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Original Research

Reliability and Test-Retest Agreement of Mechanical Variables Obtained During Countermovement Jump

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ABSTRACT

International Journal of Exercise Science 13(4): 6-17, 2020. The countermovement jump (CMJ) is often used as performance measure and monitoring tool. Traditionally, jump height (JH) is most often studied and reported, but other variables (e.g. force, velocity, power) can also be obtained during CMJ testing on a force plate. The aim of this study was to determine the intra-rater reliability of mechanical variables obtained during CMJs. For this, 41 physically active men (24 ± 4 years) performed four CMJs on a force plate with an interval of 48 to 168 hours (test-retest design). Six variables were analyzed: 1) jump height (JH), 2) peak force (PF), 3) peak power (PP), 4) velocity at takeoff (V_{TO}), 5) rate of force (RFD) and 6) power (RPD) development. Five variables showed to be reliable (i.e. CV < 10%), except RFD (CV of 12.9%). Although JH exhibited an acceptable level of reliability (r = 0.94 and CV = 5.8%), better scores were observed for PF, V_{TO}, and PP (CV ranging from 2.5 to 5.1%). The PF showed the best reliability scores (r = 0.99 and CV = 2.5%) and RPD, a relatively unexamined variable compared to the others, showed an acceptable level of reliability (r = 0.96 and CV = 7.8%). Therefore, JH, PF, PP, V_{TO}, and RPD demonstrated acceptable scores of reliability. PF seems to be the most appropriate variable to use when small changes in performance are expected. Future studies should investigate the importance of RPD for performance evaluation.

KEY WORDS: Physical performance, vertical jump, testing, measurement, intraclass correlation coefficient, Bland-Altman method

INTRODUCTION

A vertical jump can be defined as the capacity to elevate the body's center of mass from a vigorous acceleration produced by the lower limb muscles (48). Nearly a century ago, Dudley Allen Sargent developed a testing protocol using the vertical jump: the Sargent jump test (41). Since then, the jump test has become a popular physical test since it is simple, quick, and highly informative (5, 23, 29, 31). Currently, many types of jump tests have been performed (*e.g.* unipodal, drop and squat jump), but the countermovement jump (CMJ) is the most popular. The CMJ has been extensively used by researchers, coaches, athletes, and exercise practitioners in different scenarios. For example, coaches and athletes have often used CMJ to monitor training load (15, 33), test athletic performance (15, 22, 37), or to quantity the effectiveness of a training program (9, 14, 15, 21, 31, 32, 45). Additionally, the CMJ has also been used to evaluate neuromuscular function in youth (6, 7, 18) and older individuals (44), as well as monitoring disease and dysfunction (*e.g.* musculoskeletal injuries) (8, 12) and obesity (36, 39) among others. Given the widespread use of CMJ testing, it is paramount to have a deep understanding of the variables that are obtained from this test.

Traditionally, jump height is the most often tested and reported variable. In sport science, jump height is highly applicable, as improvements in jump height not only indicate greater performance of the lower limbs, but a real-life competitive advantage in sports that require jumping or reaching. To measure jump height, simple equipment can be used (25, 43, 50), but simply measuring jump height is likely not informative enough to monitor the oftentimes small effects of exercise on neuromuscular adaptations (20, 38). Therefore, analyzing variables such as force, velocity and power provide a more comprehensive evaluation of CMJ performance. In addition, the rate of force development (RFD) and rate of power development (RPD) have been gaining attention from exercise scientists due the strong relationship of these variables with sports performance and daily activities (1, 49). However, to obtain some of these measures, data must be manipulated in some fashion (*e.g.* setting different thresholds, force or power divided by time, etc.), which might magnify measurement error (17). In this regard, reliability studies are necessary to investigate whether the required data processing to obtain some variable (*e.g.* RFD and RPD) may reduce the reliability of these data. In fact, some studies have discouraged the use of RFD during CMJ, as Gathercole et al. (20), reported a coefficient of variation (CV) of 16.2% in college athletes, while an even higher CV of 33.8% has recently described in Hurling players (32). In addition, only two studies (25, 38) have investigated the RPD reliability, and these studies examined only the intra-session within-day reliability.

