

1 **TITLE**

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

5 **RUNNING TITLE**

6 VALIDATION OF AN OPTOELECTRONIC DEVICE IN RESISTANCE TRAINING

7 **KEYWORDS**

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

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24 **ABSTRACT**

25 This study analysed the validity and reliability of a new optoelectronic device
26 (Velowin) for the measurement of vertical displacement and velocity as well as to
27 estimate force and mechanical power. Eleven trained males with Mean (SD) age =
28 27.4 (4.8) years, completed an incremental squat exercise test with 5 different loads
29 (<30 – 90% of their 1-repetition maximum) while displacement and vertical velocity
30 of the barbell were simultaneously measured using an integrated 3D system (3D
31 motion capture system + force platform) and Velowin. Substantial to almost perfect
32 correlation (concordance correlation coefficient = 0.75 – 0.96), root mean square error
33 as coefficient of variation $\pm 90\%$ confidence interval $\leq 10\%$ and good to excellent
34 intraclass correlation coefficient = 0.84 – 0.99 were determined for all the variables.
35 Passing and Bablock regression methods revealed no differences for average velocity.
36 However, significant but consistent bias were determined for average or peak force
37 and power while systematic and not proportional bias was found for displacement. In
38 conclusion, Velowin, in holds of some potential advantages over traditionally used
39 accelerometer or linear transducers, represents a valid and reliable alternative to
40 monitor vertical displacement and velocity as well as to estimate average force and
41 mechanical power during the squat exercise.

42 **Introduction**

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

49 Specifically, velocity assessment has been shown to be useful for different purposes.
50 Real-time vertical velocity monitoring allows coaches and trainees to tailor the training load
51 during different RT exercises to attain specific training adaptations (Pareja-Blanco et al.,
52 2017), or estimate the 1-repetition maximum (1RM), for various RT exercises without the
53 need to perform the actual 1RM test (Bazuelo-Ruiz et al., 2015; Naclerio & Larumbe-Zabala,
54 2017a). Furthermore, velocity loss within a set has been shown to be an indicator of
55 neuromuscular fatigue (Sanchez-Medina & Gonzalez-Badillo, 2011). Therefore, monitoring
56 velocity is a suitable way to determine the RT zones in which trainees perform their lifts
57 (Chapman et al., 2017).

58 Velocity is assessed with different devices, including but not limited to linear
59 transducers (LT), (Naclerio & Larumbe-Zabala, 2017b) wearable devices (Balsalobre-
60 Fernández et al., 2017), apps (Balsalobre-Fernandez, Marchante, Munoz-Lopez, & Jimenez,
61 2017), advanced video analysis (Sanudo, Rueda, Pozo-Cruz, de Hoyo, & Carrasco, 2016),
62 and 3-D motion capture systems (3D) (Swinton, Stewart, Keogh, Agouris, & Lloyd, 2011).
63 Among these, 3D has been considered the “gold standard” method to assess velocity
64 (Ceseracciu, Sawacha, & Cobelli, 2014).

65

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

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

81 In this respect, a new optoelectronic system (Velowin 1.6.314, Deportec, Spain) has
82 recently been marketed. The Velowin consists of an infrared camera that tracks the vertical
83 position changes of a reflective marker fixed to the implement (barbell). This planar device
84 is capable of measuring displacement, peak and average vertical velocity, in real time during
85 RT exercises. Based on these measurements, the software (VELOWIN 1.6.314) provides
86 estimation of peak and average values for force and power. Furthermore, the novel
87 optoelectronic device is more affordable than traditional LT or accelerometers. While the
88 LT requires a cable to be attached to the implement, the Velowin does not require any
89 physical connection and consequently eliminates the risk of cable rupture, which is one of
90 the most frequent issues associated with the LT. Accelerometers are delicate devices, being

91 easily damaged by any shock, and provide a lower level of accuracy (Dugan, Doyle,
92 Humphries, Hasson, & Newton, 2004). These disadvantages are overcome when using the
93 Velowin, because the device is placed away from the surroundings of the RT exercise and it
94 may potentially yield similar accuracy to LT.

