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Reproducibility and Repeatability of Five Different Technologies for Bar Velocity Measurement in Resistance Training

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Abstract—This study aimed to analyze the agreement between five bar velocity monitoring devices, currently used in resistance training, to determine the most reliable device based on reproducibility (between-device agreement for a given trial) and repeatability (between-trial variation for each device). Seventeen resistance-trained men performed duplicate trials against seven increasing loads (20-30-40-50-60-70-80 kg) while obtaining mean, mean propulsive and peak velocity outcomes in the bench press, full squat and prone bench pull exercises. Measurements were simultaneously registered by two linear velocity transducers (LVT), two linear position transducers (LPT), two optoelectronic camera-based systems (OEC), two smartphone video-based systems (VBS) and one accelerometer (ACC). A comprehensive set of statistics for assessing reliability was used. Magnitude of errors was reported both in absolute (m s^{-1}) and relative terms (%1RM), and included the smallest detectable change (SDC) and maximum errors (MaxError). LVT was the most reliable and sensitive device (SDC 0.02–0.06 m s^{-1}, MaxError 3.4–7.1% 1RM) and the preferred reference to compare with other technologies. OEC and LPT were the second-best alternatives (SDC 0.06–0.11 m s^{-1}), always considering the particular margins of error for each exercise and velocity outcome. ACC and VBS are not recommended given their substantial errors and uncertainty of the measurements (SDC $>$ 0.13 m s^{-1}).

Keywords—Standard error of measurement, Velocity-based resistance training, Exercise testing, Monitoring, Strength performance, Validity.

INTRODUCTION

Considerable research attention has been paid to monitoring movement velocity during resistance training in recent years.[14,15,26,30] Velocity-based resistance training (VBRT) has been proposed as an effective method to better characterize the resistance training stimulus and, specifically, to more precisely gauge the actual effort or intensity at which athletes train. VBRT requires the use of particular technologies to monitor bar velocity during training, and it has multiple practical applications.[15,25,28,30–33] VBRT has been found to be a robust, non-invasive and highly sensitive method to estimate key performance indicators, such as the relative loading intensity, maximum strength (one-repetition maximum, 1RM) and the level of effort and neuromuscular fatigue incurred during a training set.[15,22,25,28,31,32] These practical applications are however dependent on the actual degree of reliability exhibited by the different existing technologies and particular devices currently used for measuring bar velocity. It has been shown that small changes in the velocity developed against some reference workloads are accompanied by critical improvements in the neuromuscular and functional performance of well-trained athletes. For instance, an increment in mean concentric velocity of just 0.07 to 0.10 m s^{-1} is associated with improvements of ~ 5% 1RM strength in main resistance exercises such as the bench press (BP), full back squat (SQ) and prone bench pull (PBP).[15,22,31,32] Thus, in order to successfully implement a VBRT intervention, it is imperative to use sufficiently accurate and reliable technologies for measuring bar velocity.[16]

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One of the first commercialized technologies for measuring bar velocity was the linear position transducer (LPT), an electromechanical device which calculates velocity from time and position data from a retractable wire rope attached to the bar that moves up and down as the athlete lifts the training loads.[12,17] Linear velocity transducers (LVT) were also developed to provide direct velocity outcomes by means of a precision tachometer.[15,30] More recently, a variety of new devices have emerged using wearable, wireless or mobile phone technologies such as accelerometers (ACC),[2] wireless infrared optoelectronic cameras (OEC),[11] or smartphone video-based systems (VBS).[3,4,34] Thanks to this technological development, VBRT is becoming increasingly more accessible to strength and conditioning coaches and sports scientists. However, despite the increase in the number of available tools for monitoring bar velocity, there still exist serious concerns about the reliability of the velocity outcome measures provided by such a wide variety of technologies. For example, there is no available information about the inherent technical errors, expected ranges of values or minimal detectable changes.[7] Consequently, current evidence about the sensitivity and reliability of these devices for its use in VBRT settings can be questioned.

Some studies have analyzed the validity of emerging technologies to monitor bar velocity in resistance exercise.[2–5,11] For this purpose, it is common to test the level of agreement between a given new device and a device which is taken as the reference, criterion or gold standard. However, three main concerns can be raised here. First, the reference device must have been proved accurate, otherwise one cannot be able to identify the real changes occurring due to some treatment or training intervention.[16] Second, the Pearson correlation coefficient is often inappropriately used as a measure of agreement between the paired readings of two devices.[2–4,11] What we need to establish is whether the paired data conform to a line of equality (i.e., the 45° line through the origin or concordance line) since readings from two devices can be highly correlated but still involve the presence of a high systematic error difference between measurements.[20,34] Third, strict acceptance criteria must be previously defined based on clinical goals to ensure the inherent technical error is not exceeded.[13] Therefore, before assessing validity, reliability must be first established (since an unreliable device cannot be deemed valid). This reliability should be analyzed in two circumstances: reproducibility (i.e., the variation observed in measurements obtained from a given subject when simultaneously using two or more different methods or devices) and repeatability (i.e., the variation observed in repeated measurements or trials made on the same subject under identical conditions, measured by the same device).[6] This approach would allow us to identify the errors arising from current velocity monitoring technologies in order to objectively quantify the agreement between measurements. However, there is a lack of studies which have assessed bar velocity simultaneously measured by a variety of devices across several repeated observations or trials during the performance of actual resistance training exercises. This information constitutes a priority research gap that needs to be addressed to determine the validity of a given device[29] and, thus, to be able to guarantee its suitability for monitoring actual training adaptations occurring following VBRT interventions.[14,26–28]

Therefore, the purpose of this investigation was to analyze and compare the agreement between five bar velocity monitoring technologies, currently used in VBRT settings, in order to establish the most reliable device based on reproducibility (between-device agreement for a given trial) and repeatability (between-trial variation for each device) criteria.

METHODS

Experimental Design

Five different technologies, purposely designed and marketed to monitor bar velocity during resistance training were simultaneously used in the successive execution of two repetitions (i.e., trials) of a given training exercise in order to determine between-device agreement (reproducibility) and between-trial variation (repeatability). This approach follows previous methodological recommendations to identify the inherent technical error of the measurement and its practical consequences when assessing repeated trials.[16,18,29] For each participant, testing was conducted over six sessions. Although participants could be considered expert trainees, and had previously participated in similar studies from our laboratory, all undertook three practice and familiarization sessions using the testing protocols and exercises analyzed (BP, SQ and PBP). Then, after a full resting day, three experimental sessions (one for each exercise) were conducted in random order, separated by 48 h of recovery. In each session, the individual load-velocity relationships were determined by means of a progressive loading test. In these tests, each participant performed two repetitions against fixed loads of 20, 30, 40, 50, 60, 70 and 80 kg, with 5 min of recovery in between repetitions (i.e., duplicate trials for each load). Therefore, 7 pairs of duplicate measurements for each device, exercise and specific velocity outcome measure (explained later in detail) were obtained for each subject. This allowed to cover a broad range of velocities (from the very fast bar velocities attained against the lower loads to the very slow velocities developed when lifting the heaviest load) in a real resistance training setting.

Participants

Seventeen resistance-trained males volunteered to participate in this study (age 26.0 ± 3.6 years old, body mass 81.5 ± 6.8 kg, height 178.4 ± 8.3 cm). Their 1RM strength for the BP, SQ and PBP exercises was 92.2 ± 11.9, 100.4 ± 21.8 and 82.1 ± 12.7 kg, respectively (1.13 ± 0.15, 1.23 ± 0.26, 1.01 ± 0.16 normalized per kg of body mass). Participants' weight training experience ranged from 7 to beyond 15 years (2–3 sessions per week). No physical limitations or musculoskeletal injuries that could affect testing were reported. Participants signed a written informed consent form. The study was conducted according to the Declaration of Helsinki and approved by the Bioethics Commission of the local university.

Measurement Equipment and Data Acquisition

A Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) was used for all sessions and exercises. This machine allows only vertical displacement of the bar along a fixed pathway and its guide rods and bearings are specially designed to ensure a smooth operation, with very low friction force between the bar and the support rails. The Smith machine did not have any kind of counterweight mechanism, acting identically to free-weights (isoinertial loading). The weight of the bar, including the guidance system, totaled 20 kg. Extra load was added by sliding calibrated weight discs (Eleiko, Sport AB, Halmstad, Sweden) onto both ends of the bar.

