

# Concurrent validity of $V_{\max}$ Pro, Kinovea, and Speedograph for the assessment of peak barbell velocity during the bench press: A comparison of technological approaches and historical evolutions

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## ABSTRACT

Measurement of barbell velocity is a simple and effective way to control strength training. To assess the concurrent validity of different technological approaches measuring barbell velocity, video-analysis (Kinovea), linear velocity transducer (Speedograph), and an inertial measurement unit ( $V_{\max}$ Pro) were compared. Sixty-eight female and male sport science students lifted two repetitions in the bench press exercise at self-selected barbell loads. Peak vertical barbell velocity ( $V_{\max}$ ) was parallel measured during the concentric phase of the lift using the aforementioned devices. Concordance correlation coefficient (CCC), Deming regression (DR) and Bland-Altman analysis (BA) were used to assess relative and absolute concurrent validity of  $V_{\max}$  measured with Kinovea, Speedograph, and  $V_{\max}$ Pro. Results confirmed high concurrent validity of Speedograph and  $V_{\max}$ Pro (CCC = 0.99, standard deviation of differences [SDD] = 0.04 m·s<sup>-1</sup>) without detecting proportional or constant bias. In contrast,  $V_{\max}$  measured with Kinovea showed poor concurrent validity to Speedograph (CCC = 0.83) and  $V_{\max}$ Pro (CCC = 0.81) with significant proportional and constant bias. Regression based re-calibration of  $V_{\max}$  from Kinovea resulted in an SDD = 0.09 m·s<sup>-1</sup> compared to Speedograph and an SDD = 0.08 m·s<sup>-1</sup> compared to  $V_{\max}$ Pro. Among the three tested devices,  $V_{\max}$  assessed using Kinovea showed poor concurrent validity. Furthermore, as Kinovea showed proportional bias compared to Speedograph and  $V_{\max}$ Pro, application-specific re-calibration of Kinovea should be applied when barbell velocity data is compared to Speedograph and  $V_{\max}$ Pro.

**Keywords:** Biomechanics, Video analysis, IMU, Linear velocity transducer, Calibration.

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## INTRODUCTION

In strength training, the measurement of barbell velocity during different exercises (i.e., bench press, squat, power clean) has become a contemporary approach to control strength training (i.e., velocity based training [VBT]) (Weakley et al., 2021). VBT has been used in several strength training related contexts, such as, estimating one-repetition maximum (1RM) (Hughes, Banyard, Dempsey, & Scott, 2019; Jukic et al., 2020), describing and adjusting training intensity (Jiménez-Reyes et al., 2021; Suchomel et al., 2021), or monitoring and controlling training-induced fatigue (Hughes, Banyard, Dempsey, Peiffer, et al., 2019; Pareja-Blanco et al., 2017). Although VBT is becoming very popular in the last decade, the concept itself is not new. Early published applications of VBT can be found back in the 1970s to control training of German weightlifters (Richter, 1973). As early as the 1970s, VBT in weightlifting was used to determine the load-velocity relationship from which maximal mechanical impulse, theoretical 1RM, and training zones were estimated (Richter, 1974). At that time, collecting biomechanical data was challenging due to the existing technical standard. To provide instant feedback during training, engineers developed a simple linear velocity transducer (LVT) named “Speedograph” 50 years ago (Richter, 1974). The Speedograph used a high-precision tachogenerator to directly measure linear velocity that is comparable to today’s commercially available LVTs (e.g., T-Force, SmartCoach). Besides LVT, the assessment of movement velocity can also be realized with a linear position transducer (LPT). Compared to LVT, a LPT calculates linear velocity as first derivative of rotary position over time (Harris et al., 2010). Video-based analysis (VA) of barbell kinematics has become another popular technology to assess barbell velocity, in particular with the evolution of automated barbell tracking algorithms (e.g., OpenCV template matching) starting around 2000 (Wang et al., 2003). Compared to the LVT/LPT, VA provides some benefits: indirect measurement, video recordings of the lift, and assessment of barbell trajectory (vertical and horizontal displacement). Until today, automated VA of barbell kinematics is a widely used approach that can be conducted with free available software (i.e., Kinovea, Tracker) or even as smartphone apps (i.e., MyLift, BarSense). With the technical evolution in microelectromechanical systems, accelerometers and inertial measurement units (IMU) entered strength training to measure barbell velocity, beginning around 2008 (Koshida et al., 2008; Sato et al., 2009). Meanwhile, the current commercially available IMUs for the application in strength training are very small, easy-to-use and inexpensive systems (e.g., V<sub>max</sub>Pro, Beast Sensor).