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

103 **Methods**

104 *Participants*

105 Eleven recreationally trained males, mean (SD) of age = 27.4 (4.8) years, height =
106 177.2 (4.5) cm, body mass = 76.0 (6.6) kg, and squat 1RM = 117.5 (26.2), with a minimum
107 of 2 and a maximum of 5 years of RT experience performing squatting exercises volunteered
108 to take part in this study. All participants reported not having taken any banned substances
109 as declared by the International Olympic Committee 2014 antidoping rules (International
110 Olympic Committee, 2014). No physical limitations or musculoskeletal injuries that could
111 affect strength performance were reported. After being informed of the purpose and
112 experimental procedures, participants signed a written informed consent form before
113 participation, in accordance with the Declaration of Helsinki. The University Ethics
114 Committee approved procedures.

115 *Incremental back squat test*

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

120 The incremental back squat test was performed using free weights and a squat rack
121 according to the technique described by Ratamess (Ratamess, 2012). Briefly, participants
122 were instructed to start the exercise from standing, feet parallel and shoulder width apart
123 with toes pointing slightly outward. The bar was centred across the shoulders just below the
124 spinous process of the C7 vertebra (high-bar position) (Wretenberg, Feng, & Arborelius,
125 1996). Participants were instructed to squat down using a controlled velocity until they
126 reached the final flexed position with their posterior thigh parallel to the floor. After a
127 minimum pause (less than 1 second), aimed to provide a clear separation between repetitions
128 (Escamilla et al., 2001), participants performed the concentric squatting phase with maximal
129 possible velocity. A complete successful repetition was defined as the entire ascending phase
130 from the position where the participants stop the descending phase (velocity = 0 and thighs
131 parallels to the floor) and start the ascending moment until reaching the standing position
132 (velocity = 0). One qualified instructor controlled the appropriate range of motion during the
133 squat exercise. If a repetition was not performed with appropriate technique, the participant
134 was asked to perform another one and the invalid repetition was discarded.

135 The incremental test consisted of 5 sets of squats with 3 minutes of rest between sets.
136 The squat sets comprised 2 repetitions with the Olympic squat bar (20 kg) < 30% of the
137 estimated 1RM, 2 repetitions with 30% 1RM, 2 with 50% 1RM, 2 with 70% 1RM and 2
138 with 90% of the estimated 1RM. Before each set was performed, the participants were asked
139 to unrack the bar and stand on the FP. The total mass of the participant and the corresponding

140 squat load (bar and plates) was measured and the participants were asked to rerack the bar.
141 The total mass was then introduced in the proprietary software of the optoelectronic system.

142 ***Experimental design***

143 A laboratory-based design was used to test the concurrent validity and reliability of
144 an optoelectronic system for measuring bar displacement, peak and average movement
145 velocity as well as to estimate force and power during the back-squat exercise. Participants
146 performed 5 sets of squats while data were being simultaneously captured with an integrated
147 FP+3D camera system and the optoelectronic device (Velowin). Each participant performed
148 2 repetitions with the Olympic bar (20 kg representing <30% 1RM), and the 30, 50, 70 and
149 90% 1RM, for a total of 10 repetitions. Concentric peak and average values of velocity, force
150 and power from the resultant 110 repetitions measured with the reference system (FP and
151 3D) and the optoelectronic system were compared for validity and reliability purposes by
152 using several statistical analyses.

153 ***Familiarization***

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

156 ***3D data acquisition***

157 Retroreflective (12 mm) markers were placed on both ends of the bar. Motion was
158 captured and tracked at 200 Hz using 10 infrared cameras (Oqus 3, Qualisys Track Manager,
159 Qualisys AB, Sweden). Prior to capture, the working volume was calibrated with a mean
160 residual error of 0.6 mm. Synchronous to motion capture, ground reaction forces were
161 recorded at 200 Hz from a Kistler multicomponent force platform (Kistler Group,
162 Switzerland). All data were subsequently exported to Visual3D (C-Motion, Inc.
163 Germantown, USA) for processing. Kinematic data were filtered using a bidirectional low
164 pass filter with a cut-off frequency of 10 Hz. To obtain a marker coinciding with the vertical

165 axis of the barbell, a virtual marker was created midway between the two aforementioned
166 tracking markers. This virtual marker was then used to measure the vertical displacement
167 and vertical velocity of the bar as well as to estimate the applied force and produced
168 mechanical power.

