Test-retest Reliability of a Commercial Linear Position Transducer (GymAware PowerTool) to Measure Velocity and Power in the Back Squat and Bench Press

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Brief running head: Reliability of the GymAware PowerTool

Disclosure statement: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

ABSTRACT

This study examined the test-retest reliability of the GymAware PowerTool (GYM) to measure velocity and power in the free-weight back squat and bench press. Twenty-nine academy rugby league players (age: 17.6 ± 1.0 years; body mass: 87.3 ± 20.8 kg) completed two test-retest sessions for the back squat followed by two test-retest sessions for the bench press. GYM measured mean velocity (MV), peak velocity (PV), mean power (MP) and peak power (PP) at 20, 40, 60, 80 and 90% of one repetition maximum (1RM). GYM showed good reliability (intraclass correlation coefficient [ICC] and standard error of measurement percentage [$SEM_{\%}$], respectively) for the measurement of MV at loads of 40 (0.77, 3.9%), 60 (0.83, 4.8%), 80 (0.83, 5.8%) and 90% (0.79, 7.9%) of 1RM in the back squat. In the bench press, good reliability was evident for PV at 40 (0.82, 3.9%), 60 (0.81, 5.1%) and 80% (0.77, 8.4%) of 1RM, and for MV at 80 (0.78, 7.9%) and 90% (0.87, 9.9%) of 1RM. The measurement of MP showed good to excellent levels of reliability across all relative loads (ICC ≥ 0.75). In conclusion, GYM provides practitioners with reliable kinematic information in the back squat and bench press, at least with loads of 40 to 90% of 1RM. This suggests that strength and conditioning coaches can utilise the velocity data to regulate training load according to daily readiness and target specific components of the force-velocity curve. However, caution should be taken when measuring movement velocity at loads <40% of 1RM.

Key words: Velocity-based training; sports performance; strength and conditioning; rugby league

INTRODUCTION

Velocity-based training (VBT) has received considerable academic and practitioner interest in recent years. VBT is characterised by performing resistance training exercises with maximal intended concentric velocity and regulating training load based on the resultant velocity data. Indeed, objectively measuring velocity has been shown to effectively monitor temporal fatigue and estimate the proximity of muscle failure during isoinertial loading (31). Recent data also demonstrate that providing athletes with instantaneous velocity feedback improves motivation and attenuates the loss in barbell velocity in the free-weight back squat (41). While prescribing resistance training intensity based on velocity feedback appears to be a promising training strategy, the successful implementation of VBT relies on instruments that are reliable enough to detect small changes in barbell kinematics.

In laboratory-based environments, force platforms and three-dimensional motion capture systems are widely used to measure movement velocity and are generally considered the reference methods for comparison with other measurement tools (1, 14, 34, 38). However, transportation difficulties and high monetary costs limit the use of these techniques within many applied settings. In addition, testing a large group of athletes with force plates or motion capture systems can be time consuming and challenging in a training environment. This has given rise to the recent development of portable kinematic devices, such as linear position transducers (LPTs), to enhance the accessibility of VBT to strength and conditioning (S&C) practitioners. LPTs directly measure the vertical displacement of a cable (that is attached to the barbell) and determine velocity as the change in barbell position with respect to time (17). These kinematic data are then coupled with the system mass (i.e. external load plus body mass) to provide estimations of power through processes of double differentiation (9).

A commercially available LPT that continues to grow in popularity among researchers and practitioners is the GymAware PowerTool (GYM). GYM offers additional features such as instantaneous kinematic feedback, wireless transmission to a tablet computer and automated summary reports on a cloud-based system. Importantly, previous research suggests that GYM is highly valid at measuring velocity and power in resistance training exercises. Drinkwater et al. (11) demonstrated very high correlations between GYM and an advanced video system for the measurement of power in the free-weight bench press, Smith machine back squat and Smith machine bench throw exercises. More recently, good correlations between GYM and a laboratory-based device (consisting of four LPTs and a force plate) have been reported for the measurement of velocity and power in the free-weight back squat (5). Ostensibly due to the high validity and usability of GYM, a host of studies have used this device to quantify concentric velocity and/or power in many training movements, in particular the bench press (18, 28, 35) back squat (18, 41) and jump squat (2, 29).

Whilst the validity of GYM is reasonably well-established, there is limited information available on the reliability of this particular LPT. Hori and Andrews (21) reported that the reliability of GYM was high for the measurement of peak velocity in the jump squat using a wooden pole (0.7 kg), weightlifting barbell (20 kg) and Smith machine (24.5 kg). However, there are no published data concerning the reliability of GYM in other resistance training exercises that are regularly used by S&C coaches. It is also currently unknown whether GYM is reliable when greater external loads are lifted. Greater movement in the horizontal plane often occurs concomitantly with increasing loads (24, 27). This extraneous horizontal motion is a common source of error for methods relying exclusively on kinematic data because of an inability to account for movement outside of the vertical plane (9). Furthermore, given that GYM has been most widely used with rugby players (2, 29, 30, 35, 41), it would be prudent to assess the device's reliability in a large cohort of these athletes. Therefore, the purpose of this study was to evaluate the test-retest reliability of GYM to measure velocity and power during the free-weight back squat and bench press in academy rugby league players. We aimed to quantify the magnitude of measurement error to enable S&C practitioners to interpret whether a change in performance between repeated trials is practically significant.

