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Single-leg mechanical performance and inter-leg asymmetries during bilateral countermovement jumps: A comparison of different calculation methods

Danica Janicijevic [a,b,c], Nejc Sarabon [d,e,f], Alejandro Pérez-Castilla [g], Darjan Smajla [d,e], Andrés Fernández-Revelles [g], Amador García-Ramos [g,h,*]

[a] Research Academy of Human Biomechanics, The Affiliated Hospital of Medical School of Ningbo University, Ningbo University, Ningbo, China
[b] Faculty of Sports Science, Ningbo University, Ningbo, China
[c] University of Belgrade, Faculty of Sport and Physical Education, The Research Centre, Belgrade, Serbia
[d] University of Primorska, Faculty of Health Sciences, Izola, Slovenia
[e] InnoRenew CoE, Human Health Department, Izola, Slovenia
[f] S2P, Science to Practice, Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia
[g] University of Granada, Faculty of Sport Sciences, Department of Physical Education and Sport, Granada, Spain
[h] Universidad Catolica de la Santísima Concepcion, Faculty of Education, Department of Sports Sciences and Physical Conditioning, Concepción, Chile

A R T I C L E I N F O

Keywords:
Bilateral deficit
Force platform
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Testing

A B S T R A C T

Background: The possibility to selectively assess the force exerted by each leg during bilateral jumps has allowed sport scientists to explore inter-leg asymmetries, this metric being a rich source of research due to its potential applications to improve sports performance and reduce the risk of injury. The purpose of this study was to explore the reliability and agreement of single-leg mechanical performance and inter-leg asymmetry variables obtained by two procedures of analysis (Synchronous [simultaneous jump detection for both legs] and Asynchronous [specific jump detection for each leg]) during bilateral countermovement jumps (CMJs).
Method: During a single testing session, 74 participants performed 5 maximal height bilateral CMJs on dual force platforms (Kistler, model 9260AA6, Winterthur, Switzerland), and the 2 trials that differed the least in terms of squat depth and jump height were considered for statistical analyses. The following mechanical variables were calculated separately for each leg using the Synchronous and Asynchronous procedures: mean force, peak force, and propulsive impulse.
Results: The procedures showed comparable reliability, except for mean force and propulsive impulse of the left leg (higher for the Asynchronous procedure). The agreement between the procedures was very high, while the most reliable mechanical variable was mean force (CV≈2.9%, ICC≈0.98), followed by peak force (CV≈4.4%, ICC≈0.96) and propulsive impulse (CV≈6.4%, ICC≈0.91). Reliability of inter-leg asymmetries was greater using mean and peak force (ICC range=0.74–0.82) than using propulsive impulse (ICC range = 0.65–0.66).
Significance: Both Synchronous and Asynchronous procedures can be used to evaluate single-leg mechanical performance (mean force, peak force, and propulsive impulse) and asymmetries, whereas mean force should be used to evaluate single-leg mechanical performance and mean or peak force to assess asymmetries.

1. Introduction

The bilateral countermovement jump (CMJ) is one of the tasks most frequently used to assess lower-body ballistic performance [1,2]. CMJ height, which can be obtained with a variety of devices (e.g., contact or photocell mats, linear position transducers, inertial measurement units, optical devices, or smartphone apps), is one of the main indicators of lower-body ballistic performance [3,4]. However, more sophisticated equipment, such as force platforms, are required to evaluate other mechanical variables that provide useful and complementary information about the jump strategy [5]. Therefore, it is not surprising that force platforms continue to be recommended for obtaining more

* Corresponding author at: University of Granada, Faculty of Sport Sciences, Department of Physical Education and Sport, Granada, Spain.
E-mail address: amagr@ugr.es (A. García-Ramos).

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comprehensive information of CMJ performance [1,6]. Another potential advantage of a special type of force platforms, known as bilateral or dual force platforms, is that they discriminate the force produced by each leg during bilateral jumps [7]. The possibility to selectively assess the force exerted by each leg during bilateral jumps has allowed sport scientists to explore inter-leg asymmetries [8,9], this metric being a rich source of research due to its potential applications to improve sports performance and reduce the risk of injury [10–12]. However, it is plausible that an increase in force production capability rather than a change in asymmetry scores could be more important for improving performance and reducing injury occurrence.

