TITLE

VALIDITY AND RELIABILITY OF A NOVEL OPTOELECTRONIC DEVICE TO MEASURE MOVEMENT VELOCITY, FORCE AND POWER DURING THE BACK SQUAT EXERCISE

RUNNING TITLE

VALIDATION OF AN OPTOELECTRONIC DEVICE IN RESISTANCE TRAINING

KEYWORDS

Resistance training; 3-D motion captures systems; force plate; accelerometers; linear transducers.

Authors

Roberto Laza-Cagigas[1] Mark Goss-Sampson[1] Eneko Larumbe-Zabala[2] Leke Termkolli[1] Fernando Naclerio[1]

[1] Department of Life and Sport Science, University of Greenwich, Avery Hill, New Eltham, United Kingdom

[2] Clinical Research Institute, Texas Tech University HSC, Lubbock, TX, United States of America

Contact author

Dr. Fernando Naclerio

Department of Life and Sports Sciences, University of Greenwich, Sparrow Lane, Avery Hill, New Eltham (SE9 2BT), United Kingdom (UK)

E-mail: f.j.naclerio@gre.ac.uk

Tel +44 (0) 20 8331 8441

ABSTRACT

This study analysed the validity and reliability of a new optoelectronic device (Velowin) for the measurement of vertical displacement and velocity as well as to estimate force and mechanical power. Eleven trained males with Mean (SD) age = 27.4 (4.8) years, completed an incremental squat exercise test with 5 different loads (<30 – 90% of their 1−repetition maximum) while displacement and vertical velocity of the barbell were simultaneously measured using an integrated 3D system (3D motion capture system + force platform) and Velowin. Substantial to almost perfect correlation (concordance correlation coefficient = 0.75 – 0.96), root mean square error as coefficient of variation ±90% confidence interval ≤ 10% and good to excellent intraclass correlation coefficient = 0.84 – 0.99 were determined for all the variables. Passing and Bablock regression methods revealed no differences for average velocity. However, significant but consistent bias were determined for average or peak force and power while systematic and not proportional bias was found for displacement. In conclusion, Velowin, in holds of some potential advantages over traditionally used accelerometer or linear transducers, represents a valid and reliable alternative to monitor vertical displacement and velocity as well as to estimate average force and mechanical power during the squat exercise.

Introduction

Muscular strength is one of the key factors to sports performance (Suchomel, Nimphius, & Stone, 2016). Assessment of force, movement velocity and mechanical power helps evaluate the effects of resistance training (RT) on strength development. These variables are frequently used, among others, to design individualized training programmes and to monitor the consequent training induced adaptations (Jimenez-Reyes, Samozino, Brughelli, & Morin, 2016; Morin & Samozino, 2016).

Specifically, velocity assessment has been shown to be useful for different purposes. Real-time vertical velocity monitoring allows coaches and trainees to tailor the training load during different RT exercises to attain specific training adaptations (Pareja-Blanco et al., 2017), or estimate the 1-repetition maximum (1RM), for various RT exercises without the need to perform the actual 1RM test (Bazuelo-Ruiz et al., 2015; Naclerio & Larumbe-Zabala, 2017a). Furthermore, velocity loss within a set has been shown to be an indicator of neuromuscular fatigue (Sanchez-Medina & Gonzalez-Badillo, 2011). Therefore, monitoring velocity is a suitable way to determine the RT zones in which trainees perform their lifts (Chapman et al., 2017).

Velocity is assessed with different devices, including but not limited to linear transducers (LT), (Naclerio & Larumbe-Zabala, 2017b) wearable devices (Balsalobre-Fernández et al., 2017), apps (Balsalobre-Fernandez, Marchante, Munoz-Lopez, & Jimenez, 2017), advanced video analysis (Sanudo, Rueda, Pozo-Cruz, de Hoyo, & Carrasco, 2016), and 3-D motion capture systems (3D) (Swinton, Stewart, Keogh, Agouris, & Lloyd, 2011). Among these, 3D has been considered the “gold standard” method to assess velocity (Ceseracciu, Sawacha, & Cobelli, 2014).

Force production is assessed with force platforms (FP), which are considered the "gold standard" method (Garnacho-Castano, Lopez-Lastra, & Mate-Munoz, 2015). Once velocity is measured over a range of motion in resistance exercises, the acceleration can be calculated in order to estimate the applied force (acceleration applied to a given mass) and the produced mechanical power (Cormie, Deane, & McBride, 2007). For these variables, peak and average values are usually determined.

Although the gold standard methods are easily found in many laboratory settings, their use is usually limited by their cost, portability, or adaptability to a field-testing situation. To overcome these drawbacks, LT or accelerometers are usually considered the best cost-effective options. LT is required to be connected to the implement with a retractable cable during RT exercises, while accelerometers have to be attached either to the implement (Balsalobre-Fernández et al., 2017) or on the main body segment engaged in the exercise (Balsalobre-Fernández et al., 2017). The availability of affordable and portable devices such as LT and accelerometers allows coaches and athletes to obtain a more accurate control of training by monitoring changes in movement velocity during resistance exercises.

