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Original Article

Validity and Reliability of the VmaxPro IMU for back squat exercise in multipower machine

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Abstract:
Problem Statement: Currently, the application for velocity-based training through a 3D Motion Capture System is discarded due to the economic and personal resources involved, being used mainly as laboratory instruments. As an alternative, different device on the market make it possible to assess and control training loads, although not all use the same technology to measure execution velocity. *Approach:* Specifically, the inertial measurement unit VmaxPro is one of the new additions to the market of sensors based on accelerometry for the control of execution velocity in resistance training and the reliability and validity of this type of device need to be analysed. *Purpose:* Thus, this study aimed to conduct a concurrent validation for the velocity and range of displacement of the barbell of VmaxPro against a 3D Motion Capture System as the gold standard. The secondary purposes of this study were to analyse the reliability and measurement errors (both random and systematic) of VmaxPro. *Results:* The main results of the present study are shown in terms of reliability, validity, and accuracy of the VmaxPro. Firstly, the practical device shows excellent to good ICCs values for the reliability of the velocity and range of displacement of the barbell, respectively. Secondly, VmaxPro presents a small underestimation of the velocity of its systematic error (-0.021 m/s) in comparison to the 3D Motion Capture System, contrary to the random error (0.053 m/s), overestimating the velocity measurement, and a measurement errors both systematic and random close to 2 cm for the range of barbell displacement. Finally, VmaxPro presents valid values for both the velocity and range of displacement of the barbell, being a suitable instrument for this purpose. *Conclusions:* It would be possible for both coaches and athletes to use the inertial measurement unit VmaxPro for the control, monitoring, and evaluation of strength training.
Key Words*:* **velocity-based training, inertial measurement unit, 3D motion capture system, gold standard**.

Introduction

Sports training has undergone an evolution in the development and improvement of training methods, as well as in the control and assessment of athletes through the analysis of sports performance for the improvement of the different basic physical capacities. These basic physical capacities were defined as anatomical and physiological predispositions innate in the athlete, feasible to measure and improve, which allow movement and can be classified into two groups, based on muscular contractions (strength, endurance, and speed) or based on muscular stretching (flexibility) (Porta, 1993). Deepening strength training, there are great difficulties when it comes to training this capacity, such as the dosage of the programmed load, the control of the applied load, and finally, the assessment of the effect of the training (Badillo et al., 2017).

Specifically, in recent years, attention has been focused on analysing from a critical point of view the strength training methods that have been used for decades to increase the physical performance of many athletes, proposing new, more rational, and effective ways of training with the utmost scientific rigour (Balsalobre-Fernández & Jiménez-Reyes, 2014). One solution to the problems posed by the traditional use of 1RM (one-repetition maximum) as a reference for dosing loads, controlling them, and assessing the effect of training, is the character of the effort defined by the execution velocity (Sánchez-Medina & González-Badillo, 2011). Strength training by controlling execution velocities and its effect on performance has been contrasted in the scientific literature, as training at maximum velocities leads to a significant improvement in performance compared to lower velocities (González-Badillo et al., 2014). Consequently, the inverse relationship between load and velocity has led to an optimized training method known as velocity-based training (VBT) (Behm & Sale, 1993; González-Badillo et al., 2011; Weakley et al., 2021). Research has even been conducted to compare the accuracy of different devices to predict the 1RM from the individual load-velocity relationship (Pérez-Castilla et al., 2019).

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Currently, different devices on the market make it possible to assess and control training loads, although not all use the same technology to measure execution velocity. Therefore, these devices could be grouped into six large blocks depending on the technology used: a) linear velocity transducers (driven by wire), b) rotary or friction transducers, c) optical position transducers, d) accelerometers, e) 2D and 3D video analysis, and mobile applications and f) dynamometric platforms.

Concerning accelerometry, such devices have emerged in recent years, noting that the development of accelerometry-based devices is expanding rapidly, and more and more sensors are appearing on the market for movement assessment and physical activity recording (Cerezuela-Espejo et al., 2021; García-Pinillos et al., 2019; Imbach et al., 2020; Jaén-Carrillo et al., 2020; Navalta et al., 2019; Olaya-Cuartero et al., 2019; Olaya-Cuartero & Cejuela, 2020, 2021; Pinedo-Jauregi et al., 2022; Ruiz-Alias et al., 2022; Taboga et al., 2021). These devices comprise at least a triaxial accelerometer (measurement in *x*, *y*, and *z* axis) and a gyroscope (Olaya-Cuartero, 2019; Olaya-Cuartero & Cejuela, 2020). They usually work wirelessly to transfer data to storage devices such as smartphones or tablets. Since they do not track any marker and are not connected to measure, the direct displacement of the barbell, the execution velocity is obtained indirectly by calculating an integration from the vertical acceleration concerning time. This fact means that at low velocities where there are no changes in acceleration, they can show issues in the measurement. For this reason, they are not suitable instruments for monitoring with sub-maximal or maximum loads that require very low execution velocities.

