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Measurement of Absolute and Relative Reliability during the Countermovement and Split-Squat Jump using PUSH Pro Band 2.0

Kevin McCurdy, PhD[1], John Walker, PhD[1], David Pozuc, MS[1], Jordan Pitts, MS[1]

[1]*Texas State University, San Marcos, Texas, USA*

ABSTRACT

The purpose of this study was to determine the relative and absolute reliability using PUSH Pro Band 2.0 IMU to measure peak velocity and power during the countermovement (CMJ) and split-squat jump (SSJ). Twenty-three resistance trained males and females completed the study. After a familiarization session, each subject completed 2 identical sessions separated by a minimum of 72 hours that included 4 loads during the CMJ (body weight, body weight plus 20, 40 and 60%) and SSJ (body weight, body weight plus 15, 30 and 45%). In each session, 3 repetitions were completed at each load in randomized order with 3 minutes rest between sets and 5 minutes rest between jump types. Dumbbells held to the side were used to add load. A waist belt was worn that contained the accelerometer. High relative (intra-class coefficient ranging from 0.86-0.99) and absolute (coefficient of variation ranging from 1.7-8.0%) reliability were found for all measures of peak velocity and power during the CMJ and SSJ. The PUSH device produced highly reliable measures of jump performance across all loads between trials and across sessions.

Keywords: accelerometry, peak velocity, peak power, vertical jump

INTRODUCTION

Inertial measurement units (IMU) are commonly used to measure bar or body velocity during resistance exercise. The benefits include being low cost and user friendly while providing immediate feedback. With Bluetooth technology, the sensors have little to no restrictions to the exercise execution. However, accurate and consistent measures need to be evident before the use can be justified. PUSH PRO Band 2.0 (PUSH) (Push, Inc. Toronto, Canada) is a popular IMU that has been investigated for validity and reliability in several exercises (2,31,33). Still, the high rate of technological improvement warrants the need to analyze this technology on a frequent basis. With new updates to the software and after refining the algorithms, results may differ from previous findings.

The measurement of jump velocity is important to determine readiness prior to training, monitoring improvement, and optimum load for power performance. These measures require precise and consistent data. IMU reliability data may be affected by the mode of exercise and technique. The countermovement (CMJ) and split-squat jump (SSJ) are commonly implemented exercises to improve ballistic, athletic performance. Based on differences in the direction of the base of support, the CMJ provides medial-lateral stability while the SSJ is more stable anterior-posterior. Including both in training is important to provide differences in demands and subsequent adaptations. Specifically, the wide medial-lateral stance target activation of the sagittal plane musculature while the SSJ narrow base of support activates the musculature involved in frontal plane control to a greater degree (25,26). Added loads to the body weight during jump performance using these different bases of support to assess optimum loads used in training to improve power performance (21) further challenges jump execution. These added loads may affect the reliability of IMU measurements (33), thus these differences in loading conditions between the CMJ and SSJ require further analysis.

Free-weight resistance requires greater demand to control the execution in comparison to machine-weight resistance exercise (9). Resistance added to the body weight during jumps is often added with the weight held in the hands creating potential instability of the load (16). As noted, accuracy in IMU measures depend on algorithms developed from the repetitive movement pattern of the exercise. Although precise mechanics are attempted with free-weight resistance, these exercises likely differ more from the exact technique used to create the algorithm than machine exercises that control the movement pattern. IMU measures have become popular to assess performance of traditional resistance exercise (8) and jump performance (3,12,13,15,19,20,21,29,32,34). Differences in reliability in these previous studies are likely, in part, due to the demand to control the resistance. In a systematic review, Clemente et al. (8) reported inconsistent results when using PUSH technology in determining the validity and reliability in traditional resistance exercises such as the bench press, squat and rows. Balsalobre-Fernandez et al. (2) found good reliability in the smith machine squat while low reliability was found in the free-weight deadlift using PUSH IMU (6,17). The deadlift demands effort from the entire body while pulling the load from the floor, which may introduce greater error in technique compared to other free-weight exercises. Previous research findings (30) using a linear position transducer also support greater consistency when performing more stable, machine-based resistance exercise. For this reason, the freedom of motion presented with dumbbells held during jumps require further investigation to determine the repeatability of these exercises.

In addition to exercise stability, precise movement patterns may be affected by greater load as noted earlier, which is indicated by reduced reliability in the bench press from 45% 1RM [Intra-class correlation coefficient (ICC) = 0.69 and coefficient of variation (CV) = 5%] to ICC = 0.47 and CV = 19% at 85% 1RM (33). In support of this conclusion, Banyard et al. (4) found mean velocity to be valid using the PUSH device at loads under 80% 1RM during the free-weight squat and a significant decrease in reliability above 80% 1RM. Higher reliability has also been determined in the bench press up to 60% 1RM compared to 70-80% 1RM (30). Repeated jump landings with added loads present a high demand for control and require great precision for maximum performance. However, the effect of increasing load on the reliability of jump velocity and power in the CMJ and SSJ is currently unclear. Studies investigating reliability using the PUSH sensors during the CMJ have used only body weight (19,32). Montalvo et al. (32) (ICC ≥ 0.98) found the PUSH IMU to be highly reliable during the CMJ while Lake et al. (19) found good to high reliability (ICC between 0.7-0.83 and coefficient of variation of ~5%) for mean and peak velocity. However, the reliability of the SSJ using IMU technology is yet to determined.

Sensor position may also affect the reliability when using IMUs to measure velocity. PUSH IMUs have recently been developed with the freedom of choice to use either on the body or on the bar. A substantial amount of error has been found during the deadlift using bar mode (17). It is plausible that bar accelerations at higher velocities and when lifting heavy loads can cause the bar to bend with oscillations that would reduce reliability. For this reason, the sensor placed on the body may be more stable than using it on the bar. Contrasting this speculation, low reliability has also been found with the sensor placed on the forearm during the deadlift (6). However, PUSH technology during the time of this study had a sampling rate of 200 Hz, which may have had an impact on the reliability. Jumps are performed in body mode with the sensor worn in a waist belt. The difference in sensor location between jumps and other resistance exercises would suggest that generalizing PUSH reliability across exercise type is not best practice. Thus, when concluding reliability of the IMU technology, each exercise requires independent analysis to draw conclusions.