The results of recent research have led researchers to question the reliability of different metrics commonly used to quantify inter-leg asymmetries during the bilateral CMJ [13,14]. For example, Bailey et al. [14] and Pérez-Castilla et al. [13] showed that the reliability of single-leg mechanical performance variables is greater than the reliability of inter-leg asymmetry variables when quantified as a vector (i.e., asymmetry magnitude and direction) (intraclass correlation coefficient [ICC] = 0.90–0.97 and 0.74–0.77, respectively). These findings evidence the importance of refining the testing procedures of inter-leg asymmetries in order that sport practitioners can confidently use this variable to inform their training practice. A variable that is known to greatly affect the magnitude of the mechanical variables collected during vertical jumps is the squat depth [15]. The use of shallower squat depths during the CMJ allows for obtaining greater mean force and peak force values, while the propulsive impulse should be less affected by the squat depth as CMJ height is not meaningfully affected by subtle variations of the squat depth [15]. However, many researchers that assessed the reliability of inter-leg asymmetries failed to control the squat depth [13,14,16], being plausible that the reliability of inter-leg asymmetries could be increased when using more consistent squat depths. Although this result seems counterintuitive because squat depth should not differ between limbs in the same jump, inter-leg asymmetries assessed during vertical jumps have been shown to be sensitive to other factors which theoretically should impact both legs in a similar manner (e.g., variable used to quantify inter-leg asymmetries or the fatigue induced by a competitive soccer match [9,17].

Another potential source of error in the assessment of single-leg mechanical performance during bilateral CMJs is the procedure of analysis of the raw vertical ground reaction force (vGRF) data collected by dual force platforms. The jump start detection used for each leg is one of the factors that should be considered. The jump initiation in the CMJ is typically identified as the time point in which the vGRF falls below a given threshold (e.g., 10 N below body weight) [18,19]. In this regard, some authors have considered the total body weight (i.e., the sum of the vGRF of both force platforms) to select the same time point of jump initiation for both legs [7,16], while other authors have analysed the vGRF data of each force platform independently being possible to determine a different jump start for each leg [13]. Therefore, considering the limited reliability of inter-leg asymmetries variables reported in previous studies [13,14], it seems important to identify the procedure of analysis that allows obtaining the single-leg mechanical performance variables with the greatest consistency.

In order to respond to all previously mentioned inconsistencies, 74 healthy participants performed bilateral CMJs on dual force platforms and single-leg mechanical performance variables were computed utilising two procedures: (I) simultaneous jump detection for both legs (*Synchronous*), and (II) independent jump detection for each leg (*Asynchronous*). Specifically, the objectives of the present study were (I) to identify the procedure of analysis that enables to obtain single-leg mechanical performance and inter-leg asymmetry variables with the greatest reliability, and (II) to explore the agreement of single-leg mechanical performance and inter-leg asymmetry variables between the Synchronous and Asynchronous procedures. We hypothesised that (I) the Synchronous procedure would show greater reliability of mechanical and inter-leg asymmetry variables than the Asynchronous procedure due to a lower influence of the distribution of the weight between the two legs during the weighing phase, and (II) the magnitude of single-leg mechanical performance and inter-leg asymmetry variables would present a very high agreement.

2. Methods

2.1. Participants

Seventy-four sport science students, 17 females (age: 21.1 ± 2.5 years; stature: 1.65 ± 0.07 m; body mass: 60.9 ± 9.7 kg) and 57 males (age: 21.1 ± 2.3 years; stature: 1.79 ± 0.06 m; body mass: 80.6 ± 5.9 kg), participated in this study (mean ± standard deviation [SD]). All participants were free from musculoskeletal injuries that could compromise the results of the present study. Prior to the initiation of the study, participants were informed about the study purposes and all of them gave their written consent to participate. The study protocol was approved by the Institutional Review Board and adhered to the tenets of the Declaration of Helsinki.