All of the three aforementioned concepts (i.e., LVT/LPT, VA, IMU) are based on different technologies to measure barbell velocity. Therefore, the evaluation of validity and reliability of the used measurement systems are important to offer a safe and effective VBT prescription. In this context, two systematic reviews have summarized that, in general, today’s LVT/LPT and IMU are valid and reliable technologies to measure barbell velocity in various exercises with a random measurement error of  $\approx 0.05 \text{ m}\cdot\text{s}^{-1}$  (Clemente et al., 2021; Moreno-Villanueva et al., 2021). However, it should be noted that LVT are relatively rare reported in the literature compared to LPT. In contrast, the validity of VA compared to LVT/LPT and IMU to measure barbell velocity is unclear. Validity of measured barbell velocity (peak or mean) derived from VA (e.g., Kinovea) showed rather poor validity (i.e., constant and/or proportional bias, large limits of agreement) compared to IMU and LPT/LVT (Carzoli et al., 2022; Martinopoulou et al., 2022; Rum et al., 2022; Sañudo et al., 2016). In particular, the measurement error of VA shows a positive/negative trend depending on the amount of measured barbell velocity (i.e., proportional bias of VA) is often depicted but has not been corrected (e.g., calibration via linear regression) so far.

The aim of the study was, to assess concurrent validity of VA, IMU and LVT for the measurement of barbell velocity during bench press and to check for proportional bias in VA. In case of proportional bias for VA, an adjustment procedure is applied to correct the measurements (i.e., re-calibration). Based on the recent

evidence, it was hypothesized that LVT and IMU display good concurrent validity for the assessment of peak barbell velocity with a random measurement error  $\leq 0.05 \text{ m}\cdot\text{s}^{-1}$  and negligible constant and proportional bias. In contrast, it was further hypothesized, that VA showed a proportional bias compared to LVT and IMU, and even if re-calibrated, the random error component of VA was higher compared to LVT and IMU (i.e.,  $> 0.05 \text{ m}\cdot\text{s}^{-1}$ ).

## MATERIAL AND METHODS

### *Participants*

In this study, 31 female (age:  $22.6 \pm 1.2$  years) and 37 male (age:  $25.2 \pm 4.1$  years) physical active sport science students voluntarily participated in the study. Participants were free from musculoskeletal impairments at the time of data acquisition. Before any tests, all students were informed of the study protocol and were instructed on the correct execution of the bench press exercise.

### *Measures and procedures*

To assess concurrent validity of vertical peak barbell velocity ( $V_{\max}$ ) measured via VA, LVT and IMU, participants performed two repetitions in the bench press exercise, separated by 2 minutes of rest. Prior to the test, 10 minutes of individual warm-up was realized. During the bench press test, participants were free to choose barbell load and speed of execution. Individual chosen barbell loads ranged from 10 kg to 90 kg.

To assess vertical barbell  $V_{\max}$  during the concentric phase (i.e., upward movement) of the bench press, all repetitions were analysed with 50 years old LVT (Speedograph, FKS, resolution infinite) and IMU ( $V_{\max}$ Pro, BM Sports Technology, @1000 Hz), and were recorded on video (SONY Camcorder, FDR-AX43, @25 frames per second). The Speedograph was attached to the barbell next to the  $V_{\max}$ Pro (Figure 1). Further, the Speedograph was positioned that during the concentric phase of the bench press the cable moved only in the vertical direction. Speedograph and  $V_{\max}$ Pro were calibrated according to the manufacturer's instructions.

