



The Validity and Reliability of Commercially Available Resistance Training Monitoring Devices: A Systematic Review

Jonathon Weakley^{1,2} · Matthew Morrison¹ · Amador García-Ramos^{3,4} · Rich Johnston^{1,2} · Lachlan James⁵ · Michael H. Cole¹

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Abstract

Background Monitoring resistance training has a range of unique difficulties due to differences in physical characteristics and capacity between athletes, and the indoor environment in which it often occurs. Traditionally, methods such as volume load have been used, but these have inherent flaws. In recent times, numerous portable and affordable devices have been made available that purport to accurately and reliably measure kinetic and kinematic outputs, potentially offering practitioners a means of measuring resistance training loads with confidence. However, a thorough and systematic review of the literature describing the reliability and validity of these devices has yet to be undertaken, which may lead to uncertainty from practitioners on the utility of these devices.

Objective A systematic review of studies that investigate the validity and/or reliability of commercially available devices that quantify kinetic and kinematic outputs during resistance training.

Methods Following PRISMA guidelines, a systematic search of SPORTDiscus, Web of Science, and Medline was performed; studies included were (1) original research investigations; (2) full-text articles written in English; (3) published in a peer-reviewed academic journal; and (4) assessed the validity and/or reliability of commercially available portable devices that quantify resistance training exercises.

Results A total of 129 studies were retrieved, of which 47 were duplicates. The titles and abstracts of 82 studies were screened and the full text of 40 manuscripts were assessed. A total of 31 studies met the inclusion criteria. Additional 13 studies, identified via reference list assessment, were included. Therefore, a total of 44 studies were included in this review.

Conclusion Most of the studies within this review did not utilise a gold-standard criterion measure when assessing validity. This has likely led to under or overreporting of error for certain devices. Furthermore, studies that have quantified intra-device reliability have often failed to distinguish between technological and biological variability which has likely altered the true precision of each device. However, it appears linear transducers which have greater accuracy and reliability compared to other forms of device. Future research should endeavour to utilise gold-standard criterion measures across a broader range of exercises (including weightlifting movements) and relative loads.

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✉ Jonathon Weakley
Jonathon.weakley@acu.edu.au

¹ School of Behavioural and Health Sciences, Australian Catholic University, Building 211.1.26, Brisbane, QLD, Australia

² Carnegie Applied Rugby Research (CARR) Centre, Institute of Sport, Physical Activity and Leisure, Leeds Beckett University, Leeds, UK

³ Department of Sports Sciences and Physical Conditioning, Universidad Católica de la Santísima Concepción, Concepción, Chile

⁴ Department of Physical Education and Sport, University of Granada, Granada, Spain

⁵ Sport and Exercise Science, School of Allied Health, Human Services and Sport, La Trobe University, Melbourne, Australia

Key Points

For the accurate measurement of kinetic and kinematic outputs during resistance training, it is advised that linear transducers are utilised. These devices have demonstrated greater accuracy and reproducibility when compared to other technology.

It is strongly advised that future validity studies utilise gold-standard criterion measures across a range of relative intensities and exercises.

For the assessment of reliability, technological and biological error must be acknowledged and separated, so that the precision of each device during exercise can be accurately reported.

1 Introduction

Resistance training is commonly used to improve strength, power, and lean body mass [1, 2], and is a fundamental part of athlete physical preparation. Traditionally, methods such as the number of repetitions or overall volume load (i.e., the multiplication of external mass, the number of repetitions and sets) have been used to quantify training loads [3–5]. However, these methods have fundamental errors that can reduce their application. For example, if an athlete utilises maximal intent or a pacing strategy, internal fatigue and adaptive responses can vastly differ [6, 7]. Furthermore, differences in exercise prescription, athlete physical capacity, and range of motion mean simple volume load equations can be misleading. This can be observed when completing differing repetition and set structures (e.g., three sets of 10 repetitions *vs.* 10 sets of three repetitions with the same external load) or when stronger athletes are compared against weaker counterparts [3, 4]. To circumvent these issues and support the accurate quantification of resistance training loads, a range of tools that assess kinetic and kinematic outputs have been developed [8–11]. By monitoring kinetic and kinematic outputs, changes in fatigue and proximity to concentric muscle failure can be closely monitored [6, 12, 13]. Furthermore, these devices have been used for a number of training purposes ranging from the immediate feedback of velocity and power outputs [14–17], to supporting full autoregulatory prescriptive methods [18, 19].

Linear position transducers (LPTs) and accelerometers are two commonly utilised tools that support the monitoring of training loads during resistance training [13, 20, 21]. While LPTs directly measure displacement and time, accelerometers are used to estimate kinetic and kinematic outputs by determining the time integral of the acceleration data. With respect to LPTs and accelerometers, there is an array of different brands, and these have been found to

demonstrate varying levels of accuracy and reproducibility [9, 10]. It should be noted that LPTs should not be confused with linear velocity transducers (LVTs), which determine kinetic and kinematic outputs through the direct measurement of instantaneous velocity. Furthermore, in recent times, there have been a range of new devices that monitor resistance training outputs, with these being made possible through advancements in technology [22]. Examples of these include optic laser devices and the cameras within smartphones [22, 23]. While validity and reliability data have been published on these new devices, they have sparingly been compared to linear transducer (i.e., either LPTs or LVTs) and accelerometer data [24]. Furthermore, the literature has not been synthesised to inform practical use and help guide future research.

To support the accurate quantification of training loads, it is important that the technology used is both valid and reliable. This is particularly important for practitioners who utilise this information to make decisions regarding subsequent training sessions. The validity of an instrument often refers to its ability to measure what it is intended to measure with accuracy and precision [25–27]. This is typically quantified by comparing the output of the respective instrument to a ‘gold-standard’ or criterion measure. An example of a gold-standard measure would be the use of 3D high-speed motion capture when assessing velocity. Typical measures of validity include systematic and random bias, coefficient of variation (CV), and standard error of the estimate (SEE) [1, 28, 29]. Due to many resistance training methods now applying velocity loss thresholds with an aim to help mitigate fatigue responses [30, 31], or making programming decisions based on the force–velocity–power characteristics of an exercise [32], it is essential that outputs being produced are accurate. Otherwise, this may lead athletes to complete inappropriate training volumes or select exercises which may induce undue fatigue or generate a sub-optimal training stimulus.

