

RESEARCH ARTICLE

Between-session reliability of performance and asymmetry variables obtained during unilateral and bilateral countermovement jumps in basketball players

Alejandro Pérez-Castilla^{1*}, Amador García-Ramos^{1,2}, Danica Janicijevic³, Gabriel Delgado-García¹, Juan Carlos De la Cruz¹, F. Javier Rojas¹, Mar Cepero⁴

1 Faculty of Sport Sciences, Department of Physical Education and Sport, University of Granada, Granada, Spain, **2** Faculty of Education, Department of Sports Sciences and Physical Conditioning, Universidad Católica de la Santísima Concepción, Concepción, Chile, **3** Faculty of Sport and Physical Education, University of Belgrade, The Research Centre, Belgrade, Serbia, **4** Faculty of Educational Sciences, Department of Didactics of Musical, Plastic and Corporal Expression, University of Granada, Granada, Spain

* alexperez@ugr.es



OPEN ACCESS

Citation: Pérez-Castilla A, García-Ramos A, Janicijevic D, Delgado-García G, De la Cruz JC, Rojas FJ, et al. (2021) Between-session reliability of performance and asymmetry variables obtained during unilateral and bilateral countermovement jumps in basketball players. PLoS ONE 16(7): e0255458. <https://doi.org/10.1371/journal.pone.0255458>

Editor: Daniel Boullosa, Universidade Federal de Mato Grosso do Sul, BRAZIL

Received: May 6, 2021

Accepted: July 16, 2021

Published: July 30, 2021

Copyright: © 2021 Pérez-Castilla et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the manuscript and its [Supporting Information](#) files.

Funding: This study was funded by the Spanish Ministry of Science and Innovation (PID2019-110074GB-I00 / SRA (State Research Agency) /10.13039/501100011033).

Competing interests: The authors have declared that no competing interests exist.

Abstract

This study aimed to evaluate the between-session reliability of single-leg performance and asymmetry variables during unilateral and bilateral countermovement jumps (CMJ). Twenty-three basketball players completed two identical sessions which consisted of four unilateral CMJs (two with each leg) and two bilateral CMJs. Mean and peak values of force, velocity and power, impulse, and jump height were obtained separately for each leg using a dual force platform. All performance variables presented an acceptable reliability ($CV_{\text{range}} = 4.05\text{--}9.98\%$) with the exceptions of jump height for the unilateral CMJs and mean power, peak velocity, peak power, and impulse for the left leg during the bilateral CMJ ($CV_{\geq 11.0\%}$). Nine out of 14 variables were obtained with higher reliability during the unilateral CMJ ($CV_{\text{ratio}} \geq 1.16$), and 4 out of 14 during the bilateral CMJ ($CV_{\text{ratio}} \geq 1.32$). Asymmetry variables always showed an unacceptable reliability ($ICC_{\text{range}} = 0.15\text{--}0.64$) and *poor/slight* levels of agreement in direction ($Kappa_{\text{range}} = -0.10$ to 0.15) for the unilateral CMJ, while an acceptable reliability ($ICC_{\text{range}} = 0.74\text{--}0.77$) and *substantial* levels of agreement in direction ($Kappa_{\text{range}} = 0.65$ to 0.74) were generally obtained for the bilateral CMJ. These results suggest that single-leg performance can be obtained with higher reliability during the unilateral CMJ, while the bilateral CMJ provides more consistent measures of inter-limb asymmetries.

Introduction

The countermovement jump (CMJ) is a ballistic exercise commonly performed on a force platform to comprehensively assess lower-body neuromuscular function [1,2]. The CMJ has been also used to measure single-leg performance and detect inter-limb asymmetries [3–5]. The assessment of inter-limb asymmetries is justified by the influence that CMJ-based asymmetry may have on athletic performance [6,7] and injury risk [4]. Both unilateral and bilateral CMJs

Abbreviations: CMJ, countermovement jump; CV, coefficient of variation; ES, effect size; ICC, intraclass correlation coefficient; SD, standard deviation.

have been used to detect inter-limb asymmetries [3–6,8]. During unilateral CMJs athletes jump from a monopodial stance with the tested leg placed on a single force platform, while during the bilateral CMJ a bipodal stance is used with each leg positioned on an individual force platform [5]. Although it is reasonable to believe that the inter-limb asymmetries measured during bilateral and unilateral CMJs should be closely related, research has shown that impulse asymmetries observed during bilateral and unilateral CMJs are unrelated [3]. In fact, it has been suggested that the unilateral CMJ represents a more robust indicator of the capacity of each limb, while the bilateral CMJ may provide more comprehensive information about the compensatory strategies between limbs [9]. Therefore, it is important to elucidate whether bilateral or unilateral CMJs provides more valuable data to accurately detect inter-limb asymmetries [10].

A high reliability is a basic requirement for any fitness test [11]. Emerging research has explored the reliability of single-leg mechanical performance variables collected with force platforms during unilateral and bilateral CMJs. Regardless of the tested leg, some studies have reported a high between-session reliability (coefficient of variation [CV] \leq 9.8%; intraclass correlation coefficient [ICC] \geq 0.75) for peak force, peak power, concentric impulse, and jump height during the unilateral CMJ [12–18]. Similar reliability outcomes were reported for the lower-limb differences in mean force, peak force, and concentric impulse during the bilateral CMJ performed with and without arm swing (CV \leq 9.2%; ICC \geq 0.68) [5,19]. The available body of literature suggests that both CMJ variants could be reliable tests to measure single-leg mechanical performance. Instead, Benjanuvattra et al. [3] have recommended the unilateral CMJ to examine impulse asymmetries because it places a greater emphasis on force production from one limb, while inter-limb asymmetries detected during the bilateral CMJ could be more affected by the weighing phase (i.e., slight shifts of the center-of-mass toward one side). It is worth mentioning that the purpose of the weighing phase is the accurate determination of body weight, which is essential in forward dynamics procedures [20]. Contrary to Benjanuvattra's et al. [3] suggestion, a recent study [19] observed that the single-leg performance for the mean force (CV_{ratio} = 1.29–1.41), concentric impulse (CV_{ratio} = 1.56–1.63), and eccentric impulse (CV_{ratio} = 1.45–1.75) was more reliable for the bilateral CMJ than unilateral CMJ in elite academy soccer players. Therefore, this lack of agreement clearly emphasizes the need to conduct additional research to elucidate which variant of CMJ exercise is more reliable to measure single-leg performance considering other mechanical variables (e.g., velocity, power, or jump height) and populations (e.g., basketball players).

On the other hand, only two studies [3,4] have examined the between-session reliability of CMJ-based asymmetry variables. Impellizzeri et al. [4] showed that “*Bilateral Strength Asymmetry*” was highly reliable for peak force (ICC = 0.91) measured with a single force platform (i.e., athletes jump with one leg placed on a force platform and the other leg on a wooden platform). Benjanuvattra et al. [3] also found that the “*Index of Asymmetry*” calculated for jump height and concentric impulse presented a high reliability (ICC \geq 0.95) during bilateral and unilateral CMJs. The scope of other studies, however, focused on answering the question of whether asymmetry consistently favored the same leg between testing sessions (i.e., “*direction of asymmetry*”) during unilateral CMJ [8,13,19]. For instance, Bishop et al. [13] found *substantial* levels of agreement (Kappa range = 0.64–0.66) for the peak force and jump height collected with a single force platform in recreational soccer and rugby athletes. By contrast, Bishop et al. [8] also reported a *slight to fair* levels of agreement (Kappa range = 0.18–0.29) for the jump height measured with the smartphone application “*My jump 2*” in national-level youth basketball athletes. Therefore, further research is warranted to examine the between-session reliability of inter-limb asymmetry variables during unilateral and bilateral CMJs in order to ensure that the magnitude and direction are consistent between sessions [21].

