

Validity and reliability of the WIMU[®] system to measure barbell velocity during the half-squat exercise

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Abstract

This study aimed at determining the reliability and concurrent validity of the WIMU[®] system when measuring barbell velocity during the half-squat exercise by comparing data with the gold standard. A total of 19 male competitive powerlifters performed an incremental loading test using the half-squat exercise. The mean velocity, mean propulsive velocity and maximum velocity of all repetitions were recorded through both WIMU and T-Force systems. As a measure of reliability, coefficient of variations ranged from 6%–17% and standard error of means ranged from 0.02–0.11 m/s, showing very close reliability of data from both devices. Validity, in terms of coefficient of correlations and pairwise comparisons, was also tested. Except for some relative loads, the Pearson correlation analysis revealed significant correlations between both devices for mean velocity, mean propulsive velocity and maximum velocity ($r > 0.6$, $p < 0.05$). The mean velocity, mean propulsive velocity and maximum velocity were underestimated for the WIMU system compared to T-Force data at some points of the load–velocity relationship. The linear regression models performed revealed a strong load–velocity relationship in the half-squat exercise for each individual using mean velocity, mean propulsive velocity and maximum velocity, regardless of the instrument used ($R^2 > 0.77$ in all cases). Bland–Altman plots revealed low systematic bias ($\leq 0.06 \text{ m s}^{-1}$) and random error ($\leq 0.07 \text{ m s}^{-1}$) for the mean velocity and mean propulsive velocity obtained from the WIMU system as compared to the T-Force, while the maximum velocity resulted in an underestimation by the WIMU system (-0.16 m s^{-1}) as compared to the linear position transducer system. The results indicate that the WIMU system is a reliable tool for tracking barbell velocity in the half squat, but these data also reveal some limitations regarding its concurrent validity as compared to the gold standard, with velocity measures slightly underestimated in the tested conditions.

Keywords

velocity-based training, accelerometer, inertial sensor, resistance training

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Introduction

Assessments of velocity, force and power are often employed to monitor training induced adaptations.^{1,2} Velocity measurement has been demonstrated to be a non-invasive methodology to estimate the one-repetition maximum (1RM, i.e. the maximum load that can be lifted only one time) of the participants based on the well-known load–velocity relationship.^{1,3–5} As indicated by few previous studies,^{1,3,4} lifting velocity and load (i.e. load–velocity relationship) are significantly correlated. Therefore, the 1RM can be estimated based on velocity data without performing an actual 1RM test.^{1,3–5} Nevertheless, the load–velocity relationship seems to be exercise-dependent and specific to the execution mode (e.g. eccentric-concentric vs concentric-only),^{6,7} so those

factors affect the accuracy of the prediction. Likewise, the type of data analysis (generalized vs individualized

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load–velocity relationship) seems to be an influencing factor on the accuracy of the 1RM prediction. For example, Pérez-Castilla et al.⁶ reported different R^2 values for generalized and individualized load–velocity relationship during the concentric-only half-squat exercise (0.920 vs 0.976, respectively).

For elite athletes, changes in these measures can be minor, yet significant. Small differences in velocity measures during a lift (i.e. < 0.1 m/s) could represent important variations in training intensity.^{1,3} For example, Conceição et al.³ reported changes in barbell velocity during a half squat (i.e. ~ 0.06 m/s) with 5% increases in the load (in terms of %1RM). As a consequence, equipment used to monitor changes in velocity should be precise. In a laboratory-based environment, linear position transducers (LPTs) are often used to accurately measure velocity. Technologies such as accelerometers or photogrammetry have been also used to track barbell velocity,^{8–14} but LPT systems are considered the gold standard by many researchers. Importantly, laboratory-based equipment (i.e. LPT systems) is limited due to the large expense, which, in most cases, is more expensive than accelerometers and inertial sensors. The presence of multiple cables in LPT systems hinders its use during measurements (i.e. wireless measurement units seem to be easier to handle and suitable for portable applications on the field). Consequently, several field-based devices, including accelerometers and inertial sensors (accelerometer plus gyroscope) have been invented to overcome these limitations.^{8–14} In addition, an increased interest in cheaper, wireless measurement tools to measure velocity without direct attachments, which makes the measurement process more affordable and easier.

