THE MARS FOR SQUAT, COUNTERMOVEMENT, AND STANDING LONG JUMP PERFORMANCE ANALYSES: ARE MEASURES REPRODUCIBLE?

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ABSTRACT

Hébert-Losier, K and Beaven, CM. The MARS for squat, countermovement, and standing long jump performance analyses: are measures reproducible? *J Strength Cond Res* 28(7): 1849–1857, 2014—Jump tests are often used to assess the effect of interventions because their outcomes are reported valid indicators of functional performance. In this study, we examined the reproducibility of performance parameters from 3 common jump tests obtained using the commercially available Kistler Measurement, Analysis and Reporting Software (MARS). On 2 separate days, 32 men performed 3 squat jumps (SJs), 3 countermovement jumps (CMJs), and 3 standing long jumps (LJs) on a Kistler force-plate. On both days, the performance measures from the best jump of each series were extracted using the MARS. Changes in the mean scores, intraclass correlation coefficients (ICCs), and coefficients of variations (CVs) were computed to quantify the between-day reproducibility of each parameter. Moreover, the reproducibility quantifiers specific to the 3 separate jumps were compared using nonparametric tests. Overall, an acceptable between-day reproducibility (mean $\pm$ SD, ICC, and CV) of SJ (0.88 ± 0.06 and $7.1 \pm 3.8\%$), CMJ (0.84 ± 0.17 and $5.9 \pm 4.1\%$), and LJ (0.80 ± 0.13 and $8.1 \pm 4.1\%$) measures was found using the MARS, except for parameters directly relating to the rate of force development (i.e., time to maximal force) and change in momentum during countermovement (i.e., negative force impulse) where reproducibility was lower. A greater proportion of the performance measures from the standing LJs had low ICCs and/or high CVs values most likely owing to the complex nature of the LJ test. Practitioners and researchers can use most of the jump test parameters from the MARS with confidence to quantify changes in the functional ability of individuals over time, except for those relating to the rate of force development

or change in momentum during countermovement phases of jumps.

KEY WORDS force, kinetics, power, reliability, testing

INTRODUCTION

The Kistler Measurement, Analysis and Reporting Software (MARS, 2012 S2P Ltd., Ljubljana, Slovenia) was developed to provide a user-friendly platform for force-plate data analysis to researchers, strength and conditioning coaches, and rehabilitation specialists. The latter fields often use jump tests because their outcomes are valid indicators of functional performance, inclusive of leg power (27), sprinting ability (28), and readiness for return-to-play after injury or surgery (3). Moreover, when measures are taken at various time points of an athlete's development, these can be used to identify gains from training programs (7) or—on the contrary—detriments from maladaptive responses to training (23,43).

Monitoring jump test performances in athletes during preseason, competition, post-season, and rehabilitation can be useful to objectively quantify the strength and potential changes in the functional capacities of individuals, e.g., decreases in lower extremity peak power output that could predict or explain decreases in sprinting velocities and indicate over-training. For this purpose, it is essential that jump test methods and measurement systems provide measures that are reproducible so that a change in the score reflects a meaningful change in an individual's function, e.g., beneficial changes in jump test parameters reflecting an increased ability to generate high muscle forces as a result of centrally or peripherally mediated adaptations. Considering the significant role and common use of jump tests in research and practice, determining the reproducibility of measurements from commercially available tools and software is vital before promotion of their widespread use. This relative importance of documenting the reproducibility of performance is reflected by the number of studies pertaining to the reproducibility of jump measures acquired using various systems (15,16,32), e.g., quantifying the performance of squat jumps (SJs), countermovement jumps (CMJs), and standing long jumps (LJs) using data from accelerometers,

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contact mats, and force-plates. Despite this array of studies, none has yet examined the reproducibility of jump test performance parameters acquired using the commercially available MARS. Determining the reproducibility of jump test measures acquired using the MARS would assist current users to interpret their data and potential users to estimate the cost-benefit of purchase of this software for use in their practical environment.

More specifically, the proper clinical application and interpretation of measures from the MARS require that the parameters most frequently extracted from common jump tests be reproducible in terms of their relative (i.e., the correlation or level of agreement between an individual's score from measure to measure) and absolute (i.e., the typical error or variation in an individual's score from measure to measure) quantifiers (2,18). Only reproducible outcomes can be used to monitor small, but nonetheless functionally meaningful, changes; document the evolution of training or injury status; and compare various testing methods or instruments in a reliable manner (18,38). In science, adequate reproducibility is a necessity to assess changes in experimental trials and/or the effectiveness of interventions (18), with intraclass correlation coefficients (ICCs) and coefficient of variations (CVs) commonly used to quantify the relative and absolute reproducibility of test measures, respectively. For SJs (8) and CMJs (8,22,29), the ICCs and CVs associated to jump height, peak force, peak power, and time-to-peak force variables derived from force-plates have been reported to range from 0.74 to 0.98% and 2.3 to 11.8%, respectively, with the time-to-peak force showing the greatest variability. For the LJ, the ICCs are reported to range from 0.63 to 0.97% and CVs from 3.6 to 15.4% when comparing peak power and horizontal distance measures collected on different days (29).