2.2. Study design

A within-session test-retest design was used to elucidate which procedure enables assessing single-leg mechanical performance and inter-leg asymmetry variables with greater reliability during bilateral CMJs performed on dual force platforms. During a single testing session participants performed 5 maximal height bilateral CMJs separated by 10 s of rest. However, only the 2 trials that differed the least in terms of squat depth and jump height were considered for statistical analyses. The following mechanical variables were calculated separately for each leg using the Synchronous and Asynchronous procedures: mean force, peak force, and propulsive impulse.

2.3. Procedures

Upon the entrance to the sports facility, participants performed a standardised warm-up consisting of 5 min of running at a self-selected pace, 5 min of dynamic stretching exercises, and 2 submaximal bilateral CMJs. Thereafter, 5 maximal height bilateral CMJs were performed separated by 10 s of passive rest. Participants began the CMJ execution standing in a comfortable bilateral stance with both legs fully extended and their feet positioned on the centre of two parallel force platforms which were separated by 3 cm. Once participants adopted the initial position for 2 s, the examiner counted "3, 2, 1″ (i.e., participants needed to stay still in a standing position), and "Jump!" (i.e., instruction for jump initiation). The same experienced examiner was responsible for supervising all jumps and for providing verbal encouragement to the participants. The instruction given to the participants was to quickly squat to a self-selected depth, to minimise the transition time between the lowering and ascending phases of the jump, to jump as high as possible, and to maintain the hands on their hips during the whole movement.

2.4. Data acquisition and analysis

All CMJs were performed on two parallel force platforms embedded in a wooden drawer (Kistler, model 9260AA6, Winterthur, Switzerland). The vGRF from each force platform were synchronously acquired at 1000 Hz via Kistler's MARS (Measurement, Analysis and Reporting Software) and low pass filtered with a 2nd order Butterworth filter (10 Hz cut-off frequency). The force platforms were zeroed before each trial. The force-time signals recorded by MARS were stored on a computer for an offline analysis using a routine written in the LabView 8.2 software (National Instruments, USA). The main characteristics of the two procedures of analysis are provided below:

Table 1
Reliability of single-leg mechanical performance and inter-leg asymmetry variables obtained using the Synchronous and Asynchronous procedures during the bilateral countermovement jump (CMJ) exercise.

Variable	Procedure	Left leg			Right leg			Asymmetry (%)	
		Mean ± SD	CV (95% CI)	ICC (95% CI)	Mean ± SD	CV (95% CI)	ICC (95% CI)	Mean ± SD	ICC (95% CI)
Weight (N)		337 ± 55	2.4 (2.0, 2.8)	0.98 (0.97, 0.99)	352 ± 55	2.2 (1.9, 2.7)	0.98 (0.97, 0.99)	4.8 ± 8.3	**0.69 (0.55, 0.79)**
Mean force (N)	Synchronous	676 ± 126	3.1 (2.7, 3.7)	0.97 (0.96, 0.98)	688 ± 130	2.9 (2.5, 3.5)	0.98 (0.96, 0.99)	2.1 ± 8.2	0.74 (0.62, 0.83)
	Asynchronous	682 ± 128	2.7 (2.3, 3.2) *	0.98 (0.97, 0.99)	693 ± 131	2.9 (2.5, 3.5)	0.98 (0.96, 0.99)	1.9 ± 7.8	0.81 (0.71, 0.87)
Peak force (N)	Synchronous	855 ± 179	4.4 (3.8, 5.2)	0.96 (0.93, 0.97)	875 ± 180	4.3 (3.7, 5.1)	0.96 (0.94, 0.97)	2.9 ± 10.2	0.82 (0.73, 0.88)
	Asynchronous	856 ± 180	4.4 (3.7, 5.2)	0.96 (0.93, 0.97)	876 ± 180	4.3 (3.7, 5.1)	0.96 (0.94, 0.97)	2.9 ± 10.1	0.82 (0.73, 0.88)
Propulsive impulse (N·s)	Synchronous	186 ± 39	6.9 (5.9, 8.2)	0.89 (0.84, 0.93)	190 ± 43	6.8 (5.8, 8.1)	0.91 (0.86, 0.94)	3.1 ± 18.3	**0.66 (0.50, 0.77)**
	Asynchronous	186 ± 38	5.6 (4.8, 6.7) *	0.93 (0.89, 0.95)	190 ± 42	6.3 (5.4, 7.5)	0.92 (0.88, 0.95)	3.1 ± 18.3	**0.65 (0.50, 0.77)**