169 *Velowin data acquisition*

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

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

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

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

190
$$v_i = \frac{p_1 - p_2}{t_1 - t_2}$$

191 Where v_i = vertical velocity at a given instant, p_1 = position of marker at instant 1, p_2 =
192 position of the marker at instant 2, t_1 = time at instant 1, and t_2 = time at instant 2.

193

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

195
$$a_i = \frac{v_1 - v_2}{t_1 - t_2}$$

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

198

199 From the values of velocity and acceleration, the software estimates the applied force (F_i)

200 from Equation 3 ($F_i = ma_i$) and the produced mechanical power (P_i) from Equation 4

201 ($P_i = F_i v_i$).

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

204 As in squatting exercises shanks and feet are relatively static and should not be
205 quantified as resistance, the total mass was calculated by adding the external load to the 90%
206 of the body mass determined by the force platform (Escamilla, Lander, & Garhammer J,
207 2000).

208 ***Statistical analysis***

209 Descriptive statistics were calculated for all variables and presented as mean and
210 standard deviation. Prior to method comparison, all data were assessed for normality of
211 differences. All dependent variables, apart from average power, showed significant
212 differences in normality thus precluding the use of Bland-Altman analysis, and therefore the
213 nonparametric Passing and Bablock regression (PBR) was used for method comparison. This

214 analysis assumes linear relationships between the two methods and was assessed using the
215 Cusum test of linearity. All method comparisons showed no deviation from linearity. The
216 H_0 tested with PBR was based on the upper (UCL) and lower (LCL) confidence limits, where
217 for the intercept $LCL < 0 < UCL$ and for the slope if $LCL < 1 < UCL$ (Bilic-Zulle, 2011).
218 The concordance correlation coefficient (CCC) was used to test for agreement between the
219 two assessment methods (Lin, 1989).

220 The root mean square error (RMSE), the coefficient of variation $\pm 90\%$ confidence
221 interval ($CV\% \pm 90\% CI$) along with the intraclass correlation coefficient (ICC), were
222 calculated to assess the validity and reliability of the optoelectronic system compared to the
223 integrated 3D system. The ICC was based on a 2-way fixed model (Weir, 2005). The device
224 was considered valid if the measured or estimated variable achieved an $ICC \geq 0.75$ and the
225 $CV\% \leq 10\%$ (Hopkins, 2000). The reliability was considered poor for values below 0.5,
226 moderate for values between 0.5 and 0.75, good for values between 0.75 and 0.90, and
227 excellent for those above 0.90 (Koo & Li, 2016). For all tests, statistical significance was
228 accepted at $P \leq 0.05$. Statistical analysis was performed with various statistical packages
229 (Stata, StataCorp LLC, USA; IBM SPSS Statistics 19, IBM Corporation, USA; XLSTAT,
230 Addinsoft).

231 **Results**

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

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

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

248 **Discussion**

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

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

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

262 Systematic but not proportional bias was found for displacement. As indicated by the
263 intercept of the PBR formula (Table 2), Velowin underestimated the bar displacement by

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

282 During the last few years, several investigations have validated LT and
283 accelerometers for measuring velocity, and estimated the applied force and the achieved
284 power during different RT exercises such as back-squat, bench press and hip thrust
285 (Balsalobre-Fernández et al., 2017; Lorenzetti, Lamparter, & Luthy, 2017). Regarding the
286 squat exercise, some authors used the Smith-machine (Banyard, Nosaka, Sato, & Haff, 2017;
287 Crewther et al., 2011), which prevents from any horizontal displacement during the lift,
288 whereas others used the free-weight back-squat (Garnacho-Castano et al., 2015). In the

289 present study the latter was chosen, as it may be transferable to a wider range of contexts
290 and accounts for the inter-participant technique variability. However, it is worth mentioning
291 that the main strength of the present study relies on comparing the values measured by the
292 optoelectronic device with those simultaneously obtained from the “gold standard” method.
293 Previous studies have considered LT as the reference system for assessing velocity
294 (Balsalobre-Fernández et al., 2017), and even force and power (Garnacho-Castano et al.,
295 2015). Since it seems clear that FP is the “gold standard” method to measure force
296 production, considering LT as the “gold standard” for measuring velocity may not be
297 appropriate. Differences between LT models and their proprietary software, which
298 influences the data processing, could explain disagreements between paired variables
299 measured with different LT models (Garnacho-Castano et al., 2015). Interestingly, accuracy
300 can be determined when comparing a new method with the “gold standard”, while the term
301 agreement should be used when comparing two methods none of which is the “gold
302 standard” (Bland & Altman, 1986). In the current study, the accuracy of the Velowin could
303 be assessed, as the optoelectronic device was compared against an integrated “gold standard”
304 method for measuring both, velocity (3D) and force (FP).

