Original Article

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Title: **Validity and reliability of an optoelectronic system to measure movement velocity during bench press and half squat in a Smith machine**

Short title: **An optoelectronic system to measure movement velocity**

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Abstract

The purpose of this study was to determine the validity and reliability of a camera-based optoelectronic system to measure movement velocity during bench press (BP) and half squat (HS) at different load intensities. Twenty-two active males (age: 28.2 ± 3.9 y; 1RM BP: 77.9 ± 19.0 kg; 1RM HS: 116.6 ± 22.5 kg) participated in this study. After an initial 1RM testing session, participants performed five repetitions for each load (40, 60 and 80% 1RM) and exercise (BP and HS) on a Smith machine in the second testing session. A third testing session was used for the test-retest reliability study. Time, displacement and mean propulsive velocity (MPV) were simultaneously determined by the reference method (T-Force system; T-F) and the Velowin system (VW). In BP, ordinary least products (OLP) regression analysis revealed low fixed biases for MPV at 40%, time at 60% and displacement at 80% 1RM (intercept= 0.065 $m \cdot s^{-1}$, -28.02 ms and 0.87 cm, respectively). In HS, low fixed biases were also detected for MPV at 40% and 80% 1RM (intercept= -0.040 and 0.023 $m \cdot s^{-1}$, respectively), time at 40% and 60% 1RM (intercept= -53.05 and -101.85 ms, respectively), and displacement at 60% 1RM (intercept= -1.95 cm). Proportional bias was only observed for MPV at 80% BP. In HS, there was proportional bias for time and MPV at 40% 1RM, and also for time at 60% 1RM. The reliability test showed low and comparable fixed and proportional biases between systems across exercises and intensities. VW confirmed to be a valid and reliable system to measure movement velocity across a wide range of intensities (40-80% 1RM) for two basic strength exercises through a robust statistical approach. VW would provide coaches and trainers with a suitable, affordable and easy-to-use equipment capable of measuring movement velocity in various exercises at different load intensities.

Key words: strength, technology, kinematics, movement velocity, testing.

Introduction

The load-velocity relationship assessment has emerged as a method for objectively monitoring and prescribing resistance training velocity [1–4]. Previous studies suggest that movement velocity can be used to accurately predict the relative load of basic resistance exercises commonly included in strength training, such as bench press (BP) or half squat (HS), among others [5–7]. Thus, the determination of the movement velocity would eliminate the need for a direct one-repetition maximum (1RM) testing, avoiding the intrinsic risks of a maximal strength test [6,8,9]. Accurate and reliable assessment of movement velocity is fundamental to sports testing, training and rehabilitation. Thus, kinematic systems are becoming increasingly popular as tools for measuring movement velocity during resistance exercise [10–12].

The linear position transducer is one of the most common systems used for load-velocity testing [6,13]. This system is characterized by the use of a tethered cable (attached to an external load) designed to measure time and displacement (distinguishing both eccentric and concentric phases) and enabling the calculation of movement velocity, which is essential for strength testing and training [6].

There are currently several commercial linear position transducers (e.g., “T-Force (T-F)”, “Tendo Weightlifting Analyzer”, “MuscleLab”, “Smart Coach” or “Chronojump”, among others) helping coaches and researchers to measure movement velocity in resistance training [13–16]. Nevertheless, most of them use a cable-based system which might cause some drawbacks, such as the need to attach a cable to the main body part engaged in the exercise or the great sensitivity of this cable-based system to be damaged by even small blows. Due to the high cost of traditional linear transducers that have often been used as the reference method (e.g., the T-F system with a cost of ~ $3500), its acquisition may not be feasible for many potential users. This has led to an increasing interest in the development of economical, wireless measurement tools and wearables to assess kinematic variables to solve the aforementioned difficulties [17,18] and facilitating its acquisition beyond a few well-funded laboratories or elite sports clubs.