The reliability of an instrument denotes its ability to reproduce measures on separate occasions when it is known that the measure of interest should not fluctuate [33]. When assessing devices that measure kinetic and kinematic outputs, both ‘intra-device’ (i.e., comparing outputs from the same device) and ‘inter-device’ (i.e., comparing outputs from two devices of the same make during the same trial) reliability are important. Intra-device reliability is essential to consider when tracking and identifying ‘meaningful’ changes over a specified period [34]. However, when assessing the reliability of an instrument, it is important to separate biological (i.e., human) and technological variation [22]. This is particularly pertinent during resistance training, where fluctuations in strength and readiness to train can cause substantial alterations in velocity and power outputs despite the same relative load

being used [31, 35]. Therefore, research assessing reliability of devices needs to account for, and preferably remove, biological variation to gain a true insight into a device's reproducibility. Inter-device reliability is important to consider when several devices of the same brand are being used in practice (e.g., two devices are being used to monitor two separate barbells when multiple athletes are training) [36, 37]. To ensure a true representation of each athlete's capacity, the reproducibility of each device needs to be considered. Typical measures of reliability include typical/standard error of measurement (TEM/SEM), CV, and intra-class correlations (ICC) [25, 36, 38].

While there is an abundance of research that assesses the kinetic and kinematic outputs of commercially available devices during resistance training [1, 39, 40], there has not been a review assessing the validity and reliability of these different forms of technology. Due to the growing use of this equipment during resistance training, it is appropriate that a systematic review is completed to guide practitioners and researchers. Therefore, the aim of this review is to establish the level of evidence for: (1) the validity of all commercially available portable resistance training devices that monitor force, velocity, and power outputs; and, (2) the intra-device and inter-device reliability of these devices.

2 Methods

2.1 Search Strategy

Following PRISMA guidelines for systematic reviews [41], the academic databases SPORTDiscus, Web of Science, and Medline were systematically searched in August 2020 using titles, abstracts, keywords, and Boolean operators (AND/OR) to identify English-language peer-reviewed original research studies that investigated the validity and/or reliability of commercially available, portable devices that quantify kinetic and/or kinematic variables during resistance training. Studies were identified by searching abstracts, titles, and keywords for pre-determined terms relevant to the scope of this review (Table 1). All search results were extracted and imported into a reference manager (EndNote X9, Thomson Reuters, Philadelphia, PA, USA).

2.2 Selection Criteria

All duplicate studies were removed, and the titles and abstracts of all remaining studies were scanned for relevance by two authors (JW and MM). Studies that were deemed beyond the scope of the review were removed. The full text of the remaining studies was then assessed for

eligibility. To be eligible for inclusion, studies were required to be (1) original research investigations; (2) full-text articles written in English; (3) published in a peer-reviewed academic journal before the 3rd of August, 2020; and (4) concerned with the validity and/or reliability of commercially available, portable, resistance training devices that monitor force, velocity, and power outputs during resistance training (i.e., exercise that consisted of applying an external load to the participant). If it was deemed that a study did not meet the inclusion criteria, it was excluded from the analysis. Additionally, if the study concerned a device that was no longer commercially available, it was not included. The reference lists of all eligible studies were then manually searched for any studies that were not retrieved in the initial search. If any studies were identified through this manual search strategy, it was subjected to the same assessment as previously described. Where necessary, means and measures of dispersion were extracted from figures in the manuscripts using WebPlotDigitizer v4.0 [42].

2.3 Assessment of Reporting Quality

The reporting quality of the research was assessed using a modified version of the Downs and Black checklist [43] (Table 2). This method is valid for assessing the methodological reporting quality of observational study designs and has previously been utilised by systematic reviews pertaining to sport science [44]. Not all of the assessment criteria were applicable to the studies used in this review; thus, only 9 of the 27 criteria were used. These questions can be found in Electronic Supplementary Material Table S1. Study reporting quality was scored on a scale from '0' (unable to determine, or no) to '1' (yes). In total, a score of '9' was indicative of the highest reporting quality, with scores above 6 being considered 'good', scores of 4–6 considered 'moderate', and scores below 4 being considered 'poor' methodological reporting quality.

2.4 Criteria for 'Acceptable' Validity and Reliability

Devices were deemed to have demonstrated 'acceptable' validity if the literature reported a very high correlation (> 0.70), moderate CV ($< 10\%$), and a trivial or small ES (< 0.60) based on a modified effect size scale [45]. This is consistent with previous resistance training literature which has assessed the validity of resistance training devices [8, 22, 46]. Devices were said to demonstrate acceptable reliability if a device had an intra-class correlation coefficient ≥ 0.90 , CV $< 10\%$, and a standardised mean bias < 0.60 . This is consistent with previous resistance

Table 1 Search terms and keywords utilised in each database search. Searches 1, 2 and 3 were combined using ‘AND’

Search 1	Search 2	Search 3	Search 4
“Linear position transducer” OR “Accelerometer” OR “High-speed camera” OR “Laser optics” OR “GymAware” OR “Push Band” OR “FLEX” OR “Tendo” OR “Beast sensor” OR “Trio-OptiTrack” OR “T-Force” OR “Chronojump” OR “Speed4Lift” OR “Velowin” OR “PowerLift” OR “WIMU” OR “iLOAD”	“Validity” OR “Reliability”	“Kinetic” OR “Kinematic” OR “Force” OR “Power” OR “Velocity”	“Strength training” OR “Resistance training” OR “Plyometrics”

training literature which has assessed the reliability of resistance training devices [22, 47, 48].

3 Results

3.1 Identification of Studies

The systematic search retrieved a total of 129 studies, with 47 of these being removed as duplicates. The titles and abstracts of the remaining 82 studies were screened, with 38 being deemed to be outside the scope of the review and a further 4 being excluded as they were not written in English. The full-text manuscripts of the remaining 40 studies were reviewed, resulting in the identification of 31 studies that met the inclusion criteria. The references lists of these 31 manuscripts were subsequently assessed, which led to an additional 13 studies being identified and a total of 44 studies included in this review. The identification process is outlined in Fig. 1.

3.2 Research Reporting Quality

The methodological reporting quality of the research investigating the validity and/or reliability was relatively high [mean \pm standard deviation 8.0 ± 1.3 ; median (interquartile range) 8 (1.25)] when appraised using the modified Downs and Black checklist [43] (Table 2). Items that were consistently not achieved included question 3 (full device details reported, $n = 26$ studies), 10 (actual statistics reported, $n = 32$ studies), and 18 (appropriate statistical analysis, $n = 26$ studies). To improve the quality of future research, authors should ensure that all statistics are reported and that the model and specifications of the device being used are included within the manuscript. Additionally, pooling of repeated measures must be accounted for with an appropriate statistical approach, while future research should seek to delineate the influence of technological variation from biological variation on reliability measures.

3.3 Study Characteristics

All devices that were included within this review can be found within Table 3. Seven accelerometers (Push Band, Push Band 2.0, Beast Sensor, Bar Sensei, MyoTest, and Wimbu System, RehaGait), 10 linear transducers [GymAware, SmartCoach, 1080Q, T-Force, Chronojump, Tendo, Speed4Lift, FitroDyne (Fitronic), Open Barbell System, and Muscledlab (Ergotest)], three mobile applications (PowerLift/MyLift, iLoad, and Kinovea), and two optic devices (Velowin and Flex) were included. 36 studies assessed the validity (Tables 4, 5, 6, 7), while 28 studies investigated reliability (Tables 8, 9, 10, 11). The most common exercises assessed were the squat and bench press, either within the Smith machine or with free-weights, while velocity outputs were the most commonly assessed kinetic or kinematic variable.