Measurements were obtained from 9 single device units representatives of the 5 aforementioned technologies (LPT, LVT, OEC, VBS and ACC), which simultaneously measured and recorded concentric bar velocity for each repetition, as follows:

(1) Two T-Force Dynamic Measurement System^{TM} units (Ergotech Consulting, Murcia, Spain). This system consists of a LVT interfaced to a personal computer by means of a 14-bit resolution analog-to-digital data acquisition board and custom software (version 3.60). Instantaneous bar velocity was sampled at a frequency of 1000 Hz and subsequently smoothed with a 4th order low-pass Butterworth digital filter with no phase shift and 10 Hz cut-off frequency.

(2) Two Chronojump^{TM} units (Chronojump, Barcelona, Spain). This system consists of a LPT interfaced to a personal computer and custom free software (version 1.7.1-213-g0120ff0). Time and displacement data were sampled at a frequency of 500 Hz and subsequently smoothed using a Butterworth filter with a 10 Hz cut-off frequency.

(3) Two Velowin^{TM} units (DeporTeC, Murcia, Spain). This system consists of an infrared camera and associated software (version 1.6.314) which tracks the displacement of a reflective marker placed on the weights bar. The two OEC cameras were placed together on tripods, 1.7 m apart from the same left axis of the Smith Machine, at heights specifically adapted for each exercise (93 cm for BP, 115 cm for SQ and 70 cm for PBP). Bar position was sampled at a frequency of 500 Hz.

The retractable cables of all LVT and LPT units were attached to the same right side of the Smith machine, all of them placed very close to the vertical displacement axis (3 cm to the right and left side of the axis). This was achieved by using a purpose-built support that allowed placing one transducer on top of another. The LVT, LPT and OEC devices were interfaced to personal computers running the Windows 10 operating system (version 17.09), with the latest versions of their respective software installed.

(4) Two VBS PowerLift^{TM} apps (version 4.0 iOS), which were installed on two iPhone 6 units running iOS 11.3 (Apple Inc., California, USA). The smartphones were placed on tripods, at a horizontal distance of 1.5 m, just in front of two independent marks on the bar, one for each smartphone. The starting and finishing positions of the bar during the lift were clearly observed, strictly following the app designer's instructions.[4] The app estimates the mean bar velocity of the concentric phase by video-recording the lift at slow motion (240 fps, 1080p) using the smartphone's camera. The app allows a frame-by-frame video inspection to manually select the beginning and end of the movement, and thus determine the lift's concentric duration. Prior to testing, this app requires determining the range of motion (space covered between the starting and finishing bar positions). This was done for each exercise and participant. The start of the lift was considered as the first frame in which the bar started to ascend vertically and the end was considered as the first frame in which the bar stopped that ascension.[4]

(5) One PUSH^{TM} Band ACC (PUSH Inc., Toronto, Canada), firmware version 0.1.1. This system consists of an armband wearable device that uses wireless technology to estimate velocity from vertical acceleration. It includes a 3-axis accelerometer and a gyroscope that provides 6 degrees of freedom in its coordinate system. The armband was placed on the upper forearm following the manufacturer's instructions. This system uses a Butterworth filter to smooth the acceleration data. Velocity is calculated by the integration of acceleration with respect to time, which is sampled at 200 Hz. The system was linked to an iPad mini (Apple Inc., California, USA) running iOS 9.3.5 using a Bluetooth 4.0 LE connection and running app version 4.1.2. It was not possible to use more than one PUSH device since it is not feasible to meet the manufacturer's requirements while simultaneously wearing two units in the same participant's forearm. Thus, unlike the rest of devices analyzed, only measurements from a single ACC unit could be obtained and analyzed.

Technical characteristics and specifications for each device are presented in Table 1. Each device was assembled and calibrated according to the manufacturer's specifications before each session. No calibration procedure was needed for the PUSH^{TM} Band system to work.

Device units were randomly numbered (#1 and #2 for each technology). Intra-device reproducibility was assessed by comparing the velocity outcomes for trial 1 simultaneously obtained by each pair of the two (same brand and model) devices (#1 and #2), with the exception of the ACC due to the abovementioned limitation. Likewise, for assessing inter-device reproducibility, one device unit (#1) representative of each technology was compared against that taken as the reference. The reference was considered to be the device with the best intra-device reproducibility and best repeatability (i.e., the one showing less variation in velocity outcomes between trials). Repeatability between trials (repetition 1 vs. repetition 2) for each device was assessed using only one device unit (#1) from each technology.

Three distinct velocity outcome measures were analyzed in this study: mean velocity (MV, mean concentric velocity); mean propulsive velocity (MPV, mean velocity of the propulsive phase, defined as that portion of the concentric phase during which bar acceleration is greater than acceleration due to gravity[33]); and peak velocity (PV, maximum instantaneous velocity reached during the concentric phase). An exception to this were the ACC and VBS technologies which are unable to provide the MPV measure and the VBS which did not provide measures of PV. It must also be noticed that these two technologies could not be used in the PBP because this is an exercise for which their algorithms are not currently prepared for.

Testing Procedures

Warm-up for each session consisted of 5 min of stationary cycling at a self-selected easy pace, 5 min of gentle stretching and joint mobilization exercises, followed by two sets of five repetitions in the corresponding exercise against loads of 20 and 40 kg. As already explained, two repetitions (trials) were executed by each subject against the same seven fixed loads (20-30-40-50-60-70-80 kg) in each of the three exercises (one per session) analyzed. Unlike the eccentric phase, which was performed at a controlled mean bar velocity (~ 0.50 to 0.70 m s^{-1}) for standardization and security reasons, participants were encouraged to perform the concentric action in an explosive manner, at maximal intended velocity. Body positions as well as grip widths were measured so that they could be reproduced on every lift. Only the concentric actions (pushing for BP and SQ, and pulling for PBP) were analyzed in the present study.

A description of the BP, SQ and PBP testing protocols has been reported in detail elsewhere.[15,31,32] In the BP, participants lay supine on a flat bench, with their feet resting flat on the floor, and hands placed on the bar slightly wider (5–7 cm) than shoulder width. The position on the bench was carefully adjusted so that the vertical projection of the bar corresponded with each participant's intermammary line. Each subject was instructed to lower the bar to the chest, just above the nipples, in a slow and controlled manner and wait during a momentary pause, which lasted approximately 1.5 s, then immediately reverse motion and ascend back to the upright position. Subjects were not allowed to bounce the bar off their chests or raise the shoulders or trunk off the bench. In the SQ exercise, participants started from the upright position with the knees and hips fully extended, stance approximately shoulder-width apart with both feet positioned flat on the floor in parallel or externally rotated to a maximum of 15°. Each subject descended in a continuous motion until the top of the thighs reached below the horizontal plane, with knees flexed to a tibiofemoral angle of 35°–45° in the sagittal plane, then immediately reversed motion and ascended back to the upright position. The bar was grasped with a closed pronated grip and placed on the upper part of the trapezius, while keeping a straight-ahead gaze and stable upright trunk posture. In the PBP, subjects were instructed to lie prone and place their chin on the padded edge of a high bench. The pulling phase began

TABLE 1. Technical characteristics of the devices under study.