This study was designed to characterize and assess the reproducibility of performance parameters from 3 different jump tests acquired on 2 separate days using the commercially available MARS package. The 3 jump tests and derived performance parameters were selected on the basis of their scientific and clinical merits in the field of strength and conditioning, sports and exercise science, and rehabilitative medicine.

METHODS

Experimental Approach to the Problem

To investigate the reproducibility of jump test parameters measured using the MARS, a repeated-measures design was used that required each subject to attend 2 experimental sessions in the biomechanics laboratory of our university-affiliated sports research center. The 2 test sessions were performed within 3 days (i.e., if the first session was on a Monday, the second session was on the next Tuesday or Wednesday), at the same time of day, and were led by the same experienced researcher. The 2 data collection sessions included a standardized familiarization to the experimental protocol, a warm-up period, practice trials, and data

collection from the performance of 3 vertical SJs, 3 vertical CMJs, and 3 horizontal standing LJs. The procedures are described in detail below.

Subjects

The research protocol adhered to the latest amendment of the Declaration of Helsinki and was approved by the Regional Ethical Review Board, Umeå, Sweden, before subject recruitment. For this project, a convenience sample of 32 men (between 19 and 45 years of age, mean $\pm$ SD; age: 27.9 ± 5.6 years; body height: 181.3 ± 6.0 cm; body mass: 79.2 ± 10.0 kg; body mass index: 24.1 ± 2.8 kg·m⁻²) were recruited. The inclusion criteria were good self-reported general health (confirmed by having subjects complete a health history form), regular recreational physical activity, and no current or recent (less than 3 months) musculoskeletal injury, joint pathology, or other medical condition that could impact jump test performance. All testing procedures and risks were fully explained to the subjects, and they were provided with an "Informed Consent Form" that presented all information pertinent to the investigation. Each subject then affixed their signature to indicate that the document had been read and had given their consent to participation under the conditions described therein. Individuals were requested to refrain from strenuous physical activity (e.g., high-intensity cardiovascular exercise or exercising for over 1 hour) and lower-body resistance training (e.g., weight-training session in the gym) for the 24-hour period before the experimentation and ingestion of caffeine on the 2 test days. All data were collected within 1 month during a winter season.

Procedures

After recording body mass using a calibrated force-plate (Kistler, Winterthur, Switzerland), each subject watched an instructional video that visually demonstrated performance and verbally described the proper technique of the 3 jumps examined, performed a light-intensity 5-minute cycling warm-up on an ergometer (Monark AB, Vansbro, Sweden), and practiced the experimental tasks under supervision and guidance from the primary researcher to improve proficiency in jumping techniques. Similar to previously used protocols (28,31,40), the subjects practiced each jump task 3 to 5 times, which was followed by a 2-minute rest period before data collection.

All jump tests were performed in the center of the calibrated force-plate, which was zeroed before each data collection trial. Ground reaction force (GRF) data were sampled at 1000 Hz using the MARS v.1.0.3 (S2P Ltd., Ljubljana, Slovenia) and built-in modules for SJ, CMJ, and standing LJ. For each jump module, the subjects completed 3 trials each interspersed by a 2-minute rest period, which was deemed sufficient to limit the effects of fatigue. Because footwear can influence the human-ground interactions during ground contact (5) and jump performance (24,41), the subjects were barefoot in all trials with hands placed on hips, feet shoulder width apart, and eyes directed

forward. The testing sequence of SJ to CMJ to LJ was kept constant for all subjects throughout experimentation.

For the SJ, the subjects had to jump (vertically) upward as high as possible from a static squat position with the hips and knees bent to $\sim 90^\circ$ of flexion (as estimated from the subject and observed by the researcher) with an upright stance and the trunk, femur, and tibia aligned to describe the 180° position at the hip and knee joints. For the CMJ, the subjects had to jump (vertically) upwards as high as possible from erect standing using a prior downward countermovement motion. In both the SJ and CMJ trials, the subjects were instructed to land in a similar position to that of take-off from the force-plate (with the knees straight and the ankles plantar-flexed). For the standing LJ, the subjects were instructed to jump (horizontally) forward as far as possible from erect standing, using a prior countermovement and without falling backward upon landing. For both CMJ and LJ trials, no particular specifications were given regarding the depth or speed of the countermovement. If subjects failed to perform a trial adequately—e.g., did not maintain their hands on their hips during the trial—it was disregarded and repeated after a 2-minute rest so that each subject had 3 trials completed successfully for each jump test module. No subjects needed more than 1 extra trial to successfully complete each of the jump modules or expressed residual fatigue from preceding procedures.