Although the CMJ is widely used to monitor neuromuscular function, athletic performance, and training load, the computations that commercial softwares use in the subsequent data processing are very general and likely cannot be manipulated for different purposes (*e.g.* time-related variables - RFD and RPD). Therefore, practitioners need to be aware that before incorporating these variables in their routine, an investigation about their reliability is needed, especially when subtle changes in performance are investigated. By investigating these factors, research may help coaches and practitioner to identify variables with lower measurement error and hence greater sensitivity to detect subtle changes in performance (*e.g.* pre vs post-training). In this sense, the aim of the present study was to investigate the between-days intra-rater reliability and test-retest agreement of the main mechanical variables (*i.e.* height, force, velocity, power, RFD and RPD) obtained during CMJ on a force plate in physically active men.

METHODS

Participants

Forty-one males (24.0 ± 4.4 years, 78.6 ± 14.0 kg, 1.8 ± 0.1 m) participated in this study. The sample size was established based on the recommendations of Walter et al. (51), considering: p0

= 0.6; p1 = 0.8; α = 0.05; β = 0.20. The inclusion criteria adopted to participate required that individuals were engaged in at least 60 minutes of vigorous activity three days per week or 150 minutes of moderate intensity exercise or walking five days per week. Participants also had to be free from any chronic diseases or recent injuries that could compromise jump performance, and they reported to be engaged in some kind of exercise (*e.g.* endurance or resistance exercise) or recreational sports activities (*e.g.* martial arts). Participants also filled out the International Physical Activity Questionnaire (IPAQ) (28), which verified that 67% of the sample were classified as highly active and the remaining 33% as moderately active. They were engaged in 818 ± 552 min/week (4899 ± 3153 METs/week) of physical activities in their typical week, but were instructed to avoid any vigorous exercise 48 hours before testing days. The participants were informed about the risks and benefits of the research and signed an informed consent form. The study was approved by the local Ethical Committee (number 2.878.364). This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (34).

Protocol

The participants visited the laboratory three times. Testing was performed at the same time of day (±1 hour), and the interval between each visit was 2-7 days. The first session served as a familiarization session where participants filled out the forms (*i.e.* health, IPAQ, and informed consent forms), and completed height and body mass measurements. In the following sessions, CMJ data collection occurred (test-retest design) under the supervision of a single rater.

In order to familiarize the participants with CMJ technique, they were instructed to practice the CMJ before coming to the lab, and during the first session, they performed as many practice trials as needed (ranging from 4 to 7). Before testing, the participants performed a warm-up, including a series of barbell squats on a smith machine with 50% of body mass, and CMJs with progressive level of effort. Participants performed the CMJ with hands akimbo, standing still until the verbal command "3, 2, 1, jump" was given. They were instructed jump as fast and as high as possible, while minimizing the transition between the descending and ascending phases. Participants were free to choose the deep of the countermovement and were instructed to not perform any movement during the flight time and to land using their forefoot. During each experimental visit, participants performed four CMJs (1 min apart) with maximal effort, and the average of the performance variables were further examined for reliability purposes

The mechanical CMJ variables were obtained by a commercial software (AccuPower 2.0.3 Dickinson, ND, USA) (Figure 1). Ground reaction forces were sampled at 1 kHz and digitally low-pass filtered at 20 Hz with a critically dumped filter (40). The software uses the impulse-momentum approach to indirectly calculate the velocity and power from the directly recorded vertical ground reaction force. In addition, the jump height (JH) was obtained from flight time (i.e. $gt^2 \cdot 8^{-1}$, g is the acceleration due to gravity) with 54.3 N of detection threshold; average rate of force development (RFD) was obtained by dividing the peak force value by the time lapse from the beginning of the braking phase to time of peak force, with 20 pounds above body weight as threshold (as recommended by the software manufacture); and average rate of power development (RPD) calculated with the division of peak power by the time lapse from the lowest value and the highest value of power-time curve.