Technology	Linear velocity transducer (LVT)	Linear position transducer (LPT)	Optoelectronic camera (OEC)	Accelerometer (ACC)	Video-based system (VBS)
Device brand	T-Force Dynamic Measurement System^{TM}	Chronojump^{TM}	Velowin^{TM}	PUSH^{TM} Band	Powerlift^{TM}
Software version	3.60	1.7.1-213-g0120ff0	1.6.314	4.1.2, Firmware v. 0.1.1	4.0
Price	2500 €/2915 USD	593 €/692 USD	549 €/640 USD	289 €/337 USD	13 €/15 USD
Direct outcome measures	Velocity; Time	Distance; Time	Distance; Time	Acceleration	Time
Indirect outcome calculations	Distance; Acceleration; Force; Power	Velocity; Acceleration; Force; Power	Velocity; Acceleration; Force; Power	Velocity; Force; Power	Velocity
Sampling frequency	1000 Hz	500 Hz	500 Hz	200 Hz	240 Hz
Mechanic variables displayed by the software	Mean, peak and time to reach peak values for all direct and indirect outcomes, propulsive phase, estimated load (%1RM), 1RM prediction, number of repetitions, velocity loss (%), velocity alerts (visual and audio feedback)	Mean, peak and time to reach peak values for all direct and indirect outcomes, propulsive phase, estimated load (%1RM), 1RM prediction, number of repetitions	Mean, peak and time to reach peak values for all direct and indirect outcomes, propulsive phase, estimated load (%1RM), 1RM prediction, number of repetitions, velocity loss (%), RFD, velocity alerts (visual and audio feedback)	Mean and peak values for all direct and indirect outcomes	Mean velocity 1RM prediction
External power supply required	No	No	Yes	No	No
Installation and calibration time before the first execution[a]	2.4 min	2.5 min	5.7 min	0.7 min	1.2 min
Time to obtain the measure after execution	In real time	In real time	In real time	In real time	66 s[b]
Number of lost repetitions per each 100 cases	0.9 rep	1.2 rep	0.4 rep	7.7 rep	0 rep

[a] Estimation of mean installation and equipment calibration time spent for the performance of three consecutive repetitions.

[b] Mean time required to obtain the MV outcome value from three repetitions performed against medium to high loads ($>$ 50% 1RM).

with both elbows in full extension, while the bar was grasped with hands shoulder-width apart or slightly wider (4–5 cm). The participants were instructed to pull until the bar struck the underside of the bench, after which it was again lowered to the starting position; they were not allowed to use their legs to hold onto the bench. There was a distance of 8 cm between the underside of the bench and the subjects' chest.

Statistical Analyses

Normality and homoscedasticity assumptions were verified using the Kolmogorov–Smirnov test, the Brown–Forsythe robust test, the Q–Q plots and scattered plots of the residuals. Sphericity was checked using the Mauchly's test. Reliability (reproducibility and repeatability) analyses included the calculation of a set of statistics aimed at providing information about the level of agreement and the magnitude of errors (both in absolute and relative values) incurred when using the different technologies under study.

The following statistics were used as complementary indicators of agreement:

- The intraclass correlation coefficient (ICC) was calculated. ICC (1,k), one-way random-effects, absolute agreement, multiple raters/measurements model, was chosen due to the fact that each repetition was assessed by a different set of devices. ICC (1,k) and its 95% confidence interval ranges (CI) were calculated according to Koo and Li guidelines.[18] For the assessment of technological equipment, cut-off values of 0.95–0.99 are considered good for research and clinical practice.[23]
- The Lin's concordance correlation coefficient (CCC) was calculated to detect the agreement and systematic error between two devices by assessing how close their paired velocity outcomes were to the best-fit line and how far this line was from the 45° concordance line through the origin.[20] A CCC value of 1 represents perfect agreement, i.e., all the points lie exactly on the concordance line. CCC

TABLE 2. Levels of disagreement between a reference velocity monitoring device and a candidate device.

	Level of disagreement		
Exercise	Moderate (5% 1RM)	High (7% 1RM)	Very high (10% 1RM)
Bench press[15]	0.07–0.09	0.10–0.13	0.14–0.18
Full Squat[32]	0.07–0.10	0.11–0.14	0.15–0.20
Prone Bench Pull[31]	0.07–0.08	0.10–0.11	0.14–0.16

Differences are expressed in absolute values between the mean velocity readings of the two devices. Proposal based on previous studies from our research group.[15,31,32] Ultimately, these values would be subject to the criterion of the coach and could also depend on the relative loading magnitude (% 1RM) used in training. Values expressed in m s^{-1}.

values higher than 0.99 are indicative of almost perfect concordance, from 0.95 to 0.99 indicate good or substantial concordance, from 0.90 to 0.95 moderate concordance and values lower than 0.90 are indicative of poor concordance between measurements.[23] Percent deviation from perfect concordance was also calculated.

- Both the mean square (o quadratic) deviation (MSD) and the variance of the difference between measurements (VMD) were used as error indicators. The closer the MSD to zero the better, since this indicates a constant and proportional systematic error and random error. Similarly, the closer the VMD to zero the greater the precision (less dispersion of random error). Percent deviation from zero was also calculated for MSD and VMD.
- Linear regression analysis and Pearson's correlation coefficient (r) were used to assess the extent of the linear relationship existing between paired velocity outcomes from two devices. Linear equations ($Y = aX + b$) were fitted assuming that ideal values for the slope (a) should be close to 1 whilst the constant (b) should be close to zero to minimally alter the explanatory variable (X).
- The standard error of the estimate (SEE) was calculated as the standard deviation of the residuals as a measure of variation around the regression line. The smaller the value, the closer the data points are to the regression line and the better the estimation is.

The magnitude of error was calculated using the following statistics:

- The standard error of measurement (SEM) was calculated from the square root of the mean square error term in a repeated-measures ANOVA to determine the amount of variability caused by measurement error.[1] Results are presented both in absolute (m s^{-1}) and relative terms as a coefficient of variation (CV = 100 SEM/mean). For most sporting events and exercise performance tests, the CV should be lower than 5%.[16]
- Sensitivity was estimated by the smallest detectable change (SDC) derived from the SEM $(\sqrt{2} \times \text{SEM} \times 1.96)$ as a component of random error. The SDC is a measure of the variation in a scale due to measurement error. Thus, a change in a given variable can only be considered to represent a real change if it is larger than the SDC.[7]
- The level of agreement between paired velocity outcomes from two devices was also assessed using Bland–Altman plots and the calculation of systematic bias and its 95% limits of agreement (LoA = bias ± 1.96 SD).[9]
- Maximum errors (Max Error) at the 95% confidence interval were calculated from the SEE ($\text{Max Error}_{\text{SEE}}$) and Bland–Altman bias ($\text{Max Error}_{\text{bias}}$) for the different velocity outcomes (m s^{-1}) analyzed. In addition, and for practical reasons, values were expressed as the corresponding relative load (% 1RM) for each velocity and exercise based on previous studies.[15,22,31,32]

Levels of disagreement (Table 2) were proposed based on clinical considerations[13] and previous published evidence from our research group in the three exercises used in this study.[15,22,31,32] For instance, in the BP, a difference of 0.14–0.18 m s^{-1} in the mean velocity readings of one device compared to the reference device could be considered as a very high level of disagreement, in which estimation of load (% 1RM) from velocity measures would imply an error of ~ 10% RM.

Statistical calculations were performed using a custom Microsoft Excel spreadsheet and the SPSS statistical software version 17 (SPSS Inc., Chicago, USA). Figures were designed using GraphPad Prism 6.0 (GraphPad Software Inc., California, USA).

RESULTS

Tables 3, 4 and 5 show the results for between-device reproducibility for trial 1 in the three exercises analyzed, respectively. Results for trial 2 are almost identical (not shown due to space limitations). Comparisons between two units of the same device (intra-device reproducibility, first four data columns) indicate