The reliability and validity of a barbell velocity analysis system are essential to determine whether results are due to changes in mechanical properties or are simply systematic measurement errors. In that context, a previous study¹⁵ focused on determining the reliability and validity of the WIMU[®] system for measuring barbell velocity during resistance exercises (i.e. back squat using Smith machine). Specifically, that work determined the reliability for mean velocity (MV) measurements at 40% and 80% 1RM, as well as to compare the results from a linear encoder in terms of concurrent validity. Therefore, reliability and validity data for other mechanical variables provided by the WIMU system (i.e. mean propulsive velocity (MPV) and maximum velocity (V_{\max}) are still unknown. The aim of this study is to determine the reliability and concurrent validity of the WIMU system for measuring barbell velocity on the half-squat exercise, by comparing data with the gold standard LPT system.

Methods

With the introduction of new wireless devices, establishment of their reliability and validity are essential before practical use. In this study, the WIMU system was

compared to the T-force linear velocity transducer for measuring barbell velocity on the half-squat exercise during an incremental protocol.

Participants

A total of 19 male, national competitive powerlifters (age range: 19–30 years; mean: 23.7 ± 2.8 years old; body height: 1.77 ± 0.06 m; body mass: 79.9 ± 9.5 kg; half-squat 1RM: 147.5 ± 27.1 kg; half-squat 1RM relative to body mass: 1.85 ± 0.25 kg kg⁻¹) participated in this study. Selection criteria included having at least 3 years of experience in powerlifting training, able to lift a load greater than their body mass in the half-squat exercise. Participants reported no chronic diseases or recent injuries that could compromise test performance. They were instructed to avoid any strenuous exercise two days prior to each testing session. Participants were informed of the study procedures and signed a written informed consent form prior to participating in the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board.

Procedures

Subjects arrived at the laboratory in a well-rested condition at the start of each testing session. The warm-up routine was created based on the preferences of the participants and consisted of jogging (5 min at a comfortable speed), foam rolling (3–4 min focused on lower back and hip extensors and flexors), dynamic stretching and lower-body joint mobilization exercises (thoracic, hip and ankle mobility for 3–4 min), followed by one set of five repetitions with an absolute load of 18 kg in the half-squat exercise. Thereafter, subjects performed an incremental loading test using the half-squat exercise.

The concentric-only half-squat test was performed. Subjects first flexed their knees to 90° in a continuous and controlled manner. They maintained this position for 1.5 s, and immediately afterwards, they performed a purely concentric action at maximal intended velocity without lifting their toes off the ground. The duration of the eccentric and isometric phases was paced by auditory signals. Subjects initiated the movement in a fully extended position, feet approximately shoulder-width apart and the barbell held across the top of the shoulders and upper back. The barbell was required to be in constant contact with the subjects' shoulders and upper-back through the whole execution. The 90° knee angle was individually measured with a manual goniometer. To ensure the reproducibility of the 90° knee angle, a tripod adjustable with a telemetric photocell (Microgate, Bolzano, Italy) was placed on one side of the bar.⁶ The telemetric photocell emitted an acoustic signal when the bar crossed the depth linked to the 90° knee angle for each subject. The height of the tripod was the same over the entire testing session. For each repetition, subjects received real-time velocity

performance feedback to encourage them to give maximal effort. Trained spotters were present, and lifting belts were used to ensure safety.

During the testing session, the initial load was set at 18 kg for all subjects and progressively increased in 20 kg increments until the MPV attained was < 0.6 m/s. Then, load increments were individualized based on feedback from the participants and the protocol was continued until no further weight could be lifted. Two attempts per load were executed with a recovery period of 1 min in-between. Rests between sets were set to 3 min for the lighter loads (MPV ≥ 1.00 m/s) and 5 min for the medium loads (MPV < 1.00 m/s). Only the repetition with the highest MPV at each load (measured through the T-Force system) was selected for further analysis,^{1,6,16} apart from reliability measures which required two attempts per load. The average MPV for the heaviest load used in the incremental loading test was 0.43 ± 0.06 m/s. The average number of incremental loads tested was 8.6 ± 1.6 .