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

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

321 Considering the evidence in supporting velocity-based training, coaches may become
322 interested in acquiring equipment to assess parameters as velocity, force and power during
323 their RT sessions in a real-time fashion. Measuring these parameters is useful as, for
324 instance, velocity can be used to regularly monitor changes in performance, estimate 1RM
325 values (Naclerio & Larumbe-Zabala, 2017a) and even evaluate neuromuscular fatigue within
326 a set (Sanchez-Medina & Gonzalez-Badillo, 2011). Recent studies recommend to control
327 resistance exercises using a target velocity loss limited to 10% (Chapman et al., 2017) or
328 20% (Pareja-Blanco et al., 2017) from the maximum velocity achieved at the beginning of a
329 continuous set. This approach will allow athletes to train within a specific loading zone
330 aimed to increase the ability to perform fast actions against light to moderate loads or
331 prioritise selective adaptation of the fast twitch fiber (Pareja-Blanco et al., 2017).

332 Currently, LT are the most widespread devices, yet they are more expensive, and
333 they require a cable to be attached to the bar. This also makes LT delicate because tripping
334 over the device or bumping the cable can damage the mechanism. Accelerometers, on the
335 other hand, are gaining popularity as they are more affordable than LT and the validity of
336 several devices has been already studied (Balsalobre-Fernandez, Kuzdub, Poveda-Ortiz, &
337 Campo-Vecino, 2016; Crewther et al., 2011). However, accelerometers also require to be

338 fixed to the bar, which exposes the device to shocks and to potential damages. In the light of
339 findings of the present investigation, Velowin is presented as an alternative to both LT and
340 accelerometers, as it is valid and more affordable than LT, and it does not require any
341 physical attachment to the implement. Only a reflective marker fixed to the implement is
342 needed for the system to work. The optoelectronic device is then placed away in front of the
343 implement facing the reflective marker, which keeps the device safely at the distance.

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

347 **References**

- 348 Baker, D. (2001). A series of studies on the training of High Intensity Muscle Power in
349 Rugby League Football Player. *J. Strength Cond. Res*, 15(2), 198-209.
- 350 Balsalobre-Fernandez, C., Kuzdub, M., Poveda-Ortiz, P., & Campo-Vecino, J. D. (2016).
351 Validity and Reliability of the PUSH Wearable Device to Measure Movement
352 Velocity During the Back Squat Exercise. *J Strength Cond Res*, 30(7), 1968-1974.
353 10.1519/JSC.0000000000001284
- 354 Balsalobre-Fernández, C., Marchante, D., Baz-Valle, E., Alonso-Molero, I., Jiménez, S. L.,
355 & Muñoz-López, M. (2017). Analysis of Wearable and Smartphone-Based
356 Technologies for the Measurement of Barbell Velocity in Different Resistance
357 Training Exercises. *Frontiers in Physiology*, 8(649).
- 358 Balsalobre-Fernandez, C., Marchante, D., Munoz-Lopez, M., & Jimenez, S. L. (2017).
359 Validity and reliability of a novel iPhone app for the measurement of barbell
360 velocity and 1RM on the bench-press exercise. *J Sports Sci*, 1-7.
- 361 Banyard, H. G., Nosaka, K., Sato, K., & Haff, G. G. (2017). Validity of Various Methods
362 for Determining Velocity, Force and Power in the Back Squat. *Int J Sports Physiol*
363 *Perform*, 1-25.
- 364 Bazuelo-Ruiz, B., Padial, P., Garcia-Ramos, A., Morales-Artacho, A. J., Miranda, M. T., &
365 Feriche, B. (2015). Predicting Maximal Dynamic Strength From the Load-Velocity
366 Relationship in Squat Exercise. *J Strength Cond Res*, 29(7), 1999-2005.
- 367 Bilic-Zulle, L. (2011). Comparison of methods: Passing and Bablok regression. *Biochem*
368 *Med (Zagreb)*, 21(1), 49-52.
- 369 Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between
370 two methods of clinical measurement. *Lancet*, 1(8476), 307-310.