Parameters Calculated

The MARS automatically computes a standard set of biomechanical performance parameters from each jump trial and presents them in a report form that is specific to each jump test module. The parameters that were extracted from each module are documented in Table 1, along with the description provided by the manufacturer. For additional practical relevance, the length of the LJ was also calculated using a graduated metric tape to measure the distance from take-off to landing on the basis of the most posterior aspects of the heels. For each subject and data collection session, the data from the single jump with the greatest vertical height calculated from the take-off velocity ($height_{vel}$) during the SJs and CMJs, and with the longest predicted horizontal displacement of the center of gravity calculated from the take-off velocity vector ($distance_{COM}$) during the LJs were extracted for statistical analyses.

Statistical Analyses

Mean $\pm$ SD values were computed for all variables to describe the data. Heteroscedasticity was formally inspected by plotting the absolute difference between the values obtained on the 2 separate data collection days against the mean of both days for each individual, and then calculating the correlation coefficients through linear regression. When heteroscedasticity in the data was observed, the raw values were log transformed before analysis and interpretation of the reproducibility of measures (2). The pairwise correlation between the $distance_{COG}$ (predicted horizontal displacement

of the center of gravity calculated from the take-off velocity vector) and $distance_{heel}$ (horizontal displacement of the posterior heel from the take-off to the landing measured using a metric tape) computed from the standing LJ trials was also investigated.

The ICC with upper and lower 90% confidence limits was computed to determine the relative between-day reproducibility of measurements for each parameter listed in Table 1. A modified statistical spreadsheet was used to compute these ICC values as: $[ICC = 1 - (TEM/SD)^2]$, where TEM is the typical error in measurement and SD is the mean between-subject SD of the 2 trials obtained by weighing the variances on the basis of their degrees of freedom (20). The TEM was computed as: $[TEM = SD \text{ (between-day difference in measures)} / \sqrt{2}]$.

To quantify the absolute reproducibility, the TEM defined above was then expressed as a CV on the basis of: $[CV = (TEM/\text{mean}) \times 100\%]$, where the mean takes into consideration all 32 subjects and their 2 data collection sessions (2,18). Upper and lower 90% confidence limits of the CV values were also calculated for each jump test parameter. The TEM expressed as a CV was selected instead of the more commonly used SEM on the basis of work by Hopkins (18,19). As the interest is not in the uncertainty of a single mean, but rather that of an effect involving comparisons of 2 means, confidence intervals or related inferential statistics are preferred (21). Moreover, expressing TEM as a CV is suggested to be more useful in the presence of heteroscedastic data (2).

On the basis of commonly used thresholds; the relative reproducibility of a measure was considered poor, fair, and good when the corresponding ICC values of measures were <0.4 , $0.4\text{--}0.75$, and ≥ 0.75 (35,37). The absolute reproducibility of a measure was considered adequate when the corresponding CV values were equal to or lower than 10% (17,42).

To compare the ICC and CV values obtained between the 3 jump test modules, Kruskal-Wallis equality-of-populations rank and Wilcoxon rank-sum (in post hoc) tests were used. Nonparametric analyses were selected because the distribution of the ICC and CV data was not normal (Shapiro-Wilk tests, $p < 0.0001$). All statistical analyses were performed using Stata/IC v.11.2 (StataCorp LP, TX, USA) and Microsoft Excel 2010 (Microsoft Corp., Redmont, WA, USA) with a level of significance set at $\alpha \leq 0.05$.

RESULTS

Heteroscedasticity correlations were significant for $height_{time}$ ($r = 0.3360$, $p = 0.0066$), relative F_{max} ($r = 0.5584$, $p < 0.0001$), and time to F_{max} ($r = 0.4905$, $p = 0.0001$) for the SJ, as well as for the $height_{vel}$ ($r = 0.3081$, $p = 0.0186$), relative horizontal P_{max} ($r = 0.6990$, $p < 0.0001$), vertical FI ($r = 0.5476$, $p < 0.0001$), and positive FI ($r = 0.5073$, $p = 0.0001$) for the LJ. The log-transformed values of these parameters were therefore used to assess the reproducibility

TABLE 1. Jump test parameters calculated using the MARS and extracted from the software to determine their between-day reproducibility.*