In this respect, a new optoelectronic system (Velowin 1.6.314, Deportec, Spain) has recently been marketed. The Velowin consists of an infrared camera that tracks the vertical position changes of a reflective marker fixed to the implement (barbell). This planar device is capable of measuring displacement, peak and average vertical velocity, in real time during RT exercises. Based on these measurements, the software (VELOWIN 1.6.314) provides estimation of peak and average values for force and power. Furthermore, the novel optoelectronic device is more affordable than traditional LT or accelerometers. While the LT requires a cable to be attached to the implement, the Velowin does not require any physical connection and consequently eliminates the risk of cable rupture, which is one of the most frequent issues associated with the LT. Accelerometers are delicate devices, being easily damaged by any shock, and provide a lower level of accuracy (Dugan, Doyle, Humphries, Hasson, & Newton, 2004). These disadvantages are overcome when using the Velowin, because the device is placed away from the surroundings of the RT exercise and it may potentially yield similar accuracy to LT.

Taking the previous considerations into account, the Velowin seems promising as a practical tool to be used in the RT context, with some potential practical advantages over LT and accelerometers. However, this system has not yet been validated. The aim of the present study was therefore to assess the concurrent validity and reliability of a new optoelectronic system (Velowin) to measure displacement; peak (PV) and average (AV) velocity during the barbell back squat exercise. Additionally, the validity and reliability for estimating the applied average (AF) and peak force (PF) or peak (PP) and average mechanical power (AP) was also analysed.

Methods

Participants

Eleven recreationally trained males, mean (SD) of age = 27.4 (4.8) years, height = 177.2 (4.5) cm, body mass = 76.0 (6.6) kg, and squat 1RM = 117.5 (26.2), with a minimum of 2 and a maximum of 5 years of RT experience performing squatting exercises volunteered to take part in this study. All participants reported not having taken any banned substances as declared by the International Olympic Committee 2014 antidoping rules (International Olympic Committee, 2014). No physical limitations or musculoskeletal injuries that could affect strength performance were reported. After being informed of the purpose and experimental procedures, participants signed a written informed consent form before participation, in accordance with the Declaration of Helsinki. The University Ethics Committee approved procedures.

Incremental back squat test

On the testing day, each participant performed a standardized warm-up involving dynamic stretching and joint mobility exercises. Thereafter participants performed 3 repetitions of squats with no external resistance followed by 6 to 7 repetitions with a 20-kg barbell and 3 squat jumps.

The incremental back squat test was performed using free weights and a squat rack according to the technique described by Ratamess (Ratamess, 2012). Briefly, participants were instructed to start the exercise from standing, feet parallel and shoulder width apart with toes pointing slightly outward. The bar was centred across the shoulders just below the spinous process of the C7 vertebra (high-bar position) (Wretenberg, Feng, & Arborelius, 1996). Participants were instructed to squat down using a controlled velocity until they reached the final flexed position with their posterior thigh parallel to the floor. After a minimum pause (less than 1 second), aimed to provide a clear separation between repetitions (Escamilla et al., 2001), participants performed the concentric squatting phase with maximal possible velocity. A complete successful repetition was defined as the entire ascending phase from the position where the participants stop the descending phase (velocity = 0 and thighs parallels to the floor) and start the ascending moment until reaching the standing position (velocity = 0). One qualified instructor controlled the appropriate range of motion during the squat exercise. If a repetition was not performed with appropriate technique, the participant was asked to perform another one and the invalid repetition was discarded.

The incremental test consisted of 5 sets of squats with 3 minutes of rest between sets. The squat sets comprised 2 repetitions with the Olympic squat bar (20 kg) < 30% of the estimated 1RM, 2 repetitions with 30% 1RM, 2 with 50% 1RM, 2 with 70% 1RM and 2 with 90% of the estimated 1RM. Before each set was performed, the participants were asked to unrack the bar and stand on the FP. The total mass of the participant and the corresponding squat load (bar and plates) was measured and the participants were asked to rerack the bar. The total mass was then introduced in the proprietary software of the optoelectronic system.

Experimental design

A laboratory-based design was used to test the concurrent validity and reliability of an optoelectronic system for measuring bar displacement, peak and average movement velocity as well as to estimate force and power during the back-squat exercise. Participants performed 5 sets of squats while data were being simultaneously captured with an integrated FP+3D camera system and the optoelectronic device (Velowin). Each participant performed 2 repetitions with the Olympic bar (20 kg representing <30% 1RM), and the 30, 50, 70 and 90% 1RM, for a total of 10 repetitions. Concentric peak and average values of velocity, force and power from the resultant 110 repetitions measured with the reference system (FP and 3D) and the optoelectronic system were compared for validity and reliability purposes by using several statistical analyses.

Familiarization

All participants performed one session of familiarisation with the use of the equipment, control of proper squatting technique and the testing procedure.

3D data acquisition

Retroreflective (12 mm) markers were placed on both ends of the bar. Motion was captured and tracked at 200 Hz using 10 infrared cameras (Oqus 3, Qualisys Track Manager, Qualysis AB, Sweden). Prior to capture, the working volume was calibrated with a mean residual error of 0.6 mm. Synchronous to motion capture, ground reaction forces were recorded at 200 Hz from a Kistler multicomponent force platform (Kistler Group, Switzerland). All data were subsequently exported to Visual3D (C-Motion, Inc. Germantown, USA) for processing. Kinematic data were filtered using a bidirectional low pass filter with a cut-off frequency of 10 Hz. To obtain a marker coinciding with the vertical axis of the barbell, a virtual marker was created midway between the two aforementioned tracking markers. This virtual marker was then used to measure the vertical displacement and vertical velocity of the bar as well as to estimate the applied force and produced mechanical power.