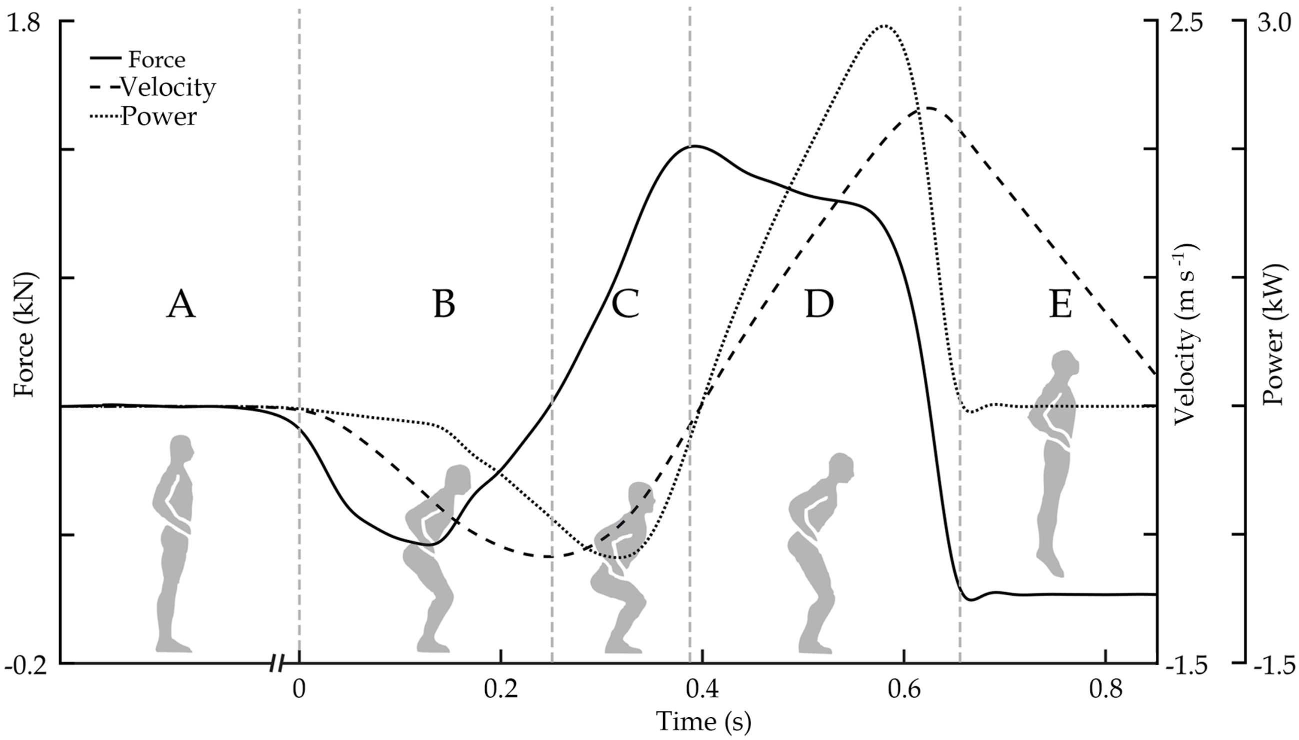

Figure 1. Countermovement jump phases (data from a typical jump collected). A) weighing the participant: participants stand still for 1-2 s to measure body weight; B) unweighting: beginning of the countermovement set as -15% of body weight; C) braking: usually results in peak force at the latter portion of this phase due to a vigorous muscle action to change movement direction; D) propulsive: vigorous extension of the lower limb joints until takeoff; E) flight: time lapse between takeoff and landing, which allows for the jump height calculation.