Module	Parameter (unit)	Description
SJ	Height _{vel} (cm)	The height of the jump calculated from the take-off velocity as calculated from the FI
	Height _{time} (cm)	The height of the jump calculated from the flight time
	Relative $F_{\max}$ (% BW)	$F_{\max}$ during the jump (i.e., push-off) divided by the BW
	Relative $P_{\max}$ ($W \cdot kg^{-1}$)	$P_{\max}$ during the jump (i.e., push-off) divided by the BW
	Vertical take-off velocity ($m \cdot s^{-1}$)	Velocity of the vertical movement at the take-off
	Flight time (s)	Time interval between the take-off and the landing
	Time to $F_{\max}$ (s)	Time interval between the start and the $F_{\max}$
	Total FI (Ns)	FI between the start and the take-off
CMJ	Height _{vel} (cm)	The height of the jump calculated from the take-off velocity as calculated from the FI
	Height _{time} (cm)	The height of jump calculated from the flight time
	Relative $F_{\max}$ (% BW)	$F_{\max}$ during the push-off divided by the BW
	Relative $P_{\max}$ ($W \cdot kg^{-1}$)	$P_{\max}$ during the push-off divided by the BW
	Vertical take-off velocity ($m \cdot s^{-1}$)	Velocity of the vertical movement at the take-off
	Flight time (s)	Time interval between the take-off and the landing
	Push-off FI (Ns)	FI between the lowest position and the take-off
	Time to $F_{\max}$ (s)	Time interval between the start and the maximal force
LJ	Negative FI (Ns)	FI between the start and the moment where the GRF equals the BW again
	Positive FI (Ns)	FI between the moment where the GRF equals the BW again and the take-off
	Distance _{COG} (cm)	Predicted horizontal displacement of the COG calculated from the take-off velocity vector
	Distance _{heel} (cm)	Horizontal displacement of the posterior heel from the take-off to the landing measured using a metric tape
	Height _{vel} (cm)	The height of the jump computed from the take-off velocity as calculated from the FI
	Height/distance ratio	Ratio between the height and the distance of the jump
	Relative horizontal $F_{\max}$ (% BW)	Maximal horizontal force during the jump divided by the body weight
	Relative vertical $F_{\max}$ (% BW)	Maximal vertical force during the jump divided by the body weight
	Relative horizontal $P_{\max}$ ($W \cdot kg^{-1}$)	Maximal power during the jump in horizontal direction divided by the BW
	Relative vertical $P_{\max}$ ($W \cdot kg^{-1}$)	Maximal power during the jump in vertical direction divided by the BW
	Vertical take-off velocity ($m \cdot s^{-1}$)	Velocity of the vertical movement at the take-off
	Horizontal take-off velocity ($m \cdot s^{-1}$)	Velocity of the horizontal movement at the take-off
	Time to $F_{\max}$ (s)	Time interval between the start and the maximal force
	Horizontal FI (Ns)	FI in horizontal direction
	Vertical FI (Ns)	FI in vertical direction
	Negative FI (Ns)	FI between the start and the moment where the GRF force equals the BW again
	Positive FI (Ns)	FI between the moment where the GRF equals the BW again and the take-off

*BW = body weight; CMJ = countermovement jump; FI = force impulse (i.e., integral of a force with respect to time); $F_{\max}$ = maximal force; GRF = ground reaction force; LJ = long jump; $P_{\max}$ = maximal power; SJ = squat jump.

of measures, whereas raw values were used for all the other jump test parameters. None of the CMJ parameters demonstrated heteroscedasticity.

A descriptive summary of the jump test performance parameters from the 32 subjects collected on the 2 different test days, as well as their between-day change in scores, are provided in Table 2. Combining the data

from both days, the vertical height_{vel} for SJs and CMJs were 33.0 ± 8.0 cm and 34.0 ± 7.0 cm, respectively; whereas, for the standing LJs, the horizontal distance_{COM} and distance_{heel} values were 89.1 ± 12.4 cm and 206.7 ± 19.8 cm, respectively. A large correlation between these 2 standing LJ distance parameters was determined ($r = 0.6514$, $p < 0.0001$).

TABLE 2. Jump test parameters calculated using the MARS and extracted from the software to determine their between-day reproducibility.*†