METHODS

Experimental Approach to the Problem

This study protocol has been described previously (33). Briefly, all participants made five separate visits to the performance suite in a repeated measures design. In the first visit, one repetition maximums (1RMs) were determined for the free-weight back squat and bench press and participants were familiarised with executing the concentric phase of each repetition with maximal intended velocity. Visits two and three to the performance suite 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. GYM (Kinetic Performance Technologies, Canberra, Australia) was used to measure mean velocity (MV), peak velocity (PV), mean power (MP) and peak power (PP) of each repetition. These metrics were chosen because they are commonly reported in VBT research and utilised by S&C practitioners (5, 13). All testing sessions took place in-season; ~72 hours after a competitive match and 24 hours following a low-intensity 'recovery' training session. Before each testing session, participants were instructed to refrain from caffeine for ≥12 hours, leisure-time or training-related physical activity for 24 hours, to maintain habitual dietary habits, and to arrive in a fully hydrated state.

Subjects

Twenty-nine male rugby league players were recruited from a Super League club's academy playing in the Under-19s competition. Baseline characteristics of study participants are presented in Table 1. All players were free from injury and typically engaged in eight training sessions across four days per week, including resistance training, rugby league skills and conditioning. Specifically, players reported engaging in structured resistance training 4.3 ± 0.5 times per week for the last 3.1 ± 1.3 years. Participants were informed of the experimental procedures to be undertaken and potential risks and benefits 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 Sport, Health and Exercise Science Ethics Committee at the University of Hull.

[INSERT TABLE 1 ABOUT HERE]

Procedures

1RM assessment

1RM testing was consistent with recognised guidelines established by the National Strength and Conditioning Association (16). An S&C coach accredited by the United Kingdom Strength and Conditioning Association and a Certified Strength and Conditioning Specialist (CSCS) were present at all times to ensure correct technique and adherence to the 1RM protocol. Briefly, participants performed a standardised warm-up consisting of dynamic stretching and preparatory exercises lasting approximately 5-10 minutes. Five repetitions of the given exercise were then completed at ~50% of participants' perceived 1RM, followed by two sets of 2-3 repetitions at loads corresponding to ~60-80% of perceived 1RM. Thereafter, the load was progressively increased and participants performed 3-5 maximal trials (one repetition sets) for 1RM determination. Three minutes of rest was given between attempts, and a five minute rest period was provided between exercises after the 1RM was established. For the back squat, the Olympic barbell (Eleiko, Halmstad, Sweden) was placed in a high-bar position inside an adjustable power rack (Perform Better Ltd, Southam, UK). Participants descended downwards until the top of the thigh was at least parallel to the floor before returning to an upright standing position. The depth of the squat was monitored by an S&C coach positioned laterally to the power rack. Participants were required to maintain constant downward force on the barbell so it did not leave the shoulders, and to keep their feet in contact with the floor during all repetitions. Safety bars were placed 5-10 cm below the lowest point of the squat movement and a two-person spot was provided for each attempt. For the bench press, 1RM testing was performed on a solid flat bench (Perform Better Ltd, Southam, UK) secured inside the power rack. Participants unracked the barbell using a self-selected grip width and 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. Any trials that involved the barbell bouncing off the chest were discarded and a one-person spot was provided for each attempt. 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 (with the aid of verbal encouragement).

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 the same standardised warm-up protocol performed in the familiarisation session, participants completed three consecutive repetitions at loads of 20%, 40%, 60% and 80% of 1RM, and two repetitions at 90% of 1RM. Different loading conditions were separated by three minutes of passive rest. These relative intensities were chosen to test the reliability of GYM across the full loading spectrum. Participants were verbally encouraged to complete each repetition with maximal concentric velocity, although no objective velocity feedback was provided to participants. Additional repetitions were performed if technical lifting requirements were not met or submaximal effort was used, as determined by a consensus from the S&C coaches.

Data analysis

GYM is a commercially available LPT consisting of a floor unit, made up of a spring-powered retractable cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder (11). The floor unit was placed on the floor perpendicular to the right collar of the barbell. The other end of the cable was vertically attached to the barbell (immediately proximal to the right collar) using a Velcro strap (33) (see Supplemental Digital Content 1). Vertical displacement of the barbell was measured from the rotational movement of the spool. GYM also incorporates a sensor measuring the angle that the cable leaves the spool, which enables vertical-only displacement to be measured by correcting for any motion in the horizontal plane (using basic trigonometry) (17). Displacement data were time-stamped at 20 millisecond time points to obtain a displacement-time curve for each repetition, which was 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 (5, 9). 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. GYM does not require a calibration process.

The participant's body mass and the barbell load used were entered into the GymAware app prior to each repetition. Values of MV and MP obtained by 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) was used for analysis.

Statistical analyses

In order to determine the test-retest reliability of GYM across the loading spectrum, each relative load was analysed separately (i.e. 20%, 40%, 60%, 80%, and 90% of 1RM). Relative reliability was determined using the intraclass correlation coefficient (ICC). ICC estimates and their 95% confidence intervals (95% CIs) were calculated using SPSS for Windows (IBM SPSS, version 24.0, Chicago, IL) based on a single-rating, absolute agreement, two-way random effects model [i.e. ICC (2,1)] (26, 39). ICC estimates of <0.5, 0.50 to 0.74, 0.75 to 0.89, and ≥0.9 were considered poor, moderate, good and excellent, respectively (26). All other data were analysed using custom-designed Microsoft Excel spreadsheets (Microsoft Corporation, Redmond, Washington, USA) (20). Absolute reliability was examined with the standard error of measurement (SEM) and mean bias with 95% limits of agreement (LOA). The SEM was calculated as the standard deviation (SD) of the difference between trials divided by $\sqrt{2}$ (19). SEM was also expressed as a percentage of the mean ($SEM_{\%}$) using the formula: ([SEM/mean] x 100). The smallest worthwhile change (SWC), calculated as the between-subject SD multiplied by 0.2 (19), represented the smallest difference between repeated trials that was not due to measurement error or individual variation. The following criteria were used to rate the standardised mean bias: 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) (20). The level for all confidence intervals (CI) was set at 95%.