Velowin (VW) was developed as an optoelectronic equipment that measures displacement through an infrared reflector attached to a bar (or any part of the body) captured by an infrared camera (see Fig. 1). This wireless system would allow the tested participant to perform a greater range of exercises without bumping a cable that could render the measurements useless. Any exercise employing a range of motion over the frontal plane (potentially both vertical- and horizontal-based movements) could be performed as long as the infrared reflector is positioned in the appropriate plane view for the camera. Additionally, VW software computes displacement and time to calculate several kinematic variables.

VW was launched in 2017 and there are currently three validation studies stating that this device is valid and reliable to assess movement velocity during free-weight HS and countermovement jump (CMJ) [19–21]. However, from a profound examination of these studies, the authors detect some limitations that make the present study necessary. It is crucial to consider that the VW device is a camera-based system, only able to assess movement velocity two-dimensionally. This requires the assessed exercise to be strictly executed in the frontal plane, since any movement performed in the sagittal plane would be undetected, biasing the measurement. This limitation adds an important error to the measurement due to the inter-individual variability in the exercise technique, which would be avoided by restricting the movement pattern (i.e., by using a Smith machine). In addition to this, the validation of VW using further resistance exercises (e.g., BP) would be needed to expand the practical application of this system. Finally, there is an important limitation in the statistical analyses used by two of the three existing studies validating VW [20,21]. While the 'gold standard' method to assess movement velocity is the 3-D capture motion system, and not T-F, Model I linear regression analysis (e.g., least squared regression) should not be used since this statistical method does not assume a potential error in the reference method (T-F in this case). Instead, Model II regression analysis [e.g., Ordinary Least Products (OLP) regression] should be used to allow for a more accurate determination of bias and therefore confirm the real validity of VW [22]. Hence, the main purpose of this study was to evaluate the validity and reliability of the VW system to assess time, displacement and mean propulsive velocity (MPV) in two strength training exercises, BP and HS, over a range of intensities (40, 60 and 80% 1RM) in a Smith machine. It was hypothesized that VW measurements would be valid and reliable, in comparison with T-F, irrespective of the load or the exercise performed.

Material and methods

Experimental approach to the problem

A validation and reliability study was designed to compare time, displacement and MPV as measured by T-F (used as the 'gold standard') and VW during BP and HS exercises executed at three different intensities (40, 60, 80% 1RM) on a Smith machine. Although it is not the gold standard method to assess movement velocity, T-F has been widely used to assess both kinematic and kinetic characteristics in resistance training [6] and has also been used as a reference method in several validation studies [17,23,24]. Different exercises and load intensities were selected to test the validity of VW at different velocities and ranges of displacement. Participants were required to attend the laboratory on three occasions, separated by at least 48 h between visits. The first session was used to assess 1RM in both exercises for each participant. Validity testing was conducted with all 1232 repetitions performed during second and third testing sessions, as every repetition was measured simultaneously with T-F and VW. Finally, the third session was used for the reliability test by comparing the data obtained in sessions two and three.

Subjects

Twenty-two healthy, active males (mean age: 28.2 ± 3.9 y; height: 177.8 ± 7.5 cm; body mass: 74.7 ± 7.9 kg; strength training volume: 151.9 ± 96.7 min/week; 1RM BP: 77.9 ± 19.0 kg; 1RM HS: 116.6 ± 22.5 kg) voluntarily participated in this study. Participants met the following inclusion criteria: men from 20 to 35 years old with at least one year of experience in strength training, specially familiarized with BP and HS exercises. Participants with musculoskeletal injuries or any medical condition that could alter performance were excluded. Participants were not allowed to exercise in the 48 h preceding a test session.

Since meaningful changes in muscle function have been observed in females depending on the menstrual cycle phase (e.g. increase in muscle strength at mid-cycle, when compared with both follicular and luteal phases [25]), the authors opted not to include females in the present study.

Participants were informed about the protocol of the study, as well as potential risks and benefits. Prior to data collection, each participant completed and signed an informed consent form. This study was performed following the Declaration of Helsinki 1964 (revision of Fortaleza 2013) and the protocol was approved by the Ethics Committee of Clinical Research from the Government of Aragon (CEICA, Spain) [C.I. PI17/0126].