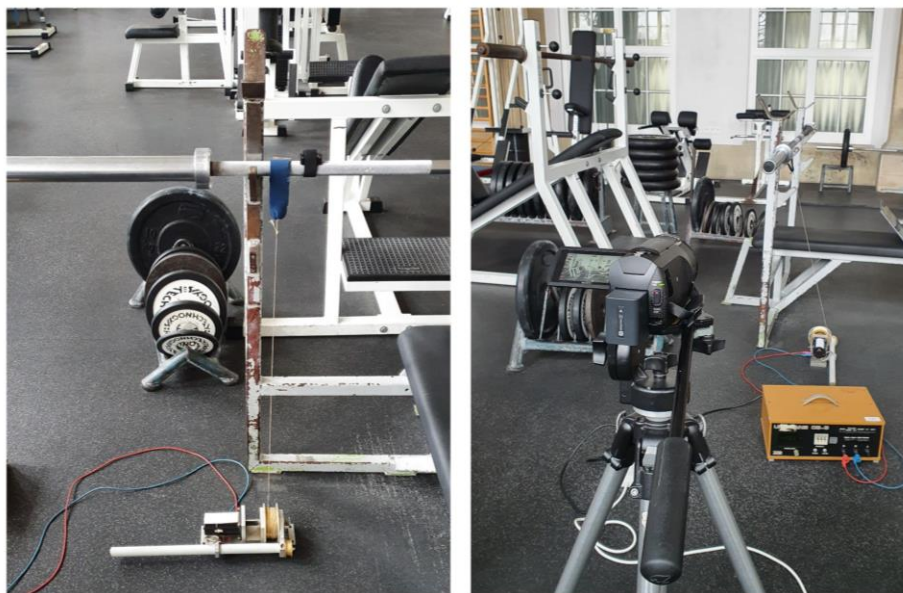


Figure 1. Measurement setup depicting the positions of IMU and LVT on the barbell (left) and camcorder position for video recordings (right).

Video-recorded barbell movement were analysed with the implemented tracking tool using Kinovea software. In detail, the outer end of the barbell was used as tracking target during the concentric phase of the lifts. After tracking, first, raw data of vertical distance were calibrated in Kinovea via the vertical distance of the rack (1.05 m) to obtain real distance data. Second, using the “*Linear Kinematics*” tool in Kinovea, real vertical distance data were filtered and  $V_{max}$  was extracted from the calculated vertical barbell velocity time-series data.

### Statistical analysis

Normal distribution of differences (LVT vs. IMU, IMU vs. VA, VA vs. LVT) were checked and confirmed using Shapiro-Wilk test. The absence of heteroscedasticity (i.e., the measurement error is related to the magnitude of the measured variable) of the measurements was confirmed using the Breusch–Pagan test. Therefore, no log-transformation of the raw data was necessary. Relative validity was tested using Lin’s concordance correlation coefficient (CCC) with 95% confidence limits (CL). Strength-of-agreement criteria for CCC were categorized as poor (CCC < 0.9), moderate (CCC < 0.95), substantial (CCC < 0.99), and almost perfect (CCC ≥ 0.99) (McBride, 2005). For the assessment of absolute validity, first, a Deming regression was performed to test for constant and proportional bias between the approaches. Significant constant bias was present if the range of the 95% CL of the intercept did not contain the value 0 and significant proportional bias was present if the range of the 95% CL of the slope did not contain the value 1 (Payne, 1997). In case of significant proportional and/or constant bias, the regression equation was used to correct (i.e., re-calibration) the measurements (Ungerer & Pretorius, 2018). After the correction, Bland-Altman analysis was performed on the re-calibrated measurements to compute 95% limits of agreement (LOA) and standard deviation of measurement differences (SDD; random measurement error). If no significant proportional or constant bias was present in Deming regression, a Bland-Altman analysis was performed on the original “raw” measurements.