Statistical Analysis

Data normality was verified by the Shapiro-Wilk test. Then the mean and standard deviation were used to report CMJ variables, except for RPD data which were described as median and interquartile range (non-normal distribution). The Student *t*-test for paired samples was used to identify systematic error in the test-retest measurements ($p < 0.05$). Similarly, Wilcoxon signed-rank test was used for RPD data. Intraclass Correlation Coefficient ($ICC_{3,k}$) was determined for relative reliability (27), while typical error of measurements (TEM) and coefficient of variation (CV) were determined for absolute reliability (24). In addition, bias and the limits of agreement were established by plotting the test-rest differences against the mean of the measurement (4). Statistical Package for the Social Sciences (SPSS version 22.0) was used for statistical analyses, while a custom-made spreadsheet (Microsoft Excel) was used for TEM and CV calculations.

RESULTS

The results from CMJ performance as well as the relative and absolute data reliability are shown in Table 1. The ICC was classified as excellent for all variables ($r = 0.94$ to 0.99) except for V_{TO}

that was classified as good ($r = 0.88$) (27). No systematic bias was found between testing days ($p > 0.05$) and most of the variables presented an adequate relative (ICC = .88 to .99) and absolute (CV = 2.5 to 7.8%) reliability. Only RFD presented a CV higher than > 10%. The test-retest agreement of all variables is shown in Figure 2.

Table 1. Reliability of mechanical variables obtained during countermovement jump.

Variables	Day 1	Day 2	ICC (95% CI)	TEM	CV	*p* values
RPD ($kW \cdot s^{-1}$)	18.4 ± 6.1	18.1 ± 5.7	0.96 (0.93 – 0.98)	1.61	7.8	0.21
RFD ($kN \cdot s^{-1}$)	6.1 ± 2.3	5.9 ± 2.2	0.94 (0.88 – 0.97)	0.77	12.9	0.16
PP (kW)	4.2 ± 0.8	4.2 ± 0.8	0.97 (0.94 – 0.98)	0.22	5.1	0.22
PF (kN)	1.9 ± 0.4	1.9 ± 0.4	0.99 (0.98 – 1.00)	0.47	2.5	0.12
JH (cm)	29.5 ± 5.2	30.2 ± 5.5	0.94 (0.89 – 0.97)	1.74	5.8	0.07
V_{TO} ($m \cdot s^{-1}$)	2.6 ± 0.3	2.6 ± 0.3	0.88 (0.79 – 0.94)	0.13	5.0	0.10

Note: ICC: intraclass correlation coefficient; CI: confidence interval; TEM: typical error of measurement; CV: coefficient of variation; RPD: average rate of power development; RFD: average rate of force development; JH: jump height; PF: peak force; PP: peak power; V_{TO}: velocity at takeoff.

DISCUSSION

The aim of the present study was to examine the intra-rater reliability of important mechanical variables obtained during CMJ performance in a force plate on physically active men. The results indicated that the majority (5 from 6) of the investigated variables were reliable (*i.e.* CV < 10%). The main findings of the study were that PF was the most reliable variable (r = 0.99 and CV = 2.5 %), whereas RFD was the least reliable ($r = 0.94$ and CV = 12.9%). It is worth mentioning that JH demonstrated acceptable scores of reliability ($r = 0.94$ e CV = 5.8%), but may not be the best target variable to assess for those investigating subtle differences in performance. Lastly, despite RPD being an indirectly manipulated variable, it demonstrated an acceptable level of reliability ($r = 0.96$ and CV = 7.8 %).