Module	Parameter (unit)	Day 1	Day 2	Δmean
SJ	Height _{vel} (cm)	33.9 ± 8.5	32.2 ± 7.4	-1.7 ± 4.0
	Height _{time} (cm)‡	31.7 ± 6.5	30.9 ± 6.3	-0.8 ± 3.0
	Relative $F_{\max}$ (% BW)‡	238.8 ± 39.5	247.0 ± 46.9	8.2 ± 20.0
	Relative $P_{\max}$ (W·kg ⁻¹)	51.4 ± 10.0	51.0 ± 9.6	-0.5 ± 3.3
	Vertical take-off velocity (m·s ⁻¹)	2.5 ± 0.2	2.5 ± 0.2	-0.03 ± 0.11
	Flight time (s)	0.23 ± 0.07	0.21 ± 0.07	-0.03 ± 0.05
	Time to $F_{\max}$ (s)‡	0.12 ± 0.02	0.12 ± 0.03	0.002 ± 0.02
CMJ	Total FI (Ns)	200.5 ± 31.9	197.0 ± 30.6	-3.54 ± 11.19
	Height _{vel} (cm)	34.0 ± 7.1	33.9 ± 6.9	-0.1 ± 2.5
	Height _{time} (cm)	35.7 ± 6.9	35.4 ± 7.0	-0.3 ± 2.3
	Relative $F_{\max}$ (% BW)	236.1 ± 27.0	245.0 ± 29.4	8.9 ± 20.5
	Relative $P_{\max}$ (W·kg ⁻¹)	48.3 ± 8.1	48.2 ± 8.0	-0.04 ± 2.3
	Vertical take-off velocity (m·s ⁻¹)	2.6 ± 0.2	2.6 ± 0.3	-0.01 ± 0.1
	Flight time (s)	0.54 ± 0.05	0.54 ± 0.05	-0.002 ± 0.02
	Time to $F_{\max}$ (s)	0.59 ± 0.12	0.57 ± 0.11	-0.01 ± 0.12
	Push-off FI (Ns)	203.7 ± 33.1	203.6 ± 31.4	-0.1 ± 9.4
	Negative FI (Ns)	-101.0 ± 20.9	-108.0 ± 20.9	-7.0 ± 17.9
	Positive FI (Ns)	306.7 ± 51.6	314.5 ± 49.4	7.7 ± 23.0
LJ	Distance _{COG} (cm)	89.9 ± 13.2	88.4 ± 11.6	-1.5 ± 5.6
	Distance _{heel} (cm)§	202.8 ± 21.6	210.6 ± 17.9	7.8 ± 12.0
	Height _{vel} (cm)‡	16.7 ± 4.7	15.8 ± 4.2	-1.0 ± 2.5
	Height/distance ratio	18.2 ± 2.9	17.6 ± 2.7	-0.6 ± 2.7
	Relative horizontal $F_{\max}$ (% BW)	75.1 ± 9.9	77.4 ± 11.2	2.2 ± 6.5
	Relative vertical $F_{\max}$ (% BW)	204.7 ± 26.5	204.3 ± 25.2	-0.4 ± 17.2
	Relative horizontal $P_{\max}$ (W·kg ⁻¹)‡	16.0 ± 3.4	16.6 ± 3.3	0.6 ± 2.5
	Relative vertical $P_{\max}$ (W·kg ⁻¹)	31.4 ± 6.2	30.4 ± 6.3	-1.0 ± 3.5
	Vertical take-off velocity (m·s ⁻¹)	1.8 ± 0.2	1.7 ± 0.2	-0.05 ± 0.14
	Horizontal take-off velocity (m·s ⁻¹)	2.5 ± 0.2	2.5 ± 0.2	0.03 ± 0.20
	Time to $F_{\max}$ (s)	0.8 ± 0.3	0.7 ± 0.2	-0.1 ± 0.2
	Horizontal FI (Ns)	199.1 ± 31.9	200.9 ± 25.0	1.8 ± 16.8
	Vertical FI (Ns)‡	143.3 ± 28.0	142.1 ± 29.9	-1.2 ± 12.8
	Negative FI (Ns)	-71.5 ± 33.0	-71.2 ± 35.9	0.3 ± 12.6
	Positive FI (Ns)‡	218.0 ± 44.3	217.9 ± 46.7	-0.1 ± 17.6

*BW = body weight; CMJ = countermovement jump; FI = force impulse (i.e., integral of a force with respect to time); $F_{\max}$ = maximal force; LJ = long jump; $P_{\max}$ = maximal power; SJ = squat jump.

†The mean ± SD values from the performance of SJs, CMJs, and LJs on 2 separate days by 32 male subjects are reported.

‡Heteroscedastic data observed. Therefore, raw values were log transformed before analyzing and interpreting the reproducibility of measures.

§Measured using a metric tape.

The ICC and CV values specific to each jump test parameter are reported in Table 3. The means of the ICCs were 0.88 ± 0.06 (range: 0.78–0.95) for the SJ parameters, 0.84 ± 0.17 (range: 0.45–0.96) for the CMJ parameters, and 0.80 ± 0.13 (range: 0.55–0.94) for those parameters specific to the LJ. The means of the CVs for the SJ, CMJ, and standing LJ parameters were $7.1 \pm 3.8\%$ (range: 3.3–14.6%), $5.9 \pm 4.1\%$ (range: 2.3–14.5%), and $8.1 \pm 4.1\%$ (range: 4.1–19.1), respectively. On the basis of the Kruskal-Wallis equality-of-populations rank tests, there was no difference in the ICC ($p = 0.1349$) or CV ($p = 0.1566$) values between the 3 different jump test modules.

