Validity and Reliability of a Wearable Inertial Sensor to Measure Velocity and Power in the Back Squat and Bench Press

Samuel T. Orange[1,2]*, James W. Metcalfe[1,2], Andreas Liefeith[2], Phil Marshall[1], Leigh A. Madden[3], Connor R. Fewster[4] and Rebecca V. Vince[1].

[1]Sport, Health and Exercise Science, School of Life Sciences, University of Hull, Hull, UK.

[2]School of Sport, York St John University, York, UK.

[3]Centre of Biomedical Research, School of Life Sciences, University of Hull, Hull, UK.

[4]Carnegie School of Sport, Leeds Beckett University, Leeds, UK.

*Corresponding author

Samuel T. Orange

[1]Sport, Health and Exercise Science, School of Life Sciences

University of Hull, Cottingham Road, Hull, UK, HU6 7RX.

Email: orange_1@hotmail.co.uk

Telephone: +44 (0)1482 466314

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ABSTRACT

This study examined the validity and reliability of a wearable inertial sensor to measure velocity and power in the free-weight back squat and bench press. Twenty-nine youth rugby league players (18 ± 1 years) completed two test-retest sessions for the back squat followed by two test-retest sessions for the bench press. Repetitions were performed at 20%, 40%, 60%, 80% and 90% of one repetition maximum (1RM) with mean velocity (MV), peak velocity (PV), mean power (MP) and peak power (PP) simultaneously measured using an inertial sensor (PUSH^{TM}) and a linear position transducer (GymAware PowerTool). PUSH^{TM} only demonstrated good validity (Pearson product-moment correlation coefficient [*r*]) and reliability (intraclass correlation coefficient [ICC]) for measurements of MP ($r = 0.91$; ICC = 0.83) and PP ($r = 0.90$; ICC = 0.80) at 20% of 1RM in the back squat. However, it may be more appropriate for athletes to jump off the ground with this load to optimise power output. Further research should therefore evaluate the usability of inertial sensors in the jump squat exercise. In the bench press, good validity and reliability were only evident for the measurement of MP at 40% of 1RM ($r = 0.89$; ICC = 0.83). PUSH^{TM} was unable to provide a valid and reliable estimate of any other criterion variable in either exercise. Practitioners must be cognisant of the measurement error when using inertial sensor technology to quantify velocity and power during resistance training, particularly with loads other than 20% of 1RM in the back squat and 40% of 1RM in the bench press.

Key words: Linear position transducer, rugby league, sports performance, strength and conditioning.

INTRODUCTION

The use of velocity-based feedback has recently emerged as an effective strategy to monitor loading intensity (10, 17) and estimate the proximity of repetition failure (29) during resistance training. A progressive decline in repetition velocity is also representative of acute neuromuscular fatigue during isoinertial loading (33). Furthermore, objectively measuring mechanical power during resistance training enables the strength and conditioning (S&C) practitioner to determine the load that elicits optimal power output and quantify training-induced adaptations (40). The accurate measurement of velocity and power is contingent on the development of valid and reliable instruments that are usable in the field (2).

Force platforms are widely considered the gold standard for the direct acquisition of kinetic data (14). This technique may be less appropriate for measuring barbell velocity, however, because force platforms are unable to account for barbell movements that occur independent of the body (12). In addition, force platforms are generally not available for use within a practical setting (11). Linear position transducers (LPTs) are portable kinematic systems that directly measure the vertical displacement of a cable (that is attached to the barbell) and determine velocity and power through double differentiation processes (12). GymAware PowerTool (GYM) is a commercially available LPT that provides immediate kinematic feedback and automated summary reports on a cloud-based system. GYM has recently been shown to accurately assess velocity and power output in the free-weight back squat (6) and bench press (15) compared to laboratory-based criterion measures. However, the relatively high monetary cost of GYM (~£1700 per unit) limits its widespread application to all sporting organisations. The requirement of a cable attachment to the barbell also restricts the number of resistance exercises it can accurately measure. This has given rise to the increased popularity of various wearable devices to improve the accessibility of tracking kinematic and kinetic variables during resistance training.

A wearable inertial sensor has recently been developed (PUSH^{TM}) to quantify movement velocity and power output in resistance training exercises. The device is relative economical (~£220 per unit) and is worn inconspicuously on the forearm. Good correlations between PUSH^{TM} and a LPT have previously been reported for the measurement of mean and peak velocity in the Smith machine back squat (5). Sato et al. (35) also suggested that PUSH^{TM} is highly valid at measuring movement velocity in the dumbbell biceps curl and dumbbell shoulder press. However, the Pearson correlation analyses employed in both studies (5, 35) involved combining all repetitions performed by each individual. That is, all participants provided multiple data points in each paired measure. This statistical technique, although a widespread practice, violates the assumption of independence of error between observations in the Pearson correlation analysis (4). Analysing non-independent data with techniques that assume independence often produces specious results (1, 26). Combining all repetitions for analysis also does not elucidate whether the validity of the inertial sensor is load dependent.

In the only other study evaluating the validity of PUSH^{TM} to date, Banyard and colleagues (6) compared PUSH^{TM} to a laboratory-based testing device in the free-weight back squat. Ten resistance-trained males lifted loads of 20, 40, 60, 80, 90 and 100% of one repetition maximum (1RM), with the fastest repetition from each load used for correlation analysis. Their results suggested that the validity of PUSH^{TM} to assess velocity and power in the back squat was questionable (6). Although the data were appropriately analysed and provide useful information, the applicability of these results to athlete populations is somewhat limited because the study involved a small sample of recreationally-trained men. Athletic populations require sessional and weekly training loads to be monitored with increased precision because of a typically greater training burden and the need to prepare for competition. Within-subject variation is also likely to differ between athlete and recreational populations (21). To determine the usability of PUSH^{TM} within professional sport, it is essential to evaluate its validity in a larger sample of professional athletes.

Despite receiving considerable academic and practitioner interest in recent years, the test-retest reliability of the PUSH^{TM} device is yet to be determined. Previous studies have either not employed a repeated measures design that permits a test-retest analysis (5, 35) and/or have not reported any reliability statistics (6, 35). Similarly, the smallest difference between repeated trials that is not due to measurement error or variation within individual performance, termed the smallest worthwhile change (SWC) (22), has not been established. Therefore, the purpose of this study was to evaluate the concurrent validity and test-retest reliability of a wearable inertial sensor to measure velocity and power output during the free-weight back squat and bench press in professional youth rugby league players.