Procedures

Each participant completed three testing sessions separated by at least 48 h. The first session was used for personal data compilation, body composition measurements and indirect 1RM test in BP and HS, according to Brzycki equation [26] shown in Eq. (1):

$$1\text{RM} = 100 * (\text{Weight (kg)} / 102.78 - 2.78 \cdot \text{number of repetitions}). \qquad (1)$$

Since this equation is valid for estimating 1RM when the number of repetitions is lower than 10, the weights used during all indirect 1RM tests were calculated to reach less than 10 repetitions. In addition, this equation has been previously shown to be highly accurate with resistance-trained middle-aged men [27]. Tests were performed with the assistance of two researchers to guarantee the safety of the participants.

During the second testing session, each participant performed five repetitions at maximum velocity for each load (40, 60 and 80% 1RM; following this incremental order) and exercise (BP and HS; in a randomized order) in a Smith machine, with a rest period between sets of at least 3 min. The re-test was performed in the third testing session, replicating the protocol from the second testing session, but swapping the exercise order.

Prior to each testing session, participants performed a warm-up that consisted of 5 min of low intensity cycling (Ergoline cycle ergometer, Ergoline GmbH, Bitz, Deutschland), 5 min of upper- and lower-body joint mobilizations and a set of 10 repetitions with 50% of the load used in the first attempt, for both exercises. BP exercise began with both arms in full extension with the hands grasping the barbell at a width approximately 5 cm wider than shoulder width. During eccentric action, participants took down the barbell at moderate velocity until approximately 5 cm over the chest. Adjustable safety catchers were used to control this distance. From this position, concentric action was performed at maximal voluntary velocity. For HS exercise, eccentric action was performed at moderate velocity from the position with hips and knees in full extension to 90º of knee flexion. A goniometer was used to accurately measure this knee angle, and the displacement of the bar was recorded for each individual to detect potentially incomplete repetitions during all HS tests. From this point, concentric action was also performed at maximal voluntary velocity. A pause of approximately 1.5 s between the concentric and eccentric phases was included in both BP and HS exercises. The distance covered during eccentric phase in HS was measured prior to the first testing session by the T-F system. This distance was the same in the three testing sessions. During all repetitions, participants were encouraged to perform the propulsive phase of the movement as rapidly as possible.

Measurement equipment and data acquisition

A Smith machine (Impulse IT Smith Machine, Midlothian, Scotland) was used for performing all test conditions. Displacement, time and MPV were simultaneously measured with a T-F system (T-Force Dynamic Measurement System®, Ergotech, Murcia, Spain) and VW (Velowin, DeporTEC, Murcia, Spain). T-F (sample frequency of 1000 Hz) consists of a linear velocity transducer extension cable; however, VW (sample frequency of 500 Hz) is an optoelectronic linear position transducer system that does not use a cable. Both methods automatically calculate the above-mentioned variables and provide instantaneous velocity and displacement feedback. Following VW manufacturer guidelines, “two reflective circles in line” calibration was applied each day prior to the start of each testing session. This calibration is the most accurate and consists of placing two reflective circles separated by 500 mm beside the barbell at the same plane of the reflective used during testing. In each calibration, inclination angle was approximately 90º being the mean of mm per pixel 1.459 ± 0.032 mm/px. The camera was positioned perpendicularly with respect to the plane of the marker movement, and was set high enough to encompass the tallest participant performing the HS and also the lowest point of the barbell during BP.

The T-F system has been previously used as a reference method to validate other systems [24]. Therefore, it was also used for this validity study with the same purpose. Additionally, this system has been widely used among researchers and trainers to assess kinetic and kinematic variables in strength exercises [13,28,29].