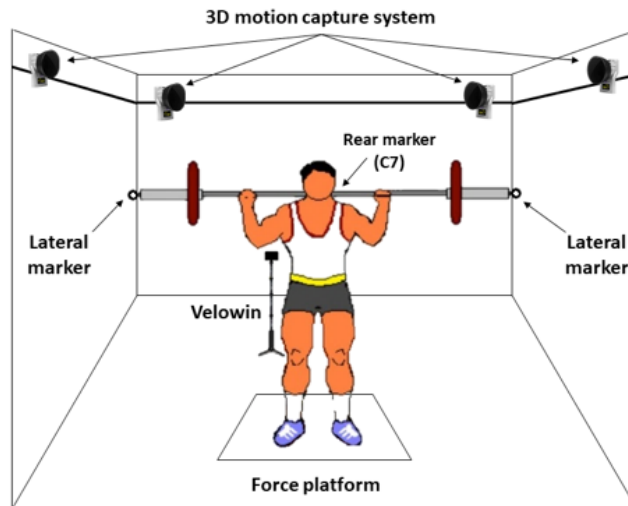
- 371 Ceseracciu, E., Sawacha, Z., & Cobelli, C. (2014). Comparison of markerless and marker-
372 based motion capture technologies through simultaneous data collection during
373 gait: proof of concept. *PLoS One*, 9(3), e87640.
- 374 Chapman, M., Larumbe-Zabala, E., Gosss-Sampson, M., Colpus, M., Triplett, N. T., &
375 Naclerio, F. (2017). Perceptual, Mechanical And Electromyographic Responses To
376 Different Relative Loads In The Parallel Squat. *J Strength Cond Res*.
377 doi:10.1519/JSC.0000000000001867
- 378 Cormie, P., Deane, R., & McBride, J. M. (2007). Methodological concerns for determining
379 power output in the jump squat. *J Strength Cond Res*, 21(2), 424-430.
- 380 Crewther, B., Kilduff, L., Cunningham, D., Cook, C., Owen, N., & Yang, G. (2011).
381 Validating two systems for estimating force and power. *Int J Sports Med*, 32(4),
382 254-258.
- 383 Dugan, E. L., Doyle, T. L., Humphries, B., Hasson, C. J., & Newton, R. U. (2004).
384 Determining the optimal load for jump squats: a review of methods and
385 calculations. *J Strength Cond Res*, 18(3), 668-674.
- 386 Escamilla, R. F., Flesing, G. S., Zhen, N., Lander, J. E., Barrentine, S. W., Andrews, J. R.,
387 . . . Moorman III, C. T. (2001). Effects of the Techniques variation on knee
388 Biomechanics during the squat and leg press. *Med and Sci. in sport and Exc.*, 33(9),
389 1552-1566.
- 390 Escamilla, R. F., Lander, J. E., & Garhammer J. (2000). Biomechanics of Powerlifting and
391 Weightlifting Exercises, Chapter 39. In W. E. Garret & D. F. Kirkendall (Eds.),
392 *Exercise and Sport Science* (pp. 585-615). Philadelphia: Lippincott Williams &
393 Willkins.
- 394 Garnacho-Castano, M. V., Lopez-Lastra, S., & Mate-Munoz, J. L. (2015). Reliability and
395 validity assessment of a linear position transducer. *J Sports Sci Med*, 14(1), 128-
396 136.
- 397 Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med*,
398 30(1), 1-15.
- 399 International Olympic Committee. (2014). *The International Olympic Committee Anti-*
400 *Doping Rules applicable to the XXII Olympic Winter Games in Sochi, in 2014,*
401 *Lausanne, Switzerland: IOC. Available at:*
402 http://www.olympic.org/Documents/Games_Sochi_2014/Anti-doping/IOC_Anti-
403 [Doping_Rules_Sochi_2014-eng.pdf](http://www.olympic.org/Documents/Games_Sochi_2014/Anti-doping/IOC_Anti-Doping_Rules_Sochi_2014-eng.pdf).
- 404 Jimenez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J. B. (2016). Effectiveness of an
405 Individualized Training Based on Force-Velocity Profiling during Jumping. *Front*
406 *Physiol*, 7, 677.
- 407 Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass
408 Correlation Coefficients for Reliability Research. *J Chiropr Med*, 15(2), 155-163.
- 409 Lin, L. I. (1989). A concordance correlation coefficient to evaluate reproducibility.
410 *Biometrics*, 45(1), 255-268.