METHODS

Experimental Approach to the Problem

Using a repeated measures design, participants visited the laboratory on five separate occasions. The first visit was a familiarisation session where 1RMs were determined for the free-weight back squat and bench press. Participants were also familiarised with executing the concentric phase of each repetition with maximal intentional velocity. Visits two and three to the laboratory involved test and retest sessions for the back squat, whereas visits four and five were test and retest sessions for the bench press. Each of these testing sessions involved the completion of repetitions at 20%, 40%, 60%, 80% and 90% of 1RM. Mean velocity (MV), peak velocity (PV), mean power (MP) and peak power (PP) of each repetition were simultaneously recorded using a commercially available LPT (GymAware PowerTool [GYM], Kinetic Performance Technologies, Canberra, Australia) and a wearable inertial sensor

(PUSH^{TM}, PUSH Inc., Toronto, Canada). Before each visit to the laboratory, participants were instructed to refrain from caffeine for ≥12 hours and strenuous physical activity for ≥24 hours.

Subjects

Twenty-nine professional male youth rugby league players (age: 18 ± 1 years [range: 16 to 19 years]; height: 1.73 ± 0.83 m; body mass: 87.3 ± 20.8 kg) from an English Super League club's academy volunteered to participate in this study. Players reported engaging in structured resistance training 4.3 ± 0.5 times per week for 3.1 ± 1.3 years before the commencement of the study. Player strength characteristics are presented in Table 1. All participants were informed of the experimental procedures to be undertaken prior to signing an institutionally approved informed consent document to participate in the study. Parental or guardian signed consent was also obtained for participants aged <18 years. Ethical approval for the study was granted by the Sports, Health and Exercise Science Ethics Committee at the University of Hull.

[INSERT TABLE 1 ABOUT HERE]

Procedures

1RM testing

1RM testing was consistent with recognised guidelines established by the National Strength and Conditioning Association (18). A UKSCA accredited S&C coach and a Certified Strength and Conditioning Specialist (CSCS) were present at all testing sessions to ensure correct technique and adherence to the 1RM protocol. For the back squat, an Olympic barbell was placed on the trapezius in a high-bar position. With their feet externally rotated 5-10° and placed shoulder-width apart, participants started in an upright bipedal position and descended downwards until the top of the thigh was at least parallel to the floor before returning to the starting position. Participants were required to maintain constant downward pressure on the barbell (13) and keep their feet in contact with the floor during all repetitions. Bench press

1RM testing was performed on a solid flat bench secured in position inside an adjustable power rack (Perform Better Ltd, Southam, UK). The position of the bench was individually adjusted so that the vertical trajectory of the barbell was in line with participants' intermammary line. Participants unracked the barbell using a self-selected grip width and lay supine on the bench with their arms fully extended. Upon verbal command, participants lowered the barbell until the chest was briefly touched, approximately 3 cm superior to the xiphoid process, before executing full elbow extension. The attempt was considered successful if the participant's head, upper back, and buttocks remained firmly placed on the bench and both feet stayed flat on the floor. The barbell was not permitted to bounce off the chest. Participants performed the eccentric phase of both exercises in a controlled manner at a self-selected velocity and completed the concentric phase as fast as possible.

Test-retest sessions

All test and retest sessions were conducted at the same time of day (7 a.m.) and were separated by seven days. Following a standardised warm-up protocol, participants completed three consecutive repetitions at loads of 20%, 40%, 60% and 80% of 1RM, and two repetitions at 90% of 1RM. These loads were chosen to represent the full loading spectrum and to aid comparisons with previous studies (5, 6). Three minutes of passive rest were provided between different loading conditions and participants were verbally encouraged to execute each repetition with maximal concentric velocity. Additional repetitions were performed if technical lifting requirements were not met or submaximal effort was used, as determined by a consensus from the UKSCA accredited S&C coach and CSCS. GYM was considered the criterion in this study because the device has previously been shown to accurately assess velocity and power in the back squat (6) and bench press (15).

Data analysis

GYM is a commercially available LPT consisting of a floor unit, made up of a steel cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder (15). The floor unit was placed on the floor perpendicular to the right collar of the barbell. In line with manufacturer's instructions, the other end of the cable was vertically attached to the barbell (immediately proximal to the right collar) using a Velcro strap. GYM measures the vertical displacement of its cable in response to changes in barbell position. The displacement data were time-stamped at 20 millisecond time points and down-sampled to 50 Hz for analysis. The sampled data were not filtered. Instantaneous velocity was determined as the change in barbell position with respect to time. Acceleration data were calculated as the change in barbell velocity over the change in time for each consecutive data point. Instantaneous force was determined by multiplying the system mass with acceleration, where system mass was the barbell load plus the relative body mass of the participant (6). Power was then calculated as the product of force and velocity. Data obtained from GYM were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.1.1 app.

PUSH^{TM} is a wearable inertial sensor consisting of a 3-axis accelerometer and a gyroscope that provides six degrees in its coordinate system. The device was worn on the participant's right forearm, 1-2 cm distal to the elbow crease, with the main button located proximally as per manufacturer's instruction. The acceleration data were smoothed using a Butterworth filter, and vertical velocity was calculated by the integration of acceleration with respect to time. Similarly to GYM, instantaneous force was calculated as the product of acceleration and the system mass, and power was determined by multiplying force with velocity. Data obtained from PUSH^{TM} were recorded at a sampling rate of 200 Hz and transmitted to the PUSH^{TM} v3.1.2 app via a Bluetooth connection with a tablet. PUSH^{TM} and GYM do not require calibration processes.

The participant's body mass and the barbell load used were entered into both apps prior to each repetition. Values of MV and MP obtained by the PUSH^{TM} and GYM were determined as the average of all the instantaneous data collected during the concentric phase of each repetition. PV and PP were calculated as the maximum value registered during the same concentric period. The maximum value of each set of repetitions performed at each load (fastest mean concentric velocity as determined by GYM) was used for analysis.