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).
* significantly more reliable than the Synchronous procedure (CV ratio > 1.15).

- *Synchronous procedure: Body weight (sum of the vGRF recorded by both force platforms) and the SD of the weighing phase were determined during the 1.5 s preceding the onset of the countermovement. The countermovement phase started 30 ms before the instant in which the total vGRF (i.e., sum of the vGRF from both force platforms) was lower than the body weight minus 5 SD of the weighing phase. This onset threshold was used as it takes into account the inherent signal noise unlike the use of arbitrary onset thresholds (e.g., 10 N below body weight)* [20]. The instant of jump initiation was identical for both legs. The take-off instant was determined separately for each leg in three steps: (I) identification of the minimum vGRF value close to the start of the flight phase, (II) selection of 100 ms after the point 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 instant was determined as the first force value lower than the mean vGRF plus 5 SD of the flight phase.
- *Asynchronous procedure: The weighing phase also considered the last 1.5 s preceding the onset of the countermovement. During the weighing phase the body weight and SD were determined separately for each force platform. The countermovement phase started 30 ms before the instant in which the vGRF recorded by a force platform was lower than the weight minus 5 SD of the weighing phase. The take-off instant was determined following the same steps described for the synchronous procedure. Therefore, the difference between the procedures was that in the asynchronous procedure the instant of jump initiation was specific for each leg whereas in the synchronous procedure the instant of jump initiation was identical for both legs.*

The following dependent variables were calculated separately for each leg by the Synchronous and Asynchronous procedures: maximal instantaneous (1 ms) value of force recorded throughout the entire movement, mean value of force during the propulsive phase (i.e., from the first instant in which the velocity of the centre of mass was positive [i.e., positive force impulse was equal to the negative force impulse] until the take-off), and the propulsive impulse (mean force of the propulsive phase × duration of the propulsive phase). The inter-leg asymmetries for the above-mentioned variables were also calculated using the standard percentage differences ([right leg – left leg] / left leg × 100).

2.5. Statistical analyses

Descriptive data are presented as means ± SD. Reliability of the dependent variables was assessed by the CV (standard error of measurement / participants' mean score × 100), ICC (model 3.1), and their corresponding 95% confidence intervals. Acceptable reliability was determined as CV < 10% and ICC > 0.70 [13,21–23]. The ratio between two CVs (higher CV value / lower CV value) was used to compare the reliability of single-leg performance variables between the Synchronous and Asynchronous procedures. The smallest important ratio between two CVs was considered to be higher than 1.15 [24]. The agreement of single-leg mechanical performance and inter-leg asymmetry variables between the Synchronous and Asynchronous procedures were examined through Bland-Altman plots showing the systematic bias, random differences, and heteroscedasticity of errors. Although it is not indicative of agreement [25], the Pearson's correlation coefficient (r) was used to explore the association of the same variables obtained by the two different procedures. The magnitude of the differences between the Synchronous and Asynchronous procedures were examined through the Cohen's d effect size (ES), while the scale used to interpret the magnitude of the ES was specific to training research: negligible (< 0.20), small (0.20–0.49), moderate (0.50–0.79), and large (≥ 0.80) [26]. The scale used to interpret the magnitude of the r coefficients was the following: *trivial* (0.00–0.09), *small* (0.10–0.29), *moderate* (0.30–0.49), *large* (0.50–0.69), *very large* (0.70–0.89), *nearly perfect* (0.90–0.99), and *perfect* (1.00) [27]. All reliability assessments were performed by means of a custom Excel spreadsheet [28], while other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL). Alpha was set at 0.05.