RESULTS

Figure 1 presents raw velocity and power data obtained in the second test-retest session. Absolute SEM and SWC data for the back squat and bench press are presented in Table 2.

[INSERT FIGURE 1 ABOUT HERE]

[INSERT TABLE 2 ABOUT HERE]

Back squat

GYM showed good reliability (ICC, $SEM_{\%}$, respectively) for the measurement of MV at loads of 40 (0.77, 3.9%), 60 (0.83, 4.8%), 80 (0.83, 5.8%) and 90% (0.79, 7.9%) of 1RM, and for PV at 20 (0.77, 4.5%), 40 (0.78, 4.3%), and 60% (0.79, 4.2%) of 1RM. Good levels of reliability were found in all measurements of MP (ICC ≥ 0.75) and for PP at 20 (0.81, 8.0%), 40 (0.84, 7.1%) and 60% (0.77, 6.5%) of 1RM. The standardised mean bias showed only trivial or small differences between repeated trials for the measurement of all criterion variables (Table 3), which were also evidenced by the narrow 95% LOA (Figures 2 to 5).

[INSERT TABLE 3 ABOUT HERE]

Bench press

Good reliability (ICC, $SEM_{\%}$, respectively) was evident for the measurement of MV at 80 (0.78, 7.9%) and 90% (0.87, 9.9%) of 1RM, and for PV at 40 (0.82, 3.9%), 60 (0.81, 5.1%) and 80% (0.77, 8.4%) of 1RM. The measurement of MP showed good to excellent reliability across all relative loads (ICC ≥ 0.75) (Figure 4). GYM also showed good to excellent reliability for PP at loads of 20 (0.87, 8.0%), 40 (0.91, 5.6%), 60 (0.89, 5.6%) and 80% (0.77, 9.3%) of 1RM. Similar to the back squat, the standardised mean bias showed trivial or small differences for the measurement of all criterion variables.

[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 test-retest reliability of GYM to measure velocity and power in free-weight resistance training exercises. GYM demonstrated good reliability for the measurement of MV at 40 to 90% of 1RM in the back squat. In the bench press, good reliability was evident for PV at 40 to 80% of 1RM, and for MV at 80 to 90% of 1RM. Furthermore, good to excellent levels of reliability were found in all measurements of MP. This suggests that GYM can provide practitioners with reliable kinetic and kinematic information during resistance training, at least with loads of 40 to 90% of 1RM.

GYM is a commercially available LPT that continues to grow in popularity among researchers and practitioners. Despite the widespread use of GYM throughout the recent literature (2, 18, 28, 29, 35, 41), the present study is the first to determine the reliability of this kinematic device in the free-weight back squat. There was evidence of good reliability for the measurement of MV at loads of 40 to 90% of 1RM. All $SEM_{\%}$ data for MV were <8% and standardised mean differences were either trivial or small (i.e. <0.6). For measurements of PV, GYM showed good reliability at 20 to 60% of 1RM. The ICC estimates for PV at 80 and 90% of 1RM, however, only indicated a moderate level of reliability. This is problematic when prescribing loads that target maximal strength development and suggests that MV may be a more appropriate variable when using heavy loads in the back squat. It is generally thought that MV better represents the overall expression of velocity through the entire concentric phase of non-aerial movements like the back squat (4, 13, 23), while PV is relevant for ballistic exercises such as jump squats and bench throws (29).

The SEM represents the typical variation in performance between repeated trials and can be used as a threshold to identify whether changes in the measurement are practically significant (19). Based on the SEM presented in this study, the measurement error for MV obtained by GYM ranges from 0.03 to 0.05 m·s^{-1} in the free-weight back squat. The SEM for PV ranged from 0.06 to 0.09 m·s^{-1} (Table 2). To put these magnitudes of measurement error into context, it has been shown recently that for every 5% increment in relative load, MV decreases by 0.05 to 0.10 m·s^{-1} (8, 37) while PV decreases by 0.06 to 0.07 m·s^{-1} (37). As noted by Sánchez-Medina et al. (37), when an athlete increases their MV attained against a given absolute load by this value (i.e. 0.05 to 0.10 m·s^{-1}), this represents a 5% increase in strength. The same reasoning is applicable to changes in PV of 0.06 to 0.07 m·s^{-1}. This suggests that the measurement error in MV recorded by GYM is small enough to detect subtle changes in lifting performance, apart from at 20% of 1RM (SEM = 0.05 m·s^{-1}). This supports the assertion that MV is a reliable metric to monitor training load in the back squat, at least with loads of 40 to 90% of 1RM. Even so, practitioners must still be cognisant of the magnitude of measurement error when interpreting changes in MV. That is, if MV is >0.05 m·s^{-1} outside the target movement velocity, coaches should consider adjusting the barbell load. A change in MV of 0.05 m·s^{-1} or less may simply be a product of noise in the measurement. These data also suggest that the measurement error present in PV may be too large to detect small yet important changes in performance. Caution should therefore be taken if PV data are used to adjust sessional training loads in the back squat.

For a more conservative estimate of absolute reliability, practitioners may refer to the 95% LOA. These data provide an approximate range that differences between test-retest measurements would fall 95% of the time. The main difference between this statistic and the SEM is that the 95% LOA calculate the test-retest differences for 95% of a population, whereas the SEM estimates the typical measurement error for an average individual in the sample (3).

Numerically, this difference equates to a factor of approximately three. However, Hopkins (19) suggests that this degree of certainty about a meaningful change in athletic performance is unrealistic. Minor changes in performance are often meaningful for professional athletes, and therefore the 95% LOA may be too strict for S&C practitioners to base their decisions on.