Statistical analysis

All data were analysed using custom-designed Microsoft Excel spreadsheets (Microsoft Corporation, Redmond, Washington, USA) (24). The concurrent validity and test-retest reliability of PUSH^{TM} were determined by examining each relative load separately (i.e. 20%, 40%, 60%, 80%, and 90% of 1RM). Validity of PUSH^{TM} was assessed using the Pearson product-moment correlation coefficient (Pearson's *r*) and mean bias with 95% limits of agreement (95% LOA). The standardised mean bias was rated as: trivial (<0.2), small, (0.2 to 0.59), moderate (0.6 to 1.19), large (1.2 to 1.99), very large (2.0 to 3.99) and extremely large (≥4.0) (24). Relative reliability was determined using the intraclass correlation coefficient (ICC). Absolute reliability was examined using the standard error of measurement (SEM) and the smallest worthwhile change (SWC). SEM was calculated using the formula $SD_{diff}/\sqrt{2}$ (22) and was also expressed as a percentage of the mean (SEM%). The SWC was calculated as the between-subject SD multiplied by 0.2 (22). The following criteria were used to interpret the strength of the Pearson's *r* used to assess validity and the ICC estimates used to assess reliability: poor (<0.5), moderate (0.50 to 0.74), good (0.75 to 0.89) and excellent (≥0.9) (27). The level for all confidence intervals (CI) was set at 95%.

RESULTS

Figure 1 presents velocity and power data across each relative intensity. The reliability (ICC, SEM%) of MV measurements obtained by GYM ranged from 0.72 to 0.87 and 3.9 to 9.9%, respectively.

[INSERT FIGURE 1 ABOUT HERE]

[INSERT TABLE 2 ABOUT HERE]

Back squat

The standardised mean bias showed small differences between PUSH^{TM} and GYM devices for the measurement of PV and MP at 20% of 1RM. There were moderate to very large underestimations of all other criterion variables (see Table, Supplemental Digital Content 1), which were also evidenced by the 95% LOA (Figures 2 to 5). Despite the evidence of systematic bias, good to excellent correlations ($r \geq 0.75$) were found between PUSH^{TM} and GYM methods for MP and PP measurements at loads of 20% to 80% of 1RM. Good correlations were also found for MV at 20%, 60%, and 80% of 1RM, and PV at 20% and 80% of 1RM.

PUSH^{TM} only demonstrated good reliability for the measurement of MP (ICC = 0.83, 95% CI: 0.66 to 0.91) and PP (ICC = 0.80, 95% CI: 0.62 to 0.90) at 20% of 1RM. The SEM% and ICC estimates tended to worsen as the relative intensity increased (Figures 2 to 5). Absolute SEM and SWC data for all measurements obtained by PUSH^{TM} are presented in Table 2.

Bench press

The standardised mean bias showed that there were no obvious under- or over-estimations of PV at 60% to 90% of 1RM and MP at 60% of 1RM. Small systematic biases were evident for the measurements of MV at 60% of 1RM, PV and MP at 20% and 40% of 1RM, and PP at 90% of 1RM. There were moderate differences between PUSH^{TM} and GYM for all other criterion variables (see Table, Supplemental Digital Content 1). Good correlations between PUSH^{TM} and GYM were found for the measurement of MV at 40% of 1RM (r = 0.84, 95% CI: 0.68 to 0.92), and for MP at 40% (r = 0.89, 95% CI: 0.77 to 0.95) and 80% (r = 0.76, 95% CI: 0.53 to 0.88) of 1RM.

PUSH^{TM} only showed good reliability for the measurement of MP (ICC = 0.83, 95% CI: 0.67 to 0.92) and PP (ICC = 0.88, 95% CI: 0.76 to 0.94) at 40% of 1RM.

[INSERT FIGURE 2 ABOUT HERE]

[INSERT FIGURE 3 ABOUT HERE]

[INSERT FIGURE 4 ABOUT HERE]

[INSERT FIGURE 5 ABOUT HERE]

DISCUSSION

This study examined the validity and reliability of a wearable inertial sensor (PUSH^{TM}) to measure velocity and power in the back squat and bench press. Our data are the first to demonstrate that the reliability and validity of PUSH^{TM} are contingent on the exercise and the external load lifted. The device was reliable and valid for the measurements of MP at 20% of 1RM in the back squat. In the bench press, PUSH^{TM} provided a reliable and valid measurement of MP at 40% of 1RM.

This study is the first to determine the test-retest reliability of PUSH^{TM}. In the free-weight back squat, there was evidence of good reliability for the measurement of MP (ICC = 0.83, 95% CI: 0.66 to 0.91) and PP (ICC = 0.80, 95% CI: 0.62 to 0.90) at 20% of 1RM. The 95% CIs of these ICC estimates suggest that the true reliability for this population likely ranges from moderate to excellent. Interestingly though, our data demonstrated that the reliability of the device tended to decrease as the external load increased, as evidenced by both the SEM% and ICC data (Figures 2 to 5). This finding aligns well with a recent study (8) reporting a trend of greater between-subject variation in MV and MP with increasing relative intensities in the back squat. This inverse relationship between reliability and intensity may be attributed to alterations in lower body kinematics with increasing loads. Kellis and colleagues (25) reported a 16º increase in forward trunk inclination between 40-70% of 1RM in the free-weight back squat. Hay and colleagues (20) also found that the absolute angle of the hip increased significantly by 22º when the external load was increased from 40% to 80% of 4RM, possibly due to greater involvement of the hip musculature and a concomitant reduction in knee extensor torque (20). Although technique and squat depth were vigilantly monitored throughout testing, this intrinsic change in lower body kinematics would conceivably alter the pathway and orientation of the inertial sensor during the squat movement. Similarly, in the bench press, horizontal displacement of the barbell has been shown to significantly increase from 86 ± 36 mm at 70% of 1RM to 123 ± 38 mm at 100% of 1RM (28). Greater horizontal displacement of the barbell at heavier loads may result from an increased effort to reduce the moment arm about the shoulder axis (16, 28), which would alter the position of the forearm relative to the barbell during the concentric phase. Caution should therefore be taken when measuring velocity and power at heavier loads in free-weight resistance exercises.