Although there is no consensus about a single method to investigate reliability (2, 35), the ICC has been largely used for this purpose. ICC values represent the proportion of variance in a set of scores that is attributable to the true score variance (52). Considering this, researchers have suggested that a measure is reliable when ICC values exceed 0.75 (16, 33), meaning that 75% of the observed score variance is due to the true score variance and the remainder is attributable to error. In the present study, ICC ranged from 0.88 to 0.99, suggesting that all investigated variables could be classified as reliable. However, Weir (52) pointed out that the ICC values vary substantially depending on which version is used and also depending on the variability in the data. In this sense, those dealing with a heterogeneous sample of participants will probably find higher ICC values than those dealing with a homogeneous sample, even if the amount of error is the same. Based on the large variability of the current data, we believe that it might have happened in the present study. For example, the range of JH was 23.7 cm (from 16.9 to 40.6 cm) and the range of PF was 1.7 kN (from 1.3 to 3.0 kN). Therefore, the sole use of ICCs to determine the reliability of a measure does not seem to be adequate and other parameters of reliability should be reported (3, 24, 52). As such, in the present study, TEM was presented since its calculation (SD_{diff} / √2) is free from any concern related to ICC and can also be described as CV (24), as well as the test-rest agreement (*i.e.* Bland & Altman plots).