Velowin data acquisition

Velowin is a low-cost and portable two-dimension single-infrared-camera system with a fixed sampling frequency of 500 Hz. During the execution of the back squat exercise, the system was placed behind the participant's back to track the ascending displacement and measured vertical velocity of a retroreflective strip (third central marker) placed at the centre of the bar. Before each testing session, the system was calibrated for distance and displacement placing the camera at a distance of 180 cm from the marker with a high of 135 cm as recommended by the manufacturer.

The device was connected to a computer through a USB interface, and the proprietary software (VELOWIN 1.6.314, Deportec, Spain) provided numeric and graphical real-time information after each repetition was performed. To ascertain the validity of all the collected repetitions, and before proceeding with the statistical analysis, two researchers worked together to determine which repetitions met the criteria of good technique and adequate range of motion. Figure 1 depicts the set up of the equipment (3D system integrated with the force plate) and the optoelectronic device (Velowin).

****Figure 1 near here****

For the present investigation, only the vertical displacement (m) and velocity ($m{\cdot}s^{-1}$) were measured during the ascending phase of the back-squat exercise. Additionally, the estimated values of the applied vertical force and produced mechanical power were also analysed. As indicated by the manufacturer, the vertical velocity was measured according to Equation 1.

$$v_i = \frac{\mathrm{p}_1 - \mathrm{p}_2}{t_1 - t_2}$$

Where v_i= vertical velocity at a given instant, $\mathrm{p}_{1=}$ position of marker at instant 1, p_2= position of the marker at instant 2, t_1= time at instant 1, and t_2 = time at instant 2.

From the vertical velocity, the software calculates the acceleration using Equation 2.

$$a_i = \frac{v_1 - v_2}{t_1 - t_2}$$

Where a_i= acceleration at a given instant, v_1 = velocity of marker at instant 1, v_2 velocity of marker at instant 2, t_1= time at instant 1, and t_2 = time at instant 2.

From the values of velocity and acceleration, the software estimates the applied force (F_i) from Equation 3 ($F_i = ma_i$) and the produced mechanical power (P_i) from Equation 4 ($P_i = F_i v_i$).

Where Fi = applied force at a given instant, m = total mass displaced, a = calculated acceleration at a given instant, v_i = velocity at a given instant.

As in squatting exercises shanks and feet are relatively static and should not be quantified as resistance, the total mass was calculated by adding the external load to the 90% of the body mass determined by the force platform (Escamilla, Lander, & Garhammer J, 2000).

Statistical analysis

Descriptive statistics were calculated for all variables and presented as mean and standard deviation. Prior to method comparison, all data were assessed for normality of differences. All dependent variables, apart from average power, showed significant differences in normality thus precluding the use of Bland-Altman analysis, and therefore the nonparametric Passing and Bablock regression (PBR) was used for method comparison. This analysis assumes linear relationships between the two methods and was assessed using the Cusum test of linearity. All method comparisons showed no deviation from linearity. The H_0 tested with PBR was based on the upper (UCL) and lower (LCL) confidence limits, where for the intercept LCL < 0 < UCL and for the slope if LCL < 1 < UCL (Bilic-Zulle, 2011). The concordance correlation coefficient (CCC) was used to test for agreement between the two assessment methods (Lin, 1989).

The root mean square error (RMSE), the coefficient of variation ± 90% confidence interval (CV% ± 90% CI) along with the intraclass correlation coefficient (ICC), were calculated to assess the validity and reliability of the optoelectronic system compared to the integrated 3D system. The ICC was based on a 2-way fixed model (Weir, 2005). The device was considered valid if the measured or estimated variable achieved an ICC ≥ 0.75 and the CV% ≤ 10% (Hopkins, 2000). The reliability was considered poor for values below 0.5, moderate for values between 0.5 and 0.75, good for values between 0.75 and 0.90, and excellent for those above 0.90 (Koo & Li, 2016). For all tests, statistical significance was accepted at $P \leq 0.05$. Statistical analysis was performed with various statistical packages (Stata, StataCorp LLC, USA; IBM SPSS Statistics 19, IBM Corporation, USA; XLSTAT, Addinsoft).

Results

The summary statistics of the assessed variables, including differences (mean, maximum and minimum values) are presented in Table 1. The CCC between Velowin and the reference system showed a substantial to almost perfect correlation (concordance correlation coefficient = 0.75 – 0.96) for all the variables except for displacement, which only showed a substantial CCC (Table 2). Passing and Bablock regression (Table 2) revealed no differences between Velowin and the reference system for AV. When comparing both systems, the 95% confidence interval (CI) for the intercept in displacement, PV, AF, PF and

PP did not include 0, which implied a significant but consistent bias. Furthermore, with respect to PV, AF, PF, AP, and PP, the 95% CI for the slope did not contain 1, which suggests proportional bias as measured with Velowin compared to the reference system. The ICC was good for displacement and PP, but excellent for the rest of the variables. In addition, all the analysed variables met the criteria for validity (ICC ≥ 0.75 and the CV% ≤ 10%, Table 3). Figures 2 and 3 depict the regression lines and the residuals plots calculated between data captured by the integrated 3D system and the Velowin for the displacement and velocity or force and mechanical power respectively.