We have provided absolute measures of reliability to enable practitioners to interpret whether training-induced changes in velocity and/or power are practically significant. The SEM represents the typical variation in performance from repeated trials and displays measurement error in the same units as the original measurement (22). It is important for coaches to minimise the SEM in order to detect subtle yet meaningful changes in performance. Sánchez-Medina et al. (34) have eloquently shown that differences in MV between each 5% increment in relative load vary between 0.05 and 0.10 $m \cdot s^{-1}$ in the back squat. Their data also show that for each 10%

increase in load, the concomitant change in MV varies between 0.11 and 0.18 m·s^{-1} (34). Based on the SEM values for MV reported in this study (Table 2), the inertial sensor appears reliable enough to detect 10%, but not 5%, changes in relative load. S&C practitioners must judge whether the magnitude of measurement error is acceptable based on the specific needs of their athletes. Clearly, an appropriate balance must be struck between usability, cost, practicality, and reliability of the testing method.

Two previous studies have supported the use of PUSH^{TM} to accurately measure movement velocity during resistance training. Sato and colleagues (35) reported good correlations between PUSH^{TM} and a 3D motion analysis capture system for the measurement of MV and PV in the dumbbell biceps curl (MV: r = 0.86; PV: r = 0.80) and shoulder press (MV: r = 0.88; PV: r = 0.92). Using a LPT as the criterion measure, Balsalobre-Fernández and colleagues (5) also suggested that PUSH^{TM} was highly valid at measuring MV (r = 0.85) and PV (r = 0.91) in the Smith machine back squat. Unlike the free-weight back squat though, the Smith machine restricts barbell displacement to a fixed linear path, which eliminates measurement error resulting from extraneous horizontal motion (12). Furthermore, the Pearson correlation analyses employed in both studies (5, 35) involved combining all repetitions performed by each individual. For example, participants in the Balsalobre-Fernández et al. (5) study performed three repetitions at loads of 20, 40, 50, 60 and 70kg, with each repetition used in the validity analyses. Therefore, all participants provided 15 data points in each paired sample. This technique violates the assumption of independence in the Pearson correlation analysis and is likely to produce erroneous results (4).

To satisfy the assumption of independence, we analysed each relative load separately using the fastest repetition at each load. Our data demonstrated good to excellent correlations between PUSH^{TM} and GYM for MP and PP measurements at loads of 20% to 80% of 1RM. We also found good correlations for measurements of MV at 20%, 60% and 80% of 1RM and for PV at 20% and 80% of 1RM. Similarly, Banyard and colleagues (6) recently reported that PUSH^{TM} was highly valid for the measurement of MV at light to moderate loads (i.e. <60% of 1RM) and for measuring PV at light loads (i.e. 20% of 1RM). However, they considered all MP and PP data obtained by PUSH^{TM} to be invalid. Differences between these results and our data are readily explained by the different validity criteria used. We employed Pearson's *r* to determine thresholds of acceptable validity, whereas Banyard and colleague's (6) included Pearson's *r*, coefficient of variation (CV) and the effect size in their validity criteria. Interestingly, if the CV was not used in their (6) analyses, the validity of PUSH^{TM} to measure MP and PP would have been considered high for all loads except for 90% and 100% of 1RM (i.e. the same results as the present study). Although the CV is commonly used to assess the validity of variables pertinent to sports medicine (3), it has been suggested that this statistic may be more representative of variability within an individual, rather than within a sample of individuals (30). This appears logical given the CV can only be directly calculated from repeated measurements on a single case (32). Additional differences between studies include the criterion measure used, the number of repetitions performed per load, and the sample population (and therefore the sample heterogeneity).

Though the inertial sensor was valid and reliable for measuring MP at 20% of 1RM in the back squat, the practical applications of prescribing this load are questionable. We instructed participants to keep their feet in contact with the floor during all repetitions in order to standardise technique between each load. Due to the inherent limitation of applying maximal force to the ground when using light loads in the back squat (34), it may be more appropriate for athletes to jump off the ground with 20% of 1RM. Indeed, peak power output in the jump squat has been shown to be approximately twofold greater compared with the back squat (13). Lighter loads (≤30% of 1RM) also elicit the highest PP output in the jump squat exercise (36).

Therefore, further research should evaluate the validity and reliability of inertial sensors to measure power in the jump squat.

In agreement with previous reports (5), we found evidence of systematic bias between the inertial sensor and LPT in the back squat. Specifically, the standardised mean bias showed moderate to very large underestimations of most criterion variables, which were also evidenced by the 95% LOA. This bias is likely underpinned by differences in calculation techniques. GYM is a portable LPT that directly measures the vertical displacement of its cable. Movement velocity and power output are calculated as derivatives of the displacement data through double differentiation processes. Conversely, the inertial sensor is worn on the forearm and encompasses a 3-axis accelerometer with a gyroscope. Differentiation of the acceleration data then permits the calculation of velocity and power. The differentiation procedures used by both systems, although based on well-established mathematical principles, require extensive data manipulation and therefore result in the amplification of noise and the consequential risk of erroneous data (12). Inertial sensors and LPTs also use different sampling frequencies and methods to correct for motion in the horizontal plane, which may further contribute to the systematic bias. The lack of agreement between PUSH^{TM} and GYM suggests that S&C practitioners should not use these two devices interchangeably and should take caution when comparing data obtained by inertial sensors to normative data obtained by LPTs in the literature.

The inertial sensor showed good reliability for the measurement of MP (ICC = 0.83, 95% CI: 0.67 to 0.92) and PP (ICC = 0.88, 95% CI: 0.76 to 0.94) at 40% of 1RM in the bench press. In addition, a good correlation between PUSH^{TM} and GYM was found at 40% of 1RM for the measurement of MP (r = 0.89, 95% CI 0.77 to 0.95), with the lower 95% CI of the Pearson correlation also exceeding the threshold for good validity. Furthermore, the mean bias with 95% LOA for this measurement were relatively narrow (32.3 ± 95.3 W), with the standardised mean bias demonstrating only a small underestimation (0.31) compared to GYM. Therefore, these data suggest that PUSH^{TM} provides a reliable and valid measurement of MP at 40% of 1RM. It is important to note that maximal MP and PP output were also achieved at 40% of 1RM (Figure 1), which is in agreement with previous research demonstrating that power production in the bench press is optimised at moderate loads (37). This finding indicates that S&C coaches are able to prescribe 40% of 1RM in the bench press to accurately quantify and develop the power-generating capabilities of their athletes.

