014; Impellizzeri et al., 2007; Jordan,  
57 Aagaard, & Herzog, 2014; Newton et al., 2006; Patterson, Raschner, & Platzer, 2009).

58

59 The increased interest in assessing force distribution between the left and right sides  
60 appears to be based on its potential to reflect previous injury, the positional demands  
61 of sport, and leg length discrepancies (Newton et al., 2006). Further, force  
62 asymmetries may lead to athletes routinely applying a larger mechanical demand to  
63 the favoured side, which may increase the potential for injury, especially if the strength  
64 and conditioning process is continued. Therefore, quantifying force asymmetry has  
65 the potential to become a critical part of athlete assessment. However, there are

66 different ways of assessing force asymmetry and currently no data exist to inform  
67 practitioners about whether the different methods agree.

68

69 A frequently used method of assessing force asymmetry is based upon performance  
70 in a bilateral vertical jump, with each foot positioned on a separate force plate (Bailey  
71 et al., 2015; Bell et al., 2014; Jordan et al., 2014; Newton et al., 2006; Patterson et al.,  
72 2009). Typically asymmetry is then quantified by identifying the side that applies the  
73 largest peak (Bailey et al., 2015; Bell et al., 2014; Benjanuvatra, Lay, Alderson, &  
74 Blanksby, 2013; Impellizzeri et al., 2007; Newton et al., 2006; Patterson et al., 2009)  
75 or mean force (Benjanuvatra et al., 2013; Iwanska et al., 2016; Jordan et al., 2014;  
76 Lawson, Stephens, Devoe, & Reiser, 2006; Newton et al., 2006) before either  
77 categorising that as the dominant limb or by calculating some form of symmetry index  
78 (Bishop, Read, Chavda, & Turner, 2016). However, there are no data to inform  
79 practitioners about agreement between these two methods. Therefore, there is  
80 currently a need to undertake research to assess whether the peak and mean force  
81 methods agree. The results of this research would provide practitioners with important  
82 information about whether these two methods can be used interchangeably. The aim  
83 of this study was to assess the agreement between the peak and mean force methods  
84 of quantifying force asymmetry during vertical jumping. It was hypothesised that the  
85 peak and mean force methods of assessing asymmetry during vertical jumping would  
86 agree.

87

## 88 ***Method***

### 89 **Participants**

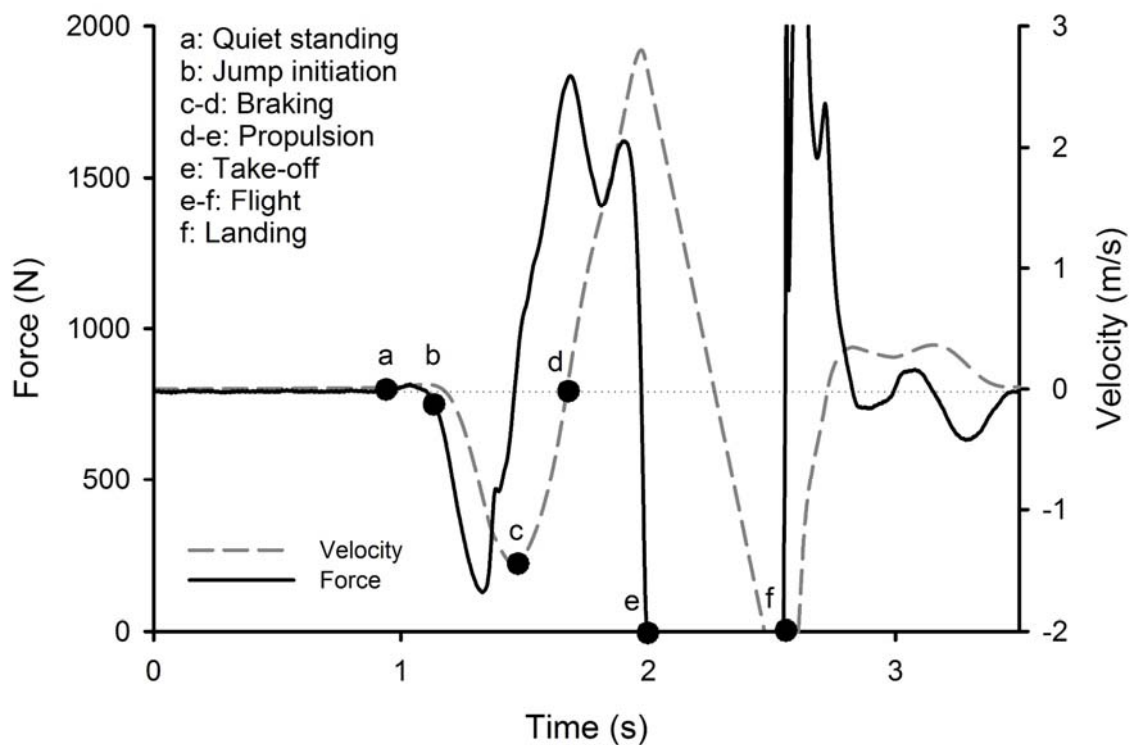
90 Forty-five men (age:  $20.83 \pm 0.84$  years, body mass:  $84.41 \pm 6.87$  kg, height:  $1.80 \pm$   
91  $0.07$  m) who regularly participated in a variety of university level sports (e.g. soccer,  
92 rugby (both codes), basketball and volleyball), volunteered to participate in this study  
93 and provided written informed consent. The study was approved in accordance with  
94 the University of Chichester's Ethical Policy Framework for research involving the use  
95 of human participants.