Minimal restrictions in movement patterns from measurement devices, afforded by IMU, is essential to allow maximum jump performance. Thus, it is necessary to better understand the ability of IMU technology to monitor jump performance. With a high demand to control the movement during the CMJ and SSJ under added load, reliability can reasonably be questioned. Therefore, the purpose of this study was to determine the reliability of peak velocity and power measures during the CMJ and SSJ with various loads using PUSH IMU technology.

METHODS

Subjects

Twenty-three, young adult males and females (age, 23.83 ± 1.72 years; height, 172.82 ± 8.15 cm; weight, 78.46 ± 14.1 kg) with an intermediate level of resistance training experience (4.52 ± 2.61 years) completed the study. Sample size was determined from Bonett's (5) estimation of correct sample size requirements for estimating the ICC. According to Bonett (5), the correct sample size for two trials with an ICC = 0.90 at alpha = 0.05 is 21 subjects while only 13 subjects would be needed for 3 trials. Consequently, 23 subjects were recruited for the study. The participants were required to have previous or current participation in athletic competition involving ballistic activity (jumping, agility, or running) for a minimum of 3 years. The participants also had to demonstrate proper technique during the exercises to be included in the study. Criteria for exclusion included any previous lower limb injury within the past 6 months or neuromuscular condition that would have prevented maximum effort and successful execution of jump performance. Each participant read and signed an informed consent form, which was approved by the university's internal review board. Completion of the study was on a volunteer basis.

PROCEDURES

Familiarization session.

The subjects provided age, height and weight measured during a familiarization session. Technique of the CMJ and SSJ was also practiced using body weight and light loads on the CMJ and SSJ. The subjects were informed to refrain from lower extremity resistance training and any strenuous exercise a minimum of 72 hours prior to reporting for all test sessions. The participants were also instructed to maintain normal dietary habits, get a normal and adequate amount of sleep, and eliminate the consumption of alcohol and caffeine 24 hours before data collection. Finally, subjects were also instructed to wear similar clothing typically worn for exercise and athletic performance in each session.

Jump Testing

The participants reported for 2 identical data-collection sessions separated by a minimum of 72 hours. In each session, the participants completed the CMJ and SSJ tests. Prior to the jumps, a 5-min jog was completed followed by a 10-minute dynamic warm-up and light stretching. After securing a belt containing a small sensor around the waist, the participants completed 3 continuous vertical jumps during each type of jump. The jump type and load were randomized with the participants completing all 4 loads within a jump type before attempting the jumps of the other jump type. Body weight and a load of 20%, 40%, and 60% body weight were completed for the CMJ while SSJ loads included body weight, 15%, 30%, and 45% body weight. Dumbbells, held in the hands to the side, were used to add load while the body-weight jumps were executed with hands on the hips. Each set of 3 repetitions was separated with 3 minutes of rest while 5 minutes was taken between exercise type. Peak velocity and peak power were analyzed for reliability between repetitions and between sessions.

The CMJ was completed with a hip-width stance. A successful jump was determined if the participant jumped and landed in the same location while continuously jumping without hesitation or losing balance. The participants were instructed to give maximum effort with each jump while reaching a comfortable depth that would produce the highest jump. Maintaining elbow extension, holding the dumbbells to the side of the body, and eliminating a shoulder shrug were also monitored as criteria for a successful jump. Similar procedures occurred during the SSJ, but the subject started in a hip width stance before cycling into alternating the lead leg. The right leg was the first lead leg in all trials.

IMU technology

PUSH Band 2.0 is a wearable sensor with a 3-axis accelerometer and gyroscope providing 6 degrees of freedom to calculate vertical velocity from proprietary algorithms. The data was captured on an iPad (Apple Inc.) using Bluetooth through an application (Application version 7.18.0). The data was collected at a sampling rate of 1000 Hz and smoothed using a Butterworth filter. No calibration was required. Peak velocity and power from the 3 repetitions were compared across each repetition to determine reliability while the mean of the 3 repetitions was used to determine test-retest reliability.

Statistical Analyses

The normality for each measure across each session and each body weight load was determined from the Shapiro-Wilk test of normality. A probability value greater than 0.05 indicates a distribution that is not significantly different from normal. For the CMJ, the probability values reported from each Shapiro-Wilk test for normality, as well as the descriptive values for peak velocity and peak power, are reported in Tables 1 and 2, respectively. For the SSJ, those values are reported in Tables 3 and 4. As reported in Table 3, for peak velocity of the right-leg during the SSJ in the first session with body weight + 45%, the distribution of these scores was significantly different from normal (W = 0.91, p = 0.04); consequently, reliability was not calculated for this measure. All other measures for each session and body weight load were not significantly different from normal, and appropriate for parametric analysis.

Relative reliability was determined from the ICC. The interpretation of ICCs has varied in previous research. Cicchetti (7) offered the following standards: r < 0.70, unacceptable; 0.70 < r < 0.80, fair; 0.80 < r < 0.90, good; r > 0.90, excellent. Ninety-five percent confidence intervals were also calculated for each ICC (1).

Absolute reliability was determined by the calculation of the standard error of measurement (SEM), smallest real difference (SRD) and CV% within subjects. The SEM is the average measurement error across trials, and was calculated as SD x $\sqrt{1 - \text{ICC}}$ (1). SEM% was calculated as the SEM divided by the overall mean, multiplied by 100 to provide a percentage value. Within each session, the overall mean was the average across the 3 trials. Between sessions, the overall mean was the average of both sessions. SEM% is useful for comparing measurement error between tests with different scales and units of measurement. SRD was calculated as 1.96 x SEM x $\sqrt{2}$, and represents a real change score at the 95% confidence level (22). SRD% was calculated as SRD divided by the overall mean, multiplied by 100 to provide a percentage value (14). The SRD% is also independent of the scale and unit of measurement, and indicates the limit for the smallest change that represents a real change for a single subject. The CV% represents the precision of a single measurement, expressed as a percent of individual mean values, and was calculated as (wSD / individual overall mean) x 100 (10), where wSD is the standard deviation within subjects across trials.