The criteria for ICC estimates of reliability used in this study were based on recent guidelines for selecting and reporting ICCs (27). For example, an ICC estimate of 0.75 or above was considered a good level of reliability. We also used the same thresholds for Pearson correlations to improve clarity in the interpretation of our data. Many studies (19, 31, 38, 39) have used a correlation threshold of ≥0.50 to denote a strong level of validity and/or reliability based on criteria put forward by Cohen (9) and Hopkins (23). On the other hand, some authors have chosen an analytic goal of *r* being above 0.70 (6, 7). We have provided mean estimates with 95% CIs for all correlation coefficients to enable the reader to make their own interpretation of the data.

In conclusion, these data show that the reliability and validity of the inertial sensor are contingent on the exercise and the external load lifted. The PUSH^{TM} device was reliable and valid for the measurement of MP at light relative loads (e.g. 20% of 1RM) in the back squat. However, the practical applications of using this load are questionable because of the intrinsic limitation of applying maximal force to the ground when lifting light loads in the back squat. In the bench press, PUSH^{TM} obtained a valid and reliable measurement of MP at 40% of 1RM, although a small systematic bias between PUSH^{TM} and GYM devices was present. Practitioners must be cognisant of the measurement error when evaluating changes in performance between repeated trials.

PRACTICAL APPLICATIONS

Though the inertial sensor was considered valid and reliable for measuring MP at 20% of 1RM in the back squat, it may be more appropriate for athletes to jump off the ground with this load in order to optimise power output. Further research should therefore evaluate the validity and reliability of inertial sensors to measure power in the jump squat exercise. Measuring MP at 40% of 1RM provides S&C coaches with a reliable and valid measurement of power output in the bench press. However, inertial sensors and LPTs should not be used interchangeably because of the systematic bias between the two systems. Practitioners should acknowledge the magnitude of measurement error between repeated trials when using inertial sensor technology to quantify velocity and power in resistance training exercises.

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Figure and Table Captions

Table 1. Baseline strength characteristics of study participants**.**

Table 2. Absolute reliability of the wearable inertial sensor in the back squat and bench press

Figure 1. Values for mean velocity (A and B), peak velocity (C and D), mean power (E and F) and peak power (G and H) in the back squat and bench press. Data are presented as means ± SD.

Figure 2. Validity and reliability of the wearable inertial sensor to measure mean velocity in the back squat and bench press. Validity was assessed using Pearson product-moment correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined using the intraclass correlation coefficient (C) and standard error of measurement as a percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 3. Validity and reliability of the wearable inertial sensor to measure peak velocity in the back squat and bench press. Validity was assessed using Pearson product-moment correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined using the intraclass correlation coefficient (C) and standard error of measurement as a percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 4. Validity and reliability of the wearable inertial sensor to measure mean power in the back squat and bench press. Validity was assessed using Pearson product-moment correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined using the intraclass correlation coefficient (C) and standard error of measurement as a

percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 5. Validity and reliability of the wearable inertial sensor to measure peak power in the back squat and bench press. Validity was assessed using Pearson product-moment correlation coefficient (A) and the mean bias with 95% limits of agreement (B). Reliability was determined using the intraclass correlation coefficient (C) and standard error of measurement as a percentage of the mean (D). Area shaded in grey represents a good level of validity/reliability. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Supplemental Digital Content 1. Standardised mean bias between PUSH^{TM} and GYM methods

Table 1. Baseline strength characteristics of study participants

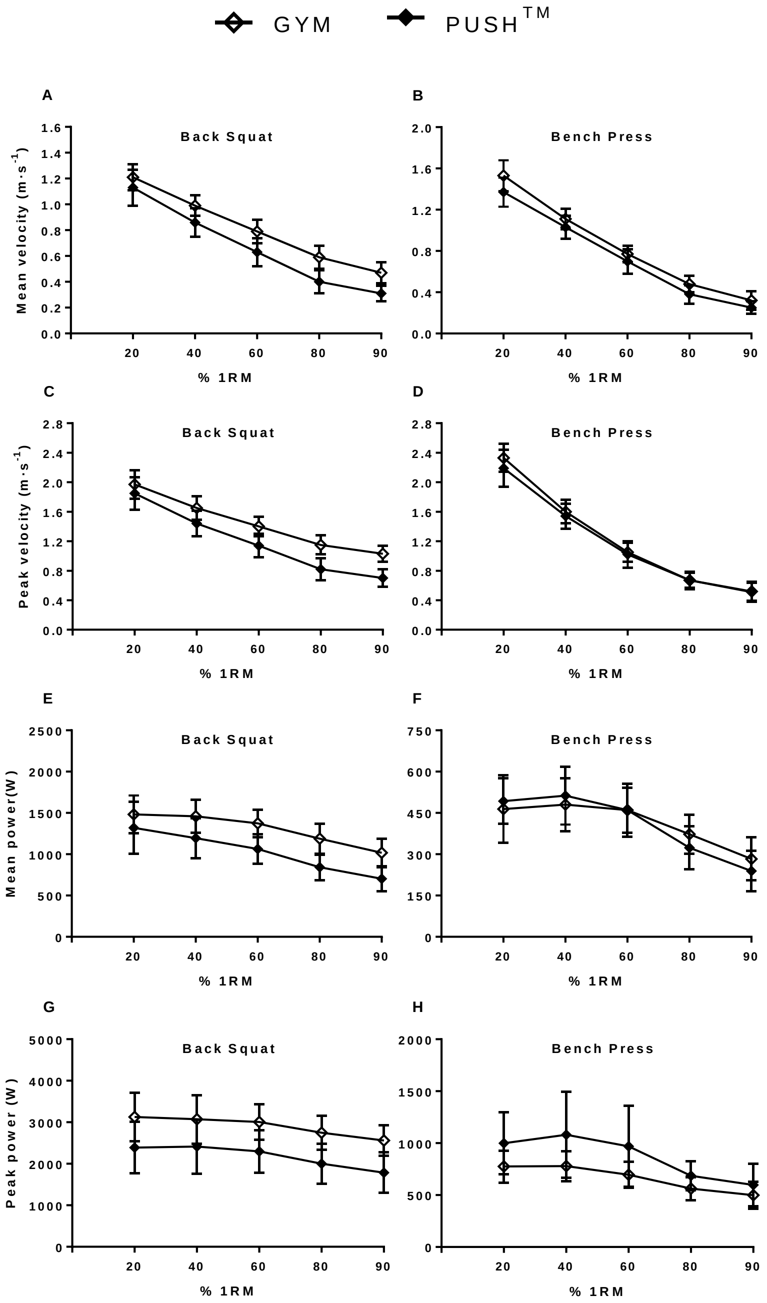
Back Squat (kg)		Bench Press (kg)	
1RM	Relative 1RM	1RM	Relative 1RM
145.5 ± 24.4	1.71 ± 0.35	100.8 ± 16.4	1.18 ± 0.26