3. Results

Descriptive data and reliability outcomes of single-leg mechanical performance and inter-leg asymmetry variables obtained using the Synchronous and Asynchronous procedures are shown in Table 1. The single-leg mechanical performance variables were ranked, according to their CV values, from the most to the least reliable as follows: mean force (CV ≈ 2.9%) > peak force (CV ≈ 4.4%) > propulsive impulse (CV ≈ 6.4%). The two procedures showed a comparable reliability (i.e., CV ratio < 1.15) in 4 out of 6 comparisons, but the mean force and propulsive impulse of the left leg were obtained with a higher reliability (CV ratio > 1.15) by the Asynchronous procedure. The reliability of inter-leg asymmetries was higher for mean force and peak force (ICC range = 0.74–0.82) than for the propulsive impulse (ICC range = 0.65–0.66).

The agreement between the Synchronous and Asynchronous procedures was extremely high (negligible differences and nearly perfect to

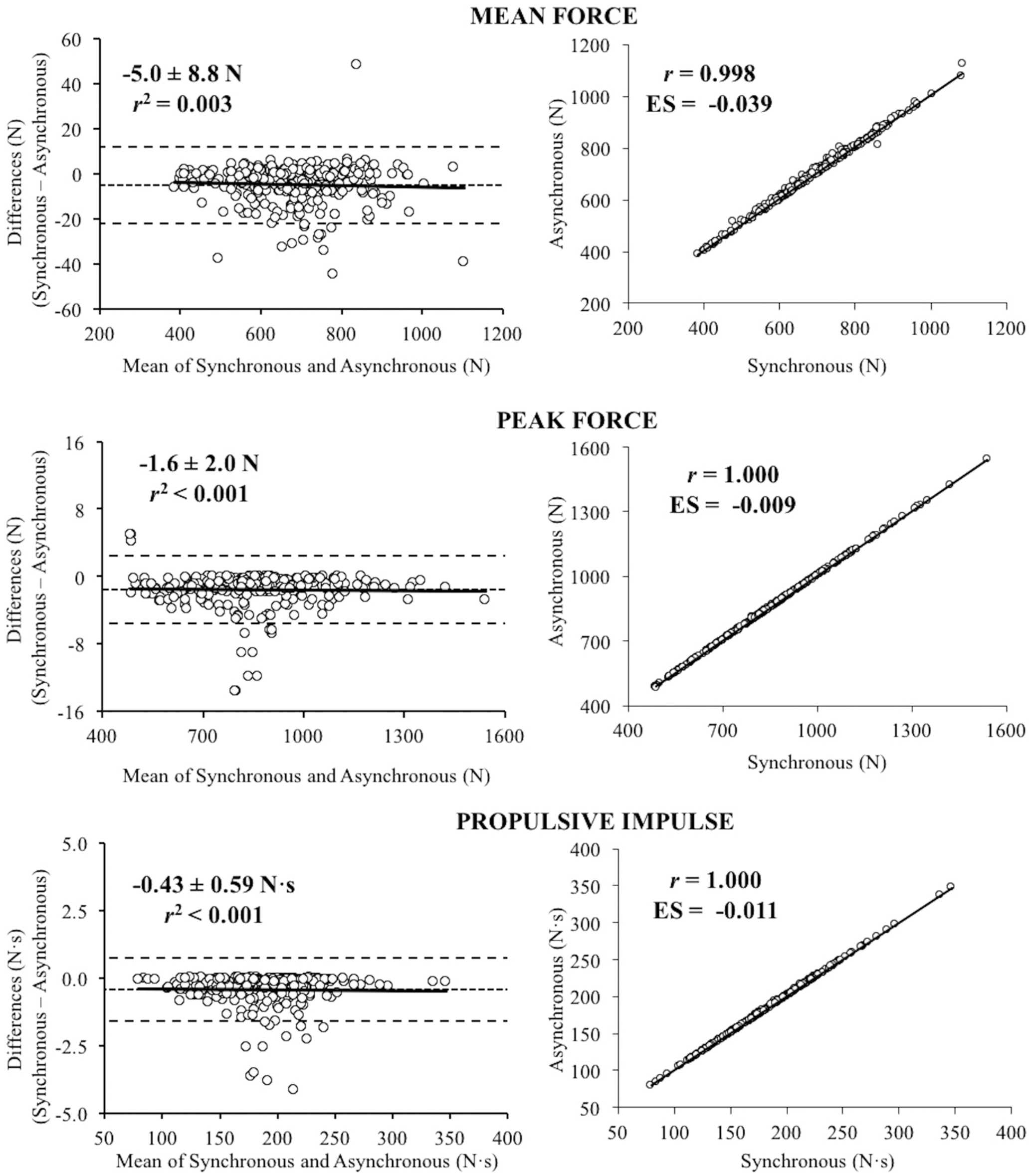

Fig. 1. Agreement between the Synchronous and Asynchronous procedures for the magnitude of single-leg mechanical performance variables. Left hand graphs present the Bland-Altman plots depicting the systematic bias ± random differences, and heteroscedasticity of errors (r^2). Right hand graphs show the relationship between the raw data obtained by the Synchronous and Asynchronous procedures depicting the Pearson's correlation coefficient (r) and effect sizes (ES; [Synchronous mean – Asynchronous mean] / SD both).

perfect correlations) for the three variables (Fig. 1). Regardless of the variable considered, the inter-leg asymmetries also presented an extremely high agreement between the Synchronous and Asynchronous procedures (negligible differences and nearly perfect to perfect correlations), and the random errors were lower for peak force and propulsive impulse (0.03%) compared to mean force (2.06%) (Fig. 2).

4. Discussion