In addition, systematic bias across mean differences was checked by paired t-tests determining whether the mean difference values between the first and second session were significantly different from zero (22). These t-tests determine whether there is a systematic mean difference between the first and second sessions. Heteroscedasticity was determined by Pearson product-moment correlation coefficients comparing the overall mean for both sessions against the difference between the first and second session (1). All statistical tests were conducted with an alpha level of .05, with SPSS 27.0 (SPSS Inc, Chicago, IL, USA).

RESULTS

For the CMJ, the descriptive values for peak velocity and peak power are reported in Tables 1 and 2, respectively. These values include means, standard deviations (SD), standard errors (SE), and 95% confidence intervals for each mean, as well as the probability values reported from each Shapiro-Wilk test for normality.

Table 1. Descriptive Values for Peak Velocity (m*sec^{-1}) for the Counter Movement Jump

	n	Mean	SE	SD	95% CI	Normal*
First Session						
Body Weight Only	23	2.50	0.07	0.35	2.35 - 2.66	0.38
Body Weight + 20%	23	2.32	0.07	0.35	2.17 - 2.47	0.58
Body Weight + 40%	23	2.06	0.07	0.34	1.91 - 2.20	0.49
Body Weight + 60%	23	1.78	0.07	0.34	1.63 - 1.92	0.43
Second Session						
Body Weight Only	23	2.53	0.07	0.32	2.39 - 2.67	0.34
Body Weight + 20%	23	2.31	0.07	0.35	2.16 - 2-46	0.62
Body Weight + 40%	23	2.05	0.07	0.34	1.91 - 2.20	0.25
Body Weight + 60%	23	1.75	0.07	0.35	1.59 - 1.90	0.21

Note. * p-value for Shapiro-Wilk test for Normality

Table 2. Descriptive Values for Peak Power (watts) for the Counter Movement Jump

	n	Mean	SE	SD	95% CI	Normal*
First Session						
Body Weight Only	23	3503	307	1476	2865 - 4142	0.39
Body Weight + 20%	23	3360	292	1403	2753 - 3967	0.97
Body Weight + 40%	23	3233	270	1296	2673 - 3794	0.48
Body Weight + 60%	23	2898	238	1139	2406 - 3391	0.09
Second Session						
Body Weight Only	23	3554	300	1438	2932 - 4175	0.29
Body Weight + 20%	23	3464	284	1362	2875 - 4053	0.41
Body Weight + 40%	23	3226	269	1290	2668 - 3784	0.38
Body Weight + 60%	23	2968	249	1195	2452 - 3485	0.42

Note. * p-value for Shapiro-Wilk test for Normality

The same descriptive values are reported for the SSJ in Tables 3 and 4. As mentioned previously, the distribution of peak velocity SSJ measures during the first session for the right leg with body weight +45% was significantly different from normal, and was excluded from the analysis. All other distributions across each session and leg were not significantly different from normal, and reliability statistics were calculated for each.

Table 3. Descriptive Values for Peak Velocity (m*sec^{-1}) for the Split Squat Jump

First Session	n	Mean	SE	SD	95% CI	Normal*
Right Leg						
Body Weight Only	23	2.15	0.07	0.33	2.01 - 2.29	0.16
Body Weight + 15%	23	2.04	0.06	0.30	1.91 - 2.17	0.31
Body Weight + 30%	23	1.89	0.05	0.25	1.78 - 2.00	0.98
Body Weight + 45%	23	1.80	0.05	0.26	1.69 - 1.92	0.04
Left Leg						
Body Weight Only	23	2.15	0.06	0.29	2.03 - 2.27	0.91
Body Weight + 15%	23	2.01	0.06	0.31	1.88 - 2.15	0.56
Body Weight + 30%	23	1.87	0.06	0.27	1.76 - 1.99	0.53
Body Weight + 45%	23	1.80	0.05	0.25	1.70 - 1.91	0.19
Second Session	n	Mean	SE	SD	95% CI	Normal*
Right Leg						
Body Weight Only	23	2.12	0.06	0.29	2.00 - 2.25	0.87
Body Weight + 15%	23	2.03	0.06	0.29	1.90 - 2.15	0.13
Body Weight + 30%	23	1.89	0.06	0.28	1.77 - 2.01	0.79
Body Weight + 45%	23	1.78	0.05	0.25	1.67 - 1.89	0.27
Left Leg						
Body Weight Only	23	2.10	0.06	0.29	1.98 - 2.23	0.23
Body Weight + 15%	23	2.03	0.06	0.29	1.91 - 2.16	0.14
Body Weight + 30%	23	1.88	0.06	0.28	1.75 - 2.00	0.08
Body Weight + 45%	23	1.79	0.05	0.24	1.64 - 1.85	0.15

Note. * p-value for Shapiro-Wilk test for Normality

Table 4. Descriptive Values for Peak Power (watts) for the Split Squat Jump

First Session	n	Mean	SE	SD	95% CI	Normal*
Right Leg						
Body Weight Only	23	2317	176	845	1952 - 2683	0.34
Body Weight + 15%	23	2540	219	1052	2085 - 2994	0.11
Body Weight + 30%	23	2557	202	969	2138 - 2976	0.80
Body Weight + 45%	23	2571	205	985	2145 - 2998	0.19
Left Leg						
Body Weight Only	23	2301	179	860	1929 - 2673	0.13
Body Weight + 15%	23	2432	209	1001	2000 - 2865	0.79
Body Weight + 30%	23	2513	203	971	2093 - 2933	0.26
Body Weight + 45%	23	2515	211	1014	2076 - 2953	0.35
Second Session	n	Mean	SE	SD	95% CI	Normal*
Right Leg						
Body Weight Only	23	2290	176	845	1925 - 2656	0.48
Body Weight + 15%	23	2437	188	904	2046 - 2828	0.69
Body Weight + 30%	23	2470	197	945	2062 - 2879	0.89
Body Weight + 45%	23	2460	195	933	2056 - 2864	0.41
Left Leg						
Body Weight Only	23	2242	174	835	1881 - 2603	0.45
Body Weight + 15%	23	2418	179	859	2047 - 2789	0.81
Body Weight + 30%	23	2376	181	868	2001 - 2752	0.54
Body Weight + 45%	23	2377	171	822	2022 - 2732	0.36