## RESULTS

Descriptive data of barbell velocities for Speedograph,  $V_{max}Pro$ , and Kinovea are displayed in Table 1.

Table 1. Descriptive data of peak vertical barbell velocity ( $V_{max}$ ) in the bench press (mean ± standard deviation).

Device	$V_{max}$ (m·s <sup>-1</sup> )
Speedograph	1.17 ± 0.40
$V_{max}Pro$	1.16 ± 0.40
Kinovea	1.45 ± 0.49

Table 2. Measures of concurrent validity of Speedograph,  $V_{max}Pro$ , and Kinovea.

	Intercept (95% CL)	Slope (95% CL)	SDD (95% CL)	lLOA (95% CL)	uLOA (95% CL)	CCC (95% CL)
$V_{max}Pro$ vs. Speedograph	-0.01 (-0.03;0.02)	1.01 (0.99;1.03)	0.04 (0.03;0.05)	-0.07 (-0.08;-0.06)	0.08 (0.07;0.10)	0.99 (0.99;1.0)
Kinovea vs. $V_{max}Pro$	-0.06 (-0.11;-0.01)*	0.86 (0.83;0.89)**	0.08 (0.08;0.10)#	-0.16 (-0.19;-0.14)#	0.17 (0.14;0.19)#	0.81 (0.77;0.85)
Kinovea vs. Speedograph	-0.06 (-0.11;-0.02)*	0.86 (0.83;0.90)**	0.09 (0.08;0.10)#	-0.18 (-0.20;-0.15)#	0.18 (0.15;0.20)#	0.83 (0.79;0.86)

Notes. SDD = standard deviation of differences (in m·s<sup>-1</sup>), lLOA = lower limits of agreement (in m·s<sup>-1</sup>), uLOA = upper limits of agreement (in m·s<sup>-1</sup>), CCC = concordance correlation coefficient, CL = confidence limits, \*intercept significant different from 0, \*\* slope significant different from 1, # calibrated value.

The main findings indicated that Speedograph and  $V_{\max}$ Pro present an almost perfect relative validity without detecting significant proportional or constant bias (Table 2). From the Bland-Altman analysis, the random measurement error (i.e., SDD) for the aforementioned comparison is  $0.04 \text{ m}\cdot\text{s}^{-1}$  with LOA ranging from  $-0.07 \text{ m}\cdot\text{s}^{-1}$  to  $0.08 \text{ m}\cdot\text{s}^{-1}$  (Figure 2).