Materials and testing

Height (Seca 202, Seca Ltd., Hamburg, Germany) and body mass (Tanita BC-418 segmental, Tokyo, Japan) were assessed in the first testing session. A Smith machine (Technogym, Barcelona, Spain) coupled with an LPT system (T-Force Dynamic Measurement System; Ergotech, Murcia, Spain), which sampled the velocity of the barbell at a frequency of 1,000 Hz, was used in the testing session.¹⁷ In addition, an inertial device (WIMU system, RealTrack systems, Almería, Spain) was attached to the bar. This device contained four three-dimensional (3D) accelerometers, among other sensors (three 3D gyroscopes and magnetometers), that detect and measure movement using a micro-electromechanical system with an adjustable sample frequency of 10–1000 Hz. The sample frequency used in this study was 1000 Hz. To measure velocity, the acceleration measured by triaxial accelerometers was used. From the acceleration, the device estimates velocity of each repetition in both the concentric and eccentric phases (only concentric data were used for the subsequent analysis). Each trial was downloaded using the manufacturer's software S PRO™ (RealTrack systems, Almería, Spain).

The MV (i.e. the average velocity from the start of the concentric phase until the bar reaches the maximum height), MPV (i.e. the average velocity from the start of the concentric phase until the acceleration of the bar is less than gravity (-9.81 m/s⁻²)) and V_{\max} (i.e. the maximum instantaneous velocity value reached during the concentric phase) of all repetitions were recorded.¹⁶ Only the repetition with the highest MPV of each loading condition (measured through the T-Force system) was used for statistical analyses. Before all attempts, both devices (T-Force and WIMU systems) were calibrated according to the manufacturer's instructions.

Statistical analysis

Descriptive statistics are represented as mean standard deviation (SD). Tests of normal distribution and homogeneity, determined by the Shapiro–Wilk and Levene's test, respectively, were conducted on all data before analysis. In order to make comparisons easier, absolute loads (i.e. kg) were converted into relative loads (i.e. %1RM). For that purpose, the best performance during the protocol, in terms of higher load lifted, was considered as 1RM (100%), and the rest of loads were calculated as percentages of 1RM. Coefficient of variation (CV, %) and standard error of the mean (SEM) were calculated as a measure of absolute reliability (within-subject variation (CV = SD*mean*100) and SD of a sampling distribution (SEM = SD* $\sqrt{1-\text{reliability}}$), respectively).^{18,19} For that purpose, the two attempts per load were used, and CV and SEM were calculated on an individual basis. To determine concurrent validity, a Pearson correlation analysis was also performed between T-Force and WIMU data. The following criteria were adopted to interpret the magnitude of correlations between measurement variables: < 0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large) and 0.9–1.0 (almost perfect).²⁰ Pairwise comparisons of means (t-test) were also conducted between data (MV, MPV and V_{\max}) from the two devices at different loads (in terms of %1RM), and linear regressions were used to analyze the load–velocity relationship for each subject. Finally, Bland–Altman plots (i.e. limits of agreement method, mean difference ± 1.96 SD)²¹ were constructed to examine the presence of systematic and proportional bias between the measured (i.e. T-Force system) and estimated values of mechanical variables (i.e. WIMU system). The level of significance used was $p < 0.05$. Data analysis was performed using SPSS (version 23, SPSS Inc, Chicago, IL).

Results

Reliability

Table 1 shows the %CV (as a measure of absolute reliability) of mechanical parameters at different loads from both systems. For the LPT system, %CV was 6.8–16.8% (MV), 8.3–17.3% (MPV) and 5.7–9.9% (V_{\max}), whereas for the WIMU system, %CV ranged between 6.2–13.8% (MV), 8.2–16.8% (MPV) and 7.2–16.8% (V_{\max}). In addition, the SEM is provided in Table 2.

Validity

The Pearson correlation analysis is shown in Table 3. The MV values from both devices showed significant correlations over the protocol ($r \geq 0.646$, $p < 0.05$), except for 20% and 70% 1RM ($r \leq 0.520$, $p \geq 0.05$). The MPV values showed significant large and very large correlations ($r \geq 0.628$, $p < 0.05$) at every

Table 1. Coefficient of variation (%) of variables related to the measurement of barbell velocity (MV, MPV and V_{\max}) in both the linear position transducer (LPT) and the WIMU system.