In the bench press, GYM showed good reliability for the measurement of MV at 80 (ICC = 0.78) and 90% (ICC = 0.87) of 1RM. ICC estimates of PV at 40 to 80% of 1RM were also indicative of good reliability. This suggests that PV may be the most appropriate metric when lifting moderate to heavy loads in the bench press, whereas MV appears to be the most reliable at near maximal loads. This finding may be related to changes in the vertical acceleration-time curve with increasing intensities. In the ascent phase of a bench press, lifting loads of ≤80% of 1RM is characterised by a large acceleration of the barbell followed by a substantial deceleration phase. In other words, the acceleration-time curve shows one positive acceleration region and one negative acceleration region (27). In contrast, the bar path at loads of ≥90% of 1RM fluctuates between periods of acceleration and deceleration throughout the concentric movement. This is caused by a sticking point in the ascent phase, usually occurring at ~30% of total bar displacement (12), which causes the barbell to decelerate before reaccelerating through a 'maximum strength region' and eventually decelerating again to stop at the end of the range (12, 27). It is conceivable that taking a mean value of velocity at ≥90% of 1RM may be a more reliable metric to represent the fluctuations in barbell kinematics that occur at near maximal loads. On the other hand, PV may better capture the rapid acceleration observed at loads of ≤80% of 1RM. However, further research is required to substantiate this reasoning and provide more firm practitioner recommendations.

Despite some ICC estimates not reaching our threshold for good reliability (i.e. ICC ≥ 0.75), the SEM data suggest a small magnitude of absolute measurement error. Similar to the back squat, previous work has identified a consistent relationship between load and velocity in the bench press (6). For each 5% increment in bench press load, MV decreases by 0.07 to 0.09 $m \cdot s^{-1}$ (13, 15, 36) and PV decreases by 0.13 to 0.14 $m \cdot s^{-1}$ (13). All absolute SEM data reported in this study are smaller than the above values, with the exception of 20% of 1RM for both MV (SEM = 0.09 $m \cdot s^{-1}$) and PV (SEM = 0.13 $m \cdot s^{-1}$). Therefore, measurements of MV and PV obtained by GYM at 40 to 90% of 1RM appear sensitive to subtle changes in bench press performance. This notion is supported by the trivial to small systematic biases found between repeated measurements.

The large within-subject variability in movement velocity at 20% of 1RM may have been caused by an intrinsic limitation to maximally generate force through the entire concentric phase. When lifting light loads in the back squat (with maximal intended velocity), the athlete must decelerate considerably in order to keep their feet in contact with the ground. Similarly, in the bench press, the barbell must decelerate prior to achieving zero velocity at the end of the ascent phase. The amount of time spent in the deceleration phase (as a percentage of total ascent time) increases with lighter barbell loads because there is less inertia to overcome, which results in greater initial acceleration at the start of the concentric movement (27). Indeed, power output in the jump squat and bench throw has been shown to be approximately twofold greater compared with the back squat and bench press, respectively (10, 32). Thus, practitioners should avoid using GYM at 20% of 1RM to regulate training load in traditional (non-aerial) resistance exercises. GYM has previously shown high within- and between-session reliability for the measurements of PV and PP in the jump squat using a 20 kg barbell (coefficient of variation = 1.3 to 9.4%) (21). Further research should endeavour to establish the reliability of GYM in other ballistic exercises such as the bench throw and push press.

GYM samples and time-stamps displacement data at 20 millisecond time points, which is down-sampled to 50 Hz for analysis. The measurement error in GYM is largely comparable to other commercially available LPTs sampling at higher frequencies (6, 40). For example, the

Tendo Weightlifting Analyser (Tendo Sports Machines, Trencin, Slovak Republic), sampling data at 1000 Hz, has been shown to measure PV at 20 to 90% of 1RM in the bench press with a similar measurement error (SEM = 0.05 to 0.12 $m \cdot s^{-1}$; $SEM_{\%}$ = 3.1 to 12.6%) (40) to that recorded by GYM in the present study (SEM = 0.05 to 0.13 $m \cdot s^{-1}$; $SEM_{\%}$ = 3.9 to 12.9%). More recently (6), the combination of four commercial LPTs (each sampling at 1000 Hz) recorded MV at 20 to 90% of 1RM in the back squat with a SEM that ranged from 0.02 to 0.03 $m \cdot s^{-1}$, which is marginally smaller than GYM (0.03 to 0.05 $m \cdot s^{-1}$). Bardella and colleagues (7) suggest that a sampling rate of 25 Hz is more than adequate to measure velocity and power during resistance training, even during explosive exercises. Therefore, LPTs with higher sampling frequencies may not provide the practitioner with appreciably greater recording precision.

GYM calculates power through processes of double differentiation. Notwithstanding the extensive data manipulation involved in differentiation procedures, good to excellent reliability was found in all measurements of MP, with the lower 95% CI of the ICC estimates also exceeding the threshold for moderate reliability. This suggests that practitioners can use GYM to provide a reliable estimate of power production across the loading spectrum in both the back squat and bench press. Interestingly, measurements of MP appeared to be more reliable than PP especially at heavy loads. This was evidenced by the 95% LOA in particular, which were much wider for measurements of PP. GYM calculates MP as the average rate of doing work over the entire concentric phase, whereas PP is determined as the maximum instantaneous value registered during the same concentric period. Given that GYM time-stamps displacement data at 20 millisecond time points, PP may result from a sharp spike in the rate of doing work lasting one-fiftieth of a second. Therefore, PP may only represent a small sample of the overall concentric phase of the lift and be more susceptible to error. Hori et al. (22) have previously suggested that PP is less reliable than MP because of problems associated with data smoothing, differentiation and integration. Ostensibly based on this reasoning, the manufacturers of GYM (Kinetic Performance Technologies) also recommend the use of MP rather than PP (25).