For the SJs and CMJs, all parameters demonstrated both a good relative (ICC ≥ 0.75) and adequate absolute (CV $\leq 10\%$) level of reproducibility, except for the flight time of SJs (CV: 14.6%) and the time to $F_{\max}$ (ICC: 0.45, CV: 14.5%) and negative FI (ICC: 0.65, CV: 12.1%) of CMJs. A good relative and acceptable absolute reproducibility was determined for 9 of the 15 standing LJ parameters. The other 6 parameters were associated with either a fair relative reproducibility (i.e., horizontal take-off-velocity) or less than acceptable absolute reproducibility (i.e., height_{vel}, relative horizontal $P_{\max}$, and negative FI) or both (i.e., height/distance ratio and time to $F_{\max}$).

TABLE 3. The relative (ICC) and absolute (CV) reproducibility of jump test parameters calculated using the MARS.*†

Module	Parameter (unit)	ICC	CV
SJ	Height _{vel} (cm)	0.88 (0.79, 0.93)	8.6 (7.1, 10.9)
	Height _{time} (cm)‡	0.90 (0.82, 0.94)	6.6 (5.5, 8.4)
	Relative $F_{\max}$ (% BW)‡	0.91 (0.84, 0.95)	5.5 (4.6, 7.1)
	Relative $P_{\max}$ (W·kg ⁻¹)	0.95 (0.91, 0.97)	4.5 (3.7, 5.7)
	Vertical take-off velocity (m·s ⁻¹)	0.90 (0.82, 0.94)	3.3 (2.7, 4.2)
	Flight time (s)	0.82 (0.70, 0.90)	14.6 (12.1, 18.6)
	Time to $F_{\max}$ (s)‡	0.78 (0.62, 0.87)	10.0 (8.2, 12.9)
CMJ	Total FI (Ns)	0.94 (0.89, 0.97)	4.0 (3.3, 5.1)
	Height _{vel} (cm)	0.94 (0.89, 0.97)	5.3 (4.4, 6.7)
	Height _{time} (cm)	0.95 (0.91, 0.97)	4.6 (3.8, 5.8)
	Relative $F_{\max}$ (% BW)	0.75 (0.58, 0.850)	6.0 (5.0, 7.6)
	Relative $P_{\max}$ (W·kg ⁻¹)	0.96 (0.93, 0.98)	3.3 (2.8, 4.2)
	Vertical take-off velocity (m·s ⁻¹)	0.94 (0.90, 0.97)	2.3 (1.9, 3.0)
	Flight time (s)	0.94 (0.90, 0.97)	2.3 (1.9, 3.0)
	Time to $F_{\max}$ (s)	0.45 (0.18, 0.66)	14.5 (12.0, 18.5)
	Push-off FI (Ns)	0.96 (0.93, 0.98)	3.3 (2.7, 4.1)
	Negative FI (Ns)	0.65 (0.43, 0.79)	12.1 (10.0, 15.4)
LJ	Positive FI (Ns)	0.90 (0.83, 0.95)	5.2 (4.3, 6.7)
	Distance _{COG} (cm)	0.91 (0.83, 0.95)	4.4 (3.6, 5.7)
	Distance _{heel} (cm)§	0.83 (0.70, 0.91)	4.1 (3.4, 5.3)
	Height _{vel} (cm)‡	0.82 (0.68, 0.90)	11.7 (9.5, 15.3)
	Height/distance ratio	0.56 (0.31, 0.74)	10.5 (8.7, 13.5)
	Relative horizontal $F_{\max}$ (% BW)	0.82 (0.70, 0.90)	6.0 (5.0, 7.6)
	Relative vertical $F_{\max}$ (% BW)	0.79 (0.64, 0.88)	5.9 (4.9, 7.6)
	Relative horizontal $P_{\max}$ (W·kg ⁻¹)‡	0.74 (0.56, 0.85)	11.4 (9.3, 14.8)
	Relative vertical $P_{\max}$ (W·kg ⁻¹)	0.85 (0.75, 0.92)	8.0 (6.6, 10.1)
	Vertical take-off velocity (m·s ⁻¹)	0.84 (0.71, 0.91)	5.5 (4.5, 7.0)
	Horizontal take-off velocity (m·s ⁻¹)‡	0.55 (0.29, 0.73)	5.7 (4.7, 7.3)
	Time to $F_{\max}$ (s)	0.62 (0.38, 0.78)	19.1 (15.7, 24.7)
	Horizontal FI (Ns)	0.84 (0.72, 0.91)	6.0 (4.9, 7.6)
	Vertical FI (Ns)‡	0.92 (0.85, 0.95)	6.1 (5.0, 7.9)
	Negative FI (Ns)	0.94 (0.89, 0.97)	12.5 (10.3, 16.0)
	Positive FI (Ns)‡	0.94 (0.90, 0.97)	5.3 (4.3, 6.8)

*The 90% confidence limits (lower, upper) of reproducibility measures are reported on the basis of the performance of SJs, CMJs, and LJs on 2 separate days by 32 male subjects, with ICC < 0.75 and CV > 10% in boldface.