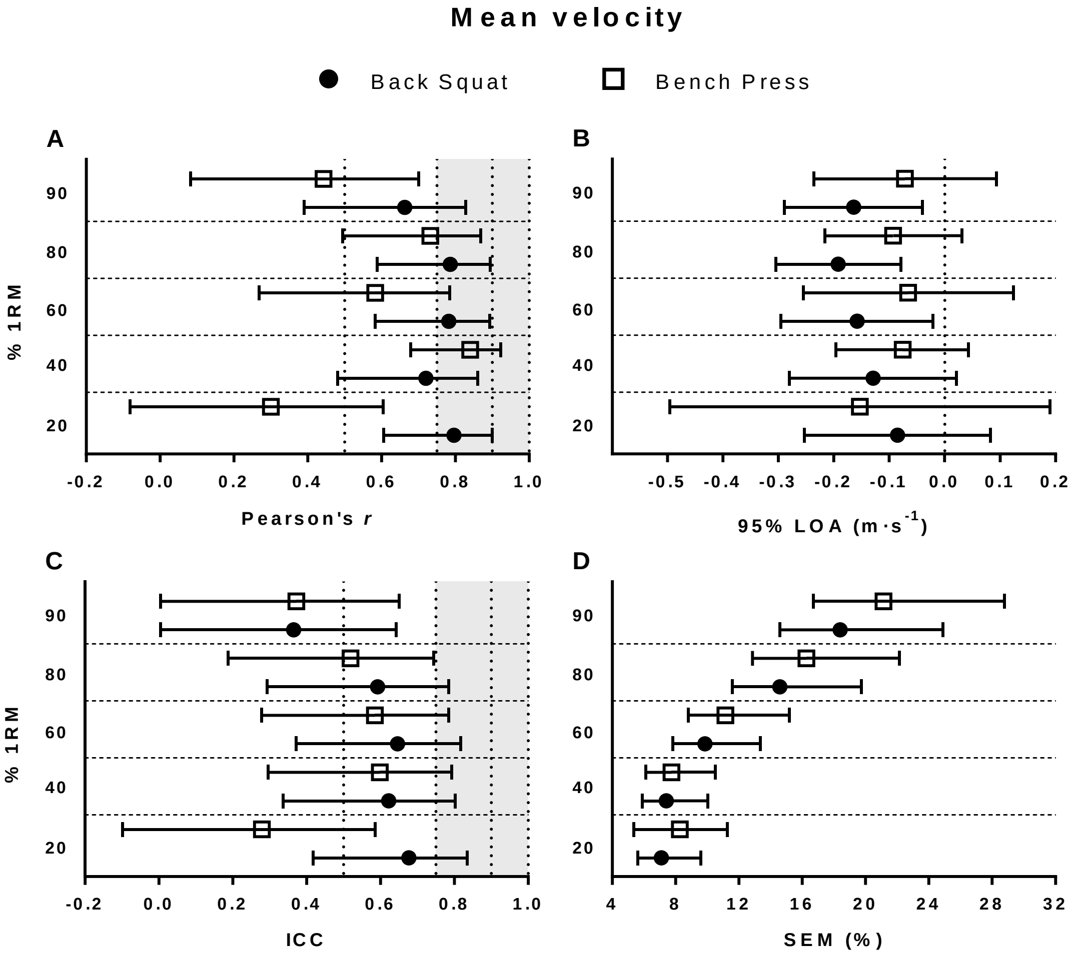
1RM = one repetition maximum; relative 1RM = one repetition maximum normalised to body mass. Data are presented as means ± SD.

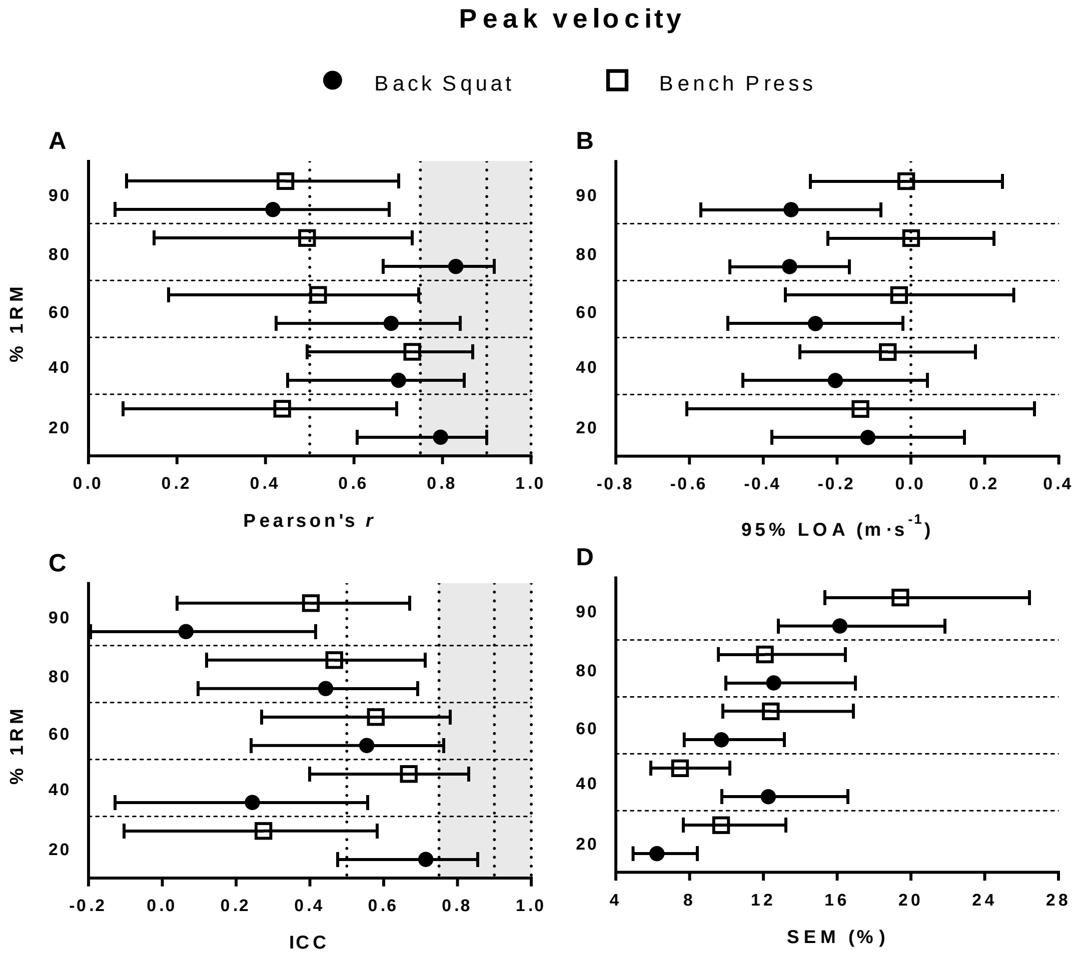
Table 2. Absolute reliability of the wearable inertial sensor in the back squat and bench press