[INSERT FIGURE 1]

Data analysis

The Statistical Package for the Social Science (SPSS; version 24.0 for Mac OS X, SPSS Inc., Chicago, IL, USA) and the statistical software R (version 3.5.1) were used for all statistical analyses. The authors separated the data analysis by load intensity and exercise since analysis of variance (ANOVA) tests indicated a significant influence of exercise type, intensity and their interaction ($\eta_p^2 =$ 0.473, 0.043 and 0.022, respectively; all $p<0.01$). Time, displacement and MPV for each load intensity and exercise were computed and statistically analyzed. Bland Altman plots were performed to reveal the agreement between VW and T-F in BP and HS, since this is the approach typically used to test agreement between methods and helps comparing with previous validity studies [30]. However, because fixed and proportional bias cannot be determined through this analysis, OLP regression analysis was performed by computing the equations provided by Ludbrook in R [31]. Validity was determined following the presence and degree of bias between methods. The degree of fixed bias was deduced from the y-intercept 95% of the confidence intervals (CIs). If the CIs for the intercept include the value of zero, then there is no fixed bias. Proportional biases were assessed from the 95% CIs for the slope. If the

CIs for the slope include the value of 1.0, then there is no proportional bias. OLP regression analysis produces different errors, intercepts and slopes than least squares regression because error is assumed for both VW and T-F. In addition, test-retest reliability for MPV was also determined through OLP regression analysis following the same procedures described above.

Results

Concurrent validity

From a total of 1320 repetitions registered, 88 were excluded due to inappropriate exercise technique or error in the measurement by either T-F or VW. As seen in Fig. 2, the box plots graphically show the distribution of the values obtained for all variables, intensities and exercises for both T-F and VW (Table 1 shows the corresponding numerical values). Table 1 summarizes the differences observed between both systems. When examining the agreement between devices in measuring MPV in BP and HS, a small mean difference across the full range of intensities was observed, as depicted in Fig. 3.

[INSERT FIGURE 2]

[INSERT TABLE 1]

[INSERT FIGURE 3]

In BP, fixed biases were detected for MPV at 40%, time at 60% and displacement at 80% 1RM (intercept= 0.065 $m \cdot s^{-1}$, -28.02 ms and 0.87 cm, respectively). In HS, fixed bias were also observed for MPV at 40% and 80% 1RM (intercept= -0.040 and 0.023 $m \cdot s^{-1}$, respectively), time at 40% and 60% 1RM (intercept= -53.05 and -101.85 ms, respectively) and, finally, displacement at 60% 1RM (intercept= -1.95 cm). Proportional biases were identified for MPV at 80% 1RM in BP (slope= 1.03). In HS, it was observed proportional biases for time at 40% and 60% 1RM (slope= 1.05 and 1.10, respectively), and also for MPV at 40% 1RM (slope= 1.06). Fig. 4 shows the OLP regression plots for MPV during both exercises at the different intensities.

[INSERT FIGURE 4]

Test-retest reliability

The test-retest reliability results for MPV in both exercises and across all intensities are provided in Table 2. In BP, fixed biases for MPV at 60% and 80% 1RM as measured with T-F were detected (intercept= 0.082 and 0.081 $m \cdot s^{-1}$, respectively), whereas VW only showed fixed bias for MPV at 80% 1RM (intercept= 0.058). In HS, only VW presented fixed bias for MPV at 80% 1RM (intercept= -0.092). In relation to the assessment of heteroscedasticity in the reliability test (Table 2), T-F presented proportional biases for MPV at 60% and 80% 1RM in BP (slope= 0.86 and 0.81, respectively), whereas VW presented heteroscedasticity for MPV at 80% 1RM during BP and 80% 1RM during HS (slope= 0.87 and 1.21, respectively).

[INSERT TABLE 2]

Discussion

The main findings of the present study confirmed that VW is a valid and reliable device to measure movement velocity during HS in a Smith machine across different intensities, and also revealed that VW is also valid and reliable to be used during BP. To the best of the authors' knowledge, this is the first study testing VW using OLP regression analysis over a range of intensities. Most of the previous validity studies not using the true gold standard method employed a combination of Bland-Altman and least squared linear regression analysis to determine bias and agreement between systems [17,24,32]. However, the use of these methods to determine the magnitude of bias, as determined by the slope of the linear correlation, assign all bias to the dependent variable (VW in this case) [22]. When not using the true gold standard for the comparison, the selection of OLP regression analysis seems more appropriate since it also assumes potential error in the reference method, allowing for a more accurate determination of fixed and proportional bias [22,31,33].

