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Bishop, Chris ORCID logoORCID: <https://orcid.org/0000-0002-1505-1287>, Lake, Jason, Loturco, Irineu, Papadopoulos, Konstantinos ORCID logoORCID: <https://orcid.org/0000-0002-4489-8540>, Turner, Anthony N. ORCID logoORCID: <https://orcid.org/0000-0002-5121-432X> and Read, Paul (2018) Interlimb asymmetries: the need for an individual approach to data analysis. *Journal of Strength and Conditioning Research* . ISSN 1064-8011 [Article] (Published online first) (doi:10.1519/JSC.0000000000002729)

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## 24 INTRODUCTION

25 Inter-limb asymmetries refers to the concept of the performance of two limbs not being equal  
26 (3,21) and have been a popular source of investigation in recent years. Historically, many  
27 studies have highlighted the prevalence of inter-limb asymmetry across a range of tests such  
28 as the back squat (1,24,33), isometric squats or mid-thigh pulls (10,14,15), and jumping-based  
29 tasks (2,20,28,31). Although interesting, their prevalence alone does little to enhance our  
30 understanding of whether these differences should be corrected during training. More recently,  
31 studies have aimed to investigate whether such asymmetries are detrimental to physical or  
32 sports performance (6) with equivocal findings. For example, Hart et al. (15) showed that  
33 asymmetries in strength of ~8% were associated with reduced kicking accuracy, whilst  
34 Dos'Santos et al. (10) reported no association between strength asymmetries (~13%) and  
35 performance during the 505 change of direction speed test. Similarly, Dos'Santos et al. (11)  
36 reported no association between single and triple leg hop asymmetries and change of direction  
37 speed (CODS) performance, although it should be noted that the reported inter-limb differences  
38 of ~7% can be considered small (6). In contrast, Bishop et al. (4) showed that both vertical and  
39 horizontal asymmetries were associated with reduced jump ( $r = -0.47$  to  $-0.56$ ) and sprint ( $r =$   
40  $0.49$  to  $0.59$ ) performance in elite youth female soccer players. Consequently, this lack of  
41 agreement highlights the need for further research.

42 The majority of literature relating asymmetries to physical performance measures have used  
43 jump tests to quantify the asymmetry component (4,11,18,26,27). Inter-limb differences from  
44 horizontal jumping (such as single, triple, and crossover hop tests) have reported asymmetries  
45 of 6-7% (4,11,30). When vertical asymmetries have been assessed via a single leg  
46 countermovement jump (SLCMJ), these differences have been shown to be significantly  
47 greater than horizontal tests (4,26,29), with values  $> 10\%$  common for this test. Finally, the use  
48 of drop jumps has highlighted individual asymmetry values  $> 50\%$  (28) in healthy adult

49 populations; thus, the available body of evidence would suggest that the magnitude of  
50 asymmetries are test-specific.

51 In addition to this varying magnitude, recent studies have displayed individual athlete  
52 asymmetry data highlighting that both the left and right (4,27) or dominant and non-dominant  
53 limbs (11,13) have the potential to score higher during jump testing. Despite these recent  
54 findings, to the authors' knowledge, no studies to date have used this approach to specifically  
55 examine if the levels of agreement in asymmetry (right versus left) is consistent across multiple  
56 tests. For example, if peak force (PF) data was obtained during two different types of unilateral  
57 jumps, such as a SLCMJ and single leg broad jump (SLBJ); would the same limb always record  
58 the larger peak force value despite the tests being different. Therefore, the aim of the present  
59 study was to assess if inter-limb asymmetries consistently occurred on the same limb during  
60 unilateral strength and power tests. When reporting inter-limb differences, it was hypothesised  
61 that both the magnitude and side which favoured the asymmetry would be test and metric-  
62 specific, and highly individual in nature, justifying the need for an individual approach to data  
63 analysis.