Regarding execution velocity and strength training, the Inertial Measurement Unit (IMU)-based VmaxPro (Blaumann & Meyer Sports Technology, Magdeburg, Germany) is one of the new additions to the market of sensors based on accelerometry for the control of execution velocity (Fritschi et al., 2021; Held et al., 2021). Although, like the rest of this type of sensor, it is designed for personal training where, based on the calculation of velocity, it establishes and samples different parameters of interest. However, this device, which works connected to an iPhone or iPad (Apple INC, Cupertino, California) via Bluetooth, allows with its simple version, the monitoring of up to 3 different athletes at the same time. Although the data offered by the distributors on their website and the research carried out so far are interesting (Fritschi et al., 2021; Held et al., 2021), more research is needed on different strength exercises and different levels of athletes. As a differentiating element of this sensor, it performs a kinematic analysis of the movement of the barbell, which allows the analysis of the displacement of the barbell that helps to give technical feedback to athletes, this being a differentiating aspect concerning its competitors.

For the analysis of 2D and 3D video and mobile applications, to carry out analysis of velocity, high-velocity cameras above 120 fps (frame per second) are required (Pueo, 2016). This is why, thanks to the technological advance of smartphones, with cameras that allow video recording at 120 fps or higher, they have given rise to the appearance of applications aimed at monitoring velocity and execution in weightlifting exercises (Balsalobre-Fernández et al., 2017, 2018). Despite the facilities offered using this type of analysis, it is necessary to carry out a video analysis after the recording, which requires a proper observation protocol with experienced observers (Pueo et al., 2018), which is a limitation due to having to depend on observers to be able to carry out the measurements. In the same line, also it is possible to control the execution velocity through 3D systems. These systems, like the rest of the devices, calculate the velocity parameters indirectly from time. However, the high qualification required by specialized operators, the complexity of data collection and processing, as well as the economic cost involved, mean that this type of technology is not easily accessible, so its use is relegated almost exclusively to biomechanical studies and specific analyses of scientific studies or projects. Although they are considered the gold standard, their use for performance evaluation and their assembly for athlete assessments is questionable due to the complexity of their use and the economic and personal resources involved (Dorrell et al., 2019). For this reason, the application for VBT of 3D capture systems is ruled out and they are mainly used as a laboratory instruments.

Therefore, the main purpose of this study was to conduct a concurrent validation study for the velocity and the range of displacement of the barbell of the VmaxPro against a 3D Motion Capture System as the criterion. The secondary purposes of this study were to analyse the reliability and measurement errors (both random and systematic) of VmaxPro.

Material & methods

Participants

Twenty recreationally active male athletes voluntarily participated in this study. The characteristics of the sample are described in Table 1. The study was carried out following the guidelines of the ethical principles of the Declaration of Helsinki. All participants provided informed written consent before the beginning of this study, which was approved by the University Institutional Review Board (IRB No. UA-2019-01-19).

Table 1. Characteristics of the sample (mean ± SD).

	Mean		SD
Age (years)	23.6	±	4.1
Height (cm)	181.9	±	5.8
Body mass (kg)	85.8	±	11.5

Procedure

Participants carried out two laboratory test sessions two weeks apart. The data collection procedure for this study is shown in Figure 1.

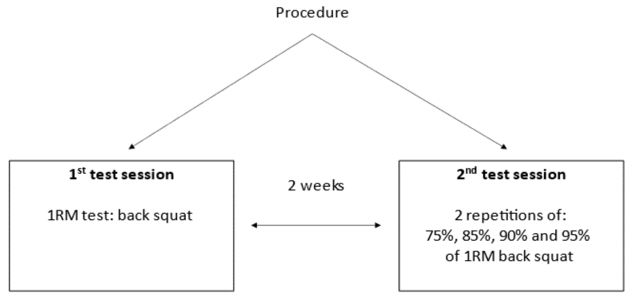

Figure 1. Data colletion procedure.