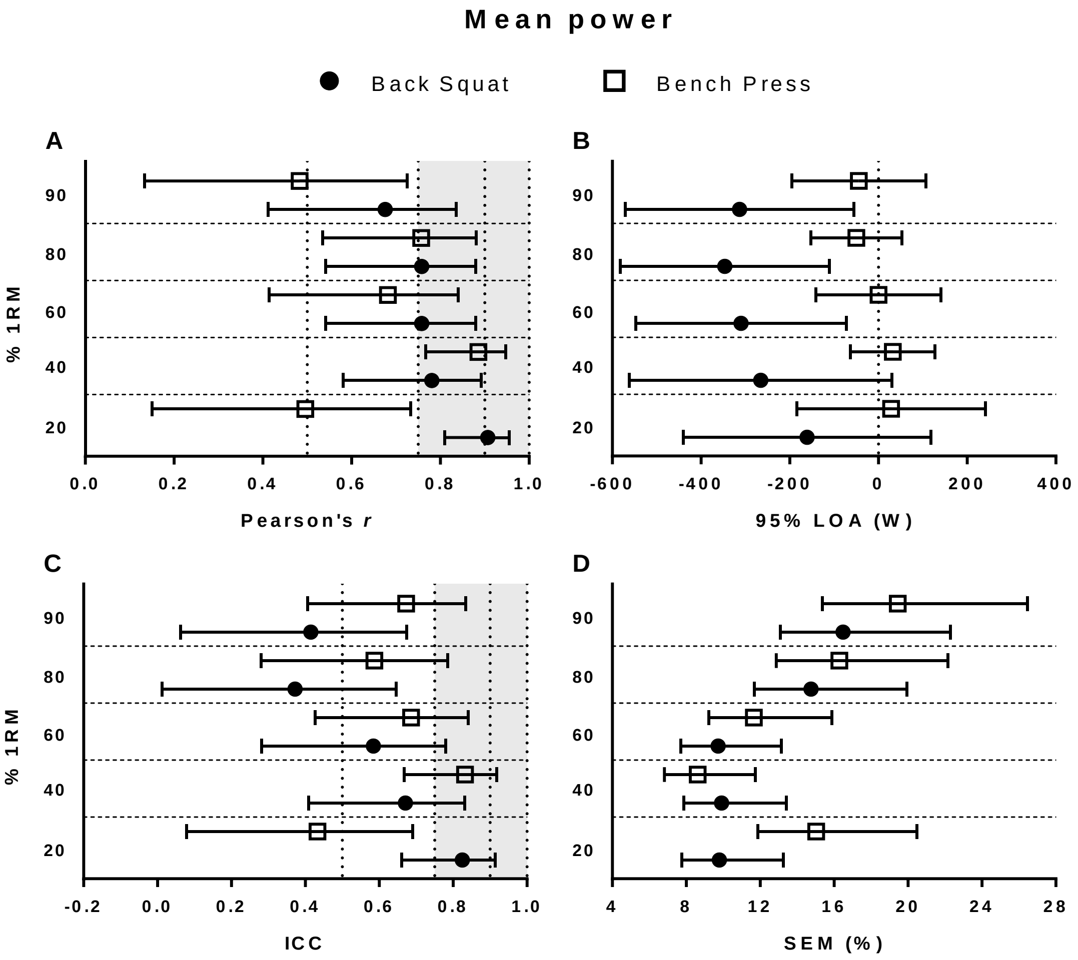
		Back Squat					Bench Press				
		20%	40%	60%	80%	90%	20%	40%	60%	80%	90%
MV ($m \cdot s^{-1}$)	SEM	0.08	0.07	0.06	0.06	0.06	0.11	0.08	0.08	0.06	0.05
	SWC	0.03	0.02	0.02	0.02	0.01	0.03	0.02	0.02	0.02	0.01
PV ($m \cdot s^{-1}$)	SEM	0.12	0.18	0.11	0.11	0.12	0.21	0.11	0.12	0.08	0.10
	SWC	0.04	0.04	0.03	0.03	0.02	0.05	0.04	0.04	0.02	0.02
MP (W)	SEM	128.3	121.5	105.9	129.5	117.0	70.6	33.8	51.6	51.3	45.7
	SWC	59.1	41.6	32.4	32.9	30.0	19.0	20.3	18.2	15.6	15.5
PP (W)	SEM	261.2	345.8	279.4	345.4	359.5	221.9	151.0	273.0	137.5	131.9
	SWC	112.3	115.6	95.9	80.7	87.5	71.1	84.2	69.2	40.0	40.8