64

## 65 **METHODS**

### 66 *Experimental Approach to the Problem*

67 The present study required subjects to partake in two sessions. The first visit was for test  
68 familiarisation. Subjects were provided with the relevant test instructions and the opportunity  
69 to practice each assessment until they reached a satisfactory level of technical competence  
70 during each test (established by an accredited strength and conditioning coach). Data collection  
71 took place on the second visit. Subjects performed three trials on each limb for the following  
72 tests: unilateral isometric squats, SLCMJ and SLBJ on a single force platform (PASPORT

73 force plate, PASCO Scientific, California, USA) sampling at 1000 Hz. Test order was  
74 randomized so as to negate any potential learning effects.

75

## 76 *Subjects*

77 Twenty-eight recreational sport athletes (age =  $27.29 \pm 4.6$  years; mass =  $80.72 \pm 9.26$  kg;  
78 height =  $1.81 \pm 0.06$  m) volunteered to take part in this study. A minimum of 27 participants  
79 was determined from a priori power analysis using G\*Power (Version 3.1, University of  
80 Dusseldorf, Germany) implementing statistical power of 0.8 and a type 1 alpha level of 0.05  
81 which has been used in comparable literature (10). Inclusion criteria required all participants  
82 to have a minimum of one year of resistance training experience. In addition, participants were  
83 excluded from the study if they had a history of lower body injury or were injured at the time  
84 of testing. Participants were required to complete informed consent forms to demonstrate that  
85 they were willing and able to undertake all testing protocols. Ethical approval was granted from  
86 the Research and Ethics Committee at the London Sport Institute, Middlesex University.

87

## 88 *Procedures*

89 A standardised dynamic warm up was conducted prior to each session consisting of dynamic  
90 stretches to the lower body (such as multi-planar lunges, inchworms, and ‘world’s greatest  
91 stretch’), in addition to three practice trials at 60, 80, and 100% perceived effort. Two minutes  
92 of rest was provided after the final warm up trial before undertaking the first test. It should be  
93 noted that although additional metrics could be quantified from the force platform, only  
94 comparable metrics across tests were computed given the focus of this study was to establish  
95 asymmetry side consistency across the different tests. Finally, although test order was  
96 randomised, trials were always conducted on the left limb first.

98 *Unilateral Isometric Squat.* A custom built 'ISO rig' (Absolute Performance, Cardiff, UK) was  
99 used for this test protocol. A goniometer was used to measure  $\sim 140^\circ$  of hip and knee flexion  
100 (14) for each participant, with full extension of the knee joint equalling  $180^\circ$ . The fulcrum of  
101 the goniometer was positioned on the lateral condyle of the femur. The stabilisation arm was  
102 lined up along the line of the fibula (in the direction of the lateral malleolus) and the movement  
103 arm was lined up with the femur (pointing towards the greater trochanter at the hip). The non-  
104 stance limb was required to hover next to the working limb, so as to try and keep the hips level  
105 during the isometric squat action; thus, aiding balance and stability. Once in position,  
106 participants were required to remain motionless for 2-seconds, without applying any upwards  
107 force (which was verified by manual detection of the force-time curve in real time). Each trial  
108 was then initiated by a "3, 2, 1, Go" countdown and participants were instructed to try and  
109 extend their knees and hips by driving up as "fast and hard as possible" (10) against the bar for  
110 three seconds. PF was recorded and was defined as the maximum force generated during the  
111 test and reported as absolute values.

112

113 *Unilateral Countermovement Jump.* Participants were instructed to step onto the force plate  
114 with their designated test leg with hands placed on hips which were required to remain in the  
115 same position for the duration of the test. The jump was initiated by performing a  
116 countermovement to a self-selected depth before accelerating vertically as explosively as  
117 possible into the air (34). The test leg was required to remain fully extended throughout the  
118 flight phase of the jump before landing back onto the force plate as per the set up. The non-test  
119 leg was flexed at the hip to  $\sim 90^\circ$  for the duration of each trial. Each trial was separated by 60  
120 seconds of rest. Recorded metrics for each trial included PF (propulsive), eccentric and

121 concentric impulse, with definitions for their quantification conducted in line with suggestions  
122 by Chavda et al. (7). Peak propulsive force was defined as the maximum force output during  
123 the propulsive phase of the jump. Eccentric impulse was defined as the force exerted multiplied  
124 by the time taken to produce it during the eccentric braking phase of the jump. Concentric  
125 impulse was defined as the force multiplied by the time taken to produce it during the  
126 concentric propulsion phase of the jump (7).