†BW = body weight; CV = coefficients of variations; CMJ = countermovement jump; FI = force impulse (i.e., integral of a force with respect to time); $F_{\max}$ = maximal force; ICC = intraclass correlation coefficient; LJ = long jump; $P_{\max}$ = maximal power; SJ = squat jump.

‡Heteroscedastic data observed. Therefore, raw values were log transformed before analyzing and interpreting the reproducibility of measures.

§Measured using a metric tape.

≤ 10%) reproducibility were determined here for 7 of 8 SJ (88%), 8 of 10 CMJ (80%), and 9 of 15 LJ (60%) performance parameters. However, the relative reproducibility was fair (ICC between 0.40 and 0.75) and the absolute reproducibility was less than adequate (CV > 10%) for certain parameters, particularly those relating to the rate of force development (i.e., time to $F_{\max}$ of the SJ, CMJ, and LJ) and change in momentum during the countermovement phase of jumps (i.e., negative force impulse of the CMJ and LJ). Furthermore, the standing LJ had the lowest proportion of parameters with both a good relative and adequate absolute reproducibility of measures. Thus, the interpretation of the change in scores in these select parameters should be made with some caution and contextual consideration.

Our results are consistent with those reported by Cronin et al. (8) where force-plate-derived performance measures from vertical jumps showed higher between-session reproducibility in the peak force than the time-to-peak force parameters. At the same time, these authors reported that the reproducibility of the time-to-peak force parameter was characterized by ICC and CV values of 0.88 and 11.8% for SJs, and 0.93 and 7.4% for CMJs, suggesting an overall better reproducibility than that was

demonstrated in our study. However, Cronin et al. (8) assessed 2 successive jumps in a series of jumps (within-session) rather than 2 jumps performed on 2 separate days (between-session), with the smaller time frame between the test sessions likely explaining the greater reproducibility of performance measures reported by Cronin et al. (8), as verified elsewhere (11).

Our data clearly demonstrate that the reproducibility of parameters directly relating to the rate of force development (i.e., time to $F_{\max}$) was amongst the poorest in all 3 jump test modules examined here. These data confirm the earlier work by Hori et al. (22) who reported that although measures of

DISCUSSION

On the basis of commonly used ICC and CV thresholds, the between-day reproducibility of force-plate-derived parameters for the squat (ICC: 0.88 ± 0.06 , CV: $7.1 \pm 3.8\%$), countermovement (ICC: 0.84 ± 0.17 , CV: $5.9 \pm 4.1\%$), and standing long (ICC: 0.80 ± 0.13 , CV: $8.1 \pm 4.1\%$) jumps was overall acceptable when using the MARS. More precisely—although there are no universally accepted standards for classifying the reproducibility of measures as acceptable (45)—good relative (ICC ≥ 0.75) and adequate absolute (CV

peak power, force, and velocity from GRF registrations during SJs and CMJs were reproducible within a test session, measures of peak rate of force development and time-to-peak power were not. Here we extend these findings to the LJ and suggest that caution be taken when applying rate of force development outcomes to assess training interventions or training induced maladaptive processes, as has been reported previously (23,43).

The reiteration of the reproducibility of peak (vertical) power production, herein described as $P_{\max}$, is of note because whole-body peak power has been reported to be the single best predictor of vertical jump performance (1). The confirmation of the reproducibility of jump height within the jump tests also allows practitioners to be confident in the ability to track this particular measure, which has been directly associated with athletic performance (6,27) and measures of quality of life in the elderly (34). Here we also report the reproducibility of vertical and horizontal as well as negative and positive mechanical force parameters, which may be of importance when using asymmetry in kinetic parameters as a tool for athletic screening and assessing risk of injury (39,47).