%IRM	MV (m/s)		MPV (m/s)		V_{\max} (m/s)	
	LPT	WIMU	LPT	WIMU	LPT	WIMU
10	8.60	9.02	11.28	11.69	9.18	11.76
20	6.76	6.19	8.29	8.14	8.17	8.45
30	11.86	11.77	14.39	12.44	7.42	14.44
40	9.95	7.90	10.87	8.32	6.64	7.48
50	9.06	7.86	11.21	8.99	6.49	7.52
60	9.27	10.41	13.81	11.23	9.91	13.62
70	9.50	13.82	12.27	16.75	8.68	16.80
80	9.09	12.04	9.07	13.23	5.67	7.18
90	11.02	12.62	11.00	16.47	7.73	11.77
100	16.77	13.27	17.26	14.21	9.79	15.66

MV: the average velocity from the start of the concentric phase until the bar reaches the maximum height; MPV: the average velocity from the start of the concentric phase until the acceleration of the bar is lower than gravity (-9.81 m s^{-2}); V_{\max} : the maximum instantaneous velocity value reached during the concentric phase; IRM: the maximum load that can be lifted only one time; LPT: linear position transducers.

Table 2. Standard error of mean (SEM) of variables related to the measurement of barbell velocity (MV, MPV and V_{\max}) in both the linear position transducer (LPT) and the WIMU system.

%IRM	MV (m/s)		MPV (m/s)		V_{\max} (m/s)	
	LPT	WIMU	LPT	WIMU	LPT	WIMU
10	0.03	0.03	0.04	0.04	0.06	0.07
20	0.02	0.02	0.03	0.03	0.05	0.05
30	0.11	0.11	0.04	0.03	0.04	0.06
40	0.09	0.06	0.03	0.02	0.03	0.03
50	0.07	0.06	0.02	0.02	0.03	0.03
60	0.02	0.02	0.03	0.02	0.04	0.05
70	0.02	0.02	0.02	0.03	0.03	0.05
80	0.02	0.02	0.02	0.02	0.02	0.03
90	0.05	0.06	0.02	0.02	0.02	0.03
100	0.02	0.01	0.02	0.01	0.02	0.03

MV: the average velocity from the start of the concentric phase until the bar reaches the maximum height; MPV: the average velocity from the start of the concentric phase until the acceleration of the bar is lower than gravity (-9.81 m s^{-2}); V_{\max} : the maximum instantaneous velocity value reached during the concentric phase; IRM: the maximum load that can be lifted only one time; LPT: linear position transducer.

Table 3. Pearson correlation between variables related to the measurement of barbell velocity (MV, MPV and V_{\max}) from the linear position transducer (LPT) and the WIMU system over an incremental test.

%IRM	10	20	30	40	50	60	70	80	90	100
MV (m/s)	0.865**	0.520	0.696**	0.877**	0.760**	0.646*	0.419	0.662*	0.739**	0.687**
MPV (m/s)	0.898**	0.398	0.813**	0.882**	0.823**	0.645*	0.628*	0.632*	0.717**	0.685**
V_{\max} (m/s)	0.971**	0.773**	0.196	0.842**	0.908**	0.729*	0.819**	0.498	0.742**	0.861**

MV: the average velocity from the start of the concentric phase until the bar reaches the maximum height; MPV: the average velocity from the start of the concentric phase until the acceleration of the bar is lower than gravity (-9.81 m s^{-2}); V_{\max} : the maximum instantaneous velocity value reached during the concentric phase; IRM: the maximum load that can be lifted only one time; LPT: linear position transducer.

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

%1RM except for 20% ($r = 0.398$, $p \geq 0.05$). The V_{\max} values from both devices showed significant correlations over the protocol ($r \geq 0.729$, $p < 0.05$), except for 30% and 80% 1RM ($r \leq 0.498$, $p \geq 0.05$).

A paired t-test (Figure 1) demonstrated significant differences ($p < 0.05$) between data from both devices at similar %1RM. The MV was underestimated for WIMU system compared to T-Force data ($p < 0.05$) with no differences at 10% and 60–80%1RM. The MPV was also underestimated for the WIMU system compared to T-Force data ($p < 0.05$) with no differences at 30% and 100%1RM. Likewise, V_{\max} was underestimated for the WIMU system over the entire protocol ($p < 0.01$).