To address the gaps in the literature, we assessed different mechanical variables separately for the left and right legs using a dual force platform during the unilateral and bilateral CMJ variants, and thereafter calculated inter-limb asymmetries. Specifically, the aim of this study was to elucidate whether single-leg performance and inter-limb asymmetries can be obtained with a higher reliability during unilateral or bilateral CMJ variants. It was hypothesized that the reliability of single-leg performance variables would be higher for the unilateral CMJ compared to the bilateral CMJ due to an expected higher variability in the weighing phase for the bilateral CMJ [3]. Regarding the comparison of the reliability of inter-limb asymmetries between the unilateral and bilateral CMJ variants, no specific hypothesis was formulated due to the contrasting findings regarding the unilateral CMJ [8,13] and the lack of straightforward evidence for the bilateral CMJ.

Material and methods

Subjects

Twenty-three amateur basketball players volunteered to participate in this study. Specifically, the study sample was composed of a senior male ($n = 11$; age = 19.2 ± 1.5 years [range: 17–22 years]; body mass = 79.3 ± 11.0 kg; body height = 1.87 ± 0.08 m) and female ($n = 12$; age = 21.1 ± 4.2 years [range: 15–29 years]; body mass = 70.6 ± 7.2 kg; body height = 1.75 ± 0.06 m) team that played in a regional-level Spanish basketball club (data presented as mean \pm standard deviation [SD]). All subjects had at least five years of competitive experience and were accustomed to performing the unilateral and bilateral CMJ exercises as part of their habitual strength and conditioning training routines. No physical limitations, health problems or musculoskeletal injuries that could compromise testing were reported. Prior to testing, subjects were informed about the research purpose and procedures, and they or their legal guardians (for subjects aged < 18 years) gave written consent to participate in the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the University of Granada Institutional Review Board (IRB approval: 1706/CEIH/2020).

Experimental design

A repeated-measures design was used to compare the between-session reliability of single-leg mechanical performance and inter-limb asymmetry variables between unilateral and bilateral CMJs. Subjects completed two identical sessions separated by seven days. Each testing session consisted of four unilateral CMJ (two trials with each leg) and two bilateral CMJs. The order of the CMJ variants was randomized in session 1, but in session 2 subjects were assigned with the same order as in session 1. Only the trial with higher jump height of each session for each CMJ variant was used for statistical analyses. All testing sessions were performed at the same facility, under the direct supervision of the same experimenter, and were held between 19:00–21:00 hours. Subjects continued with their regular training program over the course of the study, but they were asked to refrain from any strenuous physical activity for at least 24 hours prior to testing days.

Testing procedures

Body height and body mass were measured at the beginning of the first session using a wall-mounted stadiometer (Seca 202 Stadiometer; Seca Ltd., Hamburg, Germany) and an eight-electrode system (Tanita BC-418 MA; Tanita Corp., Tokyo, Japan), respectively. The warm-up consisted of 5 minutes of jogging, lower-limb dynamic stretching exercises, and three sub-maximal practice trials of each CMJ variant. The jogging pace and lower-limb dynamic

stretching exercises were self-selected by the subjects as they commonly do in their usual training. After warming-up, subjects rested 3 minutes and then they performed two trials for each CMJ variant. The order of execution of the CMJ variants was randomized in the first session, and the same order was followed in the second session. The rest between trials of the same and different CMJ variants was set to 1 and 2 minutes, respectively. The specific characteristic of the unilateral and bilateral CMJ variants were the following.

Unilateral CMJ. Subjects began the exercise execution by standing in an unilateral stance with the tested leg fully extended and placed on the center of a force platform, the alternate leg flexed to 90° at the hip and knee joints, and the hands placed on the hips [22]. Subsequently, subjects were instructed to jump as high as possible and to land on the same tested leg after performing a countermovement to a self-selected depth. Subjects had to keep their hands on their hips throughout the movement and the tested leg remained fully extended during the flight phase. The swing of the opposite leg prior to the jump was prohibited [23]. An experienced examiner asked the subjects to repeat the trial after 1 minute of rest when the jump did not comply with these instructions.

Bilateral CMJ. Subjects began the exercise execution by standing in a comfortable bilateral stance with each leg fully extended and feet hip-width apart and positioned over the center of two parallel force platforms, and with the hands placed on the hips [24]. The execution technique was identical to the unilateral CMJ, with the difference that subjects were instructed to jump and land on both legs simultaneously.

Measurement equipment and data analysis

All CMJ tests were performed on two parallel force platforms (Type 9260AA6; Kistler, Winterthur, Switzerland) embedded in a wooden drawer. The vertical ground reaction force (vGRF) data from each force platform were synchronously acquired via BioWare[®] software (Kistler, Winterthur, Switzerland) at a sampling rate of 1,000 Hz. The force platforms were zeroed before each trial. The vGRF data were exported as text files and analyzed using a customized 2019 Microsoft Excel[®] spreadsheet (version 16.32, Microsoft Corporation, Redmond, Washington, USA) [25].

During the weighing phase, subjects stood still on one (unilateral CMJs) or two (bilateral CMJ) legs for approximately 3 seconds. Body weight and the *SD* of the weighing phase were determined during the last second preceding the onset of the countermovement [26]. The countermovement phase started 30 ms before the instant in which the vGRF was lower than the body weight minus 5 *SD* of the weighing phase [27] and finished when the velocity of the center-of-mass was positive [25]. The propulsion phase was identified from this latter point until the take-off instant. The take-off and landing were determined in three steps [22,25]: (I) identification of the first force value lower than 10 N and the next force value greater than 10 N, (II) selection of 100 ms for unilateral CMJ or 300 ms for bilateral CMJ between the points identified in stage I, and (III) calculation of the mean vGRF and *SD* of the time frame representing the flight phase identified in stage II. Thereafter, the take-off and landing instants were determined as the first force value lower or greater than the mean vGRF plus 5 *SD* of the flight phase, respectively.

The impulse-momentum approach was used to calculate the dependent variables of the present study [28]. Vertical acceleration was calculated as the net vGRF divided by body mass, while vertical velocity of the center-of-mass was determined by integrating acceleration with respect to time. Vertical power was calculated as the product of force and velocity at each time point. The mean and peak values of force, velocity, and power, as well as the net vertical impulse were calculated during the propulsive phase of the jump (in the further text this

variable will be referred to as concentric impulse). Finally, the jump height was estimated from the flight time using the following equation [28,29], where g represents gravity acceleration ($-9.81 \text{ m}\cdot\text{s}^{-2}$): $\text{jump height} = g \cdot (\text{flight time})^2 / 8$.