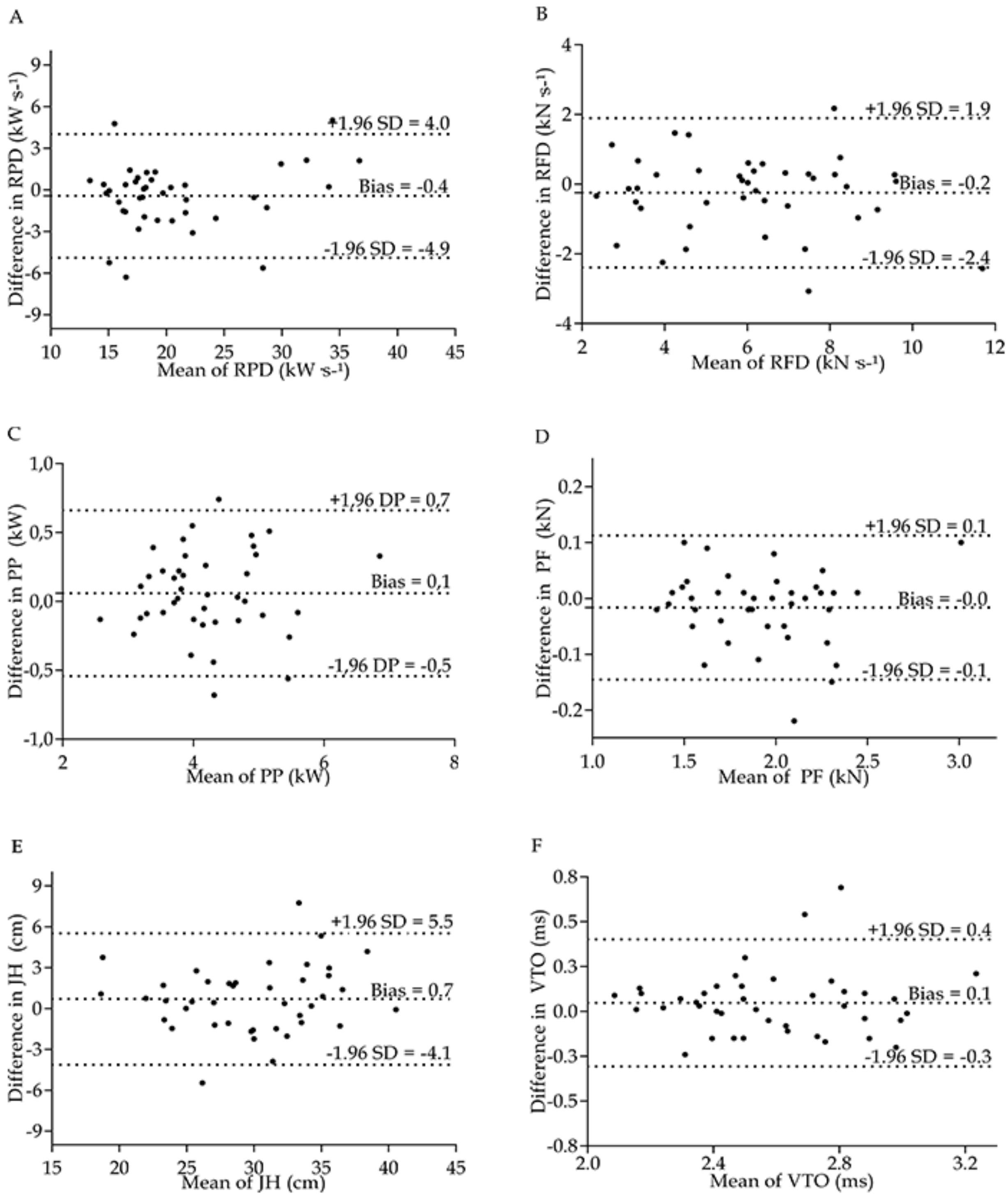

Figure 2. Bland-Altman plots showing the test-retest agreement. (A) RPD: average rate of power development; (B) RFD: average rate of force development; (C) PP: peak power; (D) PF: peak force; (E) JH: jump height; (F) V_{TO}: velocity at takeoff. In the y-axis were plotted the differences (day 2 minus day 1) against the mean of each score (x-axis). Dotted lines mean bias and superior and inferior limits of agreement.

The TEM can be used to monitor 'real' changes in performance (24). Hopkins (24) indicated that TEM × 1.5 to 2.0 seems to be a desirable threshold to be established to find confident changes in performance. For example, for those monitoring a training effect on JH, a change of 2.6 cm (1.7 of TEM × 1.5) should be adopted to state a real change in performance. However, in other populations where the magnitude of the measure may be greater or less than in the present study, CV can be yet more applicable since it describes the amount of measurement error as a percentage, which allows comparisons regardless of the magnitude of a measure.

CV is still applicable for comparisons between different sample of individuals, variables and ergometers (24). In addition, CV values ≤ 10% have been recommended for a measure be considered reliable (2, 13, 42, 46). In the present study, only the RFD exceeded this limit. Furthermore, the Bland & Altman plots showed a low systematic bias (from 1 to 4%); and a uniform variance between testing days (*i.e.* differences in day 2 minus day 1) against the mean values. The last allowed the determination of the 95% limits of agreement (95% LoA) (3). The 95% LoA allows an estimate (with 95% of confidence) of how much each variable may change when obtained in a similar scenario (*e.g.* inter-day measurement, single rater, etc.). Considering JH (95% LoA from -4.4 to 5.5 cm), it is possible to observe that 95% LoA were far superior than ± 2.6 cm calculated from TEM. Hopkins (24) argued that 95% LoA is too large, hence not applicable in sports and science. However, those interested in a measurement with a high level of confidence can use 95% LoA.

An important finding of the present study was that PF is the most reliable variable compared to the five other variables investigated. This result corroborates with others investigating the reliability of measurable variables of CMJ performance. Cormack et al. (13) demonstrated that PF was the most reliable variable with a CV of 2.2% in Australian Football athletes. Thomas et al. (46) showed the same when comparing PF (r = 0.99 and CV = 1.1%) with PP, V_{TO}, and JH (r = 0.94 to 0.98 and CV = 1.7 to 2.6%) in adolescent athletes. Additionally, more recently, Byrne et al. (10) found that PF (r = 0.95 and CV = 3.4%) was the most reliable CMJ variable in Hurling players. Considering this, it is important to mention that PF is the single variable that can be directly measured from a force plate, while the others require data manipulation via calculation(s). Therefore, it was expected that the greater the manipulation in the raw data, the greater the possibility to increase the measurement error. In support of this, Garcia-Ramos et al. (19) observed a greater measurement error in velocity data obtained in force plate compared with linear velocity transducer, which measures velocity directly. Therefore, depending on the devices used, the variable that is directly measured is likely the most reliable.