Figure 2 shows the load–velocity relationship measured with both the LPT and the WIMU system over the incremental test (in terms of %1RM). Velocity measures (MV, MPV and V_{\max}) were plotted against the load lifted. The results showed that strong load–

velocity relationship ($R^2 > 0.75$ in all cases) exists in the half-squat exercise for each individual using MV, MPV and V_{\max} , no matter which instrument was used. Specifically, similar R^2 values, although always lower for the WIMU system, were obtained with the T-Force and the WIMU for load-MV (LPT: $R^2 = 0.89$; WIMU: $R^2 = 0.86$) and load-MPV relationship (LPT: $R^2 = 0.86$; WIMU: $R^2 = 0.85$), with some differences in the load- V_{\max} relationship (LPT: $R^2 = 0.87$; WIMU: $R^2 = 0.77$).

Through Bland–Altman plots, Figure 3 shows the differences between the two devices (systematic bias and random error) and the degree of agreement between the two systems (95% limits of agreement). These plots revealed low systematic bias ($\leq 0.06 \text{ m s}^{-1}$) and random error ($\leq 0.07 \text{ m s}^{-1}$) for the MV and MPV obtained from the WIMU system as compared to the T-Force, while the V_{\max} was underestimated by the WIMU system (-0.16 m s^{-1}) as compared to the LPT

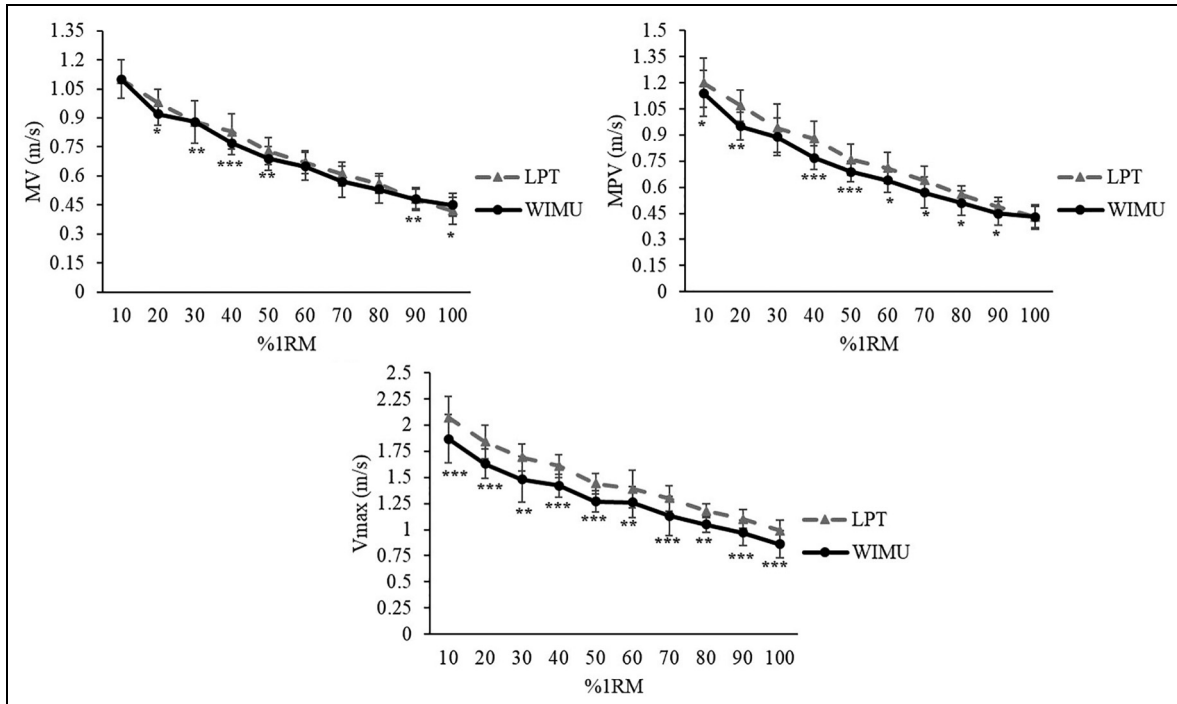


Figure 1. Paired t-test between velocity data (MV, MPV and V_{max}) from both devices (LPT vs WIMU systems) at similar loads (%IRM).