Statistical analyses

Descriptive data are presented as means, SD, and range. The normal distribution of the data was confirmed using the Shapiro-Wilk test ($P > 0.05$; except for the magnitude of the mean velocity for the right leg and jump height for the left leg during unilateral CMJs, and inter-limb asymmetries in peak power, peak velocity and concentric impulse during the unilateral CMJ). Paired samples t -tests for normally distributed variables or the Wilcoxon signed-rank test for non-normally distributed variables, in addition to the standardized mean difference (Cohen's d effect size [ES]), were used to compare the magnitude of the performance and inter-limb asymmetry variables between both testing sessions. The criteria to interpret the magnitude of the ES was the following: *trivial* (<0.20), *small* (0.20 – 0.59), *moderate* (0.60 – 1.19), *large* (1.20 – 2.00), or *very large* (>2.00) [30]. Absolute (CV% = standard error of measurement/subjects' mean score \times 100) and relative reliability (ICC, model 3.1) were calculated with their corresponding 95% confidence intervals. Acceptable reliability was determined as an ICC > 0.70 and CV $< 10\%$ [31]. The ratio between two CVs (higher CVvalue/lower CV value) was used to compare the between-session reliability of performance variables between unilateral and bilateral CMJs. The smallest important ratio between two CVs was considered to be higher than 1.15 [32].

Standard percentage differences ($100/[\text{maximum value from right and left leg}] \cdot [\text{minimum value from right and left leg}] \cdot [-1] + 100$) were calculated to assess inter-limb asymmetries during the unilateral CMJ [33]. The bilateral asymmetry index-1 ($[\text{preference leg} - \text{non-preference leg}] / [\text{preference leg} + \text{non-preference leg}] \cdot 100$) was used to assess inter-limb asymmetries during the bilateral CMJ [33]. To determine the direction of asymmetry during the unilateral CMJ, an "IF function" ($\text{IF} \cdot [\text{left leg} < \text{right leg}, 1, -1]$) was added to the end of the asymmetry equation [34]. Leg preference during the bilateral CMJ was determined via questionnaire (2 males and 1 female were left-footed) [35,36]. Finally, kappa coefficients were calculated to determine the levels of agreement for the direction of the asymmetries between both testing sessions [13]. For that, data were first coded on a subject-by-subject basis; where the direction of asymmetry was assigned as "1" when favored the right leg (unilateral CMJ)/preference (bilateral CMJ) or "0" when favored the left leg (unilateral CMJ)/non-preference (bilateral CMJ). The criteria to interpret the kappa values were as follows: *poor* (≤ 0.00), *slight* (0.01 – 0.20), *fair* (0.21 – 0.40), *moderate* (0.41 – 0.60), *substantial* (0.61 – 0.80), or *almost perfect* (0.81 – 0.99) [37]. All reliability assessments were performed by means of a custom Excel spreadsheet [38], while other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL). Alpha was set at 0.05.

Results

Descriptive data of single-leg performance and inter-limb asymmetry variables are presented in Table 1. No significant differences between both testing sessions were observed for most of the performance variables ($P > 0.05$; 21 out of 30 comparisons), while the magnitude of the differences was either *trivial* ($\text{ES} \leq 0.19$; 24 out of 30 comparisons) or *small* ($0.20 \leq \text{ES} \leq 0.29$; 6 out of 30 comparisons). All performance variables presented an acceptable reliability (CV range = 4.05–9.98%; ICC range = 0.82–0.97) with the exceptions of jump height for both unilateral CMJs and mean power, peak velocity, peak power, and concentric impulse for the left leg during the bilateral CMJ (CV $\geq 11.0\%$) (Table 2). Regarding the reliability comparison

Table 1. Descriptive data of performance and inter-limb asymmetry variables obtained during the unilateral and bilateral countermovement jump (CMJ) exercises.

Variable	Session	Unilateral CMJ			Bilateral CMJ		
		Right leg	Left leg	Asymmetry (%)	Right leg	Left leg	Asymmetry (%)
Mean force (N)	1	1061 ± 159	1051 ± 162	0.9 ± 7.7	661 ± 104	653 ± 91	-0.4 ± 3.9
	2	1082 ± 163	1099 ± 173	-1.4 ± 4.7	664 ± 102	660 ± 91	0.4 ± 3.7
Mean velocity (m·s ⁻¹)	1	1.04 ± 0.18	1.04 ± 0.16	-0.2 ± 8.3	1.40 ± 0.41	1.38 ± 0.41	5.7 ± 22.6
	2	1.08 ± 0.19	1.06 ± 0.18	2.3 ± 9.3	1.49 ± 0.42	1.34 ± 0.41	5.5 ± 24.9
Mean power (W)	1	1037 ± 271	1032 ± 249	0.0 ± 12.4	880 ± 340	835 ± 285	5.7 ± 24.6
	2	1093 ± 286	1083 ± 299	0.9 ± 10.3	937 ± 364	817 ± 295	5.8 ± 27.5
Peak force (N)	1	1306 ± 196	1275 ± 208	2.4 ± 6.9	795 ± 124	785 ± 107	-0.5 ± 3.6
	2	1326 ± 226	1328 ± 229	-0.1 ± 5.3	810 ± 124	805 ± 115	0.1 ± 2.9
Peak velocity (m·s ⁻¹)	1	1.86 ± 0.27	1.87 ± 0.24	-0.7 ± 8.6	2.53 ± 0.71	2.48 ± 0.77	5.9 ± 23.9
	2	1.88 ± 0.29	1.84 ± 0.27	1.8 ± 6.7	2.68 ± 0.76	2.39 ± 0.69	5.4 ± 24.6
Peak power (W)	1	2048 ± 490	2036 ± 497	0.2 ± 12.8	1670 ± 623	1605 ± 547	5.7 ± 25.2
	2	2079 ± 540	2024 ± 561	2.6 ± 8.0	1782 ± 686	1550 ± 503	5.2 ± 26.2
Concentric impulse (N·s)	1	121.4 ± 29.4	123.4 ± 25.8	-2.7 ± 13.5	89.2 ± 28.0	86.0 ± 26.3	4.3 ± 20.8
	2	120.7 ± 27.0	121.8 ± 28.8	-0.7 ± 9.5	92.9 ± 29.1	82.4 ± 24.7	5.4 ± 21.1
Jump height (m)	1	0.15 ± 0.05	0.16 ± 0.04	-4.9 ± 15.5			
	2	0.16 ± 0.05	0.16 ± 0.05	-3.3 ± 13.3			

Data are presented as means ± SD.

<https://doi.org/10.1371/journal.pone.0255458.t001>

between the CMJ variants, the unilateral CMJ reported a greater reliability (CV_{ratio} range = 1.16–2.10) in 2 out of 7 comparisons for the right leg (mean and peak velocity) and all comparisons for the left leg (mean and peak values of force, velocity, power, and concentric impulse) compared to the bilateral CMJ, while the bilateral CMJ was more reliable (CV_{ratio} range = 1.32–1.43) in 2 out of 7 comparisons for the right leg (mean and peak force) (Fig 1).