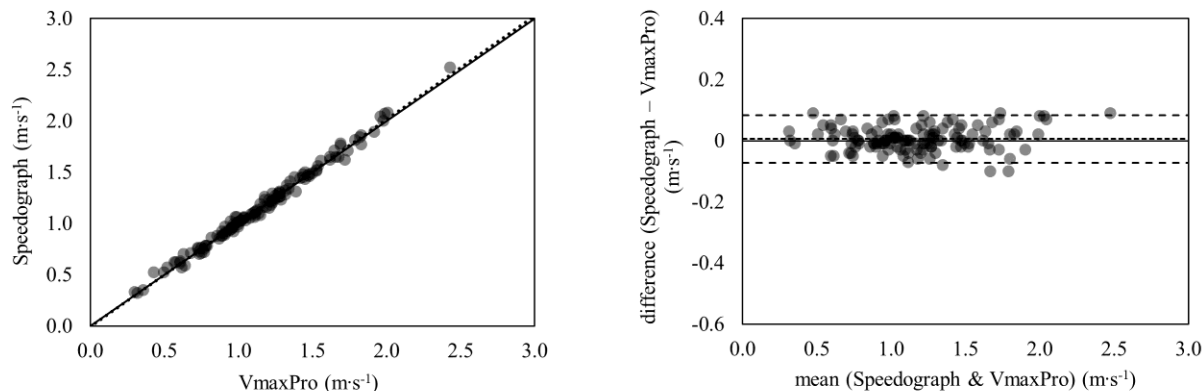


Figure 2. Graphical presentation of Deming regression (left) and Bland-Altman analysis (right) for the comparison of peak vertical barbell velocity during the bench press measured with Speedograph and  $V_{\max}$ Pro. The Deming regression plot illustrates the fitted linear model (dashed line) and the identity line (Speedograph =  $V_{\max}$ Pro, slope = 1; solid line). The Bland-Altman plot depicts mean differences between Speedograph and  $V_{\max}$ Pro (dashed line) and 95% limits of agreement (dotted lines).

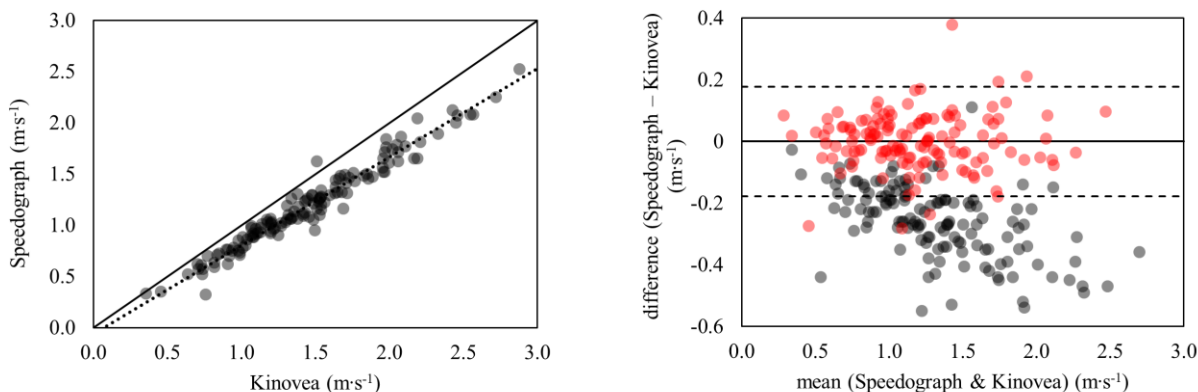


Figure 3. Graphical presentation of Deming regression (left) and Bland-Altman analysis (right) for the comparison of peak vertical barbell velocity during the bench press measured with Speedograph and Kinovea. The Deming regression plot illustrates the fitted linear model (dashed line) and the identity line (Kinovea = Speedograph, slope = 1; solid line). The Bland-Altman plot depicts mean differences (solid line) between Speedograph and re-calibrated Kinovea data (red dots) with 95% limits of agreement (dotted lines). Black dots represent mean and differences of original Kinovea-data.

In contrast, Kinovea showed poor relative validity with Speedograph and  $V_{\max}$ Pro. The Deming regression detected significant constant and proportional error for both comparisons (Table 2). Due to significant proportional bias and constant bias, data of Kinovea have been re-calibrated ( $Kinovea_{cali}$ ) with reference to

Speedograph (Equation 1) and  $V_{\max\text{Pro}}$  (Equation 2) according to the respective coefficients of the Deming regression analyses:

$$Kinovea_{cali\_Speedograph} = -0.06175 + Kinovea * 0.86327 \quad (1)$$

$$Kinovea_{cali\_VmaxPro} = -0.06035 + Kinovea * 0.8553 \quad (2)$$

From the Bland-Altman analysis with the re-calibrated Kinovea-data (Equations 1 and 2), the random measurement error (i.e., SDD) for the comparison of Kinovea vs. Speedograph is  $0.09 \text{ m}\cdot\text{s}^{-1}$  with LOA ranging from  $-0.18 \text{ m}\cdot\text{s}^{-1}$  to  $0.18 \text{ m}\cdot\text{s}^{-1}$  and for the comparison of Kinovea vs.  $V_{\max\text{Pro}}$  is  $0.08 \text{ m}\cdot\text{s}^{-1}$  with LOA ranging from  $-0.16 \text{ m}\cdot\text{s}^{-1}$  to  $0.17$  (Figures 2, 3).