127

128 *Unilateral Broad Jump.* Participants stood on the force plate with their designated test leg and  
129 hands placed on their hips. The jump was initiated by performing a countermovement to a self-  
130 selected depth before jumping forward as far as possible (34). The fronts of the participants'  
131 shoes were placed on the edge of the force plate (without going over) so that the edge of the  
132 force plate also served as 0 cm. The tape measure (which was fixed to the floor) ran  
133 perpendicular to the force plate for distance to be measured from the heel of the landing foot.  
134 Participants were required to “stick the landing” and avoid toppling forward, otherwise trials  
135 were excluded and subsequently retaken after a 60-second rest interval. Recorded metrics  
136 included PF, eccentric and concentric impulse respectively.

137

### 138 *Statistical Analyses*

139 Initially all force-time data were exported to Microsoft Excel™, expressed as means and  
140 standard deviations (SD), and later transferred into SPSS (V.24, Chicago, IL, USA) for  
141 additional analyses. Within-session reliability was quantified for each metric in both test  
142 sessions using the coefficient of variation (CV:  $SD[\text{trials 1-3}]/\text{average}[\text{trials 1-3}]*100$ ) and  
143 intraclass correlation coefficient (ICC) with absolute agreement. CV values < 10% were  
144 deemed acceptable (9) and ICC values were interpreted in line with suggestions by Koo and

145 Li, (22) where scores > 0.9 = excellent, 0.75-0.9 = good, 0.5-0.75 = moderate, and < 0.5 = poor.  
146 Noting that asymmetries may favour either the left or right limbs, a Kappa coefficient was  
147 calculated to determine the levels of agreement between asymmetries for a common metric  
148 across two tests (8). This method was chosen because the Kappa coefficient describes the  
149 proportion of agreement between two methods after any agreement by chance has been  
150 removed (8). In addition, only metrics that were common across more than one test were used  
151 for this statistic (e.g., PF for all tests). Intuitively, this made sense given that asymmetries have  
152 been shown to be both task and metric-specific (4,26,27,28,29). Kappa values were interpreted  
153 in line with suggestions from Viera and Garrett (35), where 0.01-0.20 = slight, 0.21-0.40 = fair,  
154 0.41-0.60 = moderate, 0.61-0.80 = substantial, and 0.81-0.99 = almost perfect. Finally, inter-  
155 limb asymmetries were quantified as a percentage difference between limbs (from best trials)  
156 using the formula proposed by Bishop et al. (4). Given that the quantification of asymmetry  
157 was focused on percentage difference between limbs, no reference value was required (4). In  
158 addition, it has been suggested that the easiest way to utilise this formula is in Microsoft  
159 Excel™ (4); thus, a modification was made via the use of an 'IF function' (Equation).  
160 Consequently, if an asymmetry score was positive, the right limb had the largest score between  
161 limbs and vice versa for a negative asymmetry outcome (19).