96

### 97 **Procedures**

98 Before jump testing, participants performed a standardised dynamic warm-up. This  
99 began with 5 minutes of easy stationary cycling, and was followed by 2-3 minutes of  
100 upper- and lower-body dynamic stretching. Specifically, participants performed two  
101 circuits of 10 repetitions each of 'arm swings', 'lunge walk', 'walking knee lift', and 'heel  
102 to toe lift'. Participants then performed four bilateral countermovement jumps (CMJ),  
103 interspersed by 30 s of rest. They were instructed to perform a rapid  
104 countermovement, to approximately quarter squat depth, following this with a rapid  
105 propulsion phase with the intention of jumping as high as possible. Jump  
106 performances were watched to ensure that participants kept their hands on their hips  
107 throughout each jump. Each CMJ was performed on two parallel Kistler force  
108 platforms (Type 9851B; Kistler Instruments Ltd., Hook, UK) embedded in the floor of  
109 the laboratory, each sampling at 1000 Hz. The vertical component of the ground  
110 reaction force (VGRF) from both force platforms were synchronously acquired in  
111 VICON Nexus (Version 1.7.1; Vicon Motion Systems Ltd., Oxford, UK); left and right  
112 side vertical forces were summed for the initial part of data analysis.

113



114

115 Figure 1. Identification of the braking and propulsion phases of countermovement  
116 vertical jumping.

117

### 118 Data Analysis

119 The start point of the analysis of the force-time data was standardised by identifying  
120 the start using the methods described by Owen, Watkins, Kilduff, Bevan, and Bennett  
121 (2014). Briefly, body weight was obtained by averaging 1 s of force-time data as the  
122 participants stood still while awaiting the word of command to jump (Figure 1, up to  
123 'a'). This was recorded during each trial and the participant was instructed to stand  
124 perfectly still. The standard deviation (SD) of this force-time data during the 'quiet  
125 standing' phase was also calculated and the first force value that was either less or  
126 greater than 5 SD represented jump initiation (Figure 1, point 'b'). The final part of this  
127 process was to then go back through the force-time data by 30 ms. This is because it

128 has been shown that this positions the start of force-time data integration at a point  
129 when the participant is still motionless so that the assumption of zero velocity is not  
130 compromised negatively impacting the calculation of subsequent kinetic and kinematic  
131 data (Owen et al., 2014). Calculation of CoG velocity started from this point. First, body  
132 weight (obtained from quiet standing) was subtracted from force, which was then  
133 divided by body mass to provide CoG acceleration. Then CoG acceleration was then  
134 integrated with respect to time using the trapezoid rule to provide CoG velocity.

135 The eccentric braking phase began one sample after the lowest countermovement  
136 CoG velocity occurred (Figure 1, point 'c') and ended one sample after the first  
137 occurrence of a CoG velocity of 0 m/s (Figure 1, point 'd') (McMahon, Jones,  
138 Suchomel, Lake, & Comfort, 2017); one sample after this also marked the beginning  
139 of the concentric propulsion phase, which ended at take-off (Figure 1, point 'e')  
140 (McMahon et al., 2017).

141 Take-off was determined in three stages (see Figure 1). First, the first force value less  
142 than 10 N (Figure 1, around point 'e') and the next force value greater than 10 N  
143 (Figure 1, after point 'e') were identified; second, points 30 ms after and before these  
144 points, respectively were identified to identify the centre 'flight phase' array; third,  
145 mean and SD 'flight phase' force was calculated, and mean 'flight phase' force plus 5  
146 SD was used to identify take-off.