Of the 19 studies that assessed the validity of linear transducer devices, 11 used free-weight equipment, six used a Smith machine, and one used both free-weight and Smith machine exercises. Relative loads from 20 to 100% of 1RM were used, while absolute loads were used within seven studies (refer to Table 4). Of the 23 studies that assessed the validity of accelerometer devices, 14 used free-weight equipment, eight used a Smith machine, and one used both free-weight and Smith machine exercises. Relative loads from 10 to 100% of 1RM were assessed, while absolute loads were used within six studies (refer to Table 5). In the 10 studies that assessed the validity of mobile phone and tablet applications, three used free-weight equipment and seven used a Smith machine. Relative loads ranging from 40 to 100% of 1RM were used, while six studies used either repetitions above or below a given speed (i.e., $0.80 \text{ m}\cdot\text{s}^{-1}$), absolute, or maximal (i.e., 10RM) prescriptive methods (refer to Table 6). Finally, in the eight studies that quantified the validity of optic devices, four used free-weight equipment and four used a Smith machine. Relative loads from 20 to 100% of 1RM were assessed, and one study prescribed loads at or above a given speed, while absolute loads were used within five studies (refer to Table 7).

Table 2 Methodological reporting quality of eligible studies used in systematic review

Study	Items assessed using modified Downs and Black checklist									
	Reporting						Internal validity			
	1	2	3	6	7	10	16	18	20	Total
Abbott et al. [59]	1	1	1	1	1	1	1	0	1	8
Askow et al. [25]	1	1	1	0	1	1	1	0	1	7
Balsalobre-Fernandez et al. [62]	1	1	1	1	1	1	1	0	1	8
Balsalobre-Fernandez et al. [69]	1	1	1	1	1	1	1	0	1	8
Balsalobre-Fernandez et al. [70]	1	1	1	1	1	1	1	0	1	8
Banyard et al. [8]	1	1	1	1	1	0	1	1	1	8
Beckham et al. [28]	1	1	0	1	1	0	1	1	1	7
Boehringer and Whyte [77]	1	1	0	1	1	1	1	0	1	7
Chéry and Ruf [60]	0	1	0	1	1	1	1	0	1	6
Comstock et al. [49]	0	1	0	0	0	0	0	0	1	2
Courel-Ibanez et al. [36]	1	1	1	1	0	1	1	1	1	8
Crewther et al. [50]	1	1	1	1	1	1	1	1	1	9
de Sa et al. [80]	1	1	1	1	1	1	1	1	1	9
Dorrell et al. [26]	1	1	1	1	1	1	1	1	1	9
Drinkwater et al. [27]	1	1	1	1	1	1	1	1	1	9
Fernandes et al. [55]	1	1	1	1	1	1	1	1	1	9
García-Mateo [63]	1	1	1	1	1	1	1	0	0	7
García-Pinillos et al. [61]	1	1	1	1	1	1	1	1	1	9
García-Ramos et al. [71]	1	1	1	1	1	1	1	1	1	9
Garnacho-Castano et al. [56]	1	1	0	1	1	1	1	1	1	8
Goldsmith et al. [53]	1	1	0	1	1	1	1	1	1	8
Gonzalez et al. [57]	1	1	0	1	1	1	1	1	1	8
Hughes et al. [52]	1	1	0	1	1	1	1	0	1	7
Jennings et al. [79]	1	1	0	1	1	1	1	1	1	8
Lake et al. [29]	1	1	1	1	1	1	1	1	1	9
Laza-Cagigas et al. [68]	1	1	1	1	1	1	1	1	1	9
Lorenzetti et al. [54]	1	1	1	1	0	0	1	0	1	6
Martinez-Cava et al. [51]	1	1	1	1	1	1	1	0	1	9
McGrath et al. [58]	1	1	0	1	1	0	1	0	1	7
Mitter et al. [9]	1	1	0	1	1	1	1	1	1	8
Muyor et al. [38]	1	1	1	1	1	1	1	1	1	9
Orange et al. [48]	1	1	1	1	1	1	1	1	1	9
Orange et al. [47]	1	1	1	1	1	1	1	1	1	9
Pino-Ortega et al. [66]	1	1	1	1	1	1	1	1	1	9
Peña García-Orea et al. [82]	1	1	1	1	1	0	1	0	1	9
Peña García-Orea et al. [72]	1	1	1	1	1	0	1	0	1	9
Perez-Castilla et al. [10]	1	1	1	1	1	1	1	1	1	9
Sanchez-Pay et al. [23]	1	1	1	1	1	1	1	1	1	9
Sanudo et al. [81]	1	1	1	1	1	1	1	1	1	9
Sato et al. [37]	1	1	0	1	1	1	1	0	1	7
Stock et al. [78]	1	1	0	1	0	1	1	1	1	7
Thompson et al. [24]	1	1	1	1	1	1	1	1	1	9
van den Tillaar and Ball [11]	1	1	1	1	1	1	1	0	1	8
Weakley et al. [22]	1	1	1	1	1	1	1	1	1	9