162

163 *Equation:*  $((100/(\text{maximum value})) * (\text{minimum value}) * -1 + 100) * \text{IF}(\text{left} < \text{right}, 1, -1)$

164

## 165 **RESULTS**

166 Mean values, asymmetries, and reliability data are presented in Table 1. Results showed  
167 moderate to excellent reliability (ICC) and acceptable consistency (CV) for each test and  
168 metric. Levels of agreement for inter-limb asymmetry scores were calculated using the Kappa



169 coefficient and are shown and described in Table 2. Results showed slight to fair levels of  
170 agreement (range = -0.34 to 0.32) for all comparisons with the exception of concentric impulse  
171 between the SLCMJ and SLBJ (0.79) which showed substantial levels of agreement. Individual  
172 asymmetry values for PF (across all tests) are shown in Figure 1, and for eccentric and  
173 concentric impulse for the SLCMJ and SLBJ in Figure 2. It has been suggested that  
174 asymmetries may only be 'real' if greater than the test variability (3,5,12), which in this study  
175 is represented by the CV value. Thus, the reader is encouraged to pay particular attention to  
176 Figures 1 and 2 where the asymmetry bars surpass the dotted line (which represents the largest  
177 CV value for those given metrics).

178

179 \*\*\* INSERT TABLES 1-2 ABOUT HERE \*\*\*

180 \*\*\* INSERT FIGURES 1-2 ABOUT HERE \*\*\*

181

## 182 **DISCUSSION**

183 The aim of the present study was to show whether inter-limb asymmetries were favoured for  
184 the same limb during the unilateral isometric squat, SLCMJ and SLBJ tests. Test reliability  
185 was generally good to excellent; however, levels of agreement for measures of peak force,  
186 eccentric and concentric impulse across tests was poor, with the exception of concentric  
187 impulse between the SLCMJ and SLBJ. This was also represented by individual asymmetry  
188 analyses (Figures 1-2). These data indicate that asymmetries are test-specific, highly individual  
189 in nature, and rarely favour the same limb when comparing across tests.

190 Mean scores, mean asymmetry, and reliability data are presented in Table 1. When asymmetry  
191 values are considered, previous research has suggested that ~10% might be considered a  
192 potential threshold where reductions in performance (6) and heightened injury risk occur

193 (23,32). Therefore, mean asymmetry values in the present study can be considered small. Of  
194 note though (and although these mean values are small), it is interesting to see all jumping-  
195 based asymmetry values favour the left limb (as represented by negative scores) and the  
196 isometric squat favouring the right limb (positive asymmetry outcome). Thus, the asymmetry  
197 values alone highlight how one limb may be favoured over the other from task to task. Although  
198 somewhat anecdotal, it is plausible that the majority of subjects' right limb was their dominant  
199 (often defined by the preferred kicking limb) (15,16,17), which has been shown to be  
200 outperformed by the non-dominant limb in previous research (13,15). However, due to the wide  
201 range of sporting experience from the present sample and the calculation of asymmetry focused  
202 on a percentage difference at a given time point, no reference value (i.e., dominant vs. non-  
203 dominant) was defined.

204 Table 2 shows the results of the Kappa agreement between metric analysis. The Kappa  
205 coefficient describes the proportion of agreement between two methods after any agreement  
206 by chance has been removed (8). In the present study, PF was a common metric across all tests;  
207 thus, asymmetry values were comparable (Figure 1). Noting that the present study aimed to  
208 determine how common it was for asymmetries to be present on the same limb, the Kappa  
209 values highlight slight to fair levels of agreement for PF asymmetries. For example, if an  
210 asymmetry was favoured on the right limb during the SLCMJ, it was likely that the right limb  
211 was not favoured during the isometric squat (Kappa = 0.04) or SLBJ (Kappa = 0.05),  
212 remembering that this statistic removes the possibility that this agreement may have occurred  
213 by chance. Where jumps were concerned, eccentric and concentric impulse metrics were  
214 comparable; thus, asymmetry scores for these metrics were compared (Figure 2). Of note, a  
215 comparison between concentric impulse across both jumps showed substantial levels of  
216 agreement, indicating that asymmetries for this metric were often present on the same side.  
217 This may indicate that a similar strategy was adopted prior to take off regardless of whether

218 the focus was maximal jump height or distance. As a result, asymmetries often appear to be  
219 affected in the same way for this metric during vertical and horizontal jumping tasks. When all  
220 other comparisons were drawn for impulse asymmetries, slight to fair levels of agreement were  
221 present, again highlighting the individual nature of asymmetries across tests. This is in  
222 agreement with previous research (4,29), although to the authors' knowledge, levels of  
223 agreement in respect to asymmetries are limited to date (24,25). These results demonstrate the  
224 changing nature of asymmetries from test to test, and highlights the need for a more individual  
225 approach to data analysis.