Test protocol

On the first test session, participants performed a standardized 1RM test (Pallarés et al., 2014) of back squats, consisting of two trials with a 3 min rest between repetitions, starting at 20 kg and progressively increasing in 15 kg increments until the mean velocity was lower than 0.7 m/s. Afterward, the attained load was incremented with smaller weights between 2.5 and 5 kg until the heaviest load each participant was able to lift was considered the maximum load or 1RM. On the second test session, the mean velocity values were measured to 75%, 85%, 90%, and 95% of 1RM respectively, indicating moderate to high velocities in the back squat to test the video system under the most unfavorable conditions for tracking (Pueo et al., 2021). Thus, participants performed two repetitions of each percentage with a 3 min rest between repetitions. All participants were instructed to abstain from drinking caffeinated beverages or alcohol for 24 hours before both testing sessions.

Instruments

The multipower machine (ProStrength Multi-power Professional, Pro-Gym, Barcelona, Spain) with 150×126×227 cm dimensions was used for the back squat exercise. The barbell´s instantaneous position was simultaneously monitored by the VmaxPro and 3D Motion Capture System serving as a criterion method (Pueo et al., 2020). The use of 3D motion capture systems as the gold standard criterion measure in new validity studies has been highly recommended (Weakley, Morrison, et al., 2021).

The optical motion capture system (OptiTrack Motive, Corvallis, OR, USA) comprising 8 infrared digital video cameras, was used as the gold standard. This system has also previously been used as the gold standard elsewhere (Pueo et al., 2020). All cameras were synchronized at 100 Hz, a shutter speed of 20 us to obtain 3D tracking of body markers over an area of 4 × 4 m with 1-mm resolution. To track the entire range of displacement of the markers of the barbell and machine reference points, four cross-shaped retroreflective circular markers were placed on the end of the barbell to correctly determine the centroid of the barbell when recording the movement in the sagittal plane. The range of barbell displacement was later processed by the difference between the peak height during the vertical displacement and the initial back squat position with the Mokka open-source motion kinematic & kinetic analyser software (v. 0.6, Mokka, Montréal, Canada).

The VmaxPro is a commercially available wireless IMU that includes a three-axis accelerometer, gyroscope, and magnetometer (Blaumann & Meyer Sports Technology, Magdeburg, Germany). This device also has previously been used to analyse valid and reliable barbell velocity (Held et al., 2021). Similarly, before each measurement, the VmaxPro was calibrated according to the manufacturer´s specifications (Blaumann & Meyer Sports Technology, Magdeburg, Germany).

Statistical analysis

Descriptive statistics are presented as mean ± SD, and 95% confidence intervals (95% CIs). The reliability of the IMU-based VmaxPro was tested using two-way random single measurements (absolute agreement) intraclass correlation coefficient (ICC) (2,1), and Cronbach's α (Hopkins et al., 2009). ICC values were interpreted as poor (<0.5), moderate (0.5–0.75), good (0.75–0.9), and excellent (>0.9) reliability (Koo & Li, 2016). Bland–Altman plots were also used to explore the agreement between the two instruments (Bland & Altman, 1986), which show mean outcome pairs against their difference between values to identify any random error and proportional bias with a bivariate Pearson's product-moment correlation coefficient of r^2>0.1 (Atkinson & Nevill, 1998).

Finally, the validity of the two instruments was calculated with the bivariate Pearson's product-moment correlation coefficient (*r*) with 95% confidence intervals (CIs), using the following thresholds: trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and practically perfect (>0.9) (Hopkins, 2018). All statistical analyses were computed with IBM SPSS v. 22 (IBM Corp, Armonk, NY) and an available spreadsheet for validity (Hopkins, 2017).

Results

The results derived in terms of reliability, validity, and measurement errors, both random and systematic, of the VmaxPro device analysed using a 3D Motion Capture System as the criterion are presented in Table 2. The IMU-based VmaxPro has excellent reliability values for velocity monitoring and good reliability values for the range of displacement recording.

Table 2. Results of reliability calculations of VmaxPro® vs 3D Motion Capture System.

Velocity (m/s)	
ICC (2,1)	0.986 (0.944 — 0.994)
Cronbach's α	0.995
Mean Difference	-0.021 (-0.025 — -0.016)
Range of displacement (cm)	
ICC (2,1)	0.812 (-0.048 — 0.948)
Cronbach's α	0.977
Mean Difference	1.935 (1.796 — 2.090)

Data expressed with 95% confidence intervals where appropriate; ICC: Intra-class correlation coefficient.