Regarding the inter-limb asymmetry variables, no significant differences were observed between sessions ($P > 0.05$) with the magnitude of the differences being either *trivial* ($ES \leq 0.19$; 10 out of 15 comparisons) or *small* ($0.22 \leq ES \leq 0.40$; 5 out of 15 comparisons). None of the asymmetry variables met the criterion for acceptable reliability (ICC range = 0.15–0.64) during the unilateral CMJ, while all asymmetry variables reached an acceptable reliability (ICC range = 0.74–0.77) during the bilateral CMJ, with the exception of peak force (ICC = 0.63). Finally, levels of agreement for the direction of inter-limb asymmetries between sessions were from *poor* to *slight* (Kappa range = -0.10 to 0.15) during the unilateral CMJ and *substantial* (Kappa range = 0.65 to 0.74; except for peak force [0.49]) during the bilateral CMJ. Individual comparisons between testing sessions for the inter-limb asymmetry scores are presented in Figs 2 and 3.

Discussion

This study was designed to compare the between-session reliability of single-leg performance and inter-limb asymmetry variables between unilateral and bilateral CMJ variants. The main findings revealed that i) all single-leg performance variables presented an acceptable reliability with the exceptions of jump height for the unilateral CMJs and mean power, peak velocity, peak power, and concentric impulse for the left leg during the bilateral CMJ, ii) the unilateral CMJ resulted in higher reliability in 2 out of 7 variables for the right leg (mean and peak velocity) and all variables for the left leg (mean and force values of force, velocity, power, and concentric impulse), while the bilateral CMJ was more reliable in 2 out of 7 variables for the right

Table 2. Reliability of performance and inter-limb asymmetry variables obtained during the unilateral and bilateral countermovement jump (CMJ) exercises.

Exercise	Variable	Right leg				Left leg				Asymmetry (%)		
		P	ES	CV (95% CI)	ICC (95% CI)	P	ES	CV (95% CI)	ICC (95% CI)	P	ES	ICC (95% CI)
Unilateral CMJ	Mean force	0.221	0.13	5.34 (4.13, 7.55)	0.88 (0.75, 0.95)	0.003	0.29	4.45 (3.44, 6.29)	0.93 (0.83, 0.97)	0.151	-0.36	0.34 (-0.07, 0.66)
	Mean velocity	0.390	0.26	6.17 (4.77, 8.73)	0.88 (0.74, 0.95)	0.306	0.11	5.93 (4.59, 8.39)	0.88 (0.74, 0.95)	0.288	0.29	0.22 (-0.21, 0.57)
	Mean power	0.025	0.20	7.34 (5.68, 10.4)	0.93 (0.84, 0.97)	0.032	0.19	7.14 (5.52, 10.1)	0.93 (0.85, 0.97)	0.691	0.08	0.51 (0.13, 0.76)
	Peak force	0.480	0.09	7.14 (5.52, 10.1)	0.82 (0.62, 0.92)	0.010	0.24	4.92 (3.80, 6.96)	0.92 (0.83, 0.97)	0.153	-0.40	0.15 (-0.27, 0.52)
	Peak velocity	0.415	0.07	4.08 (3.16, 5.78)	0.93 (0.85, 0.97)	0.277	-0.12	5.24 (4.05, 7.42)	0.87 (0.71, 0.94)	0.279	0.32	0.64 (0.32, 0.83)
	Peak power	0.469	0.06	6.93 (5.36, 9.81)	0.93 (0.84, 0.97)	0.794	-0.02	7.20 (5.57, 10.2)	0.93 (0.84, 0.97)	0.464	0.22	0.56 (0.20, 0.79)
	Concentric impulse	0.786	-0.02	6.87 (5.31, 9.72)	0.92 (0.82, 0.97)	0.599	-0.06	7.90 (6.11, 11.2)	0.89 (0.75, 0.95)	0.571	0.17	0.49 (0.11, 0.75)
	Jump height	0.714	0.04	12.8 (9.91, 18.1)	0.85 (0.68, 0.93)	0.975	0.02	11.5 (8.86, 16.2)	0.86 (0.69, 0.94)	0.638	0.11	0.42 (0.02, 0.70)
Bilateral CMJ	Mean force	0.751	0.02	4.05 (3.13, 5.73)	0.94 (0.86, 0.97)	0.532	0.07	5.38 (4.16, 7.61)	0.86 (0.70, 0.94)	0.206	0.19	0.77 (0.53, 0.90)
	Mean velocity	0.009	0.22	7.34 (5.68, 10.4)	0.94 (0.86, 0.97)	0.356	-0.09	9.98 (7.72, 14.1)	0.90 (0.78, 0.96)	0.963	-0.01	0.74 (0.47, 0.88)
	Mean power	0.018	0.16	8.38 (6.48, 11.9)	0.96 (0.90, 0.98)	0.550	-0.06	11.9 (9.23, 16.9)	0.89 (0.77, 0.95)	0.976	0.00	0.76 (0.51, 0.89)
	Peak force	0.226	0.12	5.01 (3.87, 7.09)	0.90 (0.79, 0.96)	0.158	0.18	5.72 (4.42, 8.09)	0.85 (0.67, 0.93)	0.352	0.17	0.63 (0.31, 0.83)
	Peak velocity	0.004	0.21	6.42 (4.97, 9.09)	0.95 (0.89, 0.98)	0.253	-0.13	11.0 (8.51, 15.6)	0.88 (0.73, 0.95)	0.895	-0.02	0.75 (0.50, 0.89)
	Peak power	0.005	0.17	7.05 (5.46, 9.98)	0.97 (0.93, 0.99)	0.393	-0.10	13.5 (10.4, 19.1)	0.85 (0.68, 0.93)	0.897	-0.02	0.75 (0.50, 0.89)
	Concentric impulse	0.039	0.13	6.28 (4.86, 8.89)	0.96 (0.92, 0.98)	0.263	-0.14	12.6 (9.70, 17.8)	0.84 (0.66, 0.93)	0.734	0.05	0.74 (0.48, 0.88)

P, P-value obtained through a paired samples t-test or Wilcoxon signed-rank test depending whether the variables were or not normally distributed between the sessions 1 and 2; ES = Cohen’s d effect size ([Session 2 –Session 1/SD both]); CV = coefficient of variation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval. Bold numbers indicate an unacceptable reliability (CV > 10% or ICC < 0.70).

<https://doi.org/10.1371/journal.pone.0255458.t002>

leg (mean force, peak force), iii) the asymmetry variables always showed an unacceptable reliability and *poor/slight* levels of agreement during the unilateral CMJ, while an acceptable reliability and *substantial* levels of agreement (except for peak force) were obtained for the bilateral CMJ. These results suggest that single-leg performance can be obtained with higher reliability during the unilateral CMJ, while the bilateral CMJ provides more consistent measures of inter-limb asymmetry.