MV: mean velocity; MPV: mean propulsive velocity; V_{max}: maximum velocity; LPT: linear position transducer; %IRM: percentage of one-repetition maximum.

*p < 0.05, **p < 0.01, ***p < 0.01.

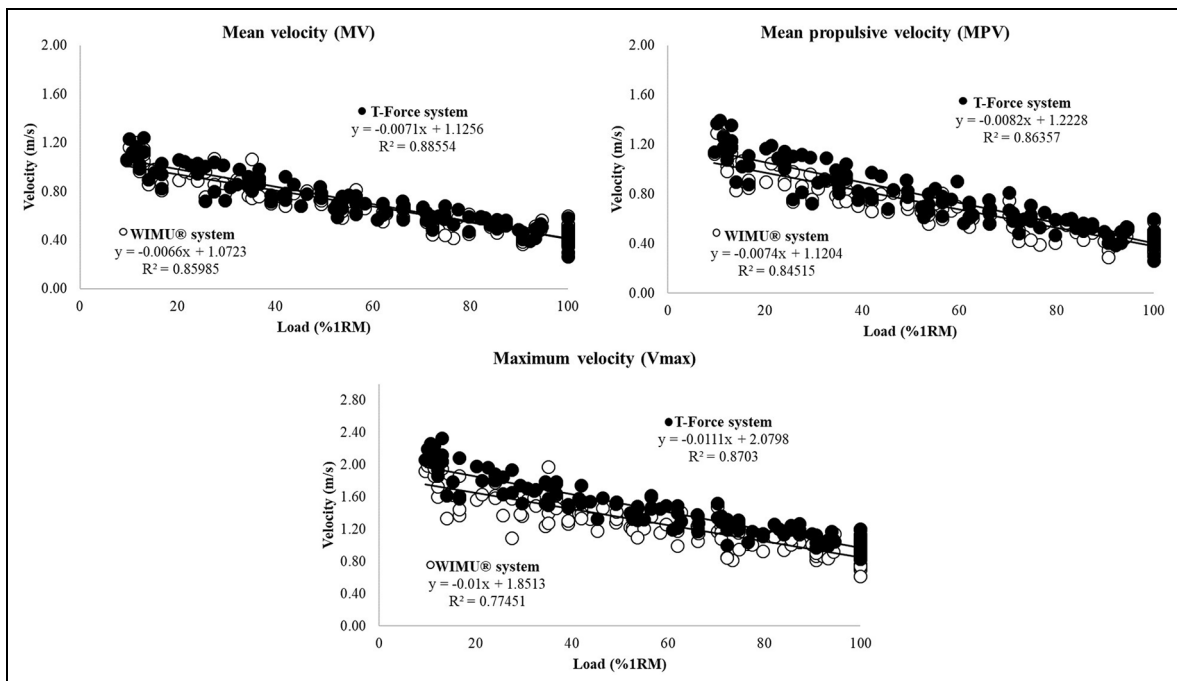


Figure 2. Load–velocity relationship measured with both the LPT and the WIMU systems over the incremental test. LPT: linear position transducer.