In conclusion, GYM is a practical field-based device that provides a reliable estimate of movement velocity in the ascent phase of resistance training exercises. Specifically, GYM showed good reliability for the measurement of MV at loads of 40 to 90% of 1RM in the back squat. In the bench press, good reliability was evident for PV at 40 to 80% of 1RM, and for MV at 80 to 90% of 1RM. The small standardised mean bias and errors of measurement reported in this study also suggest that GYM is sensitive to subtle changes in lifting performance. Furthermore, good to excellent reliability was found in all measurements of MP, indicating that practitioners can utilise GYM to quantify the expression of concentric muscle power in resistance training exercises.

PRACTICAL APPLICATIONS

GYM provides reliable kinematic information at loads of 40 to 90% of 1RM in the back squat and bench press. This suggests that S&C coaches can use the velocity data to regulate sessional training load according to daily readiness and target specific components of the hyperbolic force-velocity curve (at 40 to 90% of 1RM) depending on the stage of season and training objective. Even so, practitioners must be cognisant of the magnitude of measurement error when interpreting changes in movement velocity. That is, coaches should consider adjusting the barbell load if the change in velocity exceeds the measurement error. Our data also suggest that MV may be a more reliable measurement than PV, at least in the back squat. Furthermore, practitioners employing VBT methods should avoid using GYM at 20% of 1RM because of the large within-subject variability present at this load.

ACKNOWLEDGEMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The results of the present study do not constitute endorsement of the product by the authors or the NSCA. The authors have no conflicts of interest to declare.

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Table and Figure Captions

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

Table 2. Absolute reliability of the GymAware PowerTool in the back squat and bench press.

Table 3. Standardised mean bias between repeated trials

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

Figure 2. Reliability of the GymAware PowerTool to measure mean velocity in the back squat and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard error of measurement as a percentage of the mean ($SEM_{\%}$, panel B), and the mean bias with 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good correlation coefficient. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 3. Reliability of the GymAware PowerTool to measure peak velocity in the back squat and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard error of measurement as a percentage of the mean ($SEM_{\%}$, panel B), and the mean bias with 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good correlation coefficient. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 4. Reliability of the GymAware PowerTool to measure mean power in the back squat and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard error of measurement as a percentage of the mean ($SEM_{\%}$, panel B), and the mean bias with 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good

correlation coefficient. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Figure 5. Reliability of the GymAware PowerTool to measure peak power in the back squat and bench press. Graphs display the intraclass correlation coefficient (ICC, panel A), standard error of measurement as a percentage of the mean ($SEM_{\%}$, panel B), and the mean bias with 95% limits of agreement (95% LOA, panel C). Area shaded in grey represents a good correlation coefficient. 1RM = one repetition maximum. Data are presented as means ± 95% confidence intervals.

Supplemental Digital Content 1. Photograph of a GymAware setup on a free-weight bench press

Table 1. Baseline characteristics of study participants

Characteristic	n = 29
Age (years)	17.6 ± 1.0
Body mass (kg)	87.3 ± 20.8
Height (cm)	173.3 ± 18.3
Back squat 1RM (kg)	
Absolute	145.5 ± 24.4
Relative	1.71 ± 0.35
Bench press 1RM (kg)	
Absolute	100.8 ± 16.4
Relative	1.18 ± 0.26

1RM = one repetition maximum. Data are presented as means ± SD.

Table 2. Absolute reliability of the GymAware PowerTool 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	0.05	0.04	0.04	0.03	0.04	0.09	0.05	0.04	0.04	0.03
	SWC	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.02
PV ($m \cdot s^{-1}$)	SEM	0.09	0.07	0.06	0.06	0.06	0.13	0.06	0.05	0.06	0.07
	SWC	0.04	0.03	0.03	0.02	0.02	0.05	0.03	0.02	0.02	0.02
MP (W)	SEM	102.5	79.6	73.0	76.7	76.2	52.8	27.4	27.1	28.2	29.6
	SWC	45.7	37.4	32.8	34.5	32.1	26.5	19.1	15.8	13.5	14.9
PP (W)	SEM	250.4	219.1	196.4	217.0	202.7	60.9	43.2	38.7	51.8	78.0
	SWC	112.8	105.3	80.1	70.9	66.6	33.3	29.4	24.4	21.4	25.5