Single-leg performance evaluation has become increasingly popular in sport and clinical settings in order to provide insight into athletic performance, injury prevention, and rehabilitation [4,5,35,39]. In line with previous studies [5,12–18], our findings revealed that the different single-leg performance variables measured during unilateral and bilateral CMJs present a high between-session reliability, with the exceptions of jump height for the unilateral CMJs and mean power, peak velocity, peak power, and concentric impulse for the left leg during the bilateral CMJ. More importantly, our hypothesis was confirmed since the unilateral CMJ provided a higher reliability than the bilateral CMJ for more variables. These results may be attributed to the variability expected during the weighing phase as a consequence of any postural

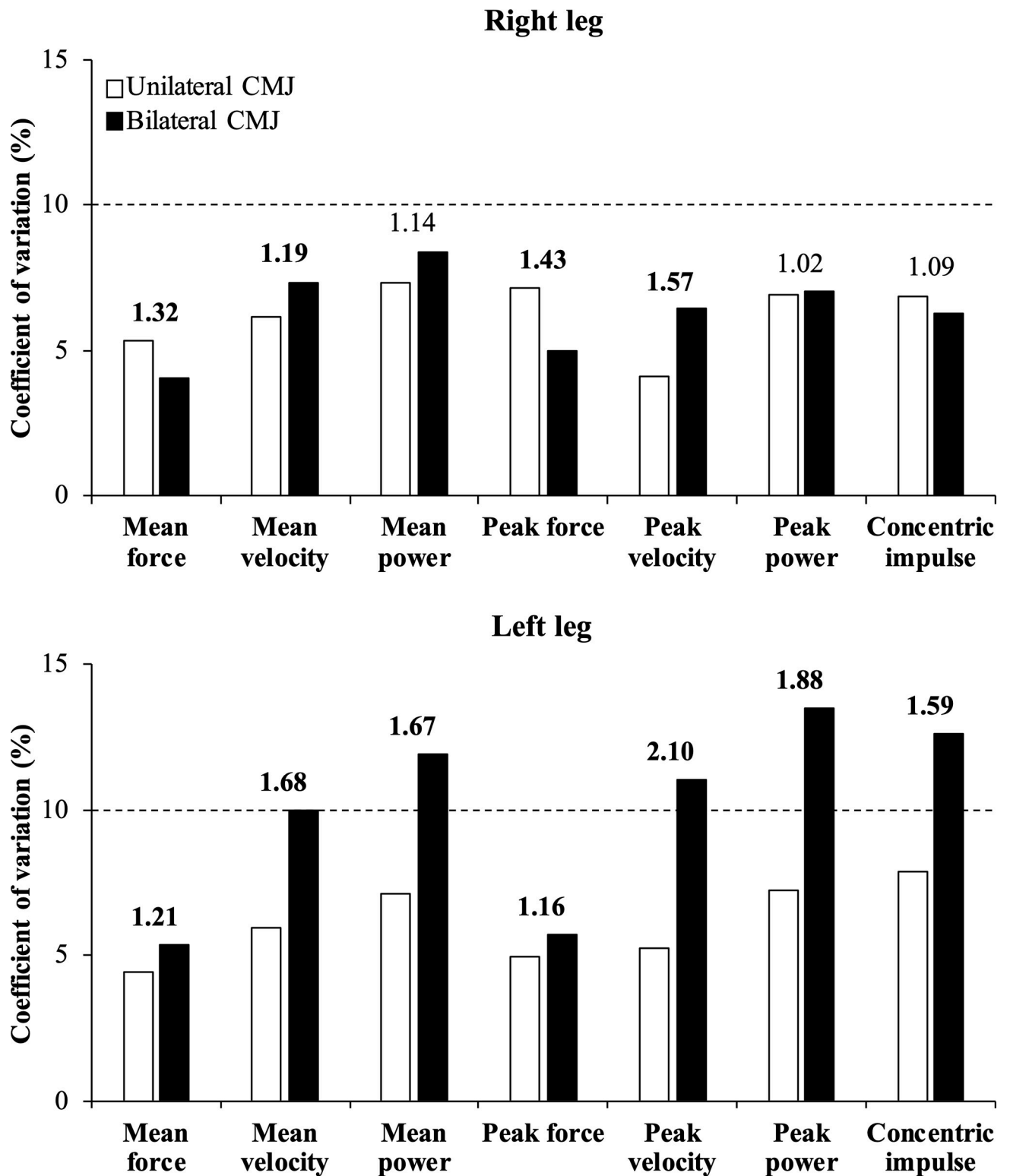


Fig 1. Comparison of the absolute reliability of the different performance variables obtained with the right (upper panel) and left (lower panel) legs between the unilateral (white bars) and bilateral (black bars) countermovement jump (CMJ) exercises. Numbers depict the ratio between two coefficients of variation ($CV_{ratio} = \text{higher value}/\text{lower value}$), while meaningful differences in reliability are indicated in bold ($CV_{ratio} > 1.15$).

<https://doi.org/10.1371/journal.pone.0255458.g001>

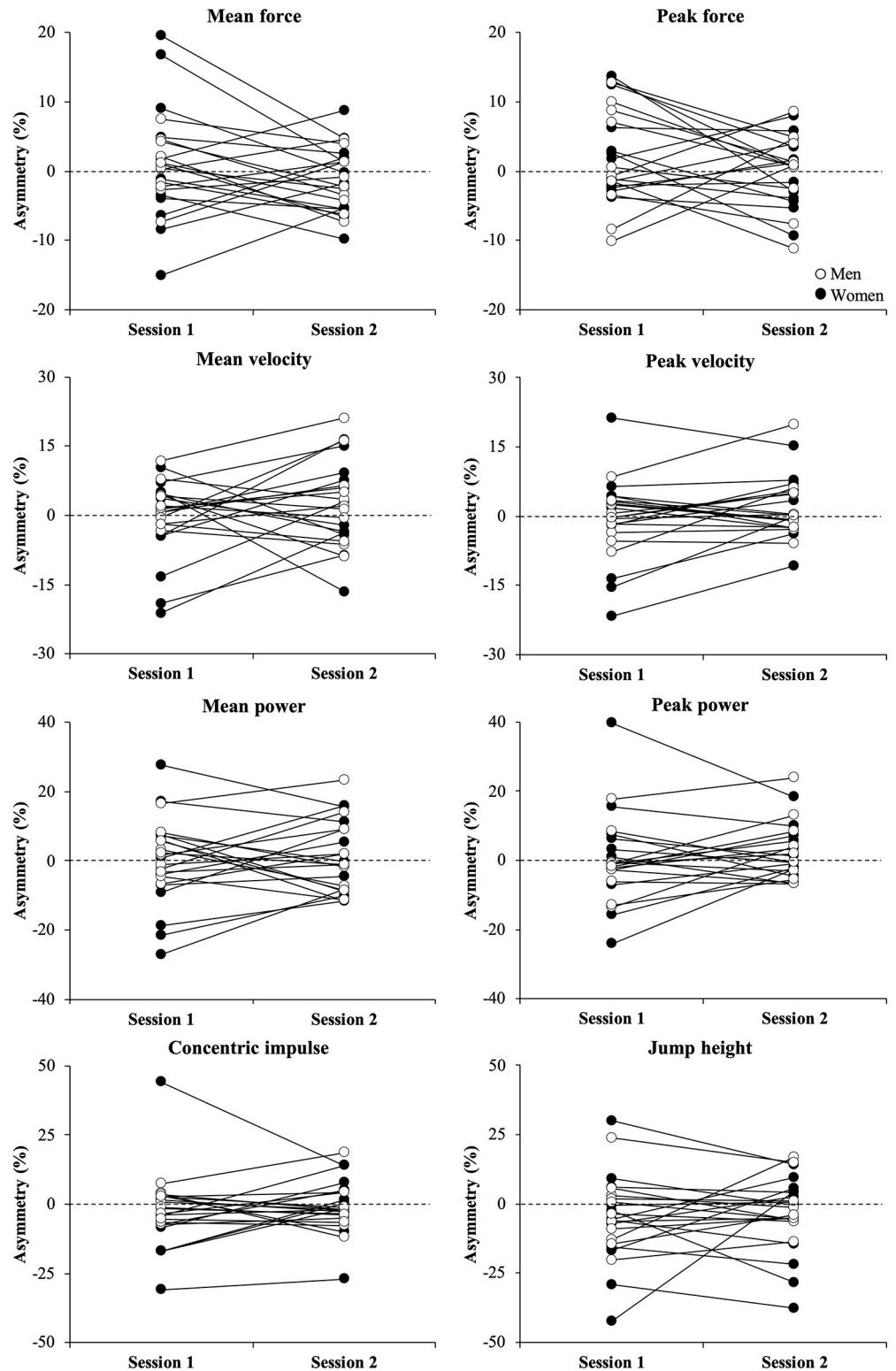


Fig 2. Individual comparisons between testing sessions for the inter-limb asymmetry scores obtained for men (white circles) and women (black circles) during the unilateral countermovement jump exercise.