TABLE 3. Between-device agreement (reproducibility) for trial 1 obtained for the three velocity outcome measures (MV, MPV and PV) in the bench press exercise.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
					LVT 1*			
Bench press (BP)	LVT 1 LVT 2	LPT 1 LPT 2	OEC 1 OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
Mean velocity (MV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.04	0.03	0.08	0.05	0.02	0.09	0.13
SDC (m s^{-1})	0.03	0.10	0.08	0.22	0.13	0.07	0.25	0.36
CV (%)	1.4	4.7	3.5	10.4	6.1	3.1	11.7	18.3
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	3.5	8.9	9.6	26.5	9.6	8.5	28.6	33.0
Max $\text{Error}_{\text{bias}}$ (% 1RM)	3.4	8.8	9.4	26.7	9.4	8.4	29.6	33.5
Agreement								
ICC	1.000	0.995	0.997	0.973	0.992	0.998	0.966	0.928
CI-95% lower	0.999	0.992	0.996	0.961	0.988	0.997	0.951	0.818
CI-95% upper	1.000	0.995	0.998	0.981	0.994	0.998	0.976	0.950
CCC	0.999	0.990	0.994	0.947	0.983	0.995	0.934	0.870
Dev (%)	0.09	0.99	0.58	5.33	1.66	0.47	6.62	13.00
MSD	0.0003	0.0024	0.0024	0.0122	0.0042	0.0012	0.0161	0.0345
Dev (%)	0.03	0.24	0.24	1.22	0.42	0.12	1.61	3.45
VMD	0.0002	0.0013	0.0015	0.0119	0.0015	0.0013	0.0146	0.0187
Dev (%)	0.02	0.13	0.15	1.19	0.15	0.13	1.46	1.87
Mean propulsive velocity (MPV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.04	0.03	–	0.06	0.03	–	–
SDC (m s^{-1})	0.03	0.11	0.08	–	0.15	0.08	–	–
CV (%)	1.3	5.2	3.4	–	6.8	3.5	–	–
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	3.4	9.7	9.8	–	11.3	9.5	–	–
Max $\text{Error}_{\text{bias}}$ (% 1RM)	3.4	9.8	9.6	–	11.3	9.6	–	–
Agreement								
ICC	1.000	0.995	0.997	–	0.997	0.997	–	–
CI-95% lower	0.999	0.992	0.996	–	0.986	0.996	–	–
CI-95% upper	1.000	0.996	0.998	–	0.993	0.998	–	–
CCC	0.999	0.989	0.995	–	0.981	0.995	–	–
Dev (%)	0.08	1.08	0.49	–	1.95	0.52	–	–
MSD	0.0003	0.0042	0.0016	–	0.0059	0.0017	–	–
Dev (%)	0.03	0.42	0.16	–	0.59	0.17	–	–
VMD	0.0002	0.0016	0.0015	–	0.0021	0.0015	–	–
Dev (%)	0.02	0.16	0.15	–	0.21	0.15	–	–
Peak velocity (PV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.02	0.03	–	0.04	0.02	–	0.23
SDC (m s^{-1})	0.03	0.06	0.08	–	0.11	0.07	–	0.65
CV (%)	0.6	1.4	2.1	–	2.8	1.7	–	17.1
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	3.0	6.7	10.2	–	10.8	7.7	–	73.3
Max $\text{Error}_{\text{bias}}$ (% 1RM)	2.9	6.5	10.2	–	10.8	8.3	–	74.7
Agreement								
ICC	1.000	1.000	0.999	–	0.998	0.999	–	0.937
CI-95% lower	1.000	0.999	0.998	–	0.998	0.999	–	0.909
CI-95% upper	1.000	1.000	0.999	–	0.999	1.000	–	0.956
CCC	1.000	0.999	0.998	–	0.997	0.999	–	0.881
Dev (%)	0.02	0.09	0.22	–	0.34	0.13	–	11.92
MSD	0.0009	0.0009	0.0019	–	0.0028	0.0045	–	0.1094
Dev (%)	0.09	0.09	0.19	–	0.28	0.45	–	10.94

TABLE 3. continued.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
					LVT 1*			
Bench press (BP)	LVT 1 LVT 2	LPT 1 LPT 2	OEC 1 OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
VMD	0.0001	0.0007	0.0017	–	0.0019	0.0011	–	0.0930
Dev (%)	0.01	0.07	0.17	–	0.19	0.11	–	9.30

See "Methods" for details.

LVT, Linear velocity transducer; LPT, Linear position transducer; OEC, Optoelectronic camera; VBS, Smartphone video-based app; ACC, Accelerometer; SEM, standard error of measurement; SDC, smallest detectable change (sensitivity); CV, SEM expressed as a coefficient of variation; SEE, standard error of the estimate; Max Error, maximum error (calculated both from the SEE and from the Bland–Altman bias); ICC, intraclass correlation coefficient, model (1,*k*); CI, confidence interval; CCC, Lin's concordance correlation coefficient; MSD, mean square deviation; VMD, variance of the difference between measurements; Dev, percent deviation from 1 (for CCC) or 0 (for MSD and VMD).

*The reference for assessing inter-device agreement was considered to be the device with the best intra-device agreement and best between-trial repeatability (see Table 6).

that the LVT exhibited the highest reproducibility for all velocity outcomes (i.e., MV, MPV and PV) and exercises under study and showed the smallest errors (ICC ≥ 0.998, CCC ≥ 0.996, CV ≤ 2.1%, SEM ≤ 0.02 m s^{-1}, SDC ≤ 0.06 m s^{-1}). The second-best reliable technologies were OEC (ICC ≥ 0.995, CCC ≥ 0.989, CV ≤ 3.6%, SEM ≤ 0.06 m s^{-1}, SDC ≤ 0.15 m s^{-1}) and LPT (ICC ≥ 0.991, CCC ≥ 0.981, CV ≤ 5.2%, SEM ≤ 0.04 m s^{-1}, SDC ≤ 0.11 m s^{-1}) whereas VBS showed greater errors and worse reliability (ICC ≥ 0.973, CCC ≥ 0.947, CV ≥ 10.4%, SEM ≥ 0.08 m s^{-1}, SDC ≥ 0.22 m s^{-1}). Results for the comparisons between unit 1 of each device with unit 1 of the reference LVT device (inter-device reproducibility) are presented in the last four columns of Tables 3, 4, 5 and Figs. 1, 2, 3.

Figures 1, 2 and 3 show the scatter plots of velocity readings from each pair of devices and best-fit regression line, together with the Bland–Altman plots for MV. The LPT and OEC showed the highest agreement and the most regular variation, but exhibited a different behavior in each exercise. In the BP and SQ (Figs. 1 and 2), the LPT showed a systematic bias in MV of ~ 0.05 m s^{-1} whereas the OEC showed a smaller, more distributed bias. Both devices showed a slightly worse agreement with the LVT when lifting the lighter loads (MV > 1.0 m s^{-1}). In the SQ, the OEC seemed to overestimate velocity at these loads. This trend was clearer in the PBP exercise (Fig. 3) where both OEC and LPT provided increasingly higher velocity readings than the LVT (and therefore departing from the 45° concordance line) when MV increased above 1.0 m s^{-1}. VBS and ACC showed the worst reproducibility and highest errors and bias (SEE ≥ 0.08 m s^{-1}, Max $\text{Error}_{\text{bias}}$ > 27.7% 1RM).

The results from between-trial repeatability are reported in Table 6. LVT exhibited the best repeatability for all velocity outcomes in all exercises. LPT and OEC showed the second-best results, with similar values in the three resistance exercises. VBS and ACC had poorer repeatability. The ACC, particularly in the PBP, showed the largest errors in MV.

DISCUSSION

The present investigation has demonstrated that the LVT is the most reliable technology, among the five analyzed, for the measurement of bar velocity in an actual VBRT setting. This superior reliability (reproducibility and repeatability of measurements) of the LVT was observed for the three velocity outcomes (MV, MPV and PV) and resistance exercises (BP, SQ and PBP) under study. The two LVT device units exhibited an almost perfect agreement when simultaneously measuring bar velocity for a given exercise performance or repetition (trial). Hence, this particular device (T-Force System) can well be considered as a reference or gold standard to identify the technical and measurement errors arising from other emerging bar velocity monitoring technologies. The present results also suggest the OEC and LPT technologies as suitable alternatives if the LVT is not available, always considering the particular margins of error for each exercise and specific velocity outcome. On the contrary, the current ACC and VBS technologies analyzed cannot be recommended as monitoring tools for VBRT purposes given their substantial errors and uncertainty of the outcomes. Among the novel data presented, we highlight the use of the SEM, SDC and MaxError (% 1RM) as valuable and very practical statistics to convey the magnitude of the measurement