****Figure 2 and 3 near here****

Discussion

Compared to the integrated force platform and 3D camera system, the optoelectronic system "Velowin" was found to be highly valid and reliable for measuring bar displacement, average and peak vertical velocity. Furthermore, valid and reliable estimations were observed for average force, peak force, average power and peak power.

The data revealed a substantial to almost-perfect correlation between the values obtained using the Velowin and the reference system (CCC = 0.75 – 0.96), which implies a good association between the systems for all the measured variables. In fact, the observed ICC between the two compared measures confirmed the results.

The PBR analyses showed that the new optoelectronic device was highly accurate for measuring AV (Figure 2, panel Ai and Bi), since neither systematic nor proportional biases were detected. Thus, Velowin could be interchanged with the reference system to measure AV, representing a valid and reliable alternative for monitoring average vertical velocity during the ascending phase of the squat exercise.

Systematic but not proportional bias was found for displacement. As indicated by the intercept of the PBR formula (Table 2), Velowin underestimated the bar displacement by about 10 cm, however the difference tended to reduce when the range of motion increased over 55 cm (Figure 2 A[i]). Furthermore, the proportional bias detected for VP, AF, PF, AP, and PP, suggest that the differences between the new optoelectronic device and the reference system are not constant throughout the full range of analysed values. Nevertheless, a closer examination of the regression lines and their corresponding 95% CI lines indicates a good level of accuracy for PV (Figure 2 panel A[iii]), AF, PF, and AP (Figure 3 panel A[i], A[ii], and A[iii]). The slope of the respective regression lines, which showed values close to 1, reinforces the observed results. Particularly, the differences in PV and the estimated AF tend to decrease as the values in both variables increase. Conversely, for the estimated PF and AP, the differences tend to increase as the values increase. These findings imply that both systems should not be used interchangeably for measuring the aforementioned variables. Furthermore, the examination of the PP regression line (Figure 3 panel A[iv]) and its slope's value revealed a tendency of Velowin to underestimate below 1800 W and to overestimate thereafter. Consequently, the new optoelectronic device (Velowin) seems to be valid and reliable for measuring bar displacement, AV, and PV, as well as to estimate AP, AF, AF and, PP. Nonetheless, it is only accurate for determining AV while presenting some limitations in accurately estimating AF, PF, AP and mainly PP during the back-squat exercise.

During the last few years, several investigations have validated LT and accelerometers for measuring velocity, and estimated the applied force and the achieved power during different RT exercises such as back-squat, bench press and hip thrust (Balsalobre-Fernández et al., 2017; Lorenzetti, Lamparter, & Luthy, 2017). Regarding the squat exercise, some authors used the Smith-machine (Banyard, Nosaka, Sato, & Haff, 2017; Crewther et al., 2011), which prevents from any horizontal displacement during the lift, whereas others used the free-weight back-squat (Garnacho-Castano et al., 2015). In the present study the latter was chosen, as it may be transferable to a wider range of contexts and accounts for the inter-participant technique variability. However, it is worth mentioning that the main strength of the present study relies on comparing the values measured by the optoelectronic device with those simultaneously obtained from the “gold standard” method. Previous studies have considered LT as the reference system for assessing velocity (Balsalobre-Fernández et al., 2017), and even force and power (Garnacho-Castano et al., 2015). Since it seems clear that FP is the “gold standard” method to measure force production, considering LT as the “gold standard” for measuring velocity may not be appropriate. Differences between LT models and their proprietary software, which influences the data processing, could explain disagreements between paired variables measured with different LT models (Garnacho-Castano et al., 2015). Interestingly, accuracy can be determined when comparing a new method with the “gold standard”, while the term agreement should be used when comparing two methods none of which is the “gold standard” (Bland & Altman, 1986). In the current study, the accuracy of the Velowin could be assessed, as the optoelectronic device was compared against an integrated “gold standard” method for measuring both, velocity (3D) and force (FP).

The present study is not without limitations, since only the free-weight back-squat exercise was tested, and with a reduced number of male participants. Future studies should ideally aim to validate this new optoelectronic device for other RT exercises using larger sample sizes including females or older populations. Furthermore, it is worth considering that with as the Optoelectronic system only analysed linear motion the bar path and the velocity is underestimated. Nonetheless, this represents a “real life” setting similar to what coaches are able to evaluate when using Velowin or similar devices during workouts on day-to-day basis.

Additionally, although is a common practice in resistance exercise to evaluate performance based on the mechanical power (Baker, 2001) estimated from changes in movement velocity (see Equations 1 and 2), the use of such derived variable can be calculated erroneously (Winter et al., 2016). Therefore, the use of impulse (mass x velocity) created by the application of force and resulting in a given velocity of the used resistance, represents a better indicator of performance. Future studies should consider the calculation of impulse instead of power as a more accurate indicator of the neuromuscular efforts (Winter et al., 2016).

Considering the evidence in supporting velocity-based training, coaches may become interested in acquiring equipment to assess parameters as velocity, force and power during their RT sessions in a real-time fashion. Measuring these parameters is useful as, for instance, velocity can be used to regularly monitor changes in performance, estimate 1RM values (Naclerio & Larumbe-Zabala, 2017a) and even evaluate neuromuscular fatigue within a set (Sanchez-Medina & Gonzalez-Badillo, 2011). Recent studies recommend to control resistance exercises using a target velocity loss limited to 10% (Chapman et al., 2017) or 20% (Pareja-Blanco et al., 2017) from the maximum velocity achieved at the beginning of a continuous set. This approach will allow athletes to train within a specific loading zone aimed to increase the ability to perform fast actions against light to moderate loads or prioritise selective adaptation of the fast twitch fibber (Pareja-Blanco et al., 2017).