<https://doi.org/10.1371/journal.pone.0255458.g002>

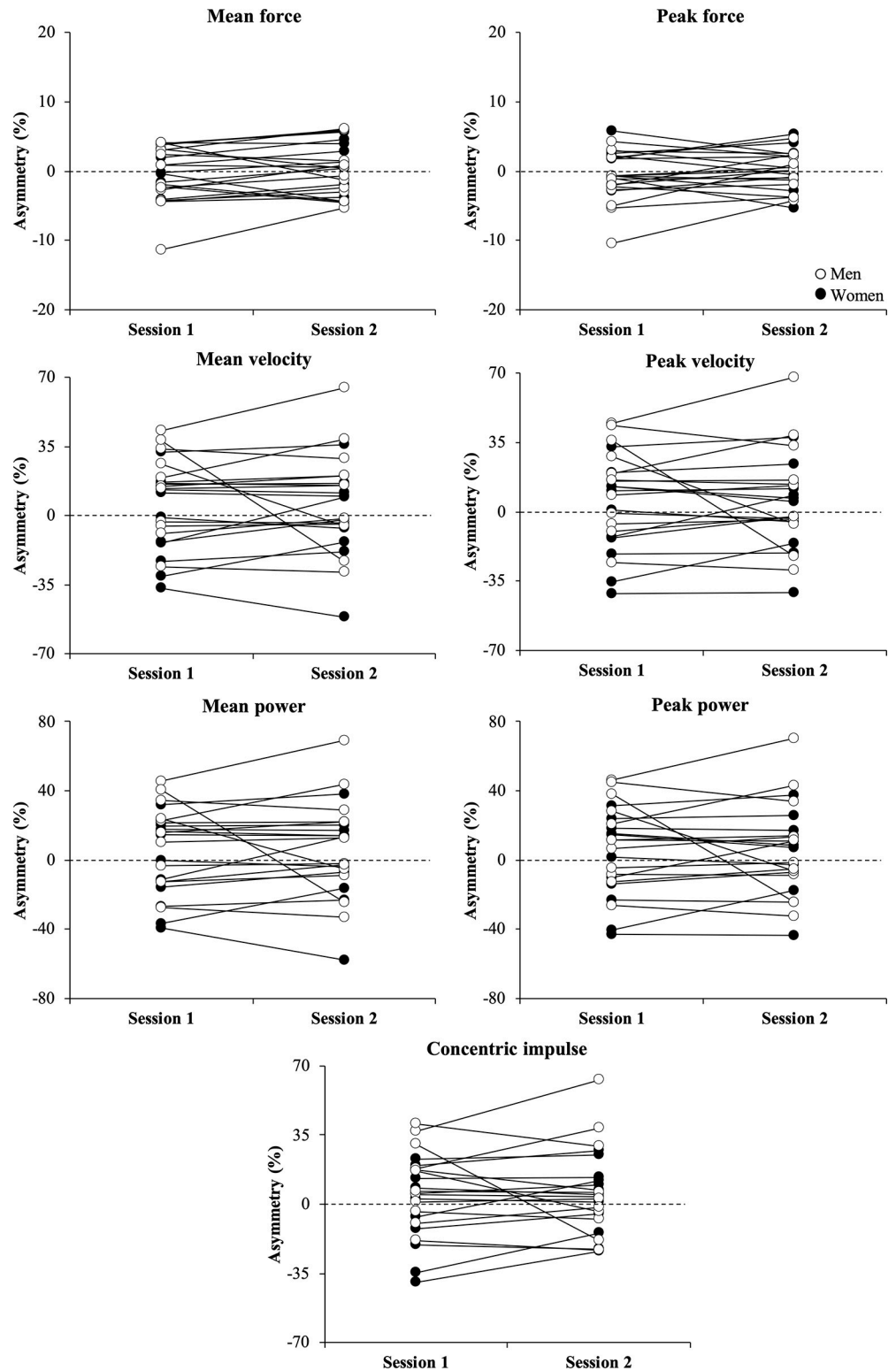


Fig 3. Individual comparisons between both testing sessions for the inter-limb asymmetry scores obtained for men (white circles) and women (black circles) during the bilateral countermovement jump exercise.

<https://doi.org/10.1371/journal.pone.0255458.g003>

adjustment prior to jumping [3]. Consequently, the dependent variables of forward dynamics procedures (e.g., velocity and power values) are affected to a greater extent by an inaccurate determination of the body weight during the bilateral CMJ [20]. By contrast, other variables that do not depend on the calculation of body weight, such as mean and peak force, were obtained with higher reliability during the bilateral CMJ [40,41]. These findings are partially in line with Bishop et al. [19] who found a higher reliability ($CV_{\text{ratio}} = 1.29\text{--}1.63$) for the bilateral CMJ compared to the unilateral CMJ in single-leg strength performance (mean force and concentric impulse). This result could be caused by the reduction in the base of support during the unilateral CMJ. From a practical perspective, these results generally support the unilateral CMJ as a more cost-effective, reliable and ecologically valid test to measure single-leg performance. The bilateral CMJ can be a more time-effective alternative to evaluate the asymmetries of force within the same repetition, while the interpretation of the rest of the single-leg performance variables should be taken with caution. In addition, since during the bilateral CMJ both legs are in contact with the ground, the bilateral CMJ may offer a better understanding of compensatory strategies between limbs [9].

Despite the growing interest in exploring inter-limb asymmetry within the scientific community [10,21,33], the evidence for the reliability of the asymmetry measurements is still scarce. Previous studies have showed that the inter-limb asymmetry calculated for peak force, jump height, and concentric impulse were highly reliable between sessions ($ICC \geq 0.91$) during the unilateral and bilateral CMJs [3,4]. The results of the present study are partially in line with those findings since the relative reliability of the different asymmetry variables was acceptable for the bilateral CMJ (except for peak force). However, the reliability was unacceptable for the unilateral CMJ. These results are probably due to the variable nature in the direction of the asymmetry not only for the leg dominance between metrics and tasks [34], but also for the same test between sessions [8,13]. Specifically, in accordance with the findings of Bishop et al. [8], the direction of asymmetry for jump height performance determined in both CMJ tests varied considerably between sessions. By contrast, Bishop et al. [13] also reported in another study *substantial* levels of agreement for the peak force and jump height asymmetries of the same CMJ exercise. Therefore, the present study confirms the importance of attending not only to the inter-limb asymmetry magnitude, but also its direction as it has been detected as one of the key factors when monitoring inter-limb asymmetries [21]. Although future studies are needed to provide insight into the underlying mechanisms responsible for this varying nature in the direction of asymmetry, the bilateral CMJ seems to be a more consistent test in term of limb dominance to measure inter-limb differences.