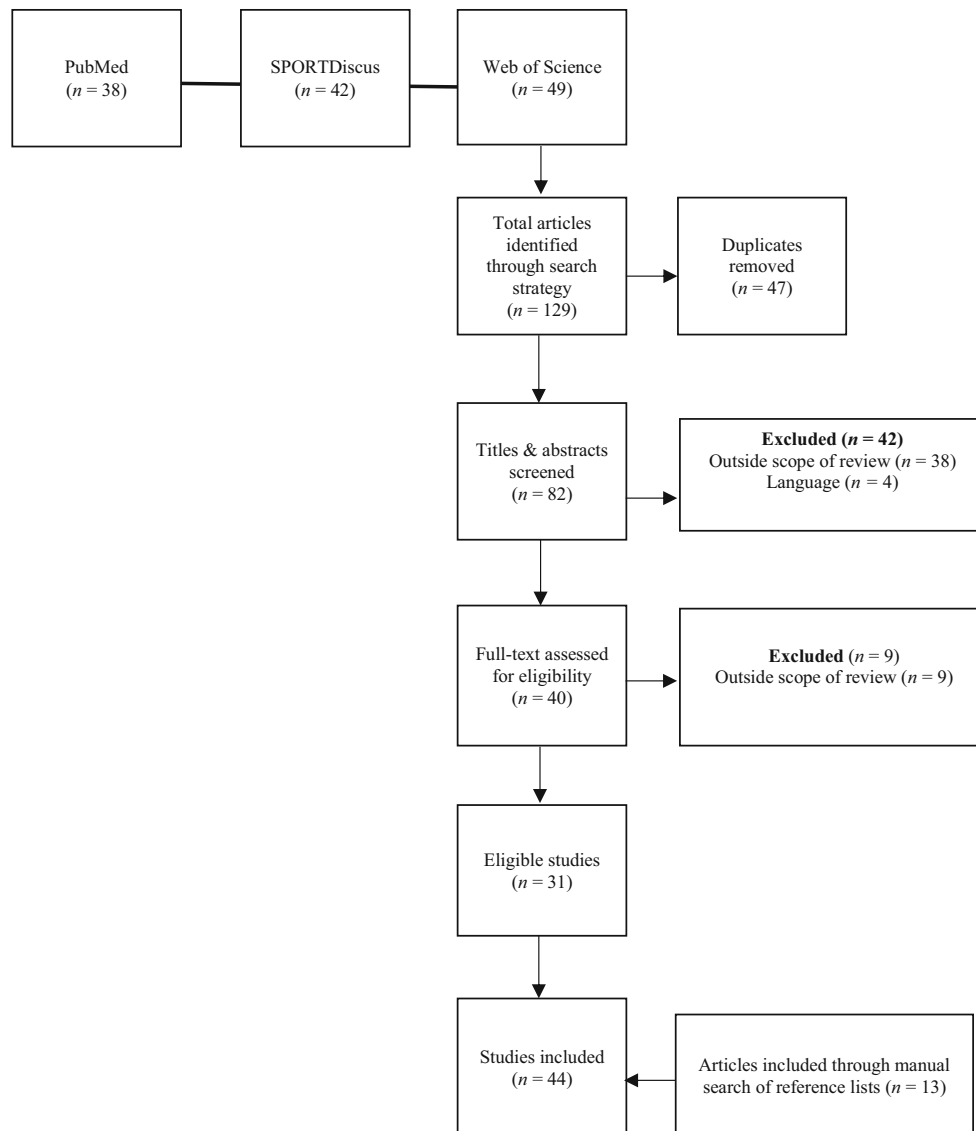


Fig. 1 Flow of selection process of eligible studies for qualitative synthesis

Of the 19 studies that quantified the reliability of linear transducer devices, 10 used free-weight equipment, eight used a Smith machine, and one used both free-weight and Smith machine exercises. Relative loads from 0 to 100% of 1RM were assessed, while absolute loads were used within seven studies (refer to Table 8). Of the 14 studies that quantified the reliability of accelerometer devices, eight used free-weight equipment, five used a Smith machine, and one used both free-weight and Smith machine exercises. Relative loads from 10 to 100% of 1RM were assessed, while absolute loads were used within five studies (refer to Table 9). In the six studies that quantified the reliability of mobile phone and tablet applications, three used free-weight equipment and three used a Smith machine. Relative loads ranging from 45 to 95% of 1RM were assessed, one study used repetitions above or below a

given speed, while absolute loads were used within one study (refer to Table 10). Finally, in the six studies that quantified the reliability of optic devices, two used free-weight equipment and four used a Smith machine. Relative loads from 20 to 100% of 1RM were assessed, while absolute loads were used within four studies (refer to Table 11).

4 Discussion

The aims of this review were to (1) establish the level of evidence for the validity of all commercially available portable resistance training devices that monitor force, velocity, and power outputs; and, (2) determine the intra-device and inter-device reliability of these devices.

Table 3 Summary of reliability and validity studies reported by device

Category	Device	Validity	Reliability	
Accelerometer	PUSH Band	Balsalobre-Fernández et al. [62], Chery and Ruf [60], Courel-Ibanez et al. [36], McGrath et al. [58], Mitter et al. [9], Orange et al. [47], Perez-Castilla et al. [10], van den Tillar et al. [11], Sato et al. [37], Banyard et al. [8], Thompson et al. [24]	Balsalobre-Fernández et al. [52], Courel-Ibanez et al. [36], Orange et al. [47], Perez-Castilla et al. [10], van den Tillar et al. [11], Thompson et al. [24]	
	PUSH Band 2.0	Hughes et al. [52], Lake et al. [29]	Hughes et al. [52], Lake et al. [29]	
	Beast Sensor	Balsalobre-Fernández et al. [69], Mitter et al. [9], Perez-Castilla et al. [10], Thompson et al. [24]	Balsalobre-Fernández et al. [69], Perez-Castilla et al. [10], Thompson et al. [24]	
	Bar Sensei	Beckham et al. [14], Thompson et al. [24], Abbott et al. [59]	Beckham et al. [14], Thompson et al. [24], Abbott et al. [59]	
	MyoTest	Comstock et al. [49], Lorenzetti et al. [54], Crewther et al. [50]	Lorenzetti et al. [54]	
	WIMU System	Garcia-Pinillos et al. [61], Muyor et al. [38], Pino-Ortega et al. [66]	Garcia-Pinillos et al. [61], Muyor et al. [38]	
	RehaGait	García-Mateo [63]	García-Mateo [63]	
	Linear transducer	GymAware	Askow [25], Dorrell [26], Lorenzetti [54], Mitter [9], Crewther [50], Fernandes [55], Banyard [8], Drinkwater [27], Thompson et al. [24]	Askow et al. [25], Beckham et al. [28], Dorrell et al. [26], Hughes et al. [52], Lorenzetti et al. [54], Orange et al. [48], Thompson et al. [24]
		SmartCoach		Balsalobre-Fernández et al. [69]
		1080Q	Boehringer [77]	Boehringer et al. [77]
T-Force		Lorenzetti [54], Perez-Castilla [10]	Courel-Ibanez et al. [3], Peña Garcia-Orea [72], Garcia-Pinillos et al. [61], Garcia-Ramos et al. [71], Lorenzetti et al. [54], Perez-Castilla et al. [10], Martinez-Cava et al. [51]	
Chronojump		Courel-Ibanez [36], Perez-Castilla [10]	Courel-Ibanez et al. [36], Perez-Castilla et al. [10]	
Tendo		Chery and Ruf [60], Garnacho-Castano et al. [56], Goldsmith et al. [53], Lorenzetti et al. [54], Gonzalez et al. [57], McGrath et al. [58]	Garnacho-Castano et al. [56], Lorenzetti et al. [54], Stock et al. [78]	
Speed4Lifts		Perez-Castilla et al. [10], Martinez-Cava et al. [51]	Perez-Castilla et al. [10], Martinez-Cava et al. [51]	
FitroDyne (fitronic)		Mitter [9], Fernandes [55]	Jennings et al. [79]	
Open Barbell System		Goldsmith [53], Gonzalez [57]		
Musclelab (Ergotest)			van den Tillar et al. [11]	
Mobile phone devices/ applications	PowerLift	Courel-Ibanez [36], Balsalobre-Fernández [69], Balsalobre-Fernández [70], Perez-Castilla [7], Thompson et al. [24], Martinez-Cava et al. [51]	Balsalobre-Fernández et al. [69], Balsalobre-Fernández et al. [70], Courel-Ibanez et al. [36], Perez-Castilla et al. [10], Thompson et al. [24], Martinez-Cava et al. [51]	
	iLoad v1.0	de Sa et al. [80]		
	Kinovea via Samsung S6	Sanchez-Pay et al. [23]		
	Kinovea via Xiaomi A1	Sanchez-Pay et al. [23]		
	Kinovea via iPhone X	Sanchez-Pay et al. [23]		
	Kinovea via Casio FH20	Sanchez-Pay et al. [23]		