226 Individual asymmetry data for PF and eccentric and concentric impulse measures are shown in  
227 Figures 1 and 2 respectively. The largest mean asymmetry value for any test was -5.3%;  
228 however, it is clear from both figures that many individual asymmetry values greatly surpassed  
229 this. It was not uncommon for asymmetries to be > 10% across all tests with some individuals  
230 demonstrating values between 20-30%. If proposed thresholds of ~10% are to be accepted as  
231 cut-offs where reduced performance (6) and increased risk of injury are present (23,32), then  
232 Figures 1 and 2 also clearly show that many individuals may require training interventions to  
233 minimise these differences. In addition, previous literature has suggested that asymmetries  
234 should be reported within the context of test variability (CV) so as to determine whether the  
235 between-limb difference is outside the associated error of the test (3,4,12). Noting that multiple  
236 CV scores exist, the authors chose to represent the greatest CV value for each metric as a  
237 proposed threshold (as represented by the dotted lines on Figures 1 and 2) to identify when  
238 inter-limb differences fell outside this value. When this is considered, it is again clear that many  
239 individuals showed substantial asymmetries in PF (Figure 1) and impulse metrics (Figure 2) as  
240 represented by bars surpassing the dotted lines. If mean asymmetry values were interpreted  
241 alone, this would not depict the full story of how imbalanced some individuals are; thus,

242 individual data analyses for side-to-side differences appears critical to further our  
243 understanding of this concept.

244 Despite the aforementioned results, readers should be mindful of a couple of limitations.  
245 Firstly, the present study used recreational sport athletes; thus, these findings cannot be  
246 attributed to elite athlete populations. Furthermore, the very premise of this paper highlights  
247 that asymmetries are both task and metric-specific, suggesting that interpreting mean data is  
248 somewhat limited. Secondly, this study used a force platform to gather data relating to  
249 asymmetries. Although this is not a limitation, it is worth acknowledging that not all  
250 practitioners will have access to this equipment. Therefore, an alternative strategy to determine  
251 whether asymmetries are favoured for the same limb is required for practitioners governed by  
252 smaller budgets. As such, previous work from Bishop et al. (4) used the SLCMJ, single leg  
253 hop, triple hop, and crossover hop for distance tests to show the changing nature of asymmetries  
254 between tasks. Practitioners who cannot access force platforms could consider such tests to  
255 determine whether asymmetries are favoured for the same side during outcome measures such  
256 as jump height and distance.

257 In summary, the results of the present study show that the levels of agreement for asymmetries  
258 being present on the same side are quite low and highlights the changing nature of inter-limb  
259 differences across tests. In addition, individual asymmetry scores were vastly different to mean  
260 values for all metrics and highlights the necessity for a more individualised approach to  
261 asymmetry analysis and will likely provide a more complete picture of the presence of inter-  
262 limb differences.

263

264 **PRACTICAL APPLICATIONS**

265 The findings from the present study highlight that asymmetries vary across commonly used  
266 strength and jumping-based tests and that the same side is also rarely favoured. As such,  
267 practitioners should always consider the individual nature of asymmetries when interpreting  
268 data relative to these side-to-side differences. If the mean values alone were used for  
269 interpretation, it would suggest that no action would be needed to correct the existing between-  
270 limb differences. However, individual asymmetry scores were vastly different and this type of  
271 analysis may offer practitioners the chance to implement training interventions to reduce these  
272 side-to-side differences on a more individual level. Noting that individualized training  
273 programmes can be a challenge when working with large groups of athletes (i.e., in a team-  
274 sport environment), assessing individual athlete data in respect to asymmetries offers  
275 practitioners a viable method of establishing which athletes may require additional exercises  
276 to their existing training programme, in an attempt to optimise physical performance and  
277 reduce the risk of future injury.