Currently, LT are the most widespread devices, yet they are more expensive, and they require a cable to be attached to the bar. This also makes LT delicate because tripping over the device or bumping the cable can damage the mechanism. Accelerometers, on the other hand, are gaining popularity as they are more affordable than LT and the validity of several devices has been already studied (Balsalobre-Fernandez, Kuzdub, Poveda-Ortiz, & Campo-Vecino, 2016; Crewther et al., 2011). However, accelerometers also require to be fixed to the bar, which exposes the device to shocks and to potential damages. In the light of findings of the present investigation, Velowin is presented as an alternative to both LT and accelerometers, as it is valid and more affordable than LT, and it does not require any physical attachment to the implement. Only a reflective marker fixed to the implement is needed for the system to work. The optoelectronic device is then place away in front of the implement facing the reflective marker, which keeps the device safely at the distance.

In conclusion, in the present study, Velowin has shown to be valid and reliable to measure vertical displacement, vertical AV and PV or to estimate AF, PF, AP and PP during the back-squat exercise with loads ranging from 30 to 90% 1RM.

References

Baker, D. (2001). A series of studies on the training of High Intensity Muscle Power in Rugby League Football Player. *J. Strength Cond. Res*, 15(2), 198-209.

Balsalobre-Fernandez, C., Kuzdub, M., Poveda-Ortiz, P., & Campo-Vecino, J. D. (2016). Validity and Reliability of the PUSH Wearable Device to Measure Movement Velocity During the Back Squat Exercise. *J Strength Cond Res*, 30(7), 1968-1974. 10.1519/JSC.0000000000001284

Balsalobre-Fernández, C., Marchante, D., Baz-Valle, E., Alonso-Molero, I., Jiménez, S. L., & Muñóz-López, M. (2017). Analysis of Wearable and Smartphone-Based Technologies for the Measurement of Barbell Velocity in Different Resistance Training Exercises. *Frontiers in Physiology*, 8(649).

Balsalobre-Fernandez, C., Marchante, D., Munoz-Lopez, M., & Jimenez, S. L. (2017). Validity and reliability of a novel iPhone app for the measurement of barbell velocity and 1RM on the bench-press exercise. *J Sports Sci*, 1-7.

Banyard, H. G., Nosaka, K., Sato, K., & Haff, G. G. (2017). Validity of Various Methods for Determining Velocity, Force and Power in the Back Squat. *Int J Sports Physiol Perform*, 1-25.

Bazuelo-Ruiz, B., Padial, P., Garcia-Ramos, A., Morales-Artacho, A. J., Miranda, M. T., & Feriche, B. (2015). Predicting Maximal Dynamic Strength From the Load-Velocity Relationship in Squat Exercise. *J Strength Cond Res*, 29(7), 1999-2005.

Bilic-Zulle, L. (2011). Comparison of methods: Passing and Bablok regression. *Biochem Med (Zagreb)*, 21(1), 49-52.

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, 1(8476), 307-310.

Ceseracciu, E., Sawacha, Z., & Cobelli, C. (2014). Comparison of markerless and marker-based motion capture technologies through simultaneous data collection during gait: proof of concept. *PLoS One*, 9(3), e87640.

Chapman, M., Larumbe-Zabala, E., Gosss-Sampson, M., Colpus, M., Triplett, N. T., & Naclerio, F. (2017). Perceptual, Mechanical And Electromyographic Responses To Different Relative Loads In The Parallel Squat. *J Strength Cond Res*. doi:10.1519/JSC.0000000000001867

Cormie, P., Deane, R., & McBride, J. M. (2007). Methodological concerns for determining power output in the jump squat. *J Strength Cond Res*, 21(2), 424-430.

Crewther, B., Kilduff, L., Cunningham, D., Cook, C., Owen, N., & Yang, G. (2011). Validating two systems for estimating force and power. *Int J Sports Med*, 32(4), 254-258.

Dugan, E. L., Doyle, T. L., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *J Strength Cond Res*, 18(3), 668-674.

Escamilla, R. F., Flesing, G. S., Zhen, N., Lander, J. E., Barrentine, S. W., Andrews, J. R., . . . Moorman III, C. T. (2001). Effects of the Techniques variation on knee Biomechanics during the squat and leg press. *Med and Sci. in sport and Exc.*, 33(9), 1552-1566.

Escamilla, R. F., Lander, J. E., & Garhammer J. (2000). Biomechanics of Powerlifting and Weightlifting Exercises, Chapter 39. In W. E. Garret & D. F. Kirkendall (Eds.), *Exercise and Sport Science* (pp. 585-615). Philadelphia: Lippincott Williams & Willkins.

Garnacho-Castano, M. V., Lopez-Lastra, S., & Mate-Munoz, J. L. (2015). Reliability and validity assessment of a linear position transducer. *J Sports Sci Med*, 14(1), 128-136.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med*, 30(1), 1-15.