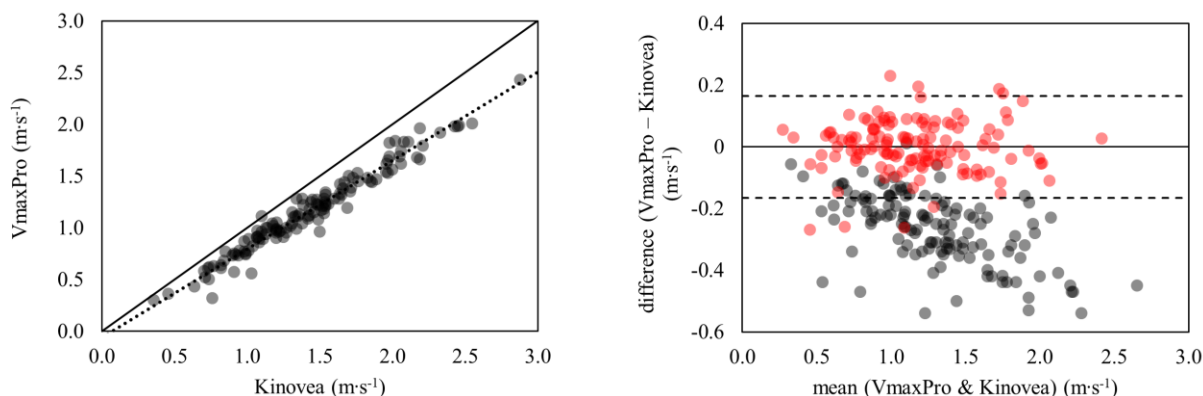


Figure 4. Graphical presentation of Deming regression (left) and Bland-Altman analysis (right) for the comparison of peak vertical barbell velocity during the bench press measured with  $V_{\max\text{Pro}}$  and Kinovea. The Deming regression plot illustrates the fitted linear model (dashed line) and the identity line ( $V_{\max\text{Pro}} = \text{Kinovea}$ , slope = 1; solid line). The Bland-Altman plot depicts mean differences (solid line) between  $V_{\max\text{Pro}}$  and re-calibrated Kinovea data (red dots) with 95% limits of agreement (dotted lines). Black dots represent mean and differences of original Kinovea-data.

## DISCUSSION

The aim of this study was to assess concurrent validity of three different technological approaches to measure concentric barbell  $V_{\max}$  during the bench press. Concurring with our hypotheses, we found high concurrent validity of IMU and Speedograph with a random error  $\leq 0.05 \text{ m}\cdot\text{s}^{-1}$  and absence of constant bias and proportional bias. Further, we confirmed that VA showed proportional bias and constant bias compared to LVT and IMU. Based on the re-calibrated Kinovea-data, concurrent validity of Kinovea compared to IMU and LVT was lower with a random error component  $> 0.05 \text{ m}\cdot\text{s}^{-1}$ .

During strength training, analysing barbell velocity can be used to monitor and guide training effects, known as VBT. Since VBT can be applied using different devices to measure barbell velocity, the validity of the single devices needs to be known. Knowledge of measurement error is essential when devices were used interchangeable during training or when comparing results of VBT between different devices. As previously pointed out, LVT/LPT and IMU are valid and reliable technologies to measure barbell velocity in various exercises (Clemente et al., 2021; Moreno-Villanueva et al., 2021). This is in agreement with the results of the