Table 3 shows the ratio of the systematic and random errors of the VmaxPro device compared to the 3D Motion Capture System for both the velocity and the range of displacement of the barbell during the technical executions. Regarding the velocity of the barbell, the IMU-based VmaxPro shows a small underestimation of its systematic error, contrary to the random error, overestimating in this case the velocity measurement. Regarding the range of barbell displacement during technical executions, it can be observed that this device presents measurement errors close to 2 cm in both the systematic error and the random error.

Table 3. Systematic and random errors of VmaxPro® vs 3D Motion Capture System.

Velocity (m/s)		Range of displacement (cm)	
Systematic error	Random error	Systematic error	Random error
-0.021	0.053	1.935	1.901

The Bland-Altman plots show the graphical representation of agreement between VmaxPro and the 3D Motion Capture System as the criterion (Figure 2). In the Bland-Altman for velocity, most of the data are between the upper and lower limits of agreement and outliers are rare and close to these limits. In the Bland-Altman for range of displacement, there is a greater dispersion of the data and outliers.

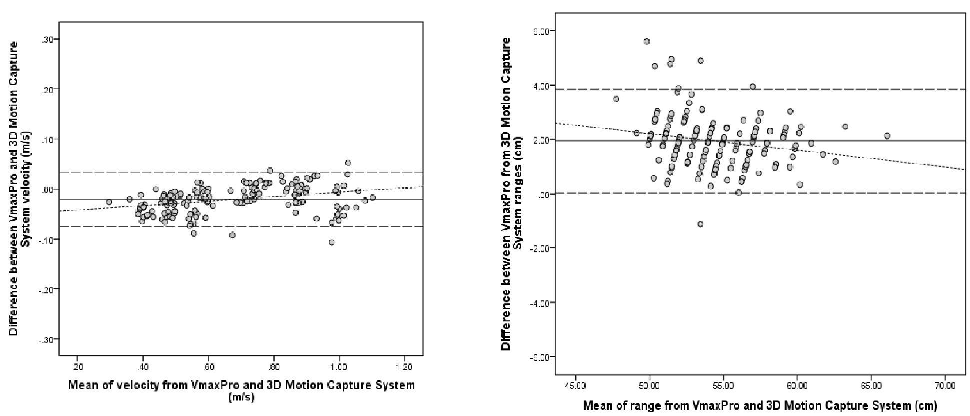

Figure 2. Bland-Altman plots for the measurements of VmaxPro and 3D Motion Capture System. Solid central line represents mean between instruments (systematic bias); upper and lower dashed lines show mean ± 1.96 SD (random error); dotted line shows regression (proportional bias) for velocity (r^2 = 0.108) and range of displacement (r^2 = 0.041).

Finally, to carry out the calculation of the validity of the VmaxPro measurement, the Pearson correlation was carried out (Table 4), as well as a graphical representation of the dispersion of points in which the linear r^2 and the regression lines were calculated for this device and 3D Motion Capture System (Figure 3). In this way, VmaxPro presents valid values for both velocity and range of displacement measurement, being a suitable instrument for this purpose.

Therefore, it would be possible to use the IMU-based VmaxPro sensor for the control, monitoring, and evaluation of strength training.

Table 4. Results of the validity analysis of the measure.

Velocity (m/s)	Range of displacement (cm)
Pearson's *r*	Pearson's *r*
0.992 (0.990 ─ 0.994)	0.957 (0.938 ─ 0.971)