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373

374

375 Table 1: Mean performance data  $\pm$  standard deviations (SD), asymmetry data, and reliability  
 376 data for isometric squat, countermovement, and broad jump metrics.

Test/Metric	Mean $\pm$ SD	Mean Asymmetry (%)	CV (%)	ICC (95% Confidence Intervals)
Iso PF (L)	1597 $\pm$ 438 N	0.8	5.4	0.94 (0.88-0.97)
Iso PF (R)	1595 $\pm$ 397 N		5.7	0.93 (0.87-0.96)
SLCMJ PF (L)	863 $\pm$ 204 N	-3.4	5.8	0.89 (0.80-0.94)
SLCMJ PF (R)	831 $\pm$ 182 N		5.3	0.93 (0.87-0.96)
SLCMJ EI (L)	70 $\pm$ 17 N·s	-4.2	8.7	0.89 (0.81-0.95)
SLCMJ EI (R)	67 $\pm$ 17 N·s		9.1	0.83 (0.71-0.91)
SLCMJ CI (L)	152 $\pm$ 21 N·s	-1.6	3.3	0.92 (0.86-0.96)
SLCMJ CI (R)	150 $\pm$ 20 N·s		4.1	0.81 (0.69-0.90)
SLBJ PF (L)	732 $\pm$ 156 N	-1.4	8.7	0.75 (0.59-0.86)
SLBJ PF (R)	722 $\pm$ 159 N		9.3	0.80 (0.66-0.89)
SLBJ EI (L)	59 $\pm$ 19 N·s	-5.3	11.9	0.85 (0.74-0.92)
SLBJ EI (R)	56 $\pm$ 17 N·s		11.1	0.87 (0.77-0.93)
SLBJ CI (L)	104 $\pm$ 17 N·s	-1.4	7.3	0.69 (0.51-0.83)
SLBJ CI (R)	102 $\pm$ 14 N·s		8.8	0.66 (0.47-0.81)

CV = coefficient of variation, ICC = intraclass correlation coefficient, Iso = isometric, SLCMJ = single leg countermovement jump, SLBJ = single leg broad jump, PF = peak force, EI = eccentric impulse, CI = concentric impulse, L = left, R = right, N = newtons, N·s = newton seconds.