Recent studies examined the validity and reliability of VW during free-weight HS over a range of intensities [19,20]. Similar to the present study, García-Ramos et al. [20] used the T-F system as the reference method, finding a low fixed bias in MPV between devices during HS (fixed bias= 0.02 by García-Ramos vs. fixed bias range= -0.04 to 0.02 in the present study). García-Ramos et al. [20] found a significant proportional bias in the assessment of MPV during HS, observing an underestimation of MPV with increasing MPV, as assessed by VW. In the present study, proportional bias was also observed in the assessment of MPV during HS, but only at 80% 1RM and in the opposite direction (i.e., VW overestimated MPV with increasing MPV). Notably, García-Ramos et al. [20] determined bias through the Bland-Altman method, which could potentially distort the results of this validity test.

It is worth noting the presence of fixed bias in the displacement during 80% 1RM BP. Since the camera was positioned at the same distance and height for both exercises to encompass the vertical movement developed during each exercise, a slight parallax error might have influenced the measurement in this case. Notably, the presence of proportional bias for MPV was only at 80% 1RM BP and 40% 1RM HS. This might be because participants performing the 80% 1RM BP were sometimes unable to fully extend the arms during all repetitions, whereas during the 40% 1RM, HS participants easily completed the whole movement, even performing a small countermovement at the end of the concentric phase. It is possible that the two different filters interpreting kinematics might have affected the precise moment of starting and finishing the concentric phase, thus increasing heteroscedasticity between systems in these cases. However, it should be considered that assessments conducted in sports science are commonly characterized by the presence of heteroscedasticity [34].

In addition to this study, Laza-Cagigas et al. [19] recently performed a comprehensive validity study of VW using the gold standard method to assess both movement velocity and force production (3D motion capture system and force platform, respectively) during free-weight HS. Although these authors did not examine MPV, they did not find neither fixed nor proportional bias in mean velocity (intercept= -0.04 and slope=1.01). Laza-Cagigas et al. [19] also reported the presence of fixed bias in the measurement of displacement, but remarkably higher than the present study (fixed bias= -10.24 cm by Laza-Cagigas vs. a fixed bias at 60% 1RM HS of -1.95 cm in the present study). Although Laza-Cagigas et al. [19] appropriately used the gold standard method to test the validity of VW, not preventing the movement from horizontal oscillations (i.e., using free-weights) when comparing a 3D device and a 2D device (i.e., VW), could alter the accuracy in the evaluation of vertical velocity as measured by VW. This additional bias could potentially explain the greater error in the measurement of displacement observed in their study.

Peña García-Orea et al. [21] also performed a validity study of VW during a loaded CMJ in a Smith Machine over a range of intensities, revealing that VW was a valid and reliable tool to measure CMJ velocity, when compared to T-F. However, these authors reported the absolute values for mean and peak velocity from each device and the concordance correlation coefficient instead of reporting fixed or proportional bias between devices [35]. This makes the comparison with the current results challenging.

While the present study also shows the degree of bias across load intensities between VW and T-F, some of the aforementioned studies did not report the specific error across different loads [19,21]. The study by García-Ramos et al. [20] found no main effects of variable x load interaction across different intensities during free-weight HS. Thus, the comprehensive examination of the bias at different load intensities and exercises reinforce preceding studies and expand the utility of VW since most athletes develop their strength training varying load intensities depending on the periodization plan [36].

Previous research examined the validity of similar instruments that also focus on the measurement of movement velocity. The PUSH band [17] found larger systematic bias in the assessment of mean velocity during HS (0.11 $m \cdot s^{-1}$ by PUSH vs. a range of -0.04 to 0.02 $m \cdot s^{-1}$ by VW in the present study). Similarly, previous research [37] carried out a similar investigation studying the validity of a video analysis software (Kinovea) for quantifying movement velocity during the BP exercise at different intensities, also reporting larger systematic bias for MPV than the present study (range from -0.43 $m \cdot s^{-1}$ to -0.16 $m \cdot s^{-1}$ for Kinovea vs. 0.01 $m \cdot s^{-1}$ to 0.07 $m \cdot s^{-1}$ for VW).