Table 3 (continued)

Category	Device	Validity	Reliability
	Kinovea via Digital Camera	Sanudo et al. [81]	
Optic devices	Velowin	Courel-Ibanez et al. [36], Peña Garcia-Orea et al. [82], Peña Garcia-Orea et al. [72], Garcia-Ramos et al. [71], Laza-Cagigas et al. [68], Perez-Castilla et al. [10]	Courel-Ibanez et al. [36], Peña Garcia-Orea et al. [82], Peña Garcia-Orea et al. [72], Garcia-Ramos et al. [71], Perez-Castilla et al. [10]
	Flex	Weakley et al. [22]	Weakley et al. [22]

Velocity was the most investigated output, with all but two studies investigating this outcome measure [49, 50]. Furthermore, it was found that most studies within this review did not utilise a gold-standard criterion measure (e.g., high-speed motion-capture set-up for measuring velocity) when assessing the validity of devices. This has likely led to under or overreporting of error for certain devices and may explain (at least in part) the inconsistent findings presented in different studies that have assessed the same device. However, when compared to a gold-standard criterion, it appears that linear transducers demonstrate greater accuracy and precision over other devices when measuring kinetic and kinematic outputs. In stating this, future research must consider utilising a broader range of exercises (e.g., Olympic weightlifting exercises and their derivatives) and loads to be confident of the reliability and validity of devices. For the assessment of reliability, only three studies have assessed the agreement between two different devices of the same brand (i.e., inter-device) [22, 36, 51]. In contrast, there has been a substantial amount of research concerning intra-device reliability [28, 48, 52]; however, it must be noted that all but one of these studies [22] failed to differentiate technological variation from biological variation to establish their respective influence on the unit's reliability. Therefore, future research must attempt to separate these different forms of error to provide a fair reflection of the intra-device reliability and the variation that can be expected.

4.1 Validity

Of the 19 studies that have assessed the validity of linear transducers, 10 utilised a gold-standard criterion of high-speed 3D motion capture when assessing velocity [10, 24–27, 51, 53, 54] or force plate when assessing force [8, 25, 26, 50] (Table 4). From the evidence provided, these types of devices tend to demonstrate greater accuracy when compared to accelerometers [8, 9, 26]. Of all linear transducer devices, the GymAware PowerTool

[8, 9, 24–27, 50, 54, 55] and Tendo Fitrodyne [36, 53, 54, 56–58] have been the most investigated, with nine and six independent validity studies, respectively. Additionally, the Fitrodyne (Fitronic) [9, 55] and Open Barbell System [53, 57] have both had two studies assessing their validity. However, when comparing the agreement of these devices [55], it appears that there are slight discrepancies. Mitter et al. [9] demonstrated greater accuracy of the GymAware PowerTool compared to the Fitrodyne (Fitronic), while Fernandes et al. [55] warned practitioners against interchanging these devices due to systematic differences (refer to Table 4). This is particularly pertinent when utilising peak velocity [55]. Differences between devices may be due to different sampling methods (e.g., through displacement or variable rate sampling), and/or the way in which the raw data signals are treated within the software (e.g., manufacturer-defined filtering routines). Thus, while linear transducers consistently demonstrate superior accuracy compared to other forms of velocity measuring devices [8–10, 53, 54], practitioners should avoid the interchangeable use of different devices during the long-term monitoring of athletes.

Ten studies have directly compared accelerometer-based devices (i.e., Push Band versions 1.0 and 2.0, Beast sensor, BarSensei, and Myotest) to gold-standard 3D motion capture [9, 10, 24, 29, 37, 54, 58, 59] or force plate (when assessing force variables) [8, 49], with the power clean [24], bench press [9, 10, 29, 58], back squat [9, 24, 59], deadlift [9], ballistic squat [54], shoulder press [37], and the biceps curl exercise [37] being assessed (Table 5). Across these studies, all outputs, except peak velocity at 60 and 90% of 1RM in the bench press for the Push Band 2.0 [29], have demonstrated questionable validity. Furthermore, there have been additional 13 studies that have assessed accelerometer-based devices against other devices, predominantly the GymAware PowerTool [28, 47, 52, 60] or the T-Force [36, 38, 61, 62] linear transducers. From this, mean and peak velocity are the most investigated outputs. The CV from these

Table 4 Summary of studies that investigated the validity of linear transducer devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Criterion	Exercise	Intensity/ load	Variable measured	Findings
Askow et al. [25]	GymAware	Qualysis Motion Capture System & AMTI Force Plate	F/W Back Squat	75–90% 1RM	Mean velocity	ICC: 0.966; ES: 0.28
					Peak velocity	ICC: 0.982; ES: – 0.57
					Mean force	ICC: 0.992; ES: 0.11
					Peak force	ICC: 0.979; ES: – 0.03
					Mean power	ICC: 0.972; ES: 0.31
Banyard et al. [8]	GymAware	4 x Celesco PT5A-250 LPT & 1 x AMTI BP6001200 Force Plate	F/W Back Squat	20% 1RM	Peak power	ICC: 0.993; ES: – 0.13
					Mean velocity	r : 0.96; CV: 3.6%; ES: 0.17; SEE: 0.04 m·s ⁻¹
					Peak velocity	r : 0.94; CV: 4.1%; ES: – 0.03; SEE: 0.08 m·s ⁻¹
					Mean force	r : 0.99; CV: 2.2%; ES: 0.57; SEE: 22.57N
					Peak force	r : 0.96; CV: 5.5%; ES: 0.61; SEE: 114.2N
					Mean power	r : 0.98; CV: 4%; ES: 0.72; SEE: 49.7W
					Peak power	r : 0.98; CV: 4.9%; ES: 0.81; SEE: 114.6W
					Mean velocity	r : 0.97; CV: 3.2%; ES: 0.19; SEE: 0.03 m·s ⁻¹
					Peak velocity	r : 0.97; CV: 2.9%; ES: 0.02; SEE: 0.05 m·s ⁻¹
					Mean force	r : 0.99; CV: 1.8%; ES: 0.37; SEE: 25.75N
					Peak force	r : 0.99; CV: 3.4%; ES: 0.38; SEE: 65.1N
					Mean power	r : 0.97; CV: 4.3%; ES: 0.6; SEE: 55.39W
					Peak power	r : 0.97; CV: 5.7%; ES: 0.67; SEE: 143.87W
					Mean velocity	r : 0.95; CV: 3.1%; ES: 0.11; SEE: 0.03 m·s ⁻¹
					Peak velocity	r : 0.96; CV: 3.7%; ES: – 0.02; SEE: 0.05 m·s ⁻¹
Mean force	r : 0.99; CV: 1.7%; ES: 0.29; SEE: 29.33N					
Peak force	r : 0.99; CV: 3.3%; ES: 0.29; SEE: 74.63N					
Mean power	r : 0.97; CV: 4.7%; ES: 0.34; SEE: 66.02W					
Peak power	r : 0.97; CV: 5.7%; ES: 0.53; SEE: 152.84W					
Mean velocity	r : 0.96; CV: 3%; ES: 0.14; SEE: 0.02 m·s ⁻¹					
Peak velocity	r : 0.97; CV: 5.4%; ES: 0.07; SEE: 0.06 m·s ⁻¹					
Mean force	r : 0.99; CV: 1.6%; ES: 0.16; SEE: 34.88N					
Peak force	r : 0.99; CV: 3.5%; ES: 0.29; SEE: 79.78N					
Mean power	r : 0.99; CV: 3.5%; ES: 0.27; SEE: 37.79W					
Peak power	r : 0.98; CV: 6%; ES: 0.36; SEE: 145.79W					
Mean velocity	r : 0.96; CV: 2.8%; ES: 0.06; SEE: 0.02 m·s ⁻¹					
Peak velocity	r : 0.95; CV: 5.8%; ES: 0.12; SEE: 0.06 m·s ⁻¹					
Mean force	r : 1.00; CV: 1.1%; ES: 0.1; SEE: 23.83N					
Peak force	r : 0.99; CV: 3.2%; ES: 0.29; SEE: 85.27N					
Mean power	r : 0.99; CV: 4.7%; ES: 0.13; SEE: 44.9W					
Peak power	r : 0.96; CV: 7.7%; ES: 0.33; SEE: 166.75W					