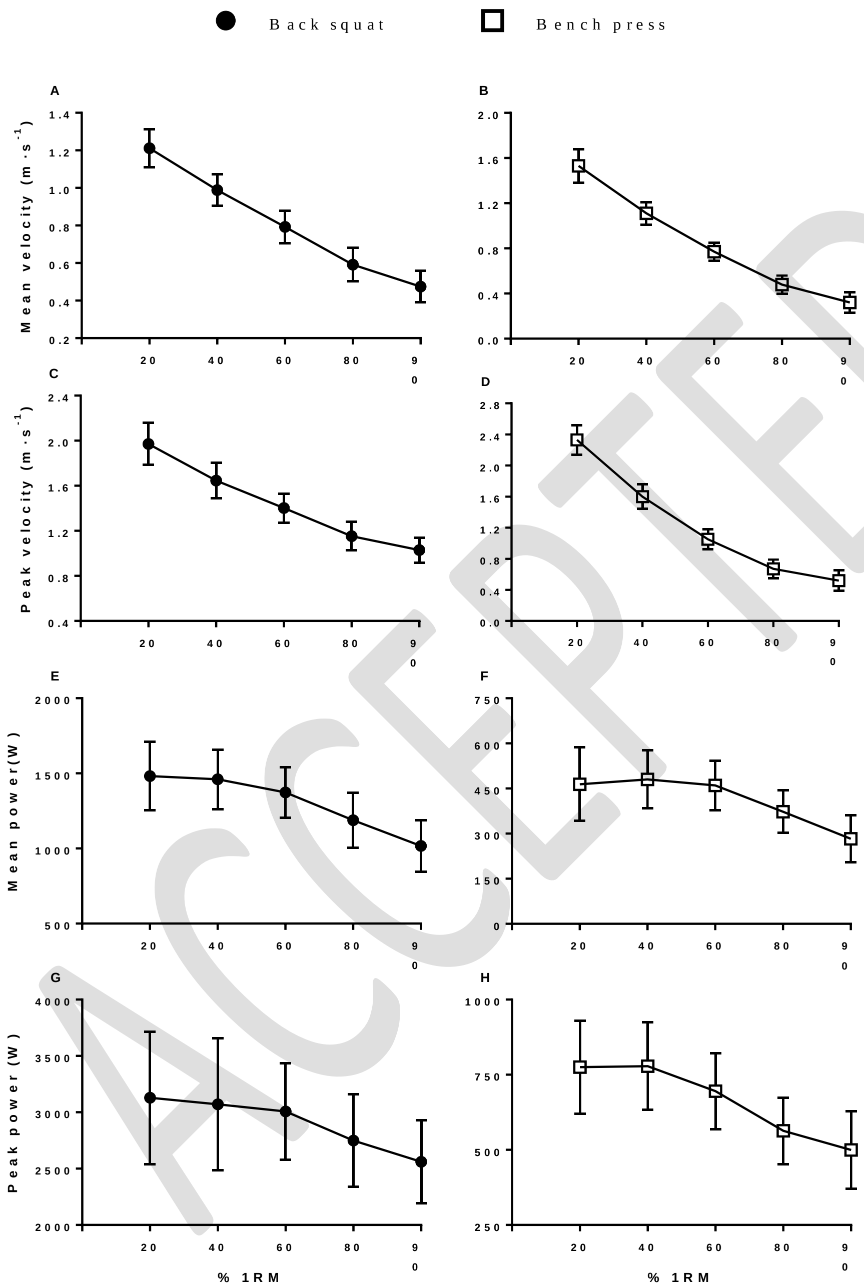
MV = mean velocity; PV = peak velocity; MP = mean power; PP = peak power; SEM = standard error of measurement; SWC = smallest worthwhile change.

Table 3. Standardised mean bias between repeated trials

	Back Squat					Bench Press				
	20%	**40%**	**60%**	**80%**	**90%**	**20%**	**40%**	**60%**	**80%**	**90%**
MV ($m \cdot s^{-1}$)	0.21	0.22	0.06	0.22	0.11	0.56	0.27	0.09	0.13	0.00
PV ($m \cdot s^{-1}$)	0.08	0.08	0.13	0.33	0.42	0.27	0.21	0.12	0.24	0.03
MP (W)	0.19	0.12	0.07	0.23	0.20	0.33	0.20	0.07	0.11	0.00
PP (W)	0.04	0.02	0.04	0.43	0.50	0.14	0.16	0.16	0.14	0.06

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 (20).

Figure 1



Back squat
Bench press
A
B
C
D
E
F
G
H
Mean velocity (m·s⁻¹)
Peak velocity (m·s⁻¹)
Mean power(W)
Peak power (W)
% 1RM
% 1RM