TABLE 4. Between-device agreement (reproducibility) for trial 1 obtained for the three velocity outcome measures (MV, MPV and PV) in the full squat exercise.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
Full squat (SQ)	LVT 1 LVT 2	LPT 1 LPT 2	LVT 1* OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
Mean velocity (MV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.03	0.02	0.05	0.04	0.03	0.06	0.07
SDC (m s^{-1})	0.02	0.08	0.06	0.13	10.6	0.10	0.17	0.20
CV (%)	1.0	3.6	2.4	6.0	10.6	4.4	7.6	8.8
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	4.0	12.0	9.3	21.6	10.6	10.5	27.7	30.0
Max $\text{Error}_{\text{bias}}$ (% 1RM)	4.0	12.0	9.1	21.7	10.6	10.8	27.7	30.3
Agreement								
ICC	0.999	0.991	0.996	0.974	0.984	0.992	0.955	0.941
CI-95% lower	0.999	0.987	0.994	0.963	0.978	0.989	0.935	0.915
CI-95% upper	0.999	0.993	0.997	0.982	0.989	0.995	0.968	0.959
CCC	0.998	0.981	0.992	0.950	0.969	0.985	0.913	0.887
Dev (%)	0.17	1.87	0.77	5.03	3.10	1.47	8.69	11.27
MSD	0.0002	0.0016	0.0008	0.0021	0.0027	0.0014	0.0161	0.0106
Dev (%)	0.02	0.16	0.08	0.21	0.27	0.14	1.61	1.06
VMD	0.0001	0.0013	0.0008	0.0044	0.0011	0.0011	0.0079	0.0086
Dev (%)	0.01	0.13	0.08	0.44	0.11	0.11	0.79	0.86
Mean propulsive velocity (MPV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.03	0.02	–	0.04	0.03	–	–
SDC (m s^{-1})	0.03	0.09	0.07	–	0.11	0.09	–	–
CV (%)	1.1	3.9	2.7	–	4.7	3.6	–	–
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	3.9	12.2	9.4	–	10.5	11.8	–	–
Max $\text{Error}_{\text{bias}}$ (% 1RM)	3.7	12.1	9.3	–	10.6	12.1	–	–
Agreement								
ICC	0.999	0.991	0.996	–	0.986	0.992	–	–
CI-95% lower	0.999	0.987	0.994	–	0.980	0.988	–	–
CI-95% upper	0.999	0.993	0.997	–	0.990	0.994		
CCC	0.998	0.982	0.991	–	0.972	0.984	–	–
Dev (%)	0.15	1.84	0.88	–	2.82	1.65	–	–
MSD	0.0002	0.0021	0.0012	–	0.0033	0.0020	–	–
Dev (%)	0.02	0.21	0.12	–	0.33	0.20	–	–
VMD	0.0002	0.0019	0.0011	–	0.0014	0.0019	–	–
Dev (%)	0.02	0.19	0.11	–	0.14	0.19	–	–
Peak velocity (PV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.03	0.02	–	0.05	0.04	–	0.10
SDC (m s^{-1})	0.03	0.08	0.07	–	0.13	0.11	–	0.28
CV (%)	0.8	1.8	1.4	–	2.9	2.3	–	6.4
Max $\text{Error}_{\text{SEE}}$ (% 1RM)	5.7	12.4	10.7	–	16.2	17.6	–	41.5
Max $\text{Error}_{\text{bias}}$ (% 1RM)	5.7	12.1	10.6	–	16.1	17.4	–	41.4
Agreement								
ICC	0.999	0.996	0.997	–	0.989	0.993	–	0.952
CI-95% lower	0.999	0.995	0.996	–	0.985	0.990	–	0.931
CI-95% upper	0.999	0.997	0.998	–	0.993	0.995	–	0.966
CCC	0.999	0.993	0.995	–	0.979	0.986	–	0.909
Dev (%)	0.15	0.74	0.49	–	2.07	1.36	–	9.09
MSD	0.0004	0.0017	0.0012	–	0.0044	0.0029	–	0.0210
Dev (%)	0.04	0.17	0.12	–	0.44	0.29	–	2.10

TABLE 4. continued.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
Full squat (SQ)	LVT 1 LVT 2	LPT 1 LPT 2	LVT 1* OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
VMD	0.0003	0.0014	0.0011	–	0.0024	0.0028	–	0.0159
Dev (%)	0.03	0.14	0.11	–	0.24	0.28	–	1.59

See "Methods" for details.
LVT, linear velocity transducer; LPT, linear position transducer; OEC, optoelectronic camera; VBS, smartphone video-based app; ACC, accelerometer; SEM, standard error of measurement; SDC, smallest detectable change (sensitivity); CV, SEM expressed as a coefficient of variation; SEE, standard error of the estimate; max error, maximum error (calculated both from the SEE and from the Bland–Altman bias); ICC, intraclass correlation coefficient, model (1,*k*); CI, confidence interval; CCC, Lin's concordance correlation coefficient; MSD, mean square deviation; VMD, variance of the difference between measurements; Dev, percent deviation from 1 (for CCC) or 0 (for MSD and VMD).
*The reference for assessing inter-device agreement was considered to be the device with the best intra-device agreement and best between-trial repeatability (see Table 6).

errors incurred when adopting a candidate technology or device.

An essential requirement for a measurement device is to provide reliable outcomes under identical conditions. Otherwise, we are unable to determine whether the results arise from biological variability or are due to the technical error.[16] Most of the available studies assessing velocity monitoring devices have analyzed reliability by quantifying the between-subject variability (i.e., the degree of agreement among subjects under the same testing condition).[2–4,11] While it is true that this analysis identifies similar outcomes among a group of athletes, it reveals neither the true source of error (biological or technical) nor the responsiveness (ability to detect within-subject changes over time) of the device.[16,29] In this study, we chose to use a comprehensive set of statistics aimed at assessing device reliability from a complementary point of view. To the best of our knowledge, this is the first study to quantify the magnitude of expected errors of each device both in absolute velocity units (m s^{-1}) and relative load units (% 1RM). Since the main and foremost goal of VBRT is to determine the actual effort (relative load) at which athletes train, being able to know error values in terms of load (% 1RM) is of great practical importance in such a way that if the expected error exceeds a certain loading magnitude, the device renders completely useless for its intended purpose.

Certainly, previous studies have attempted to validate emerging technologies used in VBRT by comparing their velocity outcomes with a predetermined "gold standard" (i.e., a valid and reliable reference device).[2–4,11,34] Hence, validity of the candidate device will depend on the extent to which its measurements agree with those of the reference device (i.e., a high level of agreement or concordance is required), allegedly the real measure.[16] The problem here is that, firstly, one must assess the reproducibility of the reference device to determine the inherent technical source of error. Surprisingly, there is very little empirical evidence demonstrating this reproducibility in devices intended for VBRT purposes. To the authors' knowledge, there are only two reports of this nature measuring bar velocity.[8,30] These two studies analyzed several units of the same brand linear transducers (GymAware LPT[8] and T-Force System LVT[30]), simultaneously measuring under exactly the same condition. The present study extends these results by providing a detailed comparison of the velocity outcomes from five of the most commonly used technologies currently used as monitoring tools for VBRT.

The LVT used in this study (T-Force System) has been shown as an extremely reliable and sensitive device for bar velocity monitoring (SDC = 0.02–0.06 m s^{-1}, MaxError = 3.4–7.1% 1RM) and the preferred reference to compare with existing and emerging technologies (Tables 3, 4 and 5). Our results corroborate previous findings showing the high precision of this LVT for the measurement of vertical displacement (error ± 0.5 mm) and MV (mean error < 0.25%) when comparing 18 device units with a high-precision digital height gauge previously calibrated by the Spanish National Institute of Aerospace Technology.[30] This LVT was also considered excellent in terms of intra-device reproducibility (ICC = 1.00, CV = 0.57% for MPV and ICC = 1.00, CV = 1.75% for PV).[30]

Recently, other technologies such as three-dimensional (3D) motion capture systems have been suggested as "gold standard" devices to assess bar velocity.[21,35] Certainly, this technology is meant to evaluate dynamic multidimensional movements through simultaneous data collection.[10,24] However, to