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings	
Boehringer and White [77]	1080Q	GymAware	S/M Bench Press	40–80% IRM	Mean velocity	$r: 0.99$; CV: 2.5%; ES: 0.39; SEE: 0.01 $\text{m}\cdot\text{s}^{-1}$	
					Peak velocity	$r: 0.96$; CV: 5.4%; ES: 0.04; SEE: 0.04 $\text{m}\cdot\text{s}^{-1}$	
					Mean force	$r: 1.00$; CV: 0.7%; ES: 0.06; SEE: 16.9N	
					Peak force	$r: 0.96$; CV: 5.5%; ES: 0.13; SEE: 140.28N	
					Mean power	$r: 0.99$; CV: 5.3%; ES: 0.26; SEE: 23.89W	
					Peak power	$r: 0.95$; CV: 7.3%; ES: 0.19; SEE: 126.8W	
					Mean velocity	MD: $0.018 \pm 0.024 \text{ m}\cdot\text{s}^{-1}$; $r: 1.00$	
					Mean force	MD: $-116.3 \pm 20.5\text{N}$; $r: 0.99$	
					Mean power	MD: $-93.8 \pm 35.3\text{W}$; $r: 0.97$	
					Peak velocity	MD: $0.033 \pm 0.026 \text{ m}\cdot\text{s}^{-1}$; $r: 1.00$	
					Peak force	MD: $193.0 \pm 126.2\text{N}$; $r: 0.91$	
					Peak power	MD: $-59.2 \pm 35.9\text{W}$; $r: 0.98$	
					Mean velocity	CV: 1.72%; MD: $0.03 \text{ m}\cdot\text{s}^{-1}$	
					Peak velocity	CV: 1.03%; MD: $-0.16 \text{ m}\cdot\text{s}^{-1}$	
Chery & Ruf [60]	Tendo	GymAware	F/W Deadlift	20% IRM	Mean velocity	CV: 2.17%; MD: $0.01 \text{ m}\cdot\text{s}^{-1}$	
				40% IRM	Peak velocity	CV: 1.47%; MD: $-0.11 \text{ m}\cdot\text{s}^{-1}$	
				60% IRM	Mean velocity	CV: 2.65%; MD: $0.01 \text{ m}\cdot\text{s}^{-1}$	
				80% IRM	Peak velocity	CV: 1.08%; MD: $-0.09 \text{ m}\cdot\text{s}^{-1}$	
				Mean velocity	CV: 2.99%; MD: $0.06 \text{ m}\cdot\text{s}^{-1}$		
				Peak velocity	CV: 1.37%; MD: $-0.06 \text{ m}\cdot\text{s}^{-1}$		
				Mean velocity	CV: 3.50%; MD: $0.04 \text{ m}\cdot\text{s}^{-1}$		
				Peak velocity	CV: 1.36%; MD: $-0.04 \text{ m}\cdot\text{s}^{-1}$		
				Mean velocity	CV: 4.07%; MD: $0.03 \text{ m}\cdot\text{s}^{-1}$		
				Peak velocity	CV: 3.76%; MD: $-0.03 \text{ m}\cdot\text{s}^{-1}$		
				Mean velocity	CV: 4.08%; MD: $0.03 \text{ m}\cdot\text{s}^{-1}$		
				Peak velocity	CV: 1.56%; MD: $-0.08 \text{ m}\cdot\text{s}^{-1}$		
				Mean velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 6.1%; ICC: 0.992		
				Mean propulsive velocity	SEM: $0.06 \text{ m}\cdot\text{s}^{-1}$; CV: 6.8%; ICC: 0.997		
Courel-Ibanez et al. [36]	Chronojump	T-Force	S/M Bench Press	20–80 kg	PEAK velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 2.8%; ICC: 0.998	
				Mean velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 10.6%; ICC: 0.984		
				Mean propulsive velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 4.7%; ICC: 0.986		
				Peak velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 2.9%; ICC: 0.989		
				Mean velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 3.9%; ICC: 0.993		
				Mean propulsive velocity	SEM: $0.03 \text{ m}\cdot\text{s}^{-1}$; CV: 3.2%; ICC: 0.994		
				Peak velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 2.8%; ICC: 0.997		
				S/M Back Squat	20–80 kg	Mean velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 10.6%; ICC: 0.984
					Mean propulsive velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 4.7%; ICC: 0.986	
					Peak velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 2.9%; ICC: 0.989	
					Mean velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 3.9%; ICC: 0.993	
					Mean propulsive velocity	SEM: $0.03 \text{ m}\cdot\text{s}^{-1}$; CV: 3.2%; ICC: 0.994	
					Peak velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 2.8%; ICC: 0.997	