Although jump test parameters derived from GRFs are often used as a “gold-standard” or reference criterion (8,16,36), extracting parameters from force-plates also has its limitations. In particular, the data manipulation required to extract the performance variables amplifies any noise in the raw signal (46), which increases the risk of accumulating error in results (12). Furthermore, assessments relying solely on GRF data require a minimum of 1 collection point where velocity is zero to accurately determine instantaneous velocity and hence calculate power through the impulse-momentum mathematical theorem (12,25). To address and minimize concerns regarding differences in technique and instruction, all subjects performed each jumping task barefoot with hands placed on hips, viewed the same standardized instructional video detailing acceptable take-off and landing technique, and received the same pre-jump commands from a single researcher. Indeed, it has been argued that the complex nature of jumping coordination with the arms makes this form of assessment unsuitable for characterizing the force producing properties of the lower limbs (26), and thereby restricting arm motion as performed in this study is believed to provide a more specific assessment of lower limb function.

Although comparing computational methods was not a formulated aim of this study, an apparent discrepancy existed between the vertical jump heights when calculated from the take-off velocity compared with the flight time. The influence of the computational approach implemented on the vertical height computed from SJs and CMJs has been reported elsewhere (9,25,36), confirming that the specific determination of jump test variables relies on the computational method chosen and limits the absolute comparability of published material using different methodologies.

Although the simplest method is to derive vertical jump height from flight time, using the force impulse approach tends to provide results that are more accurate (9,25). To increase cross-study comparisons and generalization of study findings, researchers are encouraged to report results from the 2 approaches or the between-method difference.

Similarly, despite the significant correlation between variables, a marked discrepancy was observed in the standing LJ distance measured from the propulsion of the center of gravity compared with the actual distance measured using a metric tape. These results are consistent with those reported by Papadopoulos et al. (33) where the mean horizontal displacement of the center of mass and of the toes calculated from kinematic variables was 73 ± 9 cm and 262 ± 21 cm, respectively, from standing LJs performed with free arm motion. The total horizontal distance covered during standing LJs is the sum of the distances from the take-off, flight, and landing phases, which are influenced by take-off angles and jumping techniques (44). Because of the complex nature of standing LJs, the mathematical assumptions required to estimate the displacement of the center of gravity, and the relative (i.e., ICC) and absolute (i.e., CV) reproducibility of the metric tape measurements vs. that from the force-plate, we propose that coaches and trainers use the metric tape method to assess LJ performance because it proves more practicable, objective, and reproducible.

Of note, however, is that the longest jump estimated using the horizontal propulsion of the center of gravity on the basis of force-plate data was not always the jump with the longest distance measured using the metric tape. Using the data from the LJs with the greatest metric tape measure instead of the greatest center of gravity displacement provided somewhat different results, with slightly lower reproducibility of LJ parameters from the MARS. The LJ parameters then had ICCs of 0.77 ± 0.12 (range: 0.42–0.91) and CVs of $8.9 \pm 4.8\%$ (range: 3.0–20.0%), with the relative reproducibility of the standing LJ measures being significantly less than that of the SJ ($p = 0.0118$), with a similar trend noted when compared with the CMJ ($p = 0.0522$). This change in the level of reproducibility of the standing LJ parameters is most likely associated with the level of specificity of the parameter used to define performance, i.e., the distance_{COG} was internal to the MARS but that the distance_{heel} was external to the MARS.

We acknowledge that the degree of reproducibility is relative to the frame of reference, susceptible to a learning effect, and influenced by the homogeneity of the study population (13)—all factors that can alter the interpretation of our study findings. For instance, it has been proposed that correlation indices characterizing the reproducibility of clinical measures should be above 0.70 (4,14), meaning that some of the jump test parameters derived herein should not be used in practical settings, or at least interpreted with caution. At the same time, it is highly probable that the reproducibility of our jump test parameters would improve

with further training, familiarization, or with highly (rather than recreationally) trained subjects, as reported elsewhere (10). Although shown for the SJ that a high degree of reproducibility in force parameters is obtained without the need for familiarization (30), jump performances of elite (rather than recreational) athletes quantified using the MARS would likely show a much better between-day reproducibility, even more so with standing LJ familiarization because this movement is uncommonly performed. In these latter circumstances, smaller changes in performance scores would be needed to highlight real changes in function.

PRACTICAL APPLICATIONS

Based on traditional thresholds, the relative and absolute reproducibility of several jump test performance parameters derived using the MARS were classified as adequate for squat, countermovement, and standing long jump assessments. The relative (i.e., ICC) and absolute (i.e., CV) reproducibility of measures were high for nearly all of the SJ, three-quarters of the CMJ, and two-thirds of the standing LJ parameters, suggesting that the MARS is practically useful for monitoring individuals and quantifying changes in performance. However, the parameters directly relating to the rate of force development and change in momentum during the countermovement phase of jumps showed lower reproducibility. Hence, our findings suggest that most jump test parameters extracted from the MARS are reproducible and can be used with confidence by strength and conditioning coaches, physiotherapists, and researchers to quantify changes in the functional ability of individuals over time, with the exception of parameters relating to the rate of force development and change in momentum during countermovement phases of jumps.

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