Note. * p-value for Shapiro-Wilk test for Normality

The relative and absolute reliability statistics for the CMJ for peak velocity are reported in Table 5. The ICCs within each session (0.98 to 0.99) and between sessions (0.97 to 0.98) were extremely high, and the CV%s within each session (1.7 to 2.4%) and between sessions (1.9 to 3.2%), were very low. Tables 5-10 also reveal the standard error of measurement (SEM) and smallest real difference (SRD).

Table 5. Relative and Absolute Reliability for Peak Velocity (m*sec^{-1}) for the Counter Movement Jump

	Comparison Across Three Trials Within Each Session						
	ICC	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
First Session							
Body Weight Only	0.99	0.98 - 0.99	0.035	1.4	0.097	3.9	1.7
Body Weight + 20%	0.99	0.99 - 0.99	0.035	1.5	0.097	4.2	1.7
Body Weight + 40%	0.99	0.98 - 0.99	0.034	1.7	0.094	4.6	2.2
Body Weight + 60%	0.99	0.98 - 0.99	0.034	1.9	0.094	5.3	2.4
Second Session							
Body Weight Only	0.98	0.95 - 0.99	0.045	1.8	0.125	4.9	2.3
Body Weight + 20%	0.99	0.98 - 0.99	0.035	1.5	0.097	4.2	1.7
Body Weight + 40%	0.99	0.98 - 0.99	0.034	1.7	0.09	4.6	2.1
Body Weight + 60%	0.99	0.98 - 0.99	0.035	2.0	0.097	5.5	2.4
	Comparison Between the First and Second Session						
	ICC	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Body Weight Only	0.98	0.95 - 0.99	0.046	1.8	0.128	5.1	1.9
Body Weight + 20%	0.97	0.93 - 0.99	0.059	2.6	0.164	7.1	2.6
Body Weight + 40%	0.98	0.94 - 0.99	0.047	2.3	0.130	6.3	2.5
Body Weight + 60%	0.98	0.95 - 0.99	0.048	2.7	0.133	7.6	3.2

To test for heteroscedasticity in CMJ peak velocity, the correlation between the difference in the first and second sessions and the mean peak velocity across both sessions was calculated. Heteroscedasticity was not observed for body weight only (r = 0.24, p = 0.25), body weight +20% (r = 0.01, p = 0.99), body weight +40% (r = 0.02, p = 0.91), or body weight +60% (r = 0.11, p = 0.63). Also, to test for systematic bias, paired t-tests comparing the means for the first and second sessions were calculated. The mean differences between the first and second sessions were not significantly different from zero for body weight only (t_{22} = 0.78, p = 0.37), body weight +20% (t_{22} = 0.20, p = 0.58), body weight +40% (t_{22} = 0.02, p = 0.49), or body weight +60% (t_{22} = 1.30, p = 0.10). The results of these tests indicate very reliable measurement of peak velocity, with no significant heteroscedasticity or systematic bias for the CMJ.

The relative and absolute reliability statistics for the CMJ for peak power are reported in Table 6. The ICCs within each session (0.98 to 0.99) and between sessions (0.97-0.98) were extremely high, and the CV%s within each session (2.2 to 5.5%) and between sessions (3.8 to 6.6%), were low.

For peak power for the CMJ, heteroscedasticity was not observed for body weight only (r = 0.08, p = 0.71), body weight +20% (r = 0.07, p = 0.74), body weight +40% (r = 0.02, p = 0.92), or body weight +60% (r = 0.16, p = 0.46). Also, to test for systematic bias, the mean difference between the first and second sessions was not significantly different from zero for body weight only (t22 = 0.55, p = 0.29), body weight +20% (t22 = 0.65, p = 0.26), body weight +40% (t22 = 1.11, p = 0.14), or body weight +60% (t22 = 1.15, p = 0.13). The results of these tests indicate very reliable measurement of peak power for the CMJ, with no significant heteroscedasticity or systematic bias.

The relative and absolute reliability statistics for the SSJ for peak velocity are reported in Tables 7 and 8, respectively. Comparing the three trials within each session (Table 7), the ICCs for each leg for the first session (0.94 to 0.98) and second session (0.93 to 0.96) were very high, and the CV%s for the first session (2.5 to 4.1%) and second session (3.3 to 4.5%), were very low.

Comparing SSJ peak velocity between the first and second sessions (Table 8), the ICCs for the right leg (0.86 to 0.94) and left leg (0.87 to 0.94) were slightly lower than the values within each session, but were still very high, and the CV%s for the right leg (3.2 to 3.9%) and left leg (3.1 to 4.0%), were also very low.

For peak velocity for the right leg SSJ, heteroscedasticity was not observed for body weight only (r = 0.17, p = 0.43), body weight +15% (r = 0.07, p = 0.76), or body weight +30% (r = 0.24, p = 0.26). Also, the mean difference between the first and second sessions was not significantly different from zero for body weight only (t_{22} = 0.58, p = 0.28), body weight +15% (t_{22} = 0.44, p = 0.33), or body weight +30% (t_{22} = 0.05, p = 0.48). The results of these tests indicate very reliable measurement of peak velocity for the right leg SS jump, with no significant heteroscedasticity or systematic bias. Similar results for heteroscedasticity were found for the left leg.