- 411 Lorenzetti, S., Lamparter, T., & Luthy, F. (2017). Validity and reliability of simple
 412 measurement device to assess the velocity of the barbell during squats. *BMC Res*
 413 *Notes*, 10(1), 707.
- 414 Morin, J. B., & Samozino, P. (2016). Interpreting Power-Force-Velocity Profiles for
 415 Individualized and Specific Training. *Int J Sports Physiol Perform*, 11(2), 267-272.
- 416 Naclerio, F., & Larumbe-Zabala, E. (2017a). Loading Intensity Prediction by Velocity and
 417 the OMNI-RES 0-10 Scale in Bench Press. *J Strength Cond Res*, 31(2), 323-329.
- 418 Naclerio, F., & Larumbe-Zabala, E. (2017b). Relative Load Prediction by Velocity and the
 419 OMNI-RES 0-10 Scale in Parallel Squat. *J Strength Cond Res*, 31(6), 1585-1591.
- 420 Pareja-Blanco, F., Rodriguez-Rosell, D., Sanchez-Medina, L., Sanchis-Moysi, J., Dorado,
 421 C., Mora-Custodio, R., . . . Gonzalez-Badillo, J. J. (2017). Effects of velocity loss
 422 during resistance training on athletic performance, strength gains and muscle
 423 adaptations. *Scand J Med Sci Sports*, 27(7), 724-735.
- 424 Ratamess, N. (2012). Resistance training exercises, chapter 13. In N. Ratamess (Ed.),
 425 *ACSM's Foundations of Strength Training and Conditioning* (pp. 253–330).
 426 Philadelphia, PA: Lippincott Williams & Wilkins.
- 427 Sanchez-Medina, L., & Gonzalez-Badillo, J. J. (2011). Velocity loss as an indicator of
 428 neuromuscular fatigue during resistance training. *Med Sci Sports Exerc*, 43(9),
 429 1725-1734.
- 430 Sanudo, B., Rueda, D., Pozo-Cruz, B. D., de Hoyo, M., & Carrasco, L. (2016). Validation
 431 of a Video Analysis Software Package for Quantifying Movement Velocity in
 432 Resistance Exercises. *J Strength Cond Res*, 30(10), 2934-2941.
- 433 Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular
 434 Strength in Athletic Performance. *Sports Med*, 46(10), 1419-1449.
- 435 Swinton, P. A., Stewart, A. D., Keogh, J. W., Agouris, I., & Lloyd, R. (2011). Kinematic
 436 and kinetic analysis of maximal velocity deadlifts performed with and without the
 437 inclusion of chain resistance. *J Strength Cond Res*, 25(11), 3163-3174.
- 438 Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation
 439 coefficient and the SEM. *J Strength Cond Res*, 19(1), 231-240.
- 440 Winter, E. M., Abt, G., Brookes, F. B., Challis, J. H., Fowler, N. E., Knudson, D. V., . . .
 441 Yeadon, M. R. (2016). Misuse of "Power" and Other Mechanical Terms in Sport
 442 and Exercise Science Research. *J Strength Cond Res*, 30(1), 292-300.
- 443 Wretenberg, P., Feng, Y., & Arborelius, U. P. (1996). High- and low-bar squatting
 444 techniques during weight-training. *Med Sci Sports Exerc*, 28(2), 218-224.
- 445