This study was designed to explore the reliability and agreement of single-leg mechanical performance and inter-leg asymmetry variables obtained by two procedures of analysis (Synchronous and Asynchronous) during bilateral CMJs performed on dual force platforms. The main findings revealed comparable reliability for both procedures, whereas the mechanical variables were ranked from the most to the least reliable as follows: mean force > peak force > propulsive impulse. The inter-leg asymmetries were also obtained with a higher reliability when they were computed using mean force and peak force compared to the propulsive impulse. Finally, a very high agreement between the Synchronous and Asynchronous procedures was generally observed for both the single-leg mechanical performance and inter-leg asymmetry variables, but the agreement was slightly higher for peak force and propulsive impulse compared to mean force. These results suggest that the Synchronous and Asynchronous procedures can be indistinctly used to evaluate single-leg mechanical performance and inter-leg asymmetry variables during the bilateral CMJ, whereas according to their reliability outcomes mean force should be preferably used to evaluate single-leg mechanical performance and mean force or peak force to assess inter-leg asymmetries.

A considerable number of authors have examined whether inter-leg asymmetries detected during vertical jump tests have the potential to be used as indicators of sports performance or risk of injury [10,12,29]. Some researchers have also proposed that the assessment of inter-leg asymmetries can provide valuable information for training prescription [11]. However, in recent studies the usefulness of inter-leg asymmetries was questioned due to their generally low reliability [13,14]. Therefore, the promising applications of inter-leg asymmetries, along with their relatively weak consistency, justify the researchers' efforts to refine the testing protocols in order that this metric can be obtained with the highest possible reliability.