Although the current findings provide relevant information about the between-session reliability of CMJ-based tasks to measure single-leg performance and inter-limb asymmetries, this study is not free from limitations. First, although the study sample was accustomed to performing the unilateral and bilateral CMJ, the unfamiliar nature of eliminating the arm swing may have altered the jumping strategy or performance and, ultimately, this would reduce the ecological validity of CMJ testing. However, it has been shown that the reliability of bilateral CMJ performance is even somewhat lower with the use of arm swing in collegiate basketball players [5]. Second, since the inter-limb asymmetries appear to be task-dependent [10], the current findings cannot be generalized to other jumping-based tasks. Future studies should compare the between-session reliability of the performance and asymmetry variables between unilateral and bilateral jumping-tasks performed in other planes of motion (e.g., broad jump).

In conclusion, the between-session reliability for the force platform-based assessment of CMJ performance and asymmetry appears to be task-dependent. On the one hand, the unilateral CMJ is not only a more cost-effective test to measure single-leg performance (only one force platform is needed), but also generally more reliable than the bilateral CMJ. In addition,

although the task specificity may ultimately dictate which jump test is chosen, the unilateral CMJ could be a more ecologically valid because most of the sporting actions are performed unilaterally. Instead, the bilateral CMJ is a more time-effective alternative to determine the contribution in force of each limb within the same repetition, but the reliability of the remaining variables is affected to a greater extent by the variability in the weighing phase. On the other hand, the magnitude and direction of asymmetry data was only consistent between-sessions for the bilateral CMJ variant. However, given the variable nature of inter-limb asymmetry, some caution should be taken when interpreting such data.

Supporting information

S1 Data.
(XLSX)

Acknowledgments

We would like to thank all the subjects who selflessly participated in the study.

Author Contributions

Conceptualization: Alejandro Pérez-Castilla, Amador García-Ramos, Danica Janicijevic, Juan Carlos De la Cruz, F. Javier Rojas, Mar Cepero.

Data curation: Alejandro Pérez-Castilla, Gabriel Delgado-García, F. Javier Rojas.

Formal analysis: Alejandro Pérez-Castilla, Amador García-Ramos.

Funding acquisition: F. Javier Rojas, Mar Cepero.

Investigation: Alejandro Pérez-Castilla, Amador García-Ramos, Juan Carlos De la Cruz.

Methodology: Alejandro Pérez-Castilla, F. Javier Rojas, Mar Cepero.

Resources: F. Javier Rojas, Mar Cepero.

Supervision: Amador García-Ramos, F. Javier Rojas, Mar Cepero.

Visualization: Alejandro Pérez-Castilla, Danica Janicijevic.

Writing – original draft: Alejandro Pérez-Castilla.

Writing – review & editing: Alejandro Pérez-Castilla, Amador García-Ramos, Danica Janicijevic, Gabriel Delgado-García, Juan Carlos De la Cruz, F. Javier Rojas, Mar Cepero.

References

1. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res.* 2009; 23: 177–186. <https://doi.org/10.1519/JSC.0b013e3181889324> PMID: 19077740
2. Claudino JG, Cronin J, Mezêncio B, McMaster DT, McGuigan M, Tricoli V, et al. The countermovement jump to monitor neuromuscular status: A meta-analysis. *J Sci Med Sport.* 2017; 20: 397–402. <https://doi.org/10.1016/j.jsams.2016.08.011> PMID: 27663764
3. Benjanuvattra N, Lay BS, Alderson JA, Blanksby BA. Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. *J Strength Cond Res.* 2013; 27: 2700–2707. <https://doi.org/10.1519/JSC.0b013e318280d28e> PMID: 23287834
4. Impellizzeri FM, Rampinini E, Maffiuletti N, Marcora SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Med Sci Sports Exerc.* 2007; 39: 2044–2050. <https://doi.org/10.1249/mss.0b013e31814fb55c> PMID: 17986914

5. Heishman A, Daub B, Miller R, Brown B, Freitas E, Bemben M. Countermovement jump inter-limb asymmetries in collegiate basketball players. *Sports*. 2019; 7: 103. <https://doi.org/10.3390/sports7050103> PMID: 31052258
6. Bishop C, Read P, McCubbine J, Turner A. Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *J Strength Cond Res*. 2018; 35: 56–63. <https://doi.org/10.1519/jsc.0000000000002544> PMID: 29489719
7. Fort-Vanmeerhaeghe A, Bishop C, Busca B, Aguilera-Castells J, Vicens-Bordas J, Gonzalo-Skok O. Inter-limb asymmetries are associated with decrements in physical performance in youth elite team sports athletes. *PLoS One*. 2020; 15: e0229440. <https://doi.org/10.1371/journal.pone.0229440> PMID: 32126107
8. Bishop C, Perez-Higueras Rubio M, Gullon IL, Maloney S, Balsalobre-Fernandez C. Jump and change of direction speed asymmetry using smartphone apps. *J Strength Cond Res*. 2020. In press. <https://doi.org/10.1519/JSC.0000000000003567> PMID: 32149875
9. Cohen D, Burton A, Wells C, Taberner M, Diaz MA, Graham-Smith P. Single vs double leg countermovement tests: Not half an apple! *Aspetar Sport Med J*. 2020; 9: 34–41.
10. Bishop C, Turner A, Jarvis P, Chavda S, Read P. Considerations for selecting field-based strength and power fitness tests to measure asymmetries. *J strength Cond Res*. 2017; 31: 2635–2644. <https://doi.org/10.1519/JSC.0000000000002023> PMID: 28644195
11. Hopkins WG. Measures of reliability in sports medicine and science. *Sport Med*. 2000; 30: 375–381. <https://doi.org/10.2165/00007256-200030010-00001> PMID: 10907753
12. Ceroni D, Martin XE, Delhumeau C, Farpour-Lambert NJ. Bilateral and gender differences during single-legged vertical jump performance in healthy teenagers. *J Strength Cond Res*. 2012; 26: 452–457. <https://doi.org/10.1519/JSC.0b013e31822600c9> PMID: 22233795
13. Bishop C, Read P, Chavda S, Jarvis P, Turner A. Using unilateral strength, power and reactive strength tests to detect the magnitude and direction of asymmetry: A test-retest design. *Sports*. 2019; 7: 58. <https://doi.org/10.3390/sports7030058> PMID: 30836623
14. Meylan CMP, Nosaka K, Green J, Cronin JB. Temporal and kinetic analysis of unilateral jumping in the vertical, horizontal, and lateral directions. *J Sports Sci*. 2010; 28: 454–554 <https://doi.org/10.1080/02640411003628048> PMID: 20373198
15. Bishop C, Read P, Stern D, Turner A. Effects of soccer match-play on unilateral jumping and interlimb asymmetry: A repeated-measures design. *J Strength Cond Res*. 2020. In press. <https://doi.org/10.1519/JSC.0000000000003389> PMID: 31985557
16. Bishop C, Read P, Chavda S, Jarvis P, Brazier J, Bromley T, et al. Magnitude or direction? seasonal variation of interlimb asymmetry in elite academy soccer players. *J Strength Cond Res*. 2020. In press. <https://doi.org/10.1519/JSC.0000000000003565> PMID: 32149878
17. Bishop C, Pereira LA, Reis VP, Read P, Turner AN, Loturco I. Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *J Sports Sci*. 2020; 38: 1296–1303. <https://doi.org/10.1080/02640414.2019.1649525> PMID: 31354103
18. Bishop C, Read P, Brazier J, Jarvis P, Chavda S, Bromley T, et al. Effects of interlimb asymmetries on acceleration and change of direction speed. *J Strength Cond Res*. 2019. In press. <https://doi.org/10.1519/JSC.0000000000003135> PMID: 31008864
19. Bishop C, Abbott W, Brashill C, Turner A, Lake J, Read P. Bilateral vs. unilateral countermovement jumps: Comparing the magnitude and direction of asymmetry in elite academy soccer players. *J Strength Cond Res*. 2020. In press. <https://doi.org/10.1519/JSC.0000000000003679>
20. McMahon JJ, Suchomel TJ, Lake JP, Comfort P. Understanding the key phases of the countermovement jump force-time curve. *Strength Cond J*. 2018; 40: 96–106. <https://doi.org/10.1519/SSC.0000000000000375>
21. Dos'Santos T, Thomas C, Jones PA, Dos'Santos T., Thomas C., & Jones PA, et al. Assessing interlimb asymmetries: Are we heading in the right direction? *Strength Cond J*. 2021; 43: 91–100. <https://doi.org/10.1519/SSC.0000000000000590>
22. Gonzalo-Skok O, Serna J, Rhea MR, Marín PJ. Relationships between functional movement tests and performance tests in young elite male basketball players. *Int J Sports Phys Ther*. 2015; 10: 628–638. PMID: 26491613
23. Bishop C, Brashill C, Abbott W, Read P, Lake J, Turner A. Jumping asymmetries are associated with speed, change of direction speed, and jump performance in elite academy soccer players. *J Strength Cond Res*. 2021; 35: 1841–1847. <https://doi.org/10.1519/JSC.0000000000003058> PMID: 30707141