Regarding the test-retest reliability study, both fixed and proportional biases seemed to follow the same pattern (i.e., variables with meaningful fixed biases were accompanied by proportional biases). Although these biases were small, the necessity to perform a manual calibration procedure could also be a source of error in the measurement, potentially affecting the accuracy from one day or exercise to another. The results of the present study agree with Peña García-Orea et al. [21] in that a simpler calibration process would facilitate the usability of VW and could also increase the accuracy between testing sessions.

Based on a robust statistical analysis, the results from the present study confirm that an affordable and comfortable system (VW) can be utilized to measure movement velocity during the BP and HS exercises at different intensities in a Smith machine. As far as the limitations of a 2D camera-based instrument are concerned, the accuracy of the measurements depends on whether the movement is performed on the frontal plane. Consequently, if the exercises were performed away from the vertical vector, the measurements might be distorted [37]. In the current study, all measurements were performed on a Smith machine to avoid these risks. Sports practitioners and specialists should consider this source of error and, as previously reported, the experience of the lifters could be determinant when the use of the Smith machine is not possible [37]. Another important limitation of this system is that it requires a nearby camera and laptop, which would take up floor space and might complicate simultaneous trainings. This should be considered by the coach or sports specialist to adequately organize the testing procedures in advance.

Importantly, certain limitations should be considered when interpreting the results of the present study. In particular, a wider variety of exercises and intensities are needed to provide further validation of the VW system. For example, the VW system has shown to be valid and reliable over vertical-based movements (squat, countermovement jump and BP), although its efficacy on horizontal-based movements (e.g., ball throwing, running or ball kicking) is still unknown. Finally, as only males were recruited for this study, the results cannot be directly applied to female athletes. This study reinforces the validity and reliability of VW and expands its use to a wider range of intensities (from 40% to 80% 1RM) and exercises (BP and HS) in a Smith machine.

Conclusion

The VW system has proven to be a valid and reliable tool in comparison with T-F when measuring time, displacement and MPV across different exercises and load intensities. Besides, it seems operational, easy-to-use and comfortable since it does not require a cable to perform strength exercises, as long as they are performed in the vertical plane. Notably, the use of VW could help coaches and trainers in the assessment of the load-velocity relationship, especially in field situations thanks to the portability of this camera-based system. Nevertheless, the coach should also consider that the inherent limitation in a 2D instrument might affect the accuracy of exercises performed out of the vertical plane. The economical cost of VW in comparison with the reference method (T-F) would allow a wider range of coaches or sports clubs to afford this equipment.

Declaration of Conflicting Interests

The authors declare no conflict of interests with respect to the publication of the present study.

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Table 1. Concurrent validity of T-Force vs. Velowin. Values of Time (ms), Displ (cm) and MPV ($m \cdot s^{-1}$).

Table 2. Test-retest reliability of MPV ($m \cdot s^{-1}$) measured by Velowin and T-Force.

Figure 1. Measurement scheme of the optoelectronic Velowin system.

Figure 2. Time, displacement, and Mean Propulsive Velocity (MPV) obtained in bench press and half squat exercises by T-Force (T-F) and Velowin (VW) systems. The boxes represent the median values with the 25th percentile and 75th percentiles, with the lower and upper error bars indicating the minimum and maximum values, respectively (black dots represent the outliers).

Figure 3. Comparison of Mean Propulsive Velocity (MPV) between T-Force (T-F) and Velowin (VW) in bench press and half squat. The center line determines the mean difference between systems, whereas the dashed lines represent the 95% limits of agreement (standard error ± 1.96 × standard deviation).

Figure 4. Ordinary Least Products regression plots of the relation between the Mean Propulsive Velocity (MPV) determined by T-Force (T-F) and Velowin (VW) at different intensities and exercises. Regression and confidence intervals lines are displayed.