In the present study, RFD presented a CV of 12.8%. This result was expected, since previous studies have shown a lower reliability of RFD data (10, 25, 30). Hori et al. (25) reported an unacceptable level of reliability in physically active individuals (r = 0.66 and CV = 24%) and the same was observed by McLellan et al. (30), which reported a CV of 16.3%. Furthermore, and even worse value was shown in Hurling players (CV = 33.8%) (10). A possible explanation for these results may be due to participant's change in jump strategy. Kennedy & Drake (26) reported that PF can be reached in either braking or propulsive phases of the CMJ. It does not seem to substantially affect PF measurement, but would affect RFD, since the propulsive phase usually take place 200 ms later. It is possible to speculate that CMJ is not an adequate test to measure RFD. Otherwise, the squat jump (*i.e.* jump starting from bottom position) which does not have braking phase may be a better choice when RFD is a measurement of interest and ecological validity is important for the test. Otherwise, more laboratory-specific devices such as isokinetic dynamometers should be used that allow for more sensitive RFD measurements (11).

In the present study, JH demonstrated acceptable reliability (r = 0.94 and CV = 5.8%). This result was similar to other studies with CV around 5% (10, 13). JH has been one of the most used variables to monitor jump performance. In fact, JH can be easily estimated from low cost equipment (*e.g.* jump mat, smartphone app, etc.). In the present study, JH was obtained from flight time, so the fact that a calculation is applied to estimate JH may increase the chance of measurement error. Furthermore, any change in posture during the flight time or even a dorsiflexion just before landing may artificially increase flight time.

An interesting finding was the acceptable level of reliability of RPD (r = 0.96 and CV = 7.8%), since similar to RFD, this measure required more complex manipulation of the raw data. To our knowledge, the reliability of the RPD has not been sufficiently investigated. To date only two studies (25, 38) have investigated the intra-session within-day reliability during the CMJ. Hori et al. (25) reported an acceptable reliability for average RPD (r = 0.91 and CV = 8.2%), but not for peak RPD (r = 0.66 and CV = 24.0%). More recently, Rago et al. (38) also investigated the intra-session RPD reliability and did not demonstrate an acceptable level of reliability when RPD was obtained from different devices, including the force plate (CV = 10.1 and 16.0%). Therefore, this is the first study to investigate the between-days RPD reliability. These finds are very relevant since RPD has lately gained attention from the sports science community, and reflects the capacity to produce power in a short period of time, which may be one of the most valuable capacity for sports performance and daily activities (1, 49).

Although this study provides information regarding the reliability of commonly assessed CMJ parameters, this study is not free from limitation. The sample of participants was composed by physically active individuals. The criteria established as threshold was likely too broad "60 min of vigorous activities and/or 150 min of moderate activities or walking" allowing to participate to the present study individuals with varied levels of activity. These criteria created a heterogeneous sample of individuals with a large range of performance, which may limit the application of the current findings to other populations that typically use CMJs as performance measurements such as specialized athletes. Furthermore, there are a multitude of other measurements that can be derived from force plate data that were not assessed in the present study (*e.g.* impulse), but such variables are rarely incorporated in user-friendly commercial software packages. As this study sought to investigate the reliability of the most commonly used variables in these software packages, future research should investigate the reliability of other variables not included in the present study, which may be useful for coaches who wish to spend more time and effort delving in to their CMJ data.

CONCLUSION

The present study examined the intra-rater reliability of important variables obtained during CMJ performance in physically active men. The results suggest that PF, V_{TO}, PP, JH, and RPD are reliable variables, with PF being the most reliable. Although JH is the most used measure of jump performance, PF may be a more appropriate variable to analyze when subtle changes in performance are expected. Lastly, due to its lack of published evidence, future studies are needed to further investigate the importance of RPD in CMJ performance evaluation.

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