International Olympic Committee. (2014). *The International Olympic Committee Anti-Doping Rules applicable to the XXII Olympic Winter Games in Sochi, in 2014, Lausanne, Switzerland: IOC. Available at: http://www.olympic.org/Documents/Games_Sochi_2014/Anti-doping/IOC_Anti-Doping_Rules_Sochi_2014-eng.pdf.*

Jimenez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J. B. (2016). Effectiveness of an Individualized Training Based on Force-Velocity Profiling during Jumping. *Front Physiol*, 7, 677.

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*, 15(2), 155-163.

Lin, L. I. (1989). A concordance correlation coefficient to evaluate reproducibility. *Biometrics*, 45(1), 255-268.

Lorenzetti, S., Lamparter, T., & Luthy, F. (2017). Validity and reliability of simple measurement device to assess the velocity of the barbell during squats. *BMC Res Notes*, 10(1), 707.

Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *Int J Sports Physiol Perform*, 11(2), 267-272.

Naclerio, F., & Larumbe-Zabala, E. (2017a). Loading Intensity Prediction by Velocity and the OMNI-RES 0-10 Scale in Bench Press. *J Strength Cond Res*, 31(2), 323-329.

Naclerio, F., & Larumbe-Zabala, E. (2017b). Relative Load Prediction by Velocity and the OMNI-RES 0-10 Scale in Parallel Squat. *J Strength Cond Res*, 31(6), 1585-1591.

Pareja-Blanco, F., Rodriguez-Rosell, D., Sanchez-Medina, L., Sanchis-Moysi, J., Dorado, C., Mora-Custodio, R., . . . Gonzalez-Badillo, J. J. (2017). Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scand J Med Sci Sports*, 27(7), 724-735.

Ratamess, N. (2012). Resistance training exercises, chapter 13. In N. Ratamess (Ed.), *ACSM'scFoundations of Strength Training and Conditioning* (pp. 253–330). Philadelphia, PA: LippincottWilliams &Wilkins.

Sanchez-Medina, L., & Gonzalez-Badillo, J. J. (2011). Velocity loss as an indicator of neuromuscular fatigue during resistance training. *Med Sci Sports Exerc*, 43(9), 1725-1734.

Sanudo, B., Rueda, D., Pozo-Cruz, B. D., de Hoyo, M., & Carrasco, L. (2016). Validation of a Video Analysis Software Package for Quantifying Movement Velocity in Resistance Exercises. *J Strength Cond Res*, 30(10), 2934-2941.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. *Sports Med*, 46(10), 1419-1449.

Swinton, P. A., Stewart, A. D., Keogh, J. W., Agouris, I., & Lloyd, R. (2011). Kinematic and kinetic analysis of maximal velocity deadlifts performed with and without the inclusion of chain resistance. *J Strength Cond Res*, 25(11), 3163-3174.

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*, 19(1), 231-240.

Winter, E. M., Abt, G., Brookes, F. B., Challis, J. H., Fowler, N. E., Knudson, D. V., . . . Yeadon, M. R. (2016). Misuse of "Power" and Other Mechanical Terms in Sport and Exercise Science Research. *J Strength Cond Res*, 30(1), 292-300.

Wretenberg, P., Feng, Y., & Arborelius, U. P. (1996). High- and low-bar squatting techniques during weight-training. *Med Sci Sports Exerc*, 28(2), 218-224.

Disclosure statement

The authors report no conflicts of interest.

Figures

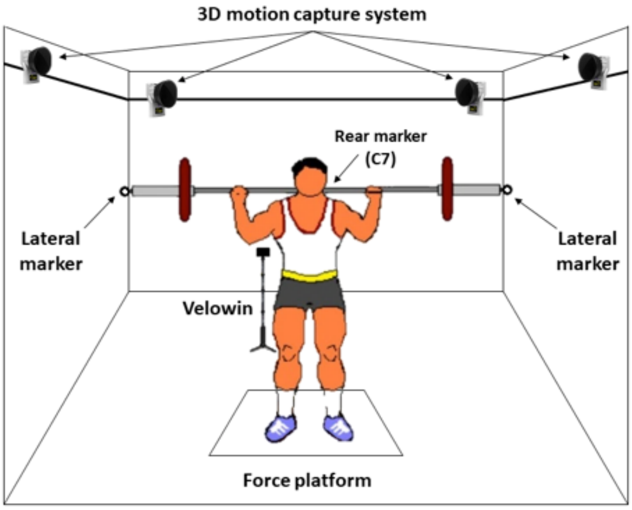

Figure 1. Setup of the used equipment: integrated 3D camera with the force plate system and the optoelectronic system (Velowin).