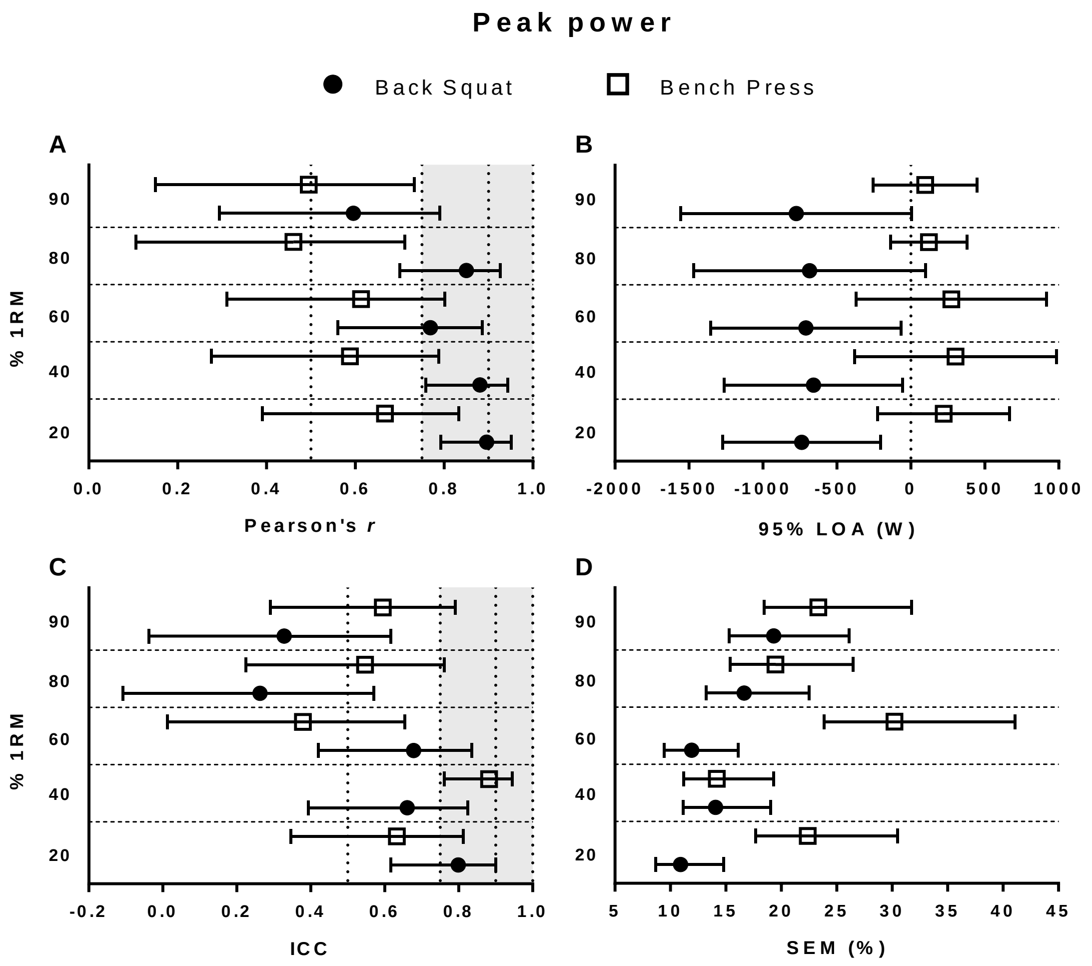
MV = mean velocity; PV = peak velocity; MP = mean power; PP = peak power; SEM = standard error of measurement; SWC = smallest worthwhile change.


GYM
PUSH™
A
Back Squat
Mean velocity (m·s⁻¹)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
20
40
60
80
90
% 1RM
B
Bench Press
2.0
1.6
1.2
0.8
0.4
0.0
20
40
60
80
90
% 1RM
C
Back Squat
Peak velocity (m·s⁻¹)
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
20
40
60
80
90
% 1RM
D
Bench Press
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
20
40
60
80
90
% 1RM
E
Back Squat
Mean power(W)
2500
2000
1500
1000
500
0
20
40
60
80
90
% 1RM
F
Bench Press
750
600
450
300
150
0
20
40
60
80
90
% 1RM
G
Back Squat
Peak power (W)
5000
4000
3000
2000
1000
0
20
40
60
80
90
% 1RM
H
Bench Press
2000
1500
1000
500
0
20
40
60
80
90
% 1RM


Mean velocity
● Back Squat
☐ Bench Press
A
% 1RM
90
80
60
40
20
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
Pearson's *r*
B
90
80
60
40
20
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
95% LOA (m·s^{-1})
C
% 1RM
90
80
60
40
20
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
D
90
80
60
40
20
4
8
12
16
20
24
28
32
SEM (%)

Peak velocity
Back Squat
Bench Press
A
% 1RM
90
80
60
40
20
0.0
0.2
0.4
0.6
0.8
1.0
Pearson's *r*
B
90
80
60
40
20
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
95% LOA ($m \cdot s^{-1}$)
C
% 1RM
90
80
60
40
20
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
D
90
80
60
40
20
4
8
12
16
20
24
28
SEM (%)


Mean power
● Back Squat
☐ Bench Press
A
B
C
D
% 1RM
90
80
60
40
20
0.0
0.2
0.4
0.6
0.8
1.0
Pearson's r
-600
-400
-200
0
200
400
95% LOA (W)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
4
8
12
16
20
24
28
SEM (%)


Peak power
● Back Squat
☐ Bench Press
A
B
C
D
% 1RM
90
80
60
40
20
0.0
0.2
0.4
0.6
0.8
1.0
Pearson's r
-2000
-1500
-1000
-500
0
500
1000
95% LOA (W)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
5
10
15
20
25
30
35
40
45
SEM (%)

Supplemental Digital Content 1. Standardised mean bias between PUSH^{TM} and GYM methods

	Back Squat					Bench Press				
	20%	**40%**	**60%**	**80%**	**90%**	**20%**	**40%**	**60%**	**80%**	**90%**
MV ($m·s^{-1}$)	0.61	1.17	1.41	2.23	2.61	1.06	0.68	0.55	1.03	1.12
PV ($m·s^{-1}$)	0.53	1.20	1.58	2.23	2.74	0.55	0.37	0.18	0.00	0.10
MP (W)	0.51	1.10	1.73	2.24	2.08	0.35	0.31	0.00	0.64	0.60
PP (W)	1.20	1.01	1.39	1.43	1.59	0.74	0.73	0.70	0.88	0.48

MV = mean velocity; PV = peak velocity; MP = mean power; PP = peak power. Standardised mean bias of <0.2, 0.2 to 0.59, 0.6 to 1.19, 1.2 to 1.99, 2.0 to 3.99 and ≥4.0 were considered trivial, small, moderate, large, very large and extremely large, respectively.