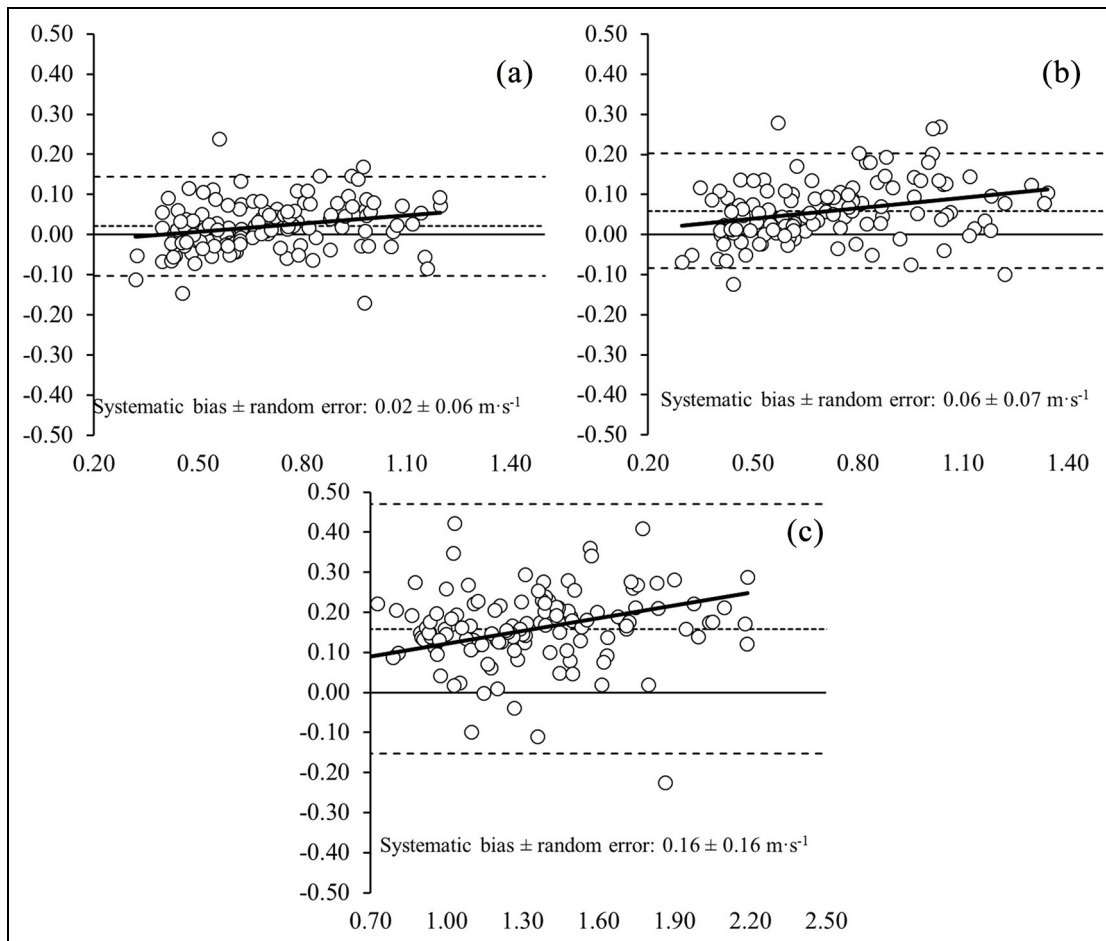


Figure 3. Bland–Altman plots for the measurement of mechanical variables for both systems (T-Force vs WIMU): (a) mean velocity, (b) mean propulsive velocity, and (c) maximum velocity.

The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed lined), along with the regression line (solid line).

system. Limits of agreement showed a similar width, though slightly wider for the V_{\max} as compared to the MV and MPV.

Discussion

This study aimed to determine the reliability and concurrent validity of the WIMU system compared to the T-Force system for measuring barbell velocity on the half-squat exercise. As a measure of within-subject variation and SD of a sampling distribution, the CV ranged from $\sim 6\text{--}17\%$ and the SEM ranged from $\sim 0.02\text{--}0.11 \text{ m/s}$, showing very close reliability data from both devices. Velocity measures, in terms of MV, MPV and V_{\max} , were very similar from both devices. However, there were some differences between the two devices as revealed by the paired samples t-test, which showed that the velocities measured with the WIMU tended to be slightly lower than those measured with the LPT. To reinforce the concurrent validity analysis, a Pearson correlation analysis was conducted for each variable. The magnitude of correlations between measurement

variables from both devices were large and very large²⁰ for MV, MPV and V_{\max} over the entire protocol, except MPV and V_{\max} values at light loads (i.e. $\sim 20\%\text{--}30\%$ 1RM). The linear regression model and Bland–Altman plots support the validity analysis. The two regression lines virtually overlap when plotted on the same graph, showing a solid load–velocity relationship ($0.80 < R^2 > 0.90$), with lower R^2 values for the WIMU system, whereas the Bland–Altman plots report an assumable systematic bias for MV and MPV, but too high for V_{\max} .