The relative and absolute reliability statistics for the SSJ for peak power are reported in Tables 9 and 10, respectively. Comparing the three trials within each session (Table 9), the ICCs for each leg for the first session (0.97 to 0.98) and second session (0.96 to 0.98) were extremely high, and the CV%s for the first session (4.7 to 7.6%) and second session (5.1 to 8.0%), were low.

Table 6. Relative and Absolute Reliability for Peak Power (watts) for the Counter Movement Jump

	Comparison Across Three Trials Within Each Session						
	ICC	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
First Session							
Body Weight Only	0.99	0.98 - 0.99	147.6	4.2	409.1	11.7	4.2
Body Weight + 20%	0.98	0.96 - 0.99	198.4	5.9	549.9	16.4	5.5
Body Weight + 40%	0.99	0.99 - 0.99	129.6	4.0	359.2	11.1	2.2
Body Weight + 60%	0.99	0.98 - 0.99	113.9	3.9	315.7	10.9	3.9
Second Session							
Body Weight Only	0.99	0.97 - 0.99	143.8	4.0	398.6	11.2	5.1
Body Weight + 20%	0.99	0.98 - 0.99	136.2	3.9	377.5	10.9	3.5
Body Weight + 40%	0.99	0.99 - 0.99	129.0	4.0	357.6	11.1	3.6
Body Weight + 60%	0.99	0.99 - 0.99	119.5	4.0	331.20	11.2	3.8
	Comparison Between the First and Second Session						
	ICC	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Body Weight Only	0.97	0.93 - 0.99	248.9	7.1	689.8	19.5	4.6
Body Weight + 20%	0.98	0.94 - 0.99	191.3	5.6	530.3	15.5	6.6
Body Weight + 40%	0.98	0.95 - 0.99	181.8	5.6	504.0	15.6	3.8
Body Weight + 60%	0.98	0.92 - 0.99	163.3	5.6	452.6	15.4	5.0

Table 7. Relative and Absolute Reliability for Peak Velocity (m*sec-1) for the Split Squat Jump

Comparison Across Three Trials Within Each Session							
First Session	**ICC**	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Right Leg							
Body Weight Only	0.98	0.96 - 0.99	0.047	2.2	0.130	6.1	2.9
Body Weight + 15%	0.97	0.93 - 0.99	0.052	2.6	0.144	7.1	3.0
Body Weight + 30%	0.94	0.88 - 0.97	0.061	3.2	0.169	9.0	3.9
Left Leg							
Body Weight Only	0.97	0.94 - 0.99	0.050	2.3	0.139	6.5	2.5
Body Weight + 15%	0.96	0.92 - 0.98	0.062	3.1	0.172	8.6	3.6
Body Weight + 30%	0.96	0.91 - 0.98	0.054	2.9	0.150	8.0	3.6
Body Weight + 45%	0.94	0.89 - 0.97	0.061	3.4	0.169	9.4	4.1
Second Session	**ICC**	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Right Leg							
Body Weight Only	0.95	0.90 - 0.98	0.065	3.1	0.180	8.5	3.7
Body Weight + 15%	0.96	0.92 - 0.98	0.058	2.9	0.161	7.9	3.3
Body Weight + 30%	0.95	0.90 - 0.98	0.063	3.3	0.174	9.2	3.9
Body Weight + 45%	0.95	0.89 - 0.98	0.056	3.1	0.155	8.7	3.9
Left Leg							
Body Weight Only	0.96	0.91 - 0.98	0.058	2.8	0.161	7.7	3.4
Body Weight + 15%	0.95	0.91 - 0.98	0.065	3.2	0.180	8.9	3.5
Body Weight + 30%	0.93	0.85 - 0.97	0.074	3.9	0.205	10.9	4.5
Body Weight + 45%	0.93	0.86 - 0.97	0.064	3.7	0.176	10.1	4.4

Table 8. Relative and Absolute Reliability for Peak Velocity (m*sec^{-1}) for the Split Squat Jump

	Comparison Between the First and Second Session						
	ICC	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Right Leg							
Body Weight Only	0.86	0.77 - 0.94	0.109	5.1	0.301	14.1	3.3
Body Weight + 15%	0.94	0.85 - 0.97	0.069	3.4	0.190	9.4	3.2
Body Weight + 30%	0.94	0.86 - 0.98	0.064	3.4	0.177	9.3	3.9
Left Leg							
Body Weight Only	0.92	0.82 - 0.97	0.079	3.7	0.220	10.3	3.1
Body Weight + 15%	0.94	0.87 - 0.98	0.071	3.5	0.197	9.7	3.5
Body Weight + 30%	0.91	0.79 - 0.96	0.078	4.2	0.216	11.6	3.8
Body Weight + 45%	0.87	0.79 - 0.95	0.083	4.7	0.230	13.0	4.0

For peak velocity for the right leg SSJ, heteroscedasticity was not observed for body weight only (r = 0.17, p = 0.43), body weight +15% (r = 0.07, p = 0.76), or body weight +30% (r = 0.24, p = 0.26). Also, the mean difference between the first and second sessions was not significantly different from zero for body weight only (t_{22} = 0.58, p = 0.28), body weight +15% (t_{22} = 0.44, p = 0.33), or body weight +30% (t_{22} = 0.05, p = 0.48). The results of these tests indicate very reliable measurement of peak velocity for the right leg SS jump, with no significant heteroscedasticity or systematic bias. Similar results for heteroscedasticity were found for the left leg.

The relative and absolute reliability statistics for the SSJ for peak power are reported in Tables 9 and 10, respectively. Comparing the three trials within each session (Table 9), the ICCs for each leg for the first session (0.97 to 0.98) and second session (0.96 to 0.98) were extremely high, and the CV%s for the first session (4.7 to 7.6%) and second session (5.1 to 8.0%), were low.

Comparing SSJ peak power between the first and second sessions (Table 10), the ICCs for the right leg (0.86 to 0.94) and left leg (0.90 to 0.94) were also not as high as the values within each session, but still mostly high, and the CV%s for the right leg (4.9 to 7.1%) and left leg (5.8 to 7.6%), were also low.