Figure 2

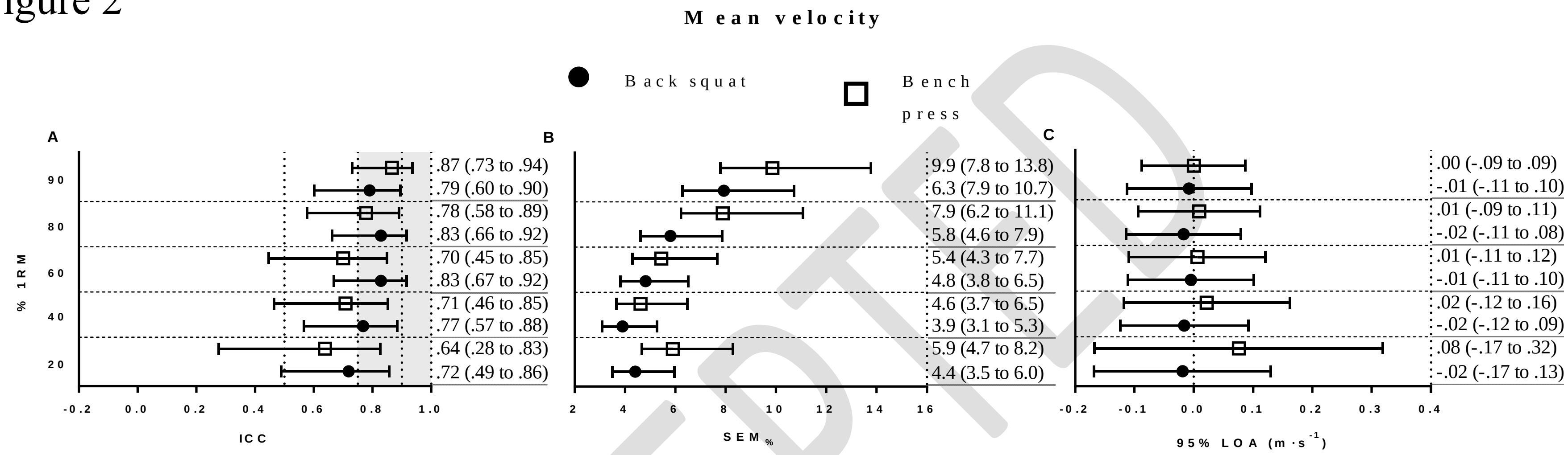

Mean velocity
Back squat
Bench press
A
B
C
% 1RM
90
80
60
40
20
.87 (.73 to .94)
.79 (.60 to .90)
.78 (.58 to .89)
.83 (.66 to .92)
.70 (.45 to .85)
.83 (.67 to .92)
.71 (.46 to .85)
.77 (.57 to .88)
.64 (.28 to .83)
.72 (.49 to .86)
ICC
9.9 (7.8 to 13.8)
6.3 (7.9 to 10.7)
7.9 (6.2 to 11.1)
5.8 (4.6 to 7.9)
5.4 (4.3 to 7.7)
4.8 (3.8 to 6.5)
4.6 (3.7 to 6.5)
3.9 (3.1 to 5.3)
5.9 (4.7 to 8.2)
4.4 (3.5 to 6.0)
SEM%
.00 (-.09 to .09)
-.01 (-.11 to .10)
.01 (-.09 to .11)
-.02 (-.11 to .08)
.01 (-.11 to .12)
-.01 (-.11 to .10)
.02 (-.12 to .16)
-.02 (-.12 to .09)
.08 (-.17 to .32)
-.02 (-.17 to .13)
95% LOA (m·s-1)

Figure 3

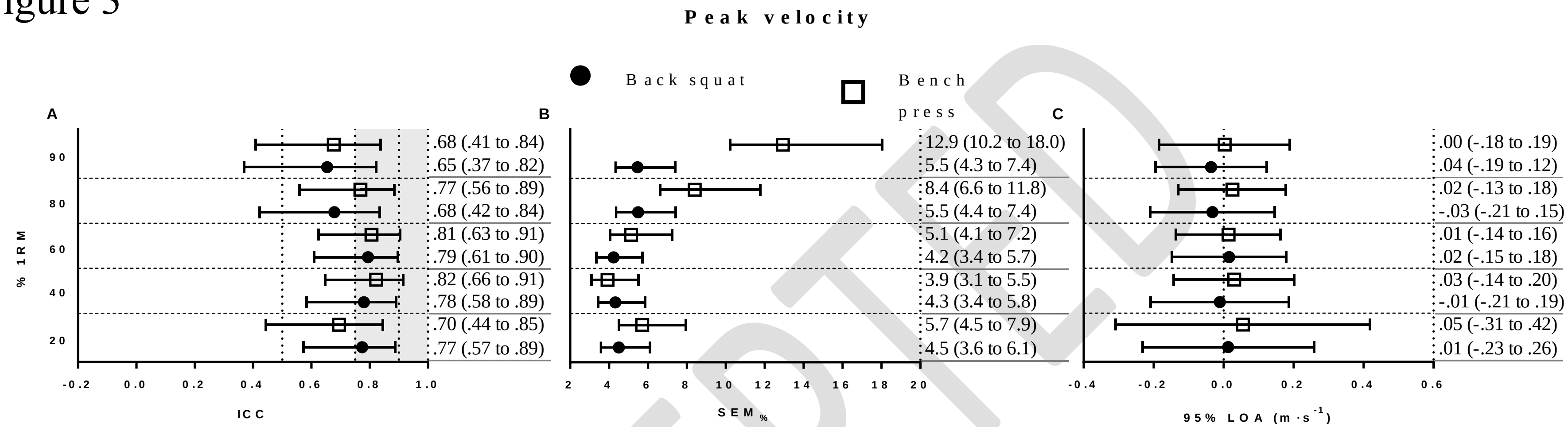

Peak velocity
Back squat
Bench press
A
B
C
% 1RM
90
80
60
40
20
.68 (.41 to .84)
.65 (.37 to .82)
.77 (.56 to .89)
.68 (.42 to .84)
.81 (.63 to .91)
.79 (.61 to .90)
.82 (.66 to .91)
.78 (.58 to .89)
.70 (.44 to .85)
.77 (.57 to .89)
ICC
12.9 (10.2 to 18.0)
5.5 (4.3 to 7.4)
8.4 (6.6 to 11.8)
5.5 (4.4 to 7.4)
5.1 (4.1 to 7.2)
4.2 (3.4 to 5.7)
3.9 (3.1 to 5.5)
4.3 (3.4 to 5.8)
5.7 (4.5 to 7.9)
4.5 (3.6 to 6.1)
SEM %
.00 (-.18 to .19)
.04 (-.19 to .12)
.02 (-.13 to .18)
-.03 (-.21 to .15)
.01 (-.14 to .16)
.02 (-.15 to .18)
.03 (-.14 to .20)
-.01 (-.21 to .19)
.05 (-.31 to .42)
.01 (-.23 to .26)
95% LOA (m·s-1)