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Crewther et al. 2011 [50]	GymAware	Force plate	F/W Loaded Squat Jump	20 kg	Peak force	$r: 0.59$; bias: $202 \pm 579\text{N}$
				40 kg	Peak power	$r: 0.67$; bias: $401 \pm 879\text{W}$
					Peak force	$r: 0.83$; bias: $108 \pm 255\text{N}$
				60 kg	Peak power	$r: 0.82$; bias: $178 \pm 611\text{W}$
				80 kg	Peak force	$r: 0.87$; bias: $39 \pm 255\text{N}$
Dorrell et al. [26]	GymAware	Rapture-E 3D cameras and force plate	F/W Back Squat	80% IRM	Peak power	$r: 0.74$; bias: $45 \pm 748\text{W}$
					Peak force	$r: 0.87$; bias: $57 \pm 414\text{N}$
					Peak power	$r: 0.62$; bias: $198 \pm 762\text{W}$
					Bar displacement	MD: $-0.009 \pm 0.005\text{m}$
					Peak velocity	MD: $0.005 \pm 0.007 \text{ m}\cdot\text{s}^{-1}$
Drinkwater et al. [27]	GymAware	Sony Digital Video Recorder DRC-TRV900E (High speed camera)	S/M Back Squat	80% IRM	Mean velocity	MD: $0.029 \pm 0.010 \text{ m}\cdot\text{s}^{-1}$
					Bar displacement	MD: $-0.009 \pm 0.009\text{m}$
					Peak velocity	MD: $0.002 \pm 0.007 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	MD: $0.017 \pm 0.016 \text{ m}\cdot\text{s}^{-1}$
					Bar displacement	MD: $-0.016 \pm 0.009\text{m}$
					Peak velocity	MD: $0.004 \pm 0.004 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	MD: $0.100 \pm 0.037 \text{ m}\cdot\text{s}^{-1}$
					Mean power (ecc)	SEE: 3.6W ; CV: 1.16% ; $r: 1.00$
					Mean power (con)	SEE: 4.1W ; CV: 1.08% ; $r: 1.00$
					Peak power (ecc)	SEE: 11.2W ; CV: 1.43% ; $r: 1.00$
Fernandes et al. [55]	FitroDyne (ftironic)	GymAware	S/M Bench Press	40 kg	Peak power (con)	SEE: 14.4W ; CV: 2.16% ; $r: 1.00$
					Mean power (con)	SEE: 10.8W ; CV: 2.78% ; $r: 0.97$
					Max power (con)	SEE: 14.0W ; CV: 1.85% ; $r: 0.99$
					Mean power (ecc)	SEE: 7.1W ; CV: 2.27% ; $r: 0.99$
					Mean power (con)	SEE: 3.7W ; CV: 1.50% ; $r: 1.00$
					Peak power (ecc)	SEE: 7.8W ; CV: 1.33% ; $r: 1.00$
					Peak power (con)	SEE: 13.2W ; CV: 3.02% ; $r: 0.99$
					Peak velocity	LoA: $11.2 \pm 25.9 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.86$
					Mean velocity	LoA: $-4.8 \pm 13.6 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.92$
					Peak velocity	LoA: $10.7 \pm 22.9 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.79$
Fernandes et al. [55]	FitroDyne (ftironic)	GymAware	S/M Bench Press	20% IRM	Mean velocity	LoA: $-2.0 \pm 13.1 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.88$
				30% IRM	Peak velocity	LoA: $10.7 \pm 12.1 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.92$
				40% IRM	Mean velocity	LoA: $-0.9 \pm 9.3 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.89$
				50% IRM	Peak velocity	LoA: $10.1 \pm 4.5 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.98$
				60% IRM	Mean velocity	LoA: $0.1 \pm 9.5 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.86$
				70% IRM	Peak velocity	LoA: $7.7 \pm 3.8 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.99$
					Mean velocity	LoA: $0.0 \pm 11.6 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.86$
					Peak velocity	LoA: $7.5 \pm 9.6 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.95$
					Mean velocity	LoA: $0.2 \pm 7.4 \text{ cm}\cdot\text{s}^{-1}$; $r: 0.93$

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Gamacho-Castano et al. [56]	Tendo	T-Force	S/M Back Squat	80% IRM	Peak velocity	LoA: $5.5 \pm 10.1 \text{ cm s}^{-1}$; r : 0.96
					Mean velocity	LoA: $1.0 \pm 6.8 \text{ cm s}^{-1}$; r : 0.94
				20% IRM	Peak velocity	LoA: $12.0 \pm 8.8 \text{ cm s}^{-1}$; r : 1.00
					Mean velocity	LoA: $2.0 \pm 6.3 \text{ cm s}^{-1}$; r : 0.98
				30% IRM	Peak velocity	LoA: $10.6 \pm 9.3 \text{ cm s}^{-1}$; r : 0.99
					Mean velocity	LoA: $0.6 \pm 7.5 \text{ cm s}^{-1}$; r : 0.97
				40% IRM	Peak velocity	LoA: $10.4 \pm 9.1 \text{ cm s}^{-1}$; r : 0.99
					Mean velocity	LoA: $1.2 \pm 5.4 \text{ cm s}^{-1}$; r : 0.98
				50% IRM	Peak velocity	LoA: $9.2 \pm 7.4 \text{ cm s}^{-1} \text{ ms}^{-1}$; r : 0.99
					Mean velocity	LoA: $2.3 \pm 3.3 \text{ cm s}^{-1}$; r : 0.99
				60% IRM	Peak velocity	LoA: $8.5 \pm 5.8 \text{ cm s}^{-1}$; r : 1.00
					Mean velocity	LoA: $2.0 \pm 3.0 \text{ cm s}^{-1}$; r : 0.99
				70% IRM	Peak velocity	LoA: $8.3 \pm 5.4 \text{ cm s}^{-1}$; r : 1.00
					Mean velocity	LoA: $2.2 \pm 2.1 \text{ cm s}^{-1}$; r : 1.00
				80% IRM	Peak velocity	LoA: $8.0 \pm 6.5 \text{ cm s}^{-1}$; r : 1.00
					Mean velocity	LoA: $1.1 \pm 6.0 \text{ cm s}^{-1}$; r : 0.94
				20% IRM	Peak velocity	LoA: $14.6 \pm 25.0 \text{ cm s}^{-1}$; r : 0.94
					Mean velocity	LoA: $-0.1 \pm 12.0 \text{ cm s}^{-1}$; r : 0.96
				30% IRM	Peak velocity	LoA: $14.6 \pm 18.9 \text{ cm s}^{-1}$; r : 0.93
					Mean velocity	LoA: $-0.8 \pm 7.3 \text{ cm s}^{-1}$; r : 0.97
40% IRM	Peak velocity	LoA: $13.6 \pm 12.0 \text{ cm s}^{-1}$; r : 0.97				
	Mean velocity	LoA: $0.4 \pm 11.6 \text{ cm s}^{-1}$; r : 0.91				
50% IRM	Peak velocity	LoA: $10.6 \pm 6.8 \text{ cm s}^{-1}$; r : 0.98				
	Mean velocity	LoA: $0.6 \pm 4.9 \text{ cm s}^{-1}$; r : 0.98				
60% IRM	Peak velocity	LoA: $7.3 \pm 18.2 \text{ cm s}^{-1}$; r : 0.92				
	Mean velocity	LoA: $-0.3 \pm 6.0 \text{ cm s}^{-1}$; r : 0.97				
70% IRM	Peak velocity	LoA: $7.7 \pm 15.3 \text{ cm s}^{-1}$; r : 0.91				
	Mean velocity	LoA: $-0.2 \pm 4.2 \text{ cm s}^{-1}$; r : 0.98				
80% IRM	Peak velocity	LoA: $7.3 \pm 14.9 \text{ cm s}^{-1}$; r : 0.92				
	Mean velocity	LoA: $-0.2 \pm 3.9 \text{ cm s}^{-1}$; r : 0.98				
40–60 kg, 85% IRM	S/M Back Squat	T-Force			Mean velocity	Bias: $0.02 \pm 0.07 \text{ m s}^{-1}$; ICC: 0.985
					Peak velocity	Bias: $-0.08 \pm 0.13 \text{ m s}^{-1}$; ICC: 0.963
					Mean power	Bias: $0.8 \pm 44.31\text{W}$; ICC: 0.966
					Peak power	Bias: $-209.99 \pm 153.92\text{W}$; ICC: 0.853
					Mean velocity	Bias: $0.01 \pm 0.06 \text{ m s}^{-1}$; ICC: 0.989
					Peak velocity	Bias: $-0.06 \pm 0.10 \text{ m s}^{-1}$; ICC: 0.963
					Mean power	Bias: $5.29 \pm 38.48\text{W}$; ICC: 0.968
					Peak power	Bias: $-105.13 \pm 109.76\text{W}$; ICC: 0.905