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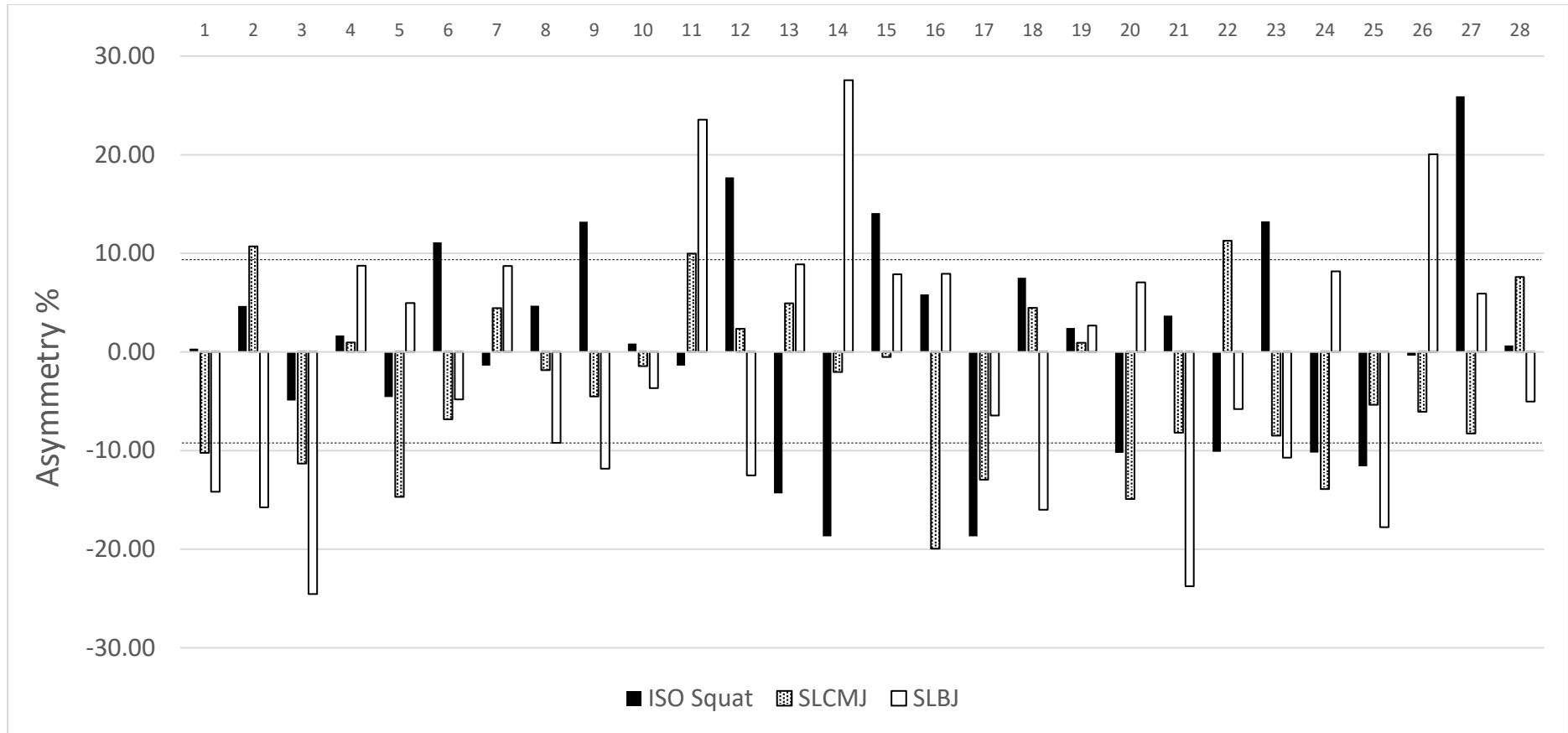
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382 Table 2: Kappa values and descriptive levels of agreement between the favored and non-  
 383 favored sides for peak force, and eccentric and concentric impulse metrics across common  
 384 tests.

<b>Test Methods</b>	<b>Kappa Coefficient</b>	<b>Level of Agreement</b>
<i>Peak Force:</i>		
Iso Squat – SLCMJ	0.04	Slight
Iso Squat – SLBJ	-0.34	Fair
SLCMJ – SLBJ	0.05	Slight
<i>Impulse:</i>		
SLCMJ Ecc – SLBJ Ecc	0.32	Fair
SLCMJ Con – SLBJ Con	0.79	Substantial
SLCMJ Ecc – SLCMJ Con	0.07	Slight
SLBJ Ecc – SLBJ Con	< 0.01	Slight
SLCMJ Ecc – SLBJ Con	0.21	Fair
SLBJ Ecc – SLCMJ Con	-0.25	Fair
Iso = isometric, SLCMJ = single leg countermovement jump, SLBJ = single leg broad jump, Ecc = eccentric, Con = concentric		