Of special note is that in the present study, unlike previous studies examining the reliability of inter-leg asymmetries during vertical jumps

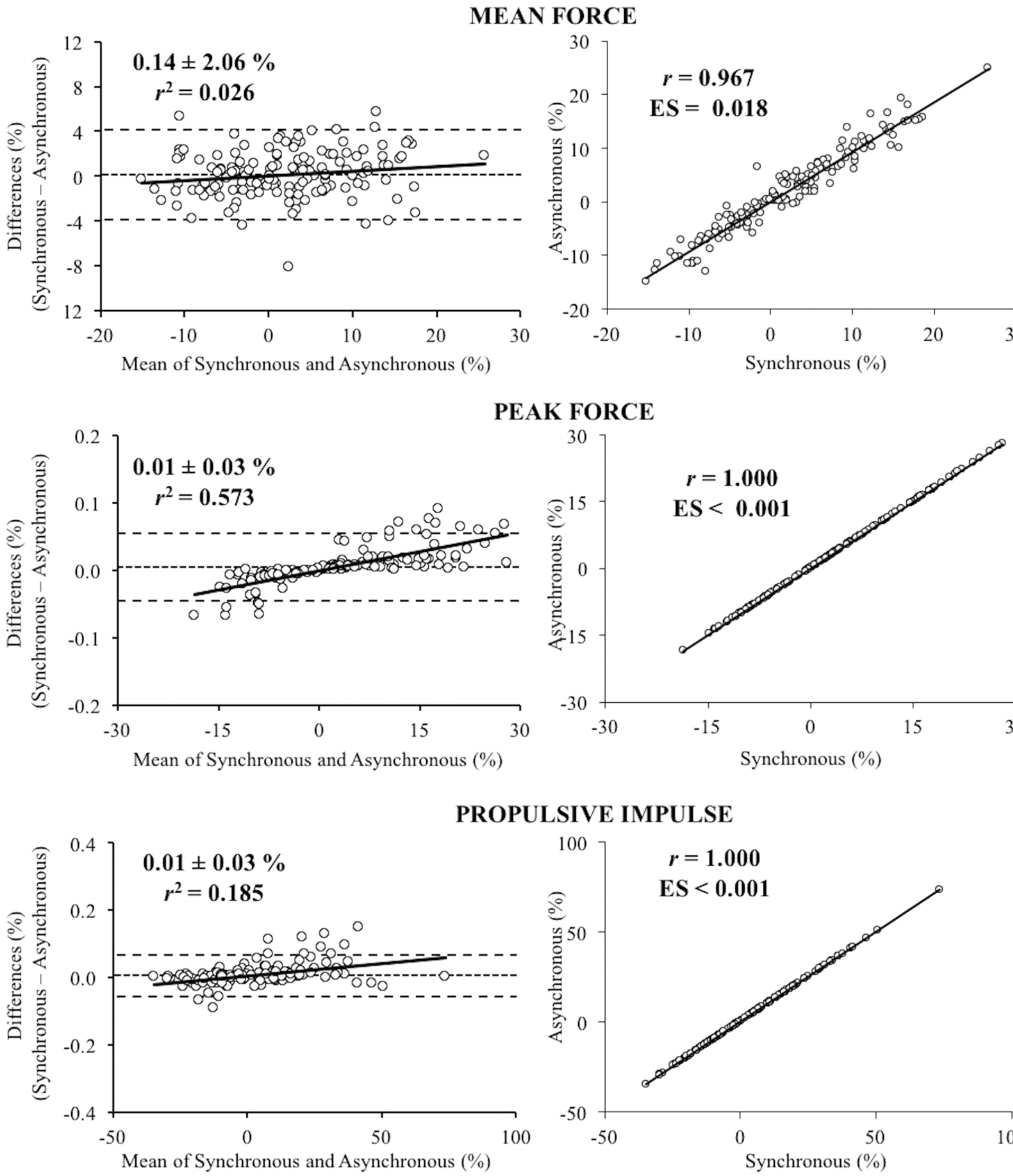

Fig. 2. Agreement between the Synchronous and Asynchronous procedures for the inter-limb asymmetries calculated using different mechanical variables. Left hand graphs present the Bland-Altman plots depicting the systematic bias ± random differences, and heteroscedasticity of errors (r^2). Right hand graphs show the relationship between the raw asymmetry data obtained by the Synchronous and Asynchronous procedures depicting the Pearson's correlation coefficient (*r*) and effect sizes (ES; [Synchronous mean – Asynchronous mean] / SD both).