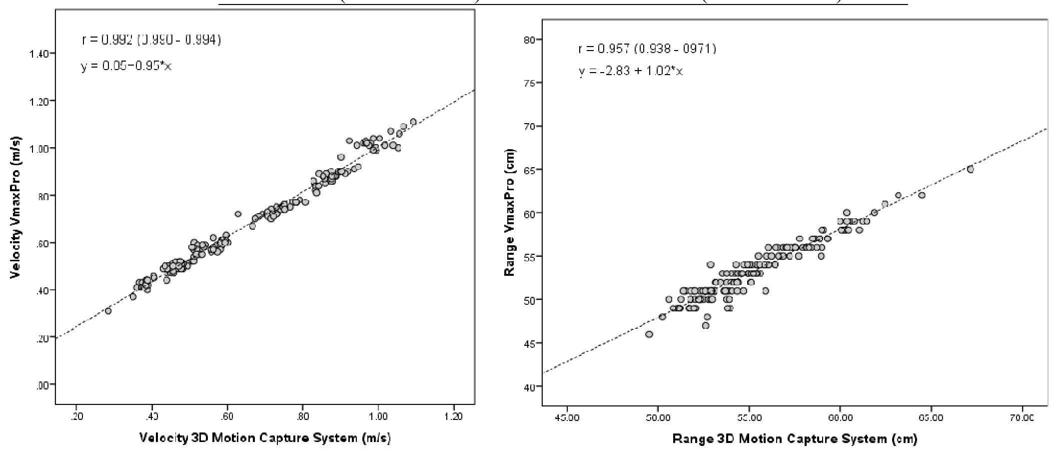

Figure 3. Relationship between measurements derived from VmaxPro® and 3D Motion Capture System. Dotted line represents linear regression; upper and lower dashed lines show 95% confidence intervals. Pearson's product-moment correlation coefficient (*r*) is shown with 95% confidence interval between brackets for velocity and range of displacement.

Discussion

Previous studies have highlighted that VBT is a contemporary method used by sports coaches to prescribe the optimal load based on the velocity of movement of a lifted load (Pueo et al., 2021). Currently, there are different devices on the market that allow training loads to be assessed and monitored, although not all use the same technology to measure the execution velocity. Earlier research show that the IMU-based VmaxPro seems to be absent from the peer-reviewed literature and lacks unbiased support for its validity, with further studies needed to solidify the findings to date (Fritschi et al., 2021). For this reason, it was necessary to analyse the results of the VmaxPro in terms of reliability, accuracy, and validity. This study has provided a concurrent validation analysis of the VmaxPro using a 3D Motion Capture System as a criterion.

Firstly, in terms of validity, the results of the present study are supported by Held et al. (2021) in considering the VmaxPro to be a valid and reliable tool for the assessment of mean concentric barbell velocity. In this study (Held et al., 2021) excellent to good ICCs are shown for the squat, indicating acceptable validity for mean concentric barbell velocity (0.94 (0.92-0.95)) and displacement (0.88 (0.43 ─ 0.95)) respectively, in this case in comparison to the Speed4Lift sensor. Similarly, our results show a practically perfect bivariate Pearson product-moment correlation coefficient for the barbell velocity (0.992 (0.990 ─ 0.994)) and range of displacement (0.957 (0.938 ─ 0.971)), in this case in comparison to the 3D Motion Capture System as a criterion. Furthermore, these results are also supported by Fritschi et al. (2021) who provide practically perfect bivariate Pearson's product-moment correlation coefficients data for the mean velocity (0.99 (0.94 ─ 0.96)) and the peak velocity (0.99 (0.92 ─ 0.99)) in comparison with other VBT devices.

Secondly, similar values were found concerning the reliability of this device. Due to the design of the study, the reliability of this device is analysed within-day, in the case of the study of Held et al. (2021) showing good to excellent ICCs values of reliability for velocity (0.88 (0.71 ─ 0.95)) and barbell displacement (0.91 (0.79 ─ 0.97)), respectively. In contrast, in the present study are found excellent (0.986 (0.944 ─ 0.994)) and good ICCs (0.812 (-0.048 ─ 0.948)) results of reliability for velocity and range of displacement, respectively.

Lastly, regarding the accuracy, Fritschi et al. (2021) pointed out that the mean velocity from the hang power snatch may be systematically underestimated due to fixed measurement biases of as little as ~0.1 m/s. In this way, our results suggest that regarding the velocity, the IMU-based VmaxPro shows a small underestimation (-0.021 m/s) of its systematic error in comparison to the 3D Motion Capture System, in this case in the back squat. For the range of barbell displacement, it can be observed that this device presents measurement errors close to 2 cm in both the systematic error and the random error.

Conclusions

This study presents a concurrent validation analysis of the IMU-based VmaxPro using a 3D Motion Capture System as the criterion. This validation data is for both velocity monitoring and range of displacement recording. Regarding velocity monitoring, this device shows excellent reliability values and a small underestimation of its systematic error, contrary to the random error, overestimating in this case the velocity measurement. Concerning the range of barbell displacement, this device shows good reliability values and measurement errors close to 2 cm in both the systematic error and the random error. In this sense, the device presents valid values for both velocity and range of displacement measurement and can be a suitable instrument for this purpose. For this reason, coaches and athletes can be confident to use the IMU-based VmaxPro sensor for the control, monitoring, and evaluation of strength training. Further research is needed on different strength exercises in different levels of athletes to obtain a robust assessment of the velocity monitoring and range of displacement recording using the VmaxPro.

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Conflicts of interest - The authors declare no conflict of interest.

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