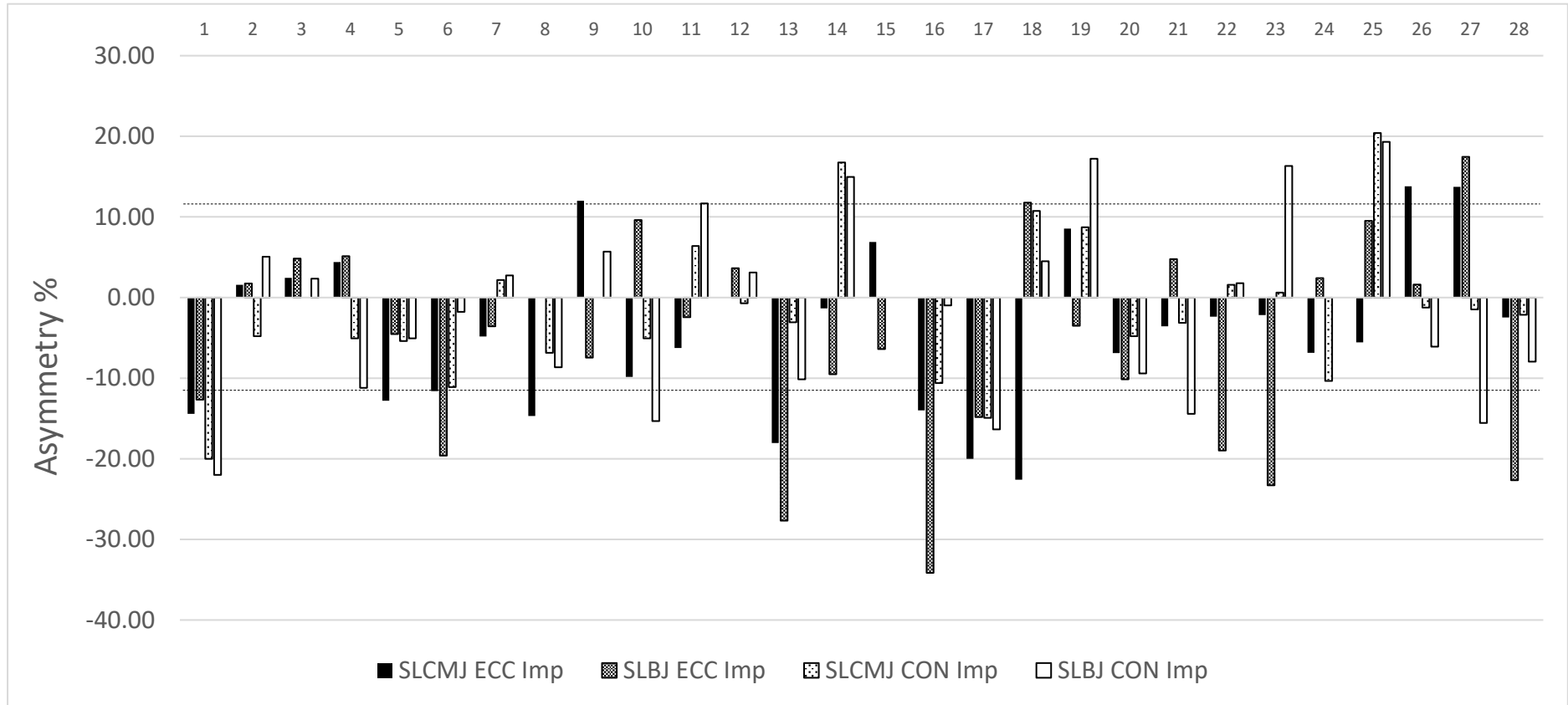
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400 Figure 1: Individual asymmetry data for peak force (PF) during the isometric squat (ISO Squat), single leg countermovement jump (SLCMJ),  
 401 and single leg broad jump (SLBJ). Note: above the line indicates raw score is greater on the right limb and below the line indicates raw score is  
 402 greater on the left limb. Dashed lines indicate largest coefficient of variation value for all PF measures.



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406 Figure 2: Individual asymmetry data for eccentric (ECC) and concentric (CON) impulse (Imp) during the single leg countermovement jump  
 407 (SLCMJ) and single leg broad jump (SLBJ) tests. Note: above the line indicates raw score is greater on right limb and below the line indicates raw  
 408 score is greater on left limb. Dashed lines indicate greatest coefficient of variation value for either eccentric or concentric impulse measures.