TABLE 5. Between-device agreement (reproducibility) for trial 1 obtained for the three velocity outcome measures (MV, MPV and PV) in the prone bench pull exercise.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
					LVT 1*			
Prone bench pull (PBP)	LVT 1 LVT 2	LPT 1 LPT 2	OEC 1 OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
Mean velocity (MV)								
Magnitude of error								
SEM (m s^{-1})	0.02	0.04	0.04	–	0.04	0.09	–	–
SDC (m s^{-1})	0.06	0.10	0.11	–	0.11	0.25	–	–
CV (%)	2.1	3.3	3.6	–	3.9	8.1	–	–
Max Error$_{\text{SEE}}$ (% 1RM)	6.9	14.4	16.7	–	12.4	19.9	–	–
Max Error$_{\text{bias}}$ (% 1RM)	6.9	14.3	16.8	–	16.7	28.6	–	–
Agreement								
ICC	0.998	0.995	0.995	–	0.993	0.967	–	–
CI-95% lower	0.997	0.993	0.992	–	0.990	0.952	–	–
CI-95% upper	0.999	0.997	0.996	–	0.995	0.978	–	–
CCC	0.996	0.991	0.989	–	0.986	0.937	–	–
Dev (%)	0.42	0.93	1.06	–	1.43	6.28	–	–
MSD	0.0010	0.0029	0.0038	–	0.0035	0.0184	–	–
Dev (%)	0.10	0.29	0.38	–	0.35	1.84	–	–
VMD	0.0006	0.0026	0.0036	–	0.0036	0.0104	–	–
Dev (%)	0.06	0.26	0.36	–	0.36	1.04	–	–
Mean propulsive velocity (MPV)								
Magnitude of error								
SEM (m s^{-1})	0.02	0.04	0.04	–	0.03	0.25	–	–
SDC (m s^{-1})	0.06	0.10	0.11	–	0.09	0.09	–	–
CV (%)	1.9	3.4	3.5	–	3.2	8.1	–	–
Max Error$_{\text{SEE}}$ (% 1RM)	6.6	14.9	16.5	–	12.5	17.2	–	–
Max Error$_{\text{bias}}$ (% 1RM)	7.1	14.8	16.6	–	13.6	25.5	–	–
Agreement								
ICC	0.998	0.995	0.995	–	0.994	0.967	–	–
CI-95% lower	0.998	0.992	0.992	–	0.991	0.952	–	–
CI-95% upper	0.999	0.996	0.996	–	0.996	0.977	–	–
CCC	0.997	0.989	0.989	–	0.990	0.938	–	–
Dev (%)	0.32	1.06	1.06	–	0.99	6.24	–	–
MSD	0.0008	0.0029	0.0037	–	0.0025	0.0182	–	–
Dev (%)	0.08	0.29	0.37	–	0.25	1.82	–	–
VMD	0.0007	0.0028	0.0035	–	0.0023	0.0083	–	–
Dev (%)	0.07	0.28	0.35	–	0.23	0.83	–	–
Peak velocity (PV)								
Magnitude of error								
SEM (m s^{-1})	0.01	0.04	0.06	–	0.05	0.03	–	–
SDC (m s^{-1})	0.04	0.11	0.15	–	0.13	0.09	–	–
CV (%)	0.8	2.4	3.2	–	2.8	1.9	–	–
Max Error$_{\text{SEM}}$ (% 1RM)	2.3	6.1	17.3	–	8.3	12.3	–	–
Max Error$_{\text{bias}}$ (% 1RM)	2.7	6.0	17.1	–	10.8	12.8	–	–
Agreement								
ICC	1.000	1.000	0.998	–	0.997	0.999	–	–
CI-95% lower	1.000	0.999	0.997	–	0.996	0.998	–	–
CI-95% upper	1.000	1.000	0.998	–	0.998	0.999	–	–
CCC	1.000	0.999	0.995	–	0.994	0.997	–	–
Dev (%)	0.02	0.08	0.46	–	0.56	0.26	–	–
MSD	0.0002	0.0010	0.0042	–	0.0047	0.0021	–	–
Dev (%)	0.02	0.10	0.42	–	0.47	0.21	–	–

TABLE 5. continued.

	Intra-device agreement				Inter-device agreement			
	Ref:				Ref:			
					LVT 1*			
Prone bench pull (PBP)	LVT 1 LVT 2	LPT 1 LPT 2	OEC 1 OEC 2	VBS 1 VBS 2	LPT 1	OEC 1	VBS 1	ACC 1
VMD	0.0001	0.0005	0.0038	–	0.0015	0.0021	–	–
Dev (%)	0.01	0.05	0.38	–	0.15	0.21	–	–

See "Methods" for details.
LVT, linear velocity transducer; LPT, linear position transducer; OEC, optoelectronic camera; VBS, smartphone video-based app; ACC, accelerometer; SEM, standard error of measurement; SDC, smallest detectable change (sensitivity); CV, SEM expressed as a coefficient of variation; SEE, standard error of the estimate; max error, maximum error (calculated both from the SEE and from the Bland–Altman bias); ICC, intraclass correlation coefficient, model (1,*k*); CI, confidence interval; CCC, Lin's concordance correlation coefficient; MSD, mean square deviation; VMD, variance of the difference between measurements; Dev, percent deviation from 1 (for CCC) or 0 (for MSD and VMD).
*The reference for assessing inter-device agreement was considered to be the device with the best intra-device agreement and best between-trial repeatability (see Table 6).

TABLE 6. Between-trial variation (repeatability) for each device obtained for the three velocity outcome measures (MV, MPV and PV) in the three exercises analyzed.

	Bench press (BP)					Full squat (SQ)					Prone bench pull (PBP)				
Exercise technology	LVT	LPT	OEC	VBS	ACC	LVT	LPT	OEC	VBS	ACC	LVT	LPT	OEC	VBS	ACC
Mean velocity (MV)															
SEM ($m\ s^{-1}$)	0.02	0.04	0.04	0.05	0.08	0.03	0.04	0.04	0.04	0.06	0.04	0.07	0.06	–	–
SDC ($m\ s^{-1}$)	0.04	0.08	0.08	0.14	0.22	0.06	0.08	0.08	0.10	0.12	0.08	0.14	0.12	–	–
CV (%)	1.9	4.3	4.0	6.7	12.2	2.5	3.9	3.7	4.6	5.6	3.0	5.2	3.9	–	–
ICC	0.999	0.997	0.997	0.988	0.974	0.995	0.990	0.988	0.986	0.979	0.995	0.990	0.994	–	–
CI-95% lower	0.999	0.996	0.996	0.983	0.962	0.993	0.986	0.983	0.980	0.971	0.993	0.986	0.991	–	–
CI-95% upper	0.999	0.998	0.998	0.992	0.982	0.997	0.993	0.992	0.990	0.986	0.996	0.993	0.996	–	–
Mean propulsive velocity (MPV)															
SEM ($m\ s^{-1}$)	0.02	0.03	0.03	–	–	0.02	0.04	0.06	–	–	0.03	0.07	0.06	–	–
SDC ($m\ s^{-1}$)	0.04	0.08	0.07	–	–	0.06	0.08	0.11	–	–	0.09	0.16	0.13	–	–
CV (%)	1.8	3.6	3.2	–	–	2.6	3.8	4.6	–	–	3.0	5.4	3.9	–	–
ICC	0.999	0.997	0.998	–	–	0.996	0.991	0.987	–	–	0.995	0.987	0.994	–	–
CI-95% lower	0.999	0.996	0.997	–	–	0.994	0.987	0.982	–	–	0.993	0.981	0.991	–	–
CI-95% upper	0.999	0.998	0.998	–	–	0.997	0.993	0.991	–	–	0.997	0.991	0.996	–	–
Peak velocity (PV)															
SEM ($m\ s^{-1}$)	0.03	0.04	0.04	–	0.18	0.05	0.06	0.07	–	0.09	0.03	0.04	0.06	–	–
SDC ($m\ s^{-1}$)	0.07	0.09	0.10	–	0.49	0.13	0.15	0.16	–	0.26	0.08	0.11	0.12	–	–
CV (%)	2.0	2.4	2.6	–	13.7	2.9	3.4	3.5	–	5.9	1.8	2.3	2.6	–	–
ICC	0.999	0.999	0.998	–	0.962	0.989	0.985	0.983	–	0.944	0.999	0.998	0.998	–	–
CI-95% lower	0.999	0.998	0.998	–	0.946	0.985	0.979	0.976	–	0.973	0.998	0.997	0.997	–	–
CI-95% upper	0.999	0.999	0.999	–	0.974	0.992	0.990	0.988	–	0.961	0.999	0.999	0.999	–	–

See "Methods" for details.
LVT, linear velocity transducer; LPT, linear position transducer; OEC, optoelectronic camera; VBS, smartphone video-based app; ACC, accelerometer; SEM, standard error of measurement; SDC, smallest detectable change (sensitivity); CV, SEM expressed as a coefficient of variation; ICC, intraclass correlation coefficient, model (1,*k*); CI, confidence interval.

our knowledge, there is no evidence supporting the sensitivity and reliability of 3D systems in specific VBRT settings such as when measuring unidimensional lifts in a Smith machine (only vertical displacement). Moreover, it is arguable that the typical sampling rates (100-200 Hz) of these 3D motion capture systems used to track and record the bar velocity[19,21,35] are more accurate than a LVT directly attached to the bar and sampling velocity at 1000 Hz, especially when measuring high-velocity (MV $> 1.5\ m\ s^{-1}$) movements.