147

## 148 **Statistical Analysis**

149 Asymmetry was quantified using two methods: peak and mean force. Left and right  
150 side peak forces were identified as the highest forces applied by each side  
151 respectively during the eccentric braking phase and the concentric propulsion phase  
152 of each CMJ. Left and right side mean forces were then obtained by averaging left



153 and right side force over the eccentric braking phase and concentric propulsion phase.  
154 The dominant side was identified as the side with the largest peak and mean force  
155 respectively on a phase-by-phase basis. To assess agreement between the peak and  
156 mean force methods of assessing asymmetry, these data were first coded on a  
157 participant-by-participant basis. Where the side that was favoured agreed across the  
158 peak and mean force methods a '1' was assigned; where they disagreed a '0' was  
159 assigned. The percentage agreement between the peak and mean force methods of  
160 assessing asymmetry were calculated. However, a certain amount of this agreement  
161 is likely to have occurred by chance. Therefore, the kappa coefficient, and its 95%  
162 confidence limits, were then calculated in a spreadsheet using methods published in  
163 the literature (Cohen, 1960; O'Donoghue, 2010; Viera & Garrett, 2005). The kappa  
164 coefficient describes the proportion of agreement between the two methods after any  
165 agreement by chance has been removed (Cohen, 1960). The agreement scale  
166 presented by Viera and Garrett (2005), where kappa values of 0.01-0.20, 0.21-0.40,  
167 0.41-0.60, 0.61-0.80, and 0.81-0.99 represented slight, fair, moderate, substantial,  
168 and almost perfect agreement, respectively, was used to quantify agreement. Finally,  
169 relative reliability of peak and mean force from the braking and propulsion phase was  
170 assessed using intraclass correlation coefficients (two-way random effects model  
171 (ICC)), while the absolute reliability was assessed using percentage coefficient of  
172 variation (CV) (Banyard, Nosaka, & Haff, 2016). The magnitude of the ICC was  
173 determined using the criteria set out by Cortina (1993), where  $r \geq 0.80$  is considered  
174 highly reliable. The magnitude of the CV was determined using the criteria set out by  
175 Banyard et al. (2016), where  $>10\%$  is considered poor,  $5-10\%$  is considered moderate,  
176 and  $<5\%$  is considered good.

177

178 **Results**

179 Table 1 shows that the peak and mean forces applied during the braking and  
180 propulsion phases demonstrated high relative reliability and good absolute reliability.

181 Regarding the agreement between the peak and mean force methods of assessing  
182 asymmetry, during the eccentric braking phase the peak and mean force methods  
183 demonstrated a percentage agreement of 84% and a kappa value of 0.67 (95%  
184 confidence limits: 0.45 to 0.90), indicating substantial agreement. During the  
185 concentric propulsion phase the peak and mean force methods demonstrated a  
186 percentage agreement of 87% and a kappa value of 0.72 (95% confidence limits: 0.51  
187 to 0.93), indicating substantial agreement.

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204 Table 1. Results of the within-session reliability analysis.

	ICC (95% confidence intervals)	% CV (95% confidence intervals)
Eccentric braking peak force left	0.971 (0.952-0.983)	5.5 (4.7-6.2)
Eccentric braking peak force right	0.952 (0.921-0.972)	6.1 (5.2-7.1)
Eccentric braking mean force left	0.979 (0.965-0.988)	5.0 (4.3-5.8)
Eccentric braking mean force right	0.964 (0.941-0.979)	5.4 (4.4-6.4)
Concentric propulsion peak force left	0.980 (0.967-0.988)	3.2 (2.6-3.9)
Concentric propulsion peak force right	0.974 (0.957-0.985)	3.2 (2.5-3.9)
Concentric propulsion mean force left	0.988 (0.980-0.993)	2.6 (2.2-3.0)
Concentric propulsion mean force right	0.976 (0.960-0.986)	3.0 (2.4-3.5)

205

206

207 ***Discussion and implications***

208 The aim of this study was to assess the agreement between the peak and mean force  
209 methods of quantifying force asymmetry during vertical jumping. It was hypothesised  
210 that the peak and mean force methods of assessing force asymmetry during vertical  
211 jumping would agree perfectly. The results of this study showed substantial agreement  
212 between the two methods of assessing force asymmetry during vertical jumping.

213 However, while substantial agreement suggests a positive outcome, the hypothesis  
214 must be rejected because these methods did not agree perfectly.