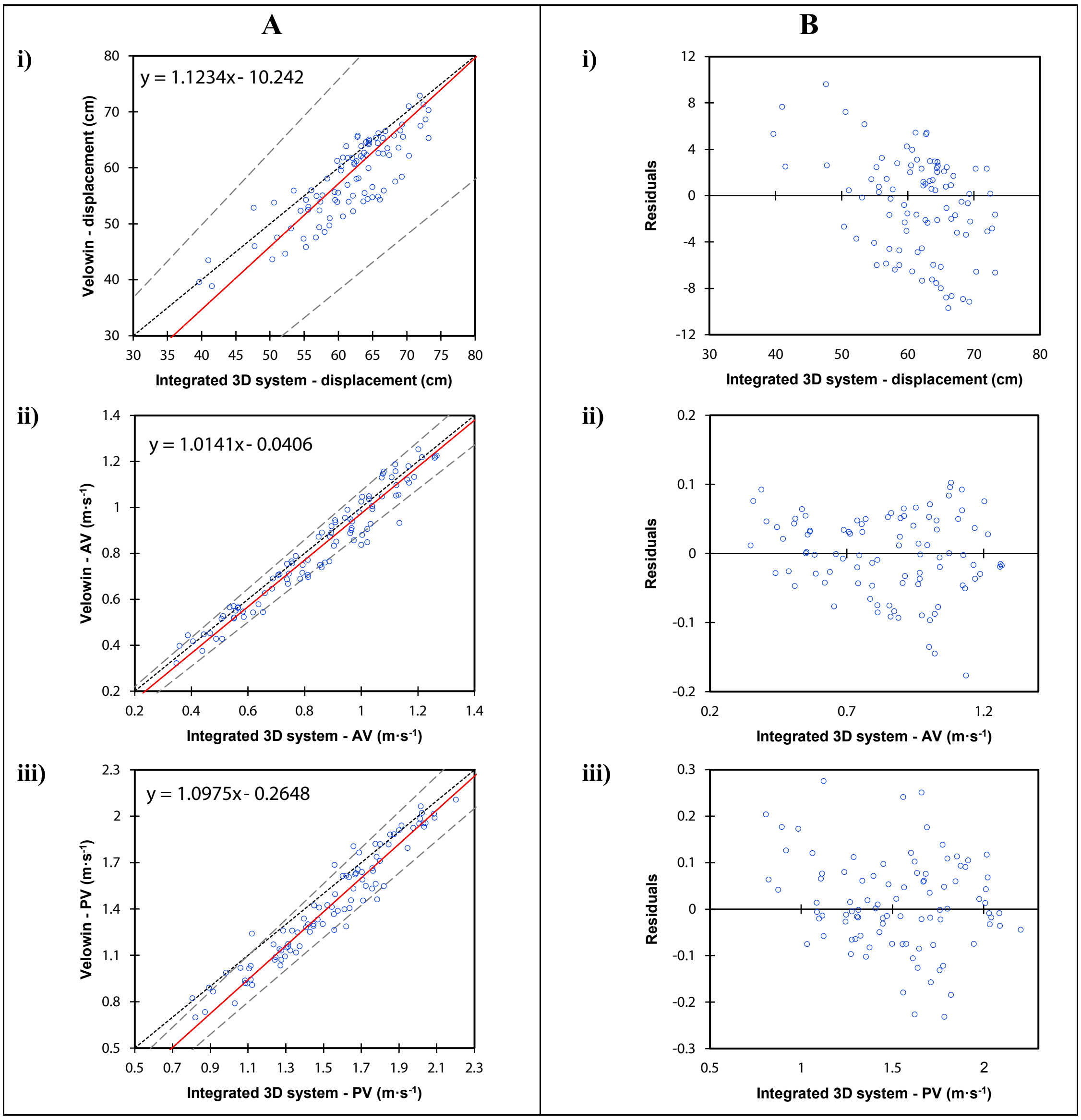

Figure 2. Regression lines ± 95% confidence intervals (panel A) depicting the concurrent validity and residual plots (panel B) depicting divergences between the integrated 3D system and Velowin for displacement, average (AV) and peak (PV) vertical velocity.