For peak power for the right leg SSJ, heteroscedasticity was not observed for body weight only (r = .01, p = 0.99), body weight +15% (r = 0.37, p = 0.08), body weight +30% (r = 0.05, p = 0.81), or body weight + 45% (r = 0.10, p = 0.67). Also, the mean differences between the first and second sessions were not significantly different from zero for body weight only (t_{22} = 0.32, p = 0.37), body weight +15% (t_{22} = 1.21, p = 0.12), body weight +30% (t_{22} = 0.90, p = 0.19), or body weight + 45% (t_{22} = 0.94, p = 0.18). Similar results for heteroscedasticity were found for the left leg.

Table 9. Relative and Absolute Reliability for Peak Power (watts) for the Split Squat Jump

Comparison Across Three Trials Within Each Session							
First Session	**ICC**	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Right Leg							
Body Weight Only	0.98	0.96 - 0.99	119,5	5.2	331.2	14.3	5.8
Body Weight + 15%	0.98	0.98 - 0.99	105.2	4.1	291.6	11.5	4.7
Body Weight + 30%	0.98	0.97 - 0.99	96.9	3.8	268.6	10.5	5.7
Body Weight + 45%	0.98	0.95 - 0.99	139.3	5.4	386.1	15.0	6.2
Left Leg							
Body Weight Only	0.98	0.94 - 0.99	121.6	5.3	337.1	14.7	5.4
Body Weight + 15%	0.98	0.97 - 0.99	141.6	5.8	392.4	16.1	6.0
Body Weight + 30%	0.97	0.94 - 0.99	168.2	6.7	466.2	18.6	7.6
Body Weight + 45%	0.98	0.96 - 0.99	143.4	5.7	397.5	15.8	6.3
Second Session	**ICC**	**95% CI**	**SEM**	**SEM%**	**SRD**	**SRD %**	**CV %**
Right Leg							
Body Weight Only	0.97	0.94 - 0.99	146.4	6.4	405.7	17.7	7.0
Body Weight + 15%	0.98	0.97 - 0.99	127.8	5.3	354.4	14.5	5.1
Body Weight + 30%	0.98	0.95 - 0.99	133.6	5.4	370.4	15.0	7.1
Body Weight + 45%	0.96	0.91 - 0.98	186.6	7.6	517.2	21.0	8.0
Left Leg							
Body Weight Only	0.98	0.96 - 0.99	118.1	5.5	327.3	14.6	6.1
Body Weight + 15%	0.98	0.96 - 0.99	121.5	5.0	336.7	13.9	6.1
Body Weight + 30%	0.96	0.93 - 0.98	173.6	7.3	481.2	20.3	7.5
Body Weight + 45%	0.96	0.92 - 0.98	164.4	6.9	455.7	19.2	6.2

Table 10. Relative and Absolute Reliability for Peak Power (watts) for the Split Squat Jump

	Comparison Between the First and Second Session						
	ICC	95% CI	SEM	SEM%	SRD	SRD %	CV %
Right Leg							
Body Weight Only	0.86	0.77 - 0.94	201.1	8.7	557.3	24.2	6.4
Body Weight + 15%	0.94	0.85 - 0.97	214.6	8.6	594.7	23.9	4.9
Body Weight + 30%	0.94	0.86 - 0.98	227.5	9.1	630.7	25.1	6.4
Body Weight + 45%	0.91	0.78 - 0.96	289.9	11.5	803.5	31.9	7.1
Left Leg							
Body Weight Only	0.92	0.82 - 0.97	201.9	8.9	559.7	24.6	5.8
Body Weight + 15%	0.94	0.87 - 0.98	237.7	9.8	658.8	27.2	6.1
Body Weight + 30%	0.91	0.79 - 0.96	264.8	10.8	734.0	30.0	7.6
Body Weight + 45%	0.90	0.78 - 0.96	278.9	11.4	773.0	31.6	6.3

DISCUSSION

PUSH IMUs were found to produce good to excellent relative reliability (ICC between 0.86-0.99) across within-session trials and between sessions for peak velocity and power during the CMJ and SSJ. Absolute reliability was also high, measured by the low CV% (1.7-8.0) across all trials and sessions. Further indication of high absolute reliability was revealed by the lower CV% in all comparisons to the SRD%, which is calculated from the SEM and is a measure of a real difference between scores. PUSH IMU accuracy is based on the development of exercise-specific algorithms that are continuously being refined and updated. A recent upgrade with this technology included an increase in sampling frequency from 200 to 1000 Hz, which warrants a need for continuous analysis of reliability. Our results are in-agreement with previous research that investigated CMJ performance using PUSH technology (19,32). However, these studies only measured reliability between trials while our study reported reliability between trials and sessions. Also different from our study, Montalvo et al. (32) analyzed jump height and reactive strength index (jump height/contact time) during the CMJ. The authors found similar ICC values with slightly higher CV% (5.4-8.9) using the same sampling rate that was used in our study (1000 Hz). Using an earlier version of the software that sampled at 200 Hz, Lake et al. (19) found slightly lower mean and peak velocity ICC of 0.83 in the CMJ. While mixed results have been demonstrated in previous studies using the PUSH devices on various resistance training exercises (6,17,28,33,35), the current findings indicate that consistent peak velocity and power can be obtained during the CMJ and SSJ.

Our findings showed that peak velocity and peak power was highly reliable across all loads during the CMJ and SSJ. A reduction in reliability with increasing loads ranging from a CV of 5.2% at 45% 1RM to 19% at 85% 1RM has been previously reported during the bench press (33). These subjects were untrained which may be a significant factor when using heavy loads. In support of this speculation, Lake et al. (19) found high reliability during a body-weight CMJ in men and women athletes of various sports using PUSH IMU. In addition, high reliability was found in participants with previous plyometric training (32), but the CMJ was also performed only with body weight. The training experience of our participants was similar to the participants in Montalvo et al. (32) lending support that training experience may influence the reliability of jumps at higher loads. While high loads may be a factor that increases the difficulty level in controlling a jump, take-off velocity and jump height is reduced, which likely minimizes the demand to control the landing. To further test this speculation, the effect of training experience and load on jump reliability requires further investigation.