24. Lake JP, Mundy PD, Comfort P, Suchomel TJ. Do the peak and mean force methods of assessing vertical jump force asymmetry agree? *Sport Biomech.* 2020; 19: 227–234. <https://doi.org/10.1080/14763141.2018.1465116> PMID: 29782223
25. Chavda S, Bromley T, Jarvis P, Williams S, Bishop C, Turner AN, et al. Force-time characteristics of the countermovement jump: Analyzing the curve in Excel. *Strength Cond J.* 2018; 40: 67–77. <https://doi.org/10.1519/SSC.0000000000000353>
26. Moir GL, Garcia A, Dwyer GB. Intersession reliability of kinematic and kinetic variables during vertical jumps in men and women. *Int J Sports Physiol Perform.* 2009; 4: 317–330. <https://doi.org/10.1123/ijspp.4.3.317> PMID: 19953820
27. Pérez-Castilla A, Rojas FJ, García-Ramos A. Reliability and magnitude of loaded countermovement jump performance variables: A technical examination of the jump threshold initiation. *Sports Biomech.* 2019. In press. <https://doi.org/10.1080/14763141.2019.1682649> PMID: 31711369
28. Linthorne NP. Analysis of standing vertical jumps using a force platform. *Am J Phys.* 2001; 69: 1198–1204.
29. Perez-Castilla A, Garcia-Ramos A, Pérez-Castilla A, García-Ramos A. Evaluation of the most reliable procedure of determining jump height during the loaded countermovement jump exercise: Take-off velocity vs. flight time. *J Strength Cond Res.* 2018; 32: 2025–2030. <https://doi.org/10.1519/JSC.0000000000002583> PMID: 29570575
30. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009; 41: 3–13. <https://doi.org/10.1249/MSS.0b013e31818cb278> PMID: 19092709
31. Cormack SJ, Newton RU, McGuigan MR, Doyle TLA. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform.* 2008; 3: 131–144. <https://doi.org/10.1123/ijspp.3.2.131> PMID: 19208922
32. Fulton SK, Pyne D, Hopkins W, Burkett B. Variability and progression in competitive performance of Paralympic swimmers. *J Sports Sci.* 2009; 27: 535–539. <https://doi.org/10.1080/02640410802641418> PMID: 19219736
33. Bishop C, Read P, Lake J, Chavda S, Turner A. Inter-limb asymmetries: Understanding how to calculate differences from bilateral and unilateral tests. *Strength Cond J.* 2018; 40: 1–6. <https://doi.org/10.1519/SSC.0000000000000371>
34. Bishop C, Lake J, Loturco I, Papadopoulos K, Turner A, Read P. Interlimb asymmetries: The need for an individual approach to data analysis. *J Strength Cond Res.* 2018; 35: 695–701. <https://doi.org/10.1519/JSC.0000000000002729> PMID: 33587548
35. Gonzalo-Skok O, Tous-Fajardo J, Suarez-Arrones L, Arjol-Serrano JL, Casajús JA, Mendez-Villanueva A. Single-leg power output and between-limbs imbalances in team-sport players: Unilateral versus bilateral combined resistance training. *Int J Sports Physiol Perform.* 2017; 12: 106–114. <https://doi.org/10.1123/ijspp.2015-0743> PMID: 27140680
36. Virgile A, Bishop C. A narrative review of limb dominance: Task specificity and the importance of fitness testing. *J Strength Cond Res.* 2021; 35: 846–858. <https://doi.org/10.1519/JSC.00000000000003851> PMID: 33470600
37. Bishop C, Weldon A, Hughes J, Brazier J, Loturco I, Turner A, et al. Seasonal variation of physical performance and inter-limb asymmetry in professional cricket athletes. *J Strength Cond Res.* 2021; 35: 941–948. <https://doi.org/10.1519/JSC.00000000000003927> PMID: 33752220
38. Hopkins W. Calculations for reliability (Excel spreadsheet). In: *A New View of Statistics.* 2000. Available at URL: <http://www.sportsci.org/resource/stats/relycalc.html#excel>. Accessed January 06, 2021.
39. Patterson BE, Crossley KM, Perraton LG, Kumar AS, King MG, Heerey JJ, et al. Limb symmetry index on a functional test battery improves between one and five years after anterior cruciate ligament reconstruction, primarily due to worsening contralateral limb function. *Phys Ther Sport.* 2020; 44: 67–74. <https://doi.org/10.1016/j.ptsp.2020.04.031> PMID: 32447259
40. Anderson KG, Behm DG. Maintenance of EMG activity and loss of force output with instability. *J Strength Cond Res.* 2004; 18: 637. [https://doi.org/10.1519/1533-4287\(2004\)18<637:MOEAAL>2.0.CO;2](https://doi.org/10.1519/1533-4287(2004)18<637:MOEAAL>2.0.CO;2) PMID: 15320684
41. Yamashita D, Murata M, Inaba Y. Effect of landing posture on jump height calculated from flight time. *Appl Sci.* 2020; 10: 776. <https://doi.org/10.3390/app10030776>