215

216 While the results of this study show that there was substantial agreement between the  
217 peak and mean force methods of assessing force asymmetry during vertical jumping,  
218 it is important to note that this means that 28-33% of the cases in the present study  
219 did not agree. From an applied perspective, this means that if practitioners use these  
220 methods interchangeably significant confusion could surround the assessment of  
221 force asymmetry in around one third of their athletes. This could have serious  
222 implications for the athlete physical preparation and rehabilitation process. Therefore,  
223 we strongly recommend that these methods are not used interchangeably. Instead  
224 practitioners should decide on which approach they use based on the relative merits  
225 of each.

226

227 To the authors' knowledge, none of the researchers that have used peak force to  
228 quantify force asymmetry during vertical jumping have explained why they have done  
229 so (Bailey et al., 2015; Bell et al., 2014; Benjanuvatra et al., 2013; Ceroni, Martin,  
230 Delhumeau, & Farpour-Lambert, 2012; Hoffman, Ratamess, Klatt, Faigenbaum, &  
231 Kang, 2007; Impellizzeri et al., 2007; Menzel et al., 2013; Newton et al., 2006;  
232 Patterson et al., 2009; Suchomel, Sato, DeWeese, Ebben, & Stone, 2016). In the  
233 present study, peak force represented the highest force recorded over one sample  
234 during the phase of interest. It is important to note that because we used a sampling  
235 frequency of 1000 Hz peak force represents the highest force applied over 1 ms.  
236 Therefore, the practitioner should decide whether differences in the forces applied by  
237 the left and right side over 1 ms provide enough information to quantify force

238 asymmetry. The literature awaits a rationale for the use of this approach. However, it  
239 should be noted that the peak force method provides insight into the symmetry  
240 strategy that an athlete uses to maximise their force application during CMJ.

241

242 In the present study mean force represented force averaged over the phase of  
243 interest. It has been suggested that this sort of approach might provide a more robust  
244 approach of assessing force asymmetry because it considers the entire phase of  
245 interest (Flanagan & Salem, 2007). Therefore, it could be argued that the mean force  
246 approach provides a more complete picture of force asymmetry. However, it should  
247 also be reiterated that only one study has suggested averaging variable(s) of interest  
248 over the phase(s) of interest (Flanagan & Salem, 2007). While the peak force  
249 approach might misrepresent force asymmetry by not considering enough of the  
250 phase of interest, it is entirely possible that the mean force approach could also  
251 misrepresent force asymmetry because it cannot consider the magnitude of  
252 differences across various sub-phases. Therefore, we recommend that practitioners  
253 and researchers should use a combined approach, studying both peak and mean  
254 force asymmetries over phases (and sub-phases) of interest. This will provide a far  
255 fuller picture about athlete force asymmetries.

256

257 While the results of this study provide some important information regarding the issues  
258 with agreement between the peak and mean force methods of assessing force  
259 asymmetry during vertical jumping, it is not without its limitations. For example, while  
260 both approaches are routinely used in the literature, force asymmetry cannot provide  
261 a complete picture of lower-body asymmetry. Recent work has shown that additional  
262 methods should be employed to gain a fuller understanding of athlete lower-body

263 asymmetries (considering athlete strength [Bailey et al., 2015], and different  
264 calculation methods [Bishop et al., 2016; Impellizzeri et al., 2007]). However, it should  
265 also be noted that while additional methods have been employed there is still  
266 considerable work to be done. For example, we currently know nothing about force  
267 asymmetry driven changes in movement strategy and so this remains an important  
268 area of research that must be undertaken, in addition to the methods mentioned  
269 above, to obtain a thorough understanding of movement asymmetry. Finally, use of  
270 the terms 'dominant' and 'non-dominant' merits discussion. In the present study  
271 'dominant' was applied to the side that was able to apply the largest peak and mean  
272 force. However, it should be noted that this term has also been used to describe the  
273 side that research participants favour, whether during day-to-day tasks, sport, or  
274 exercise, and that this does not always agree with the side that applies the largest  
275 forces (Bishop et al., 2016).

276

## 277 **Conclusion**

278 In conclusion, side-to-side differences are not reflected equally when the peak and  
279 mean force methods of assessing CMJ asymmetry are used. Therefore, the  
280 hypothesis was rejected. These methods should not be used interchangeably. Instead  
281 we recommend that practitioners use a combined approach, considering both peak  
282 and mean force, depending on the performance characteristics of concern. This will  
283 enable practitioners to more fully assess side-to-side difference in CMJ force-time  
284 curves.

285

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379 Figure and Table Captions

380 Figure 1. Identification of the braking and propulsion phases of countermovement

381 vertical jumping.

382 Table 1. Results of the within-session reliability analysis.