The stability of the exercise mode may also be a factor determining the reliability; however, our data support that minimal error in technique occurred in both exercises. Machines that control the path of motion have been shown to produce greater reliability than free-weight resistance when analyzing velocity (30). High reliability has been determined using PUSH sensors to measure mean and peak velocity during the smith-machine bench, squat, and bench pull (2,11) while mixed results have been found using PUSH in free-weight exercises (6,17,18). A higher demand to control the free-weight resistance may reduce the reliability, supported by research investigating the mean velocity during the deadlift with the sensor placed on the forearm (6) and the bar (17). Deadlift technique can vary significantly as heavy loads are suspended from the arms in front of the body requiring high demand from the core and lower body for stability. Greater muscle activity found in the free-weight bench press compared to the machine chest press was suggested by the authors to occur due to a greater demand to control the free weight (9) but could also result in inconsistent execution. In contrast, Lake et al. (18) found high reliability for mean velocity during the free-weight bench press. Due to differences in stability and technique between all free-weight exercises, measurement error likely varies for each exercise with variations dependent on the measurement device. Our subjects were able to perform the free-weight jumps with consistent performance possibly due to their training status, which may also partly explain differences in results from previous studies.

While the CMJ and SSJ are ballistic actions and free-weight resistance exercises, the PUSH sensor is secured in a waist belt that may reduce the error in measurement with placement near the body's center of mass in comparison to placing the sensor on a bar or distal limb required by other free-weight exercises (6,17,35). In addition, dumbbells were held to the side of the body with extended arms. Our instructions to avoid a shoulder shrug and flexion of the elbow was intended to isolate the use of the core and lower body to perform the jumps, which likely minimized errors in jump technique. In addition, loads held below the waist lowers the body's center of mass, a factor that likely improves the ability to produce a consistent landing and take-off. In contrast, only moderate reliability (root mean square error of 0.42) was found during a CMJ with a loaded free-weight bar placed on the shoulders in a previous study (20). Loads placed on the shoulders raise the center of mass, which likely reduces the precision of force production during jump performance.

Stability is also affected by the base of support that differs in the CMJ and SSJ. While the CMJ likely creates more medial-lateral stability, the SSJ has a more stable anterior-posterior base of support. Although the SSJ is a commonly used resistance exercise in recent years, this is the first known study to assess the reliability of the SSJ velocity and power. The CMJ is bilateral while the SSJ is utilized to create primarily a unilateral-based, loading condition similar to those encountered in many sport actions and is specifically used to improve frontal plane control (27). The greater demand in the frontal plane during exercise with a split-squat-jump stance is evident with the narrow base of support and is supported by greater muscle activation in the trunk, hip and knee that control motion in the frontal plane (24,25). Even with these differences between jump types, there appeared to be no difference in the ability to execute the jumps as it was rare for participants to lose balance requiring to dismiss and repeat the trial. With loss of balance the ability to maximize force is reduced, thus velocity of the jump would have been altered (23). However, our data revealed highly reproducible peak velocity and power with both types of jumps across all loads indicating balance disturbance was not a factor.

There were limitations of this study that need to be noted. Depth of the descent was not controlled. The participants were instructed to reach a consistent depth that would produce the highest jump. With prior jump-training experience, the participants jumped using their natural jump technique. Control in technique involved monitoring that the arms were completely extended with the dumbbells held close to the side of the body the entire jump. We also monitored the shoulder to make sure that a shoulder shrug did not occur during the ascent to improve jump consistency and minimize movement of the dumbbells. Only 3 repetitions were executed, thus the reproducibility cannot be generalized for higher repetitions in a set that would involve a greater level of fatigue. Finally, by adding weight based on percentage of body weight, relative intensity was not controlled.

CONCLUSION

The PUSH IMU produced excellent relative and absolute reliability for peak velocity and power during the CMJ and SSJ across all loads. Peak measures of each jump were analyzed since they are arguably a better indication of jump performance than mean scores. Differences in stability did not appear to affect the results. The data is reliable across a set of 3 consecutive jumps and between sessions separated by several days. Peak velocity and power are indicators of jump performance that can be measured using the PUSH IMU to detect change in jump performance over time with confidence that any observed change included minimal measurement error. Finally, the use of dumbbells appears to be an acceptable method of adding resistance to the jumps while still producing consistent results.