Since LPT systems are considered the gold standard for measuring barbell velocity,^{1,4,8–10,22} the results obtained point to the WIMU system as a reliable tool for tracking barbell velocity in the half squat, with similar CV and SEM to those reported by the T-Force system, but these data also suggest some limitations regarding its concurrent validity, as compared to the gold standard, with velocity measures slightly underestimated in the tested conditions. The LPT system used in this study directly measured the vertical displacement velocity of its cable through a sensor attached to the

barbell. Compared to other LPTs, this system transduces electrical signals, rather than differentiates cable position over time,^{1,22} showing a very high accuracy.¹⁷

As mentioned in the introduction, a previous study¹⁵ analyzed the reliability and validity of the WIMU system for measuring barbell velocity during the back squat, but in that case, only the MV measurements at loads equivalent to 40% and 80% were taken into consideration. The results from that study are similar to the results from this study, indicating that the WIMU system is a reliable tool, even though reliability was examined through test–retest analysis, whereas this study determined absolute reliability. Regarding the validity analysis, the results obtained in this study are similar to those reported by Muyor et al.,¹⁵ with barbell velocity slightly underestimated by the WIMU system as compared to the T-Force system. In addition, this study determined the dynamic of velocity-based variables (i.e. MV, MPV and V_{\max}) over an incremental protocol and analyzed the load–velocity relationship and the accuracy of 1RM estimations based on data reported from these two devices (WIMU vs T-Force systems).

Based on the evidence supporting the importance of measuring movement velocity to monitor training adaptations^{1,2} and the accuracy of velocity measurements to estimate the 1RM (taking into account the exercise, execution mode and data analysis),^{1,3–7} the measurement of the load–velocity relationship (based on a linear regression model) seems to be well justified. The load–velocity profile describes the ability of the subject to produce velocity at increasing intensities (normally, during an incremental test). The load–velocity profile has been shown to be an accurate method to estimate 1RM,^{4,23} even though it is exercise-dependent and specific to the execution mode.^{6,7} Previous studies have analyzed the load–velocity profiles of different exercises such as the full squat,³ half squat^{5,6} and bench press^{1,7} with high coefficients of determination reported when data analysis was individualized.

This study shows that load–velocity profiles derived from the velocities measured with LPT versus WIMU system reported similar results for MV and MPV (almost identical R^2 values), with varying results for V_{\max} ($R^2 = 0.87$ and 0.77 for LPT and WIMU, respectively). Despite the WIMU system showing homogeneous differences across the entire protocol (increasing loads in terms of %1RM) compared to the LPT, the authors strongly recommend not to use LPT and WIMU systems interchangeably. As reported by previous studies,^{1,3} small differences in velocity measures during a lift (i.e. < 0.1 m/s) could represent important variations in training intensity, causing training load and targets to be overestimated or underestimated.

Previous studies have assessed the reliability and validity of different low-cost and wireless devices, as compared to the T-Force system, for tracking barbell velocity.^{8–14,24} Specifically, the PUSH wearable device (<https://www.trainwithpush.com>) showed high levels of validity and reliability in comparison with a LPT ($r > 0.9$) for the measurement of movement velocity during back squats.⁹ That data slightly decreased in a more recent work during the same exercise (i.e. back squat, $r = 0.86$).¹⁰ Balsalobre-Fernández et al.¹⁰ also provide data about other wearable sensors (BEAST sensor, <https://www.thisbeast.com/en>), which showed superior values of correlation ($r > 0.96$) than the LPT system. These differences could be due to technical issues (accuracy differences), but some points need to be addressed. First, the sample frequency differed. Whereas, the WIMU system was tested at 1000 Hz, the PUSH and BEAST sensors were tested at 200 and 50 Hz, respectively. Second, each wearable sensor is designed to be placed on different body parts. The BEAST sensor is designed to be placed in a wristband or directly attached to the barbell. The PUSH band is meant to be placed just below the elbow of the subject. The WIMU system was attached to the barbell. Finally, the type of resistance exercise tested varied (in this case, full squat vs half squat). The lack of methodological consistency makes comparisons difficult.

Conclusion

The results from this study demonstrate an acceptable reliability of the WIMU system compared with an LPT system, but these data also suggest some limitations regarding its concurrent validity as compared to the gold standard, with velocity measures slightly underestimated in the test conditions.

From a practical point of view, scientists and coaches should know that both devices showed an adequate reliability for barbell velocity assessment. Therefore, velocity-based variables reported from these devices can be compared over time if using the same device. However, the clients also should be aware about the limitations of comparing data from these two devices with the WIMU system useful on an individual basis.

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