The OEC and LPT devices were the two best alternatives to the LVT, both showing a similar magnitude of errors (SDC $< 0.10\ m\ s^{-1}$ for MV). However, caution must be taken when interpreting the

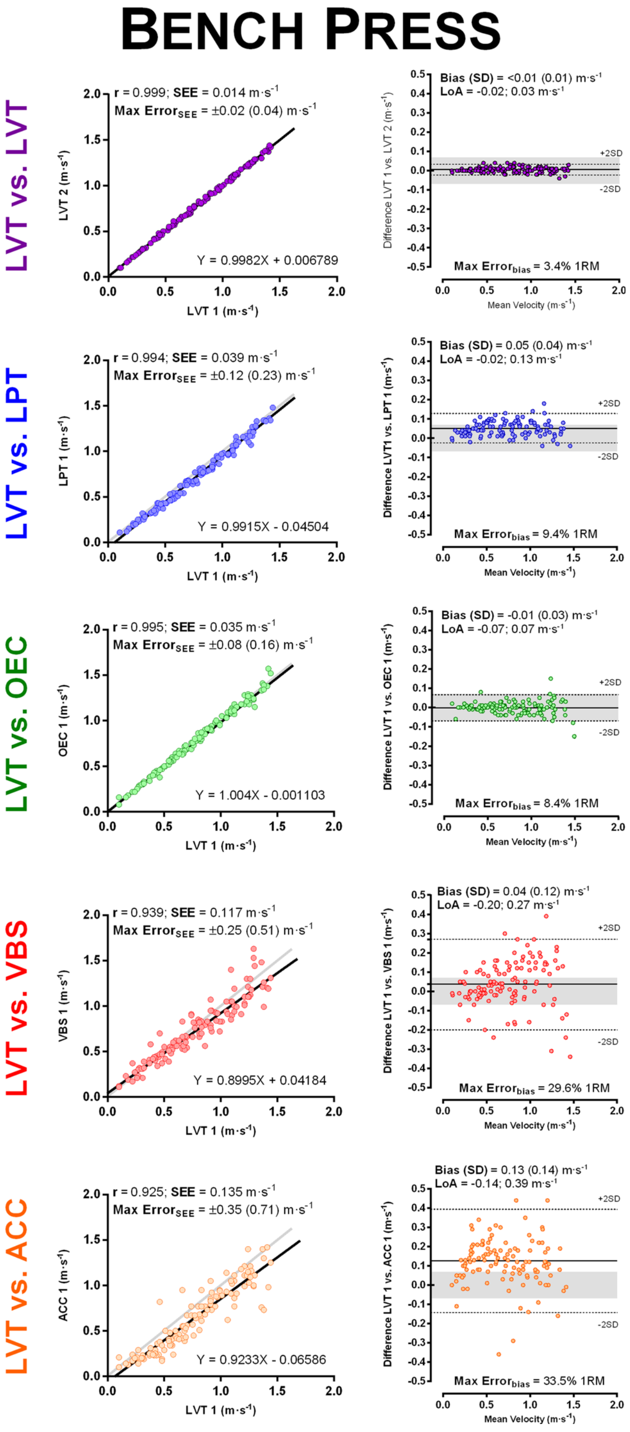

FIGURE 1. Between-device agreement (reproducibility) in mean velocity (MV) for trial 1 in the bench press exercise. Linear regression (left panels) and Bland–Altman plots (right panels) are shown. Each technology is presented in a different color and compared against the reference (LVT), which was considered to be the device showing the best between-trial repeatability. Area shaded in grey indicates an acceptable level of agreement between devices (see Table 2) which results in differences in terms of load ≤ 5% 1RM.

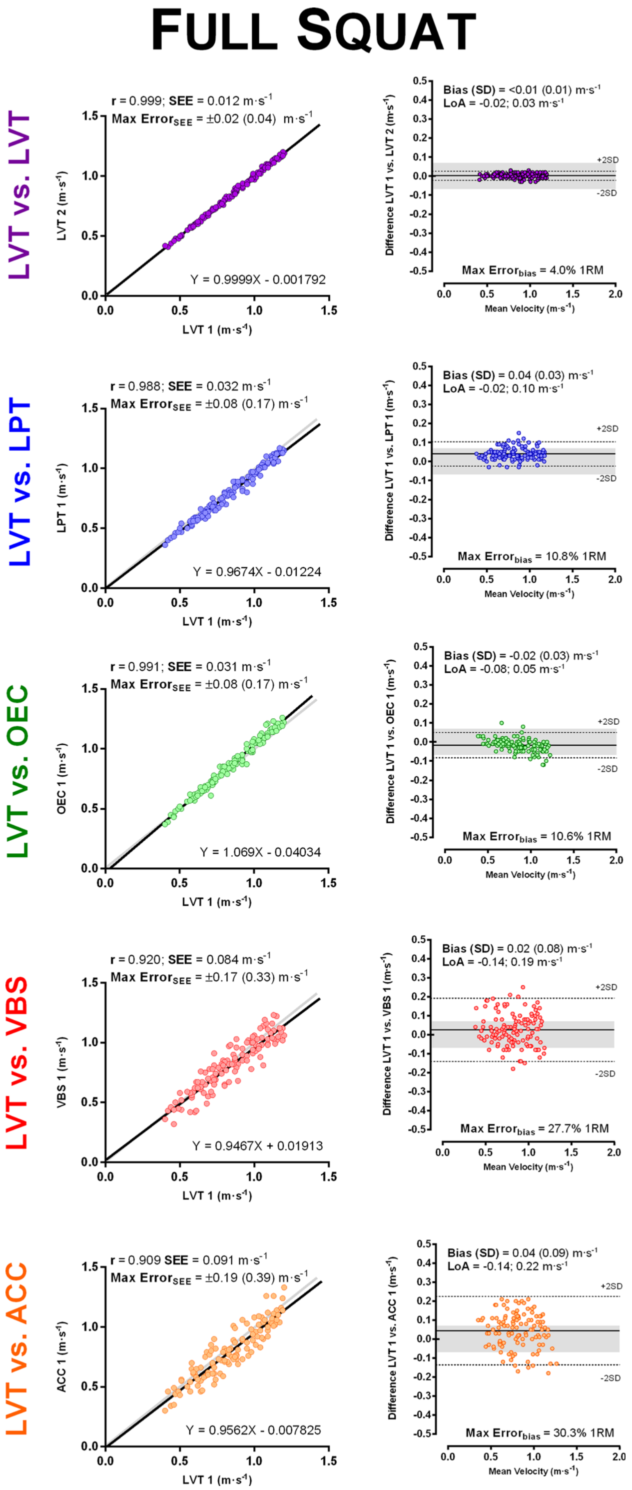

FIGURE 2. Between-device agreement (reproducibility) in mean velocity (MV) for trial 1 in the full squat exercise. Linear regression (left panels) and Bland–Altman plots (right panels) are shown. Each technology is presented in a different color and compared against the reference (LVT), which was considered to be the device showing the best between-trial repeatability. Area shaded in grey indicates an acceptable level of agreement between devices (see Table 2) which results in differences in terms of load ≤ 5% 1RM.