present study. In contrast, the assessment of  $V_{\max}$  via Kinovea showed a proportional bias and constant bias compared to LVT and IMU. More specifically, with increasing movement speed during the bench press, the measured  $V_{\max}$  assess by Kinovea was higher compared to LVT and IMU. This phenomenon has been displayed in Bland-Altman plots in previous studies analysing concurrent validity of barbell velocity using Kinovea (Carzoli et al., 2022; Jimenez-Olmedo et al., 2021; Sañudo et al., 2016) or optical-based analysis in general (Martinopoulou et al., 2022; Pérez-Castilla et al., 2019). However, none of the aforementioned studies corrected the proportional bias via re-calibration before conducting the Bland-Altman analysis. In presence of uncorrected proportional bias, Bland-Altman analysis can be misleading as systematic bias  $\pm$  LOA were not able to capture the proportional error as these metrics rely on the average of all data (Montenij et al., 2016). In addition, re-calibration is also of interest for practitioners who want either to use VA interchangeable with LPT/LVT/IMU or to replace VA against LPT/LVT/IMU for VBT. In the present study, equations have been proposed to re-calibrate  $V_{\max}$  derived from Kinovea to  $V_{\max}$  of Speedograph (equation 1) and to  $V_{\max}$  of  $V_{\max}$ Pro (Equation 2). In this context, it is worth noting that the random measurement error (i.e., SDD) of re-calibrated Kinovea  $V_{\max}$  is almost twice that of Speedograph and  $V_{\max}$ Pro.

As outlined previously, the three devices used to measure barbell  $V_{\max}$  represent technical evolutions over time. Among the three, the Speedograph is the oldest and was built around 1980. Interestingly, the Speedograph showed highly valid measurements when compared to the IMU that was engineered these days. In other words, scientists back in the 1980s were able to measure peak barbell velocity during strength training with high accuracy. Moreover, the construct of VBT was already known and used in weightlifting back in the days (Richter, 1974). This historical perspective frames one of the fundamental problems in sports science today of which the community should be aware: “*Technology and devices driving the system rather than questions being asked and answers to problems being sought*” (Hornsby et al., 2022).

This study is not without limitations that have to be acknowledged. First, while the tracking of the barbell in Kinovea is automated, errors could arise from the manually correction of the tracking and the image-calibration procedure. However, calibration error was minimized as the distance for calibration was large (1.05 m) and any error due to calibration is assumed to reflect a constant bias rather a proportional bias. Second, the video recordings have been conducted at 25 fps (i.e., 25 Hz), which in theory can explain the proportional bias with increasing lifting speed. In reality, a sampling rate of 25 Hz is considered to be adequate to measure raw speed data during resistance training exercises (Bardella et al., 2017). This recommendation is strengthened by the fact that proportional bias of  $V_{\max}$  measured by VA is also present in studies using optical recordings at higher fps ( $\geq 50$  Hz) (Martinopoulou et al., 2022; Pérez-Castilla et al., 2019; Sañudo et al., 2016). Finally, the study outcomes, in particular referring to the presented re-calibration equations, are specific to the population under investigation and to the used study protocol.

## CONCLUSIONS

This study investigated the concurrent validity of three devices ( $V_{\max}$ Pro, Kinovea, and Speedograph) for the assessment of barbell  $V_{\max}$  during the concentric phase in bench press. It can be concluded that Speedograph and  $V_{\max}$ Pro show high relative and absolute concurrent validity and therefore can be used interchangeable. As Kinovea showed proportional bias compared to Speedograph and  $V_{\max}$ Pro, application-specific re-calibration of Kinovea should be applied when barbell velocity data is compared to Speedograph and  $V_{\max}$ Pro. Irrespective of proportional bias, the re-calibrated  $V_{\max}$  from Kinovea demonstrate a higher measurement error compared to Speedograph and  $V_{\max}$ Pro. Therefore, it is recommended to focus on Speedograph and  $V_{\max}$ Pro to measure vertical peak barbell velocity during bench press.

## AUTHOR CONTRIBUTIONS

IS and MW designed the study; IS, AS, and AR conducted the study and collected the data; IS analysed the data and wrote the original manuscript draft; MW, AR, and AS reviewed the final manuscript draft.

## SUPPORTING AGENCIES

No funding agencies were reported by the authors.

## DISCLOSURE STATEMENT

No potential conflict of interest were reported by the authors.

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