Figure 4

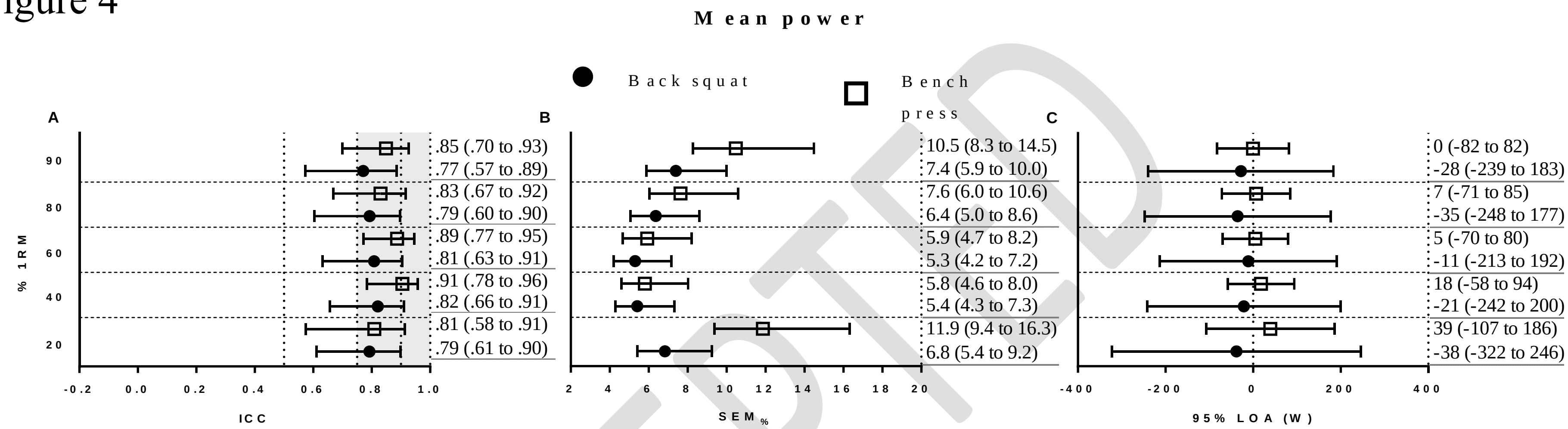
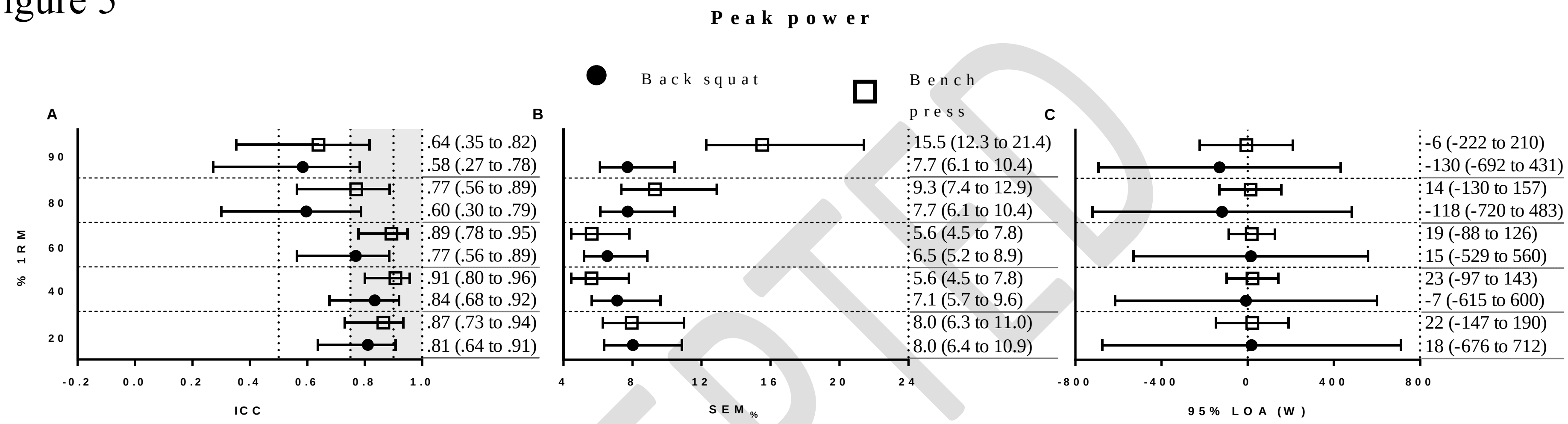

Mean power
Back squat
Bench press
A
B
C
% 1RM
90
80
60
40
20
.85 (.70 to .93)
.77 (.57 to .89)
.83 (.67 to .92)
.79 (.60 to .90)
.89 (.77 to .95)
.81 (.63 to .91)
.91 (.78 to .96)
.82 (.66 to .91)
.81 (.58 to .91)
.79 (.61 to .90)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
10.5 (8.3 to 14.5)
7.4 (5.9 to 10.0)
7.6 (6.0 to 10.6)
6.4 (5.0 to 8.6)
5.9 (4.7 to 8.2)
5.3 (4.2 to 7.2)
5.8 (4.6 to 8.0)
5.4 (4.3 to 7.3)
11.9 (9.4 to 16.3)
6.8 (5.4 to 9.2)
2
4
6
8
10
12
14
16
18
20
SEM %
0 (-82 to 82)
-28 (-239 to 183)
7 (-71 to 85)
-35 (-248 to 177)
5 (-70 to 80)
-11 (-213 to 192)
18 (-58 to 94)
-21 (-242 to 200)
39 (-107 to 186)
-38 (-322 to 246)
-400
-200
0
200
400
95% LOA (W)

Figure 5



Peak power
Back squat
Bench press
A
B
C
% 1RM
90
80
60
40
20
.64 (.35 to .82)
.58 (.27 to .78)
.77 (.56 to .89)
.60 (.30 to .79)
.89 (.78 to .95)
.77 (.56 to .89)
.91 (.80 to .96)
.84 (.68 to .92)
.87 (.73 to .94)
.81 (.64 to .91)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
ICC
15.5 (12.3 to 21.4)
7.7 (6.1 to 10.4)
9.3 (7.4 to 12.9)
7.7 (6.1 to 10.4)
5.6 (4.5 to 7.8)
6.5 (5.2 to 8.9)
5.6 (4.5 to 7.8)
7.1 (5.7 to 9.6)
8.0 (6.3 to 11.0)
8.0 (6.4 to 10.9)
4
8
12
16
20
24
SEM %
-6 (-222 to 210)
-130 (-692 to 431)
14 (-130 to 157)
-118 (-720 to 483)
19 (-88 to 126)
15 (-529 to 560)
23 (-97 to 143)
-7 (-615 to 600)
22 (-147 to 190)
18 (-676 to 712)
-800
-400
0
400
800
95% LOA (W)

Supplemental Digital Content 1. Photograph of the GymAware setup on a free-weight bench press