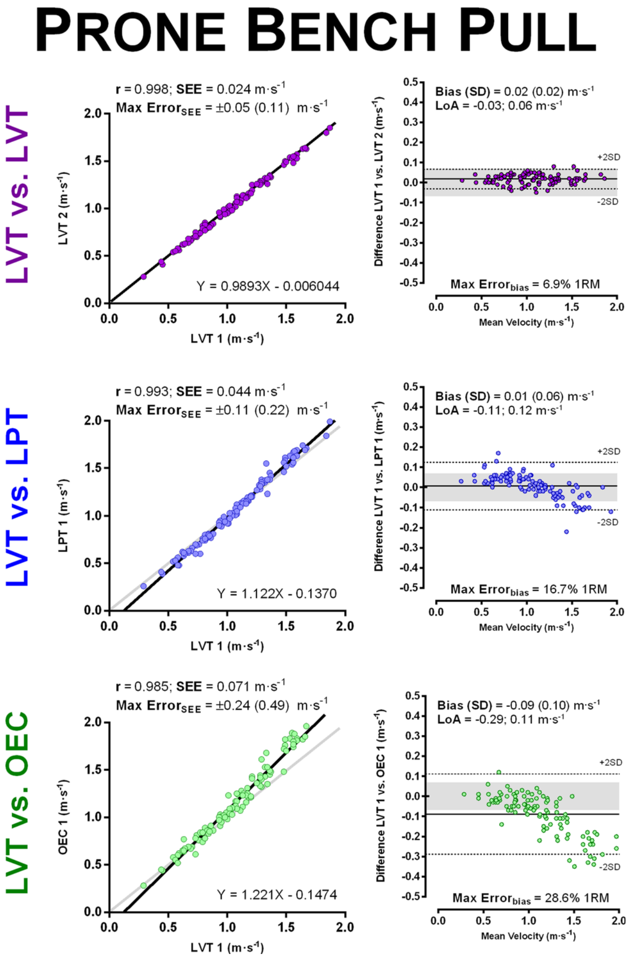

FIGURE 3. Between-device agreement (reproducibility) in mean velocity (MV) for trial 1 in the prone bench pull exercise. Linear regression (left panels) and Bland–Altman plots (right panels) are shown. Each technology is presented in a different color and compared against the reference (LVT), which was considered to be the device showing the best between-trial repeatability. Area shaded in grey indicates an acceptable level of agreement between devices (see Table 2) which results in differences in terms of load ≤ 5% 1RM.

outcomes. Since the SEM and SDC can be considered reference values to identify real changes, the use of the OEC and LPT devices for assessing strength performance should be limited to monitor velocity changes in MV of, at least, 0.04 m s^{-1} (to minimize the SEM) and, more advisably, of MV > 0.11 m s^{-1} ($\sqrt{2} \times 0.04 \times 1.96$) to ensure a real change larger than the SDC. Furthermore, the observed differences between exercises and their accuracy against high- or light-loads (slow vs. fast velocities) should be considered when using the OEC and LPT. In this regard, it is remarkable that all devices analyzed showed greater errors in the PBP. This discrepancy may be attributed to the peculiarities of this exercise, namely the sudden stop the bar experiences when it hits the underside of the bench, which can decelerate the bar up to -100 m s^{-2} when lifting very light loads.[31] Lastly, our results clearly indicate that the VBS and ACC devices are not recommended for monitoring bar velocity in VBRT settings or strength assessment protocols given the unreliability and uncertainty of the obtained measurements.

The present detailed findings may question previous studies and assertions about the reliability of technologies for bar velocity monitoring such as LPT,[12] OEC,[11,19] VBS,[3,4] and highlight the limitations of the ACC.[2] Surprisingly, the errors found in this study are not far from those previously reported, but despite those error magnitudes, devices were considered highly valid and reliable when published. For instance, Laza-Cagigas *et al.*[19] examined the validity of the same OEC device used in our study (Velowin), obtaining similar error values of 0.06 m s^{-1} in SQ (CV = 7.3%, ICC = 0.97). Balsalobre et al.[3] examined the VBS device (PowerLift) only against high loads and low velocity movements ($>$ 50% 1RM, MV $<$ 1.0 m s^{-1}), reporting SEE values of 0.04 and 0.05 m s^{-1} and Pearson correlation coefficients (an inappropriate measure of reproducibility or repeatability[20,36]) of 0.986 and 0.973 for the SQ and BP exercises, respectively. Hence, it is important to clarify that we are not questioning the veracity of these previous reports, but suggesting that more comprehensive analyses and rigorous interpretations are required to ensure the validity of a measurement device. In this regard, if we assume that a value of the ICC > 0.90 indicates good reliability, we are accepting the remaining 10% unexplained variability in measurements. While this might be valid for medical and clinical research practice, or for the social sciences, this is clearly not enough for the assessment of technological or measurement instruments.[23] In light of our findings (Tables 2, 3, 4, 5, 6), we suggest to establish a more strict range of acceptance of at least ICC > 0.997, CV $< 3.5\%$, SEM $<$ 0.03 m s^{-1} for a given device to be considered valid for measuring bar velocity, given the extreme sensitivity required to identify changes in athletes' performance.[15,22,31,32] Moreover, it is worth noticing that other devices different to the ones analyzed here, even though using the same or very similar technology, could well provide different results. For instance, another LPT device (different brand or model) or ACC device could provide better or worse results than those found in the present study. Thus, not only the technologies themselves but each particular device must be analyzed to determine its validity (reproducibility against a gold standard) and repeatability.

A main practical contribution of the present study is the data provided about the magnitude of errors when measuring two trials under similar conditions (repeatability). Coaches and researches who work daily with bar velocity monitoring devices should be aware of the consequences of using a given device. Whereas results from between-device agreement (Tables 3, 4 and 5) may help in determining major reliability limitations among available devices, the data presented in Table 6 reveal the practical consequences of these errors when monitoring velocity during repeated trials. Since the main goal of VBRT is to determine the real effort being incurred during training,[15] it is essential to identify whether the changes observed in velocity against certain workloads are due to the actual changes in athletes' neuromuscular performance or due to measurement error.[16] It is thus striking that the LVT was the only device which showed acceptable margins of errors (Table 2), which were narrow enough to discriminate true velocities achieved by the athletes in the BP and SQ exercises (SDC < 0.03 m s^{-1}). For example, previous short-term training interventions (6 weeks) using a LVT to monitor neuromuscular changes in BP and SQ reported clinical differences (0.49 effect size) at the end of the training period which were accompanied by 0.05 m s^{-1} mean increments in MPV against medium to high loads, and which resulted in improvements of 6.9 kg in 1RM strength.[14] Other recent investigations have used the same LVT technology to detect ergogenic effects following MPV increments of 0.06–0.08 m s^{-1} (0.40–0.52 effect size) against light loads (25% 1RM) in the BP and SQ, after the acute ingestion of low caffeine and pseudoephedrine doses.[27] These findings, together with those of the present study, suggest that these adaptations would have been more difficult to identify if other devices, such as LPT or OEC, had been used due to their higher associated errors for assessing between-trial variation (Table 6). Using VBS or ACC devices, and even when using MV as the outcome variable, it is very likely that these adaptations would have been impossible to detect. Despite the great practical importance of these results, there are very few studies reporting the measurement error of velocity monitoring devices, which encourage coaches and researchers to share studies of this kind.

The limitations of ACC devices for bar velocity measurement have already been noticed.[5] Conversely, our findings did not support earlier reports that VBS could be consider as a reliable tool for bar velocity measurement.[4] It is also worth noticing that technical characteristics of the ACC and VBS devices prevent them from being able to identify the propulsive phase of the concentric action, a relevant variable for resistance training and assessment,[22,33] and therefore the MPV outcome measure cannot be obtained. Furthermore, current ACC and VBS technologies used for this study were limited to a set of pre-established resistance exercises. In particular, it was not possible to obtain any velocity measure for the PBP exercise.

CONCLUSIONS

The LVT is the most reliable technology for measuring bar velocity in resistance training exercises, and the only one recommended as a reference for comparing emerging technologies. The OEC and LVT are valid alternatives, considering the particular margins of error for each exercise and velocity outcome. ACC and VBS are not recommended as monitoring tools for VBRT purposes given their substantial errors and uncertainty of the outcomes. For practical reasons, future studies assessing velocity monitoring technologies should report errors both in absolute velocity units (m s^{-1}) and their equivalent relative load units (% 1RM).

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