[13,14,16], we ensured that the two jumps considered for reliability analyses were very consistent in terms of squat depth. Note that we selected the two jumps that differed less in terms of squat depth from the five maximal CMJs that were performed by each participant. This may be an important consideration since previous studies have consistently shown that the depth of the countermovement is an important confounding factor for the magnitude of the mechanical variables collected during the concentric (upward) phase of the jump [30]. Therefore, the use of a more consistent squat depth in the present study could explain the higher reliability of both single-leg mechanical performance and inter-leg asymmetry variables in comparison to previous studies in which the squat depth have not been controlled [13,14,16]. However, since the reliability of any fitness variable can be affected by a myriad of factors (e.g., participants experience with the test, instructions provided, equipment used, etc.), authors of the future studies should specifically test the hypothesis that the squat depth is an important factor to consider for increasing the consistency of the inter-leg asymmetries detected during bilateral vertical jumps.

The effect of the jump start detection for each leg (simultaneous or independent) when analysing the force-time signal during bilateral CMJs performed on dual force platforms was also examined in the present study. An analysis of the literature reveals that there is no consensus regarding which is the most appropriate procedure of analysis [7,13,16]. We hypothesised that the Synchronous procedure would provide a greater reliability than the Asynchronous procedure due to the lower influence for the Synchronous procedure of the distribution of the weight between the two force plates during the weighing phase. However, contrary to our hypothesis, the Synchronous procedure did not provide any variable with a greater reliability than the Asynchronous procedure. In fact, the reliability of the single-leg mechanical variables was always comparable (CV ratio < 1.15 in 4 out of 6 comparisons) with the exception of the mean force and propulsive impulse of the left leg that were obtained with a higher reliability (CV ratio > 1.15) by the Asynchronous procedure. In addition, the agreement between the two procedures was extremely high. In this regard, practitioners can indistinctly use the Synchronous or Asynchronous procedures because they provide mean force, peak force and propulsive impulse with a comparable reliability (CV differences $\leq 1.3\%$) and they also present a very high agreement (negligible differences and practically perfect or perfect correlations).

While this study provides useful information to refine the testing procedures of inter-leg asymmetries during bilateral CMJs, it is not without limitations. The main limitation is that only two procedures of analysis were considered, being possible that other procedures of analysis or small modification of these procedures can further increase the reliability of the dependent variables analysed in the present study. In addition, the findings of this study should not be necessarily applicable to other jumping tasks commonly used to assess inter-leg asymmetries. Finally, the large sample size (n = 74) should be acknowledged as a strength of the present study especially considering the lower sample size commonly recruited in previous studies examining the reliability of inter-leg asymmetries during vertical jumps (n range = 13–23) [13,14].

In conclusion, single-leg mechanical performance and inter-leg asymmetry variables can be obtained with acceptable reliability during bilateral CMJs provided that the selected jumps are comparable in terms of jump strategy (i.e., squat depth) and overall performance (i.e., jump height). The higher reliability observed in this study compared to previous studies in which the squat depth was not controlled suggests that inter-leg asymmetries should be preferably monitored by comparing jumps that are performed with consistent squat depths. The comparable reliability and high agreement between the Synchronous and Asynchronous procedures also suggest that both procedures can be indistinctly used to evaluate single-leg mechanical performance and inter-leg asymmetry variables during bilateral CMJs. Finally, regarding the variable of choice, due to their greater reliability, mean force should be recommended to evaluate single-leg mechanical performance and mean force or peak force to assess inter-leg asymmetries.

5. Significance

Practitioners can freely choose the procedure of analysis which is available in their software (i.e., Synchronous or Asynchronous) as it does not impact the reliability of single-leg mechanical performance nor the inter-leg asymmetry variables. Due to its higher reliability, mean force should be the variable of choice when quantifying inter-leg asymmetries.

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Conflict of interests

The authors report there are no competing interests to declare. This manuscript has not been published and it has not been submitted simultaneously for publication elsewhere.

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