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REFERENCES

1. Atkinson G, and Nevill A. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med. 16: 217-238, 1998.
2. Balsalobre-Fernandez C, Kuzdub M, Poveda-Ortiz P, and Del Campo-Vecino J. Validity and reliability of the push wearable device to measure movement velocity during the back squat exercise. J Strength Cond Res 30: 1968-1974, 2016.
3. Bampouras T.M, Relph N.S, Orme D, and Esformes J.I. Validity and reliability of the myotest pro wireless accelerometer in squat jumps. Isokinet Exerc Sci 21: 101–105, 2013.
4. Banyard HG, Nosaka K, Sato K, and Haff GG. Validity of various methods for determining velocity, force and power in the back squat. Int J Sports Physiol Perform 12: 1170–1176, 2017.
5. Bonett D. Sample size requirements for estimating intraclass correlations with desired precision. Stat Med. 21: 1331-1335, 2002.
6. Chery C, and Ruf L. Reliability of the load-velocity relationship and validity of the push to measure velocity in the deadlift. J Strength Cond Res 33: 2370-2380, 2019.
7. Cicchetti D. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychol Assess. 6: 284-290, 1994.
8. Clemente F, Akyildiz Z, Pino-Ortega J, and Rico-Gonzalez M. Validity and reliability of the inertial measurement unit for barbell velocity assessments: a systematic review. Sensors 21: 2511, https://doi.org/10.3390/s21072511, 2021.
9. Coratella G, Tornatore G, Longo S, Esposito F, and Ce E. Specific prime movers' excitation during free-weight bench press variations and chest press machine in competitive bodybuilders. Eur J Sport Sci 20: 571-579, 2020.
10. Cormack S, Newton R, McGuigan M, and Doyle T. Reliability of measures obtained during single and repeated countermovement jumps. Int J Sports Physiol Perform. 3: 131-144, 2008.
11. Courel-Ibanez J, Martinez-Cava A, Moran-Navarro R, Escribano-Penas P, Chavarren-Cabrero J, Gonzalez-Badillo J, and Pallares J. Reproducibility and repeatability of five different technologies for bar velocity measurement in resistance training. Ann Biomed Eng. https://doi.org/10.1007/s10439-019-02265-6, 2019
12. Fathian R, Khandan A, Chiu L, and Rouhani H. Assessment of countermovement jump with and without arm swing using a single inertial measurement unit. Sports Biomech. doi: 10.1080/14763141.2022.2032296.
13. Ferro A, Flora P, Villacieros J, and Munoz-Lopez, A. Maximum velocity during loaded countermovement jumps obtained with an accelerometer, linear encoder and force platform: a comparison of technologies. J Biomech 95: 109281, doi: 10.1016/j.biomech.2019.07.025, 2019.
14. Flansbjer U, Holmback A, Downham D, Patton C, and Levell J. Reliability of gait performance tests in men and women with hemiparesis after stroke. J Rehabil Med. 37: 75-82, 2005.
15. Heredia-Jimenez J, and Orantes-Gonzalez E. Comparison of three different measurement systems to assess the vertical jump height. Rev Bras Med Esporte. 26: 143-146, 2020.
16. Hicks D, Drummond C, and Williams K. Measurement agreement between Samozino's method and force plate force-velocity profiles during barbell and hexbar countermovement jumps. J Strength Cond Res 2020, Online Ahead of Print doi: 10.1519/JSC.0000000000004144.
17. Jovanovic M, and Jukic I. Within-unit reliability and between-units agreement of the commercially available linear position transducer and barbell-mounted inertial sensor to measure movement velocity. J Strength Cond Res 2020, Online Ahead of Print doi: 10.1519/JSC.0000000000003776
18. Lake J, Augustus S, Austin K, Comfort P, McMahon J, Mundy P, and Haff G. The reliability and validity of the bar-mounted push band tm 2.0 during bench press with moderate and heavy loads. J Sports Sci 37: 2685–2690, 2019.
19. Lake J, Augustus S, Austin K, Mundy P, McMahon J, Comfort P, and Haff G. The validity of the push band 2.0 during vertical jump performance. Sports 6: 140, doi: 10.3390/sports6040140,

2018.
20. Lorenzetti S, Lamparter T, and Lüthy F. Validity and reliability of simple measurement device to assess the velocity of the barbell during squats. BMC Res Notes 10: 707, doi: 10.1186/s13104-017-3012-z, 2017.
21. Loturco I, Nakamura F, Tricoli V, Kobal R, Abad C, Kitamura K, et al. PLOS ONE doi: 10.1371/journal.pone.0140102, 2015.
22. Lu Y, Lin J, Hsiao S, Liu M, Chen S, and Lue Y. The relative and absolute reliability of leg muscle strength testing by a handheld dynamometer. J Strength Cond Res. 25: 1065-1071, 2011.
23. McBride J, Cormie P, and Deane R. Isometric squat force output and muscle activity in stable and unstable conditions. J Strength Cond Res 20: 915-8, 2006.
24. McCurdy K, Kutz M, O'Kelley E, Langford G, and Ernest J. (2010). External oblique activity during the unilateral and bilateral free weight squat. Clin Kinesiol, 64(1), 16-21.
25. McCurdy K, O'Kelley E, Kutz M, Langford G, Ernest J, and Torres M. (2010). Comparison of lower extremity EMG activity between the two-leg squat and modified single-leg squat in female athletes. J Sport Rehabil, 19, 57-70.
26. McCurdy K, Walker J, and Yuen D. (2018). Gluteus maximus and hamstring activation during selected resistance exercises, J Strength Cond Res, 32(3), 594-601.
27. McCurdy K, and Conner, C. (2003). Unilateral support resistance training incorporating the hip and knee. Strength Cond J, 25(2), 45-51.
28. McGrath GA, Flanagan EP, O'Donovan P, Collins, D.J. and Kenny, IC. Velocity based training: validity of monitoring devices to assess mean concentric velocity in the bench press exercise. J Aus Strength Cond 26: 23–30, 2018.
29. McMaster D, Gill N, Cronin J, and McGuigan M. Is wireless accelerometry a viable measurement system for assessing vertical jump performance? Sports Technol. 6: 86–96, 2013.
30. Miller R, Freitas E, Heishman A, Koziol K, Galletti B, Kaur J, and Bemben G. Test-retest reliability between free weight and machine-based movement velocities J Strength Cond Res 34: 440-444, 2020.
31. Mitter B, Holbling D, Bauer P, Stockl M, Baca A, and Tschan H. Concurrent validity of field-based diagnostic technology monitoring movement velocity in powerlifting exercises. J Strength Cond Res 35: 2170-2178, 2021.
32. Montalvo S, Gonzalez M, Dietze-Hermosa M, Eggleston J, and Dorgo, S. Common vertical jump and reactive strength index measuring devices: a validity and reliability analysis. J Strength Cond Res 2021, Online Ahead of Print. doi:10.1519/JSC.0000000000003988.
33. Perez-Castilla A, Piepoli A, Delgado-Garcia G, Garrido-Blanca G, and Garcia-Ramos A. Reliability and concurrent validity of seven commercially available devices for the assessment of movement velocity at different intensities during the bench press. J Strength Cond Res 33: 1258-1265, 2019.
34. Picerno P, Camomilla V, and Capranica L. Countermovement jump performance assessment using a wearable 3D inertial measurement unit. J Sports Sci, 29: 139-146, 2011.
35. Van Den Tillaar R, and Ball N. Validity and reliability of kinematics measured with push band vs linear encoder in bench press and push-ups. Sports 7: 207, doi: 10.3390/sports7090207, 2019.