446 **Disclosure statement**

447 The authors report no conflicts of interest.

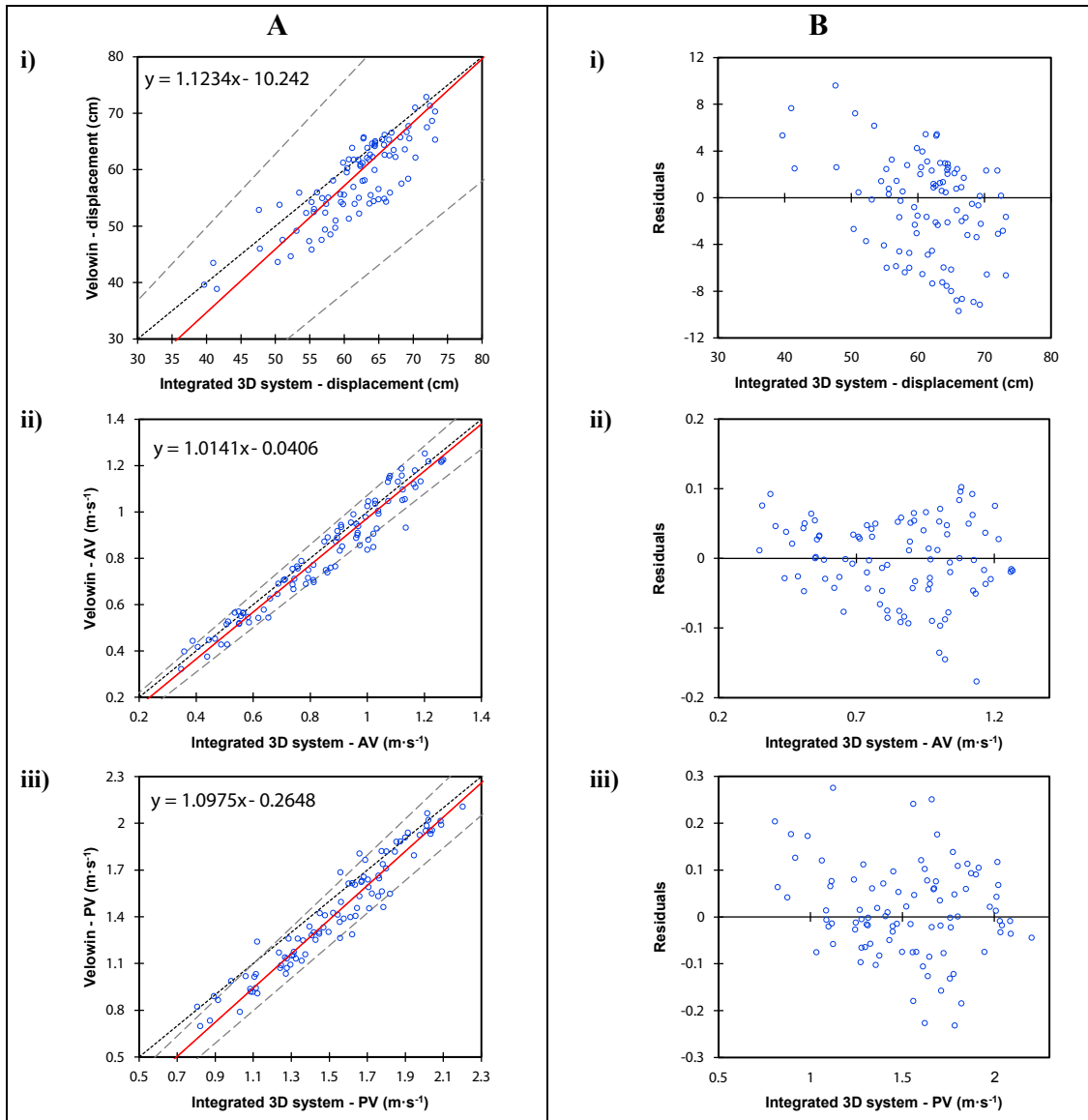
448 **Figures**



449

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

452



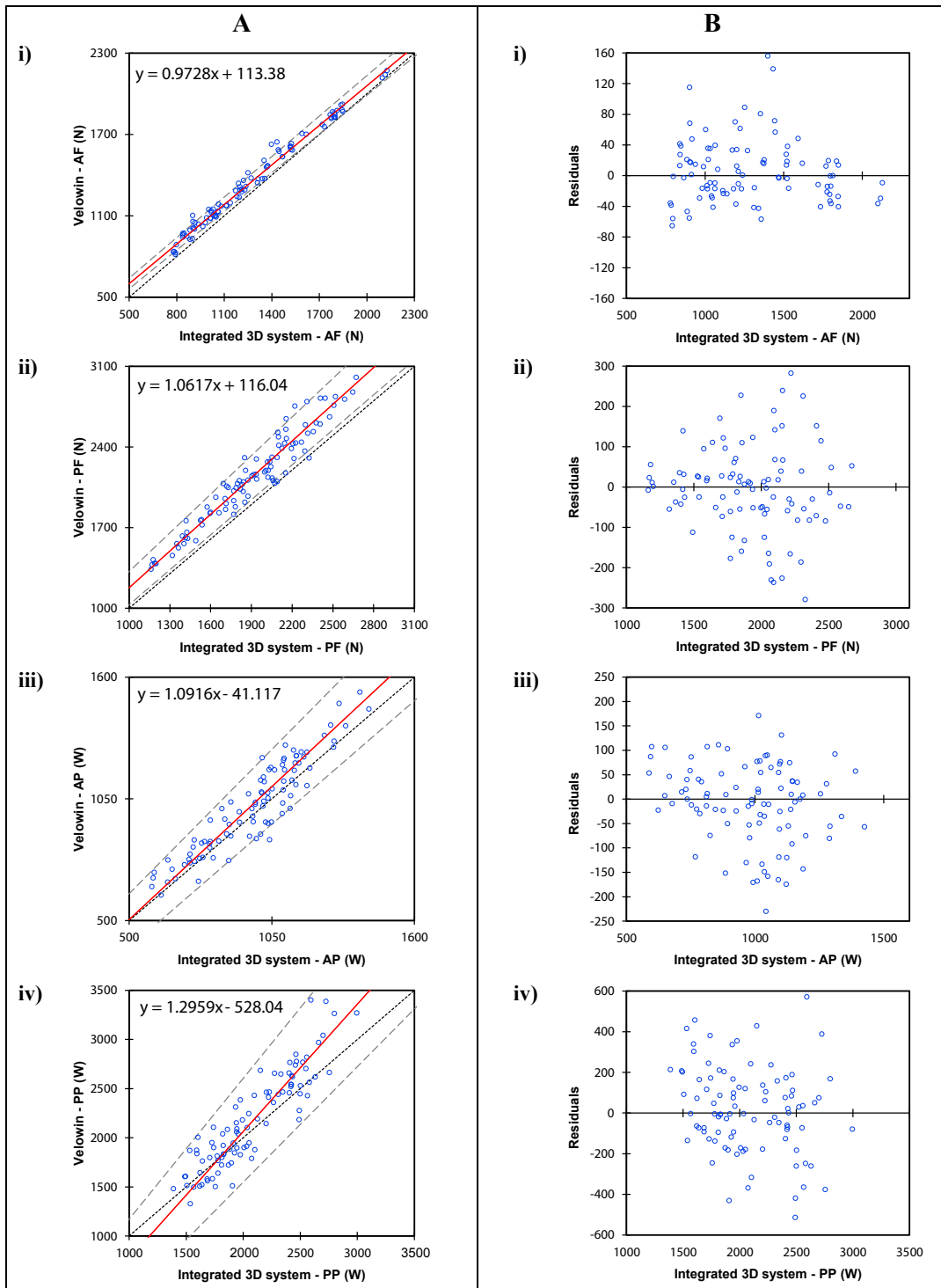
453

454 **Figure 2.** Regression lines \pm 95% confidence intervals (panel A) depicting the concurrent

455 validity and residual plots (panel B) depicting divergences between the integrated 3D

456 system and Velowin for displacement, average (AV) and peak (PV) vertical velocity.

457



458

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

463 **Tables**

464 **Table 1.** Descriptive values (mean and Standard Deviation, SD) and differences (mean, maximum and
 465 minimum) between systems [integrated 3D system vs. the new optoelectronic device (Velowin)] for the 7
 466 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 · s⁻¹) | 0.85 (0.24) | 0.82 (0.24) | -0.03 | 0.08 | -0.20 |
| Peak velocity (m · 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 |

467

468 **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 · 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 · 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.

469

470 **Table 3.** Intraclass correlation coefficients (ICC), coefficient of variation $\pm 90\%$ confidence interval (CV%
 471 $\pm 90\%$ CI), and the root mean square error (RMSE) between the integrated 3D system and Velwin.

| Variables | RMSE | CV% (± 90 CI) | ICC |
|---|-------------|-------------------------------------|------------|
| Displacement (cm) | 3.73 | 6.6 (5.9 – 7.6) | 0.84 |
| Average velocity ($m \cdot s^{-1}$) | 0.06 | 7.3 (6.5 – 8.4) | 0.97 |
| Peak velocity ($m \cdot s^{-1}$) | 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 |

472