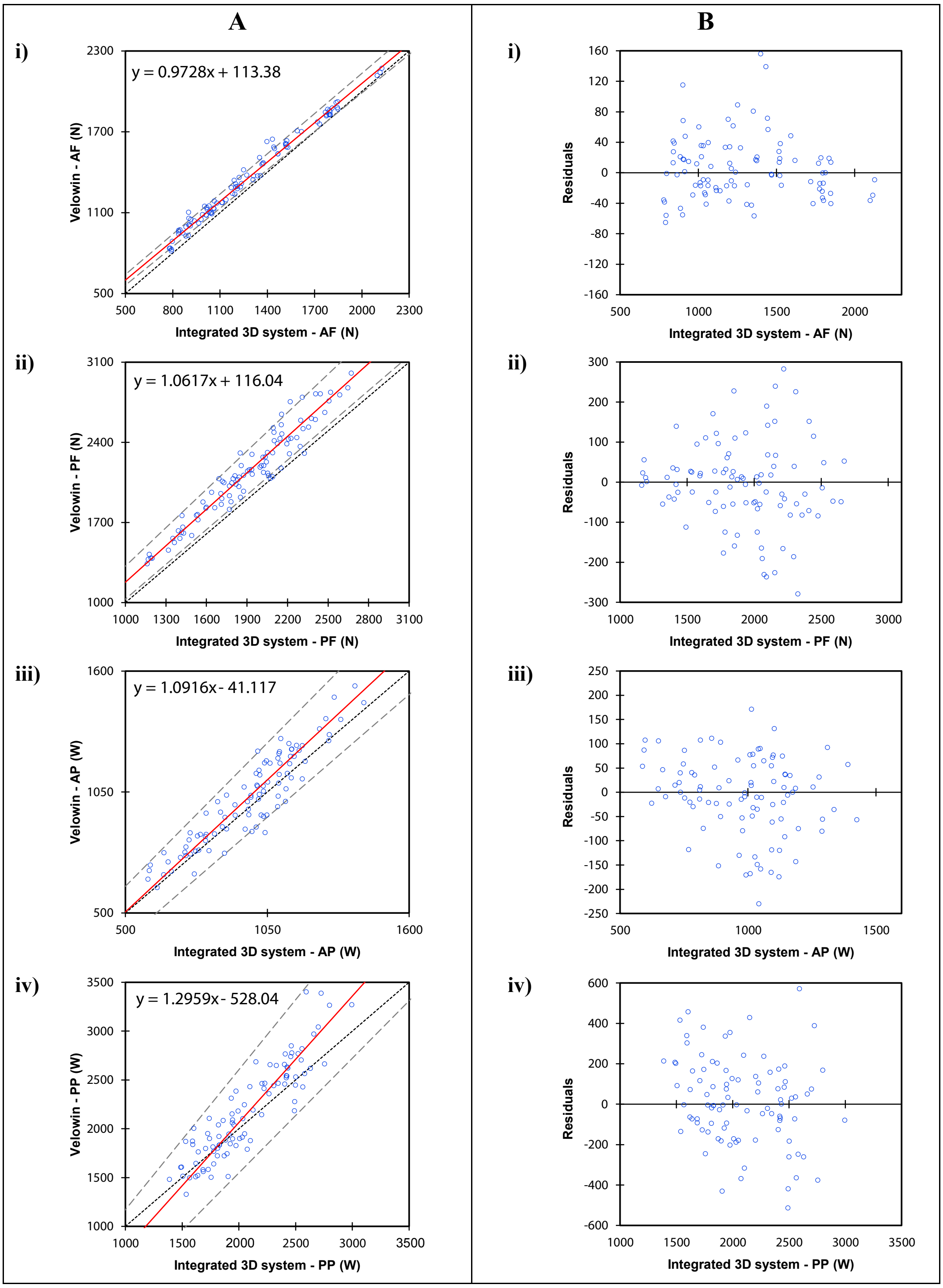

Figure 3. Regression lines ± 95% confidence intervals (panel A) depicting the concurrent validity and residual plots (panel B) depicting divergences between the integrated 3D system and Velowin for the estimated values of force [average (AF) and peak (PF)] and power [average (AP) and peak (PP)].

Tables

Table 1. Descriptive values (mean and Standard Deviation, SD) and differences (mean, maximum and minimum) between systems [integrated 3D system vs. the new optoelectronic device (Velowin)] for the 7 analysed variables.

Variables	**Integrated 3D system**	**Optoelectronic system**	**Differences between systems**		
	Mean (SD)	**Mean (SD)**	Mean	Maximum	Minimum
Displacement (cm)	61.52 (6.82)	58.06 (7.28)	3.46	5.25	-11.77
Average velocity ($m \cdot s^{-1}$)	0.85 (0.24)	0.82 (0.24)	-0.03	0.08	-0.20
Peak velocity ($m \cdot s^{-1}$)	1.53 (0.33)	1.42 (0.36)	-0.10	0.15	-0.33
Average force (N)	1283 (358)	1367 (348)	84.75	231.59	20.03
Peak force (N)	1910 (366)	2141 (394)	230.88	536.05	-19.33
Average power (W)	979 (191)	1021 (208)	41.30	233.09	-174.59
Peak power (W)	2075 (374)	2179 (483)	103.83	810.75	-393.72

Table 2. Correlation between systems, regression line´s intercept and slope.

Variables	**CCC**	**95% CI**	**Intercept**	**95% CI**	**Slope**	**95% CI**
Displacement (cm)	0.75	0.67 to 0.83	-10.24	-21.24 to -2.16	1.12	0.99 to 1.30
Average velocity ($m \cdot s^{-1}$)	0.96	0.95 to 0.98	-0.04	-0.08 to 0.01	1.01	0.96 to 1.06
Peak velocity ($m \cdot s^{-1}$)	0.92	0.89 to 0.95	-0.26	-0.35 to -0.18	1.10	1.04 to 1.16
Average force (N)	0.96	0.95 to 0.98	113.38	86.43 to 143.86	0.97	0.95 to 0.99
Peak force (N)	0.81	0.76 to 0.86	116.04	17.71 to 201.21	1.06	1.01 to 1.12
Average power (W)	0.90	0.87 to 0.94	-41.12	-129.39 to 29.34	1.09	1.01 to 1.18
Peak power (W)	0.85	0.80 to 0.90	-528.04	-802.88 to -262.83	1.30	1.18 to 1.43

CCC = Concordant Correlation Coefficient, CI = Confidence Interval.

Table 3. Intraclass correlation coefficients (ICC), coefficient of variation ±90% confidence interval (CV% ±90% CI), and the root mean square error (RMSE) between the integrated 3D system and Velowin.

Variables	**RMSE**	**CV% (±90 CI)**	**ICC**
Displacement (cm)	3.73	6.6 (5.9 – 7.6)	0.84
Average velocity (m · s^{-1})	0.06	7.3 (6.5 – 8.4)	0.97
Peak velocity (m · s^{-1})	0.09	6.5 (5.8 – 7.4)	0.96
Average force (N)	43	3.6 (3.2 – 4.1)	0.99
Peak force (N)	100	5.2 (4.6 – 6.0)	0.98
Average power (W)	73	8.2 (7.3 – 9.4)	0.92
Peak power (W)	160	8.3 (7.3 – 9.5)	0.85