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings	
Goldsmith et al. [53]	Tendo	OptoTrak	F/W Back Squat	70% IRM	Mean velocity	LoA (95% CI): -0.006357 (-0.06042 to 0.04771) m·s ⁻¹ ; ICC: 0.9364	
					Peak concentric velocity	LoA (95% CI): 0.07569 (-0.05406 to 0.2054) m·s ⁻¹ ; ICC: 0.9362	
	Open Barbell System	OptoTrak	F/W Back Squat	70% IRM	Mean velocity	LoA (95% CI): -0.01163 (-0.06855 to 0.04528) m·s ⁻¹ ; ICC: 0.8696	
					Peak concentric velocity	LoA (95% CI): 0.03986 (-0.1016 to 0.1813) m·s ⁻¹ ; ICC: 0.8351	
					Peak velocity	MD: 0.11 + 0.01 m·s ⁻¹	
					Mean velocity	MD: 0.01 + 0.01 m·s ⁻¹	
					Peak velocity	r: 0.95; Bias: 0.163 m·s ⁻¹	
					Mean velocity	r: 0.27; Bias: 0.012 m·s ⁻¹	
	Open Barbell System	Tendo	F/W Back Squat	Overall	Peak velocity	r: 0.73; Bias: 0.125 m·s ⁻¹	
					Mean velocity	r: 0.35; Bias: 0.007 m·s ⁻¹	
Peak velocity					r: 0.87; Bias: 0.086 m·s ⁻¹		
Mean velocity					r: 0.03; Bias: 0.008 m·s ⁻¹		
Open Barbell System	Tendo	F/W Back Squat	30% IRM	Peak velocity	r: 0.58; Bias: 0.053 m·s ⁻¹		
				Mean velocity	r: 0.25; Bias: 0.009 m·s ⁻¹		
				50% IRM	Peak velocity	MD: 0.11 + 0.01 m·s ⁻¹	
					Mean velocity	MD: 0.01 + 0.01 m·s ⁻¹	
				70% IRM	Peak velocity	r: 0.86; Bias: 0.158 m·s ⁻¹	
					Mean velocity	r: 0.44; Bias: 0.010 m·s ⁻¹	
Gonzalez et al. [57]	Open Barbell System	Tendo	F/W Front Squat	Overall	Peak velocity	r: 0.76; Bias: 0.119 m·s ⁻¹	
					Mean velocity	r: -0.27; Bias: 0.012 m·s ⁻¹	
					Peak velocity	r: 0.84; Bias: 0.091 m·s ⁻¹	
					Mean velocity	r: 0.29; Bias: 0.013 m·s ⁻¹	
					Peak velocity	r: 0.49; Bias: 0.055 m·s ⁻¹	
					Mean velocity	r: 0.60; Bias: 0.007 m·s ⁻¹	
					30% IRM	Peak velocity	RMSE: 0.070 m·s ⁻¹ ; MD: 0.062 m·s ⁻¹
						Mean velocity	RMSE: 0.151 m·s ⁻¹ ; MD: 0.199 m·s ⁻¹
					50% IRM	Peak velocity	RMSE: 0.026s; MD: 0.010s
						Mean velocity	RMSE: 0.167 m·s ⁻¹ ; MD: 0.102 m·s ⁻¹
70% IRM	Peak velocity	RMSE: 0.263 m·s ⁻¹ ; MD: 0.150 m·s ⁻¹					
	Mean velocity	RMSE: 0.045s; MD: -0.007s					
Lorenzetti et al. [54]	T-Force	Vicon	F/W Back Squat	70% IRM	Maximum velocity		
					Time to maximum velocity		
					25 kg	Mean velocity	RMSE: 0.167 m·s ⁻¹ ; MD: 0.102 m·s ⁻¹
						Maximum velocity	RMSE: 0.263 m·s ⁻¹ ; MD: 0.150 m·s ⁻¹
					25 kg	Time to maximum velocity	RMSE: 0.045s; MD: -0.007s
						Time to maximum velocity	

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings		
Martinez-Cava et al. [51]	Tendo	Vicon	F/W Back Squat	70% IRM	Mean velocity	RMSE: 0.046 m·s ⁻¹ ; MD: 0.020 m·s ⁻¹		
					Maximum velocity	RMSE: 0.194 m·s ⁻¹ ; MD: 0.159 m·s ⁻¹		
					Time to maximum velocity	RMSE: 0.041s; MD: 0.031s		
			F/W Ballistic Squat	25 kg	Mean velocity	RMSE: 0.157 m·s ⁻¹ ; MD: -0.083 m·s ⁻¹		
					Maximum velocity	RMSE: 0.315 m·s ⁻¹ ; MD: 0.217 m·s ⁻¹		
					Time to maximum velocity	RMSE: 0.064s; MD: 0.046s		
	GymAware	Vicon	F/W Back Squat	70% IRM	Mean velocity	RMSE: 0.064 m·s ⁻¹ ; MD: 0.046 m·s ⁻¹		
					Maximum velocity	RMSE: 0.163 m·s ⁻¹ ; MD: 0.128 m·s ⁻¹		
					Time to maximum velocity	RMSE: 0.042s; MD: 0.037s		
			F/W Ballistic Squat	25 kg	Mean velocity	RMSE: 0.160 m·s ⁻¹ ; MD: -0.091 m·s ⁻¹		
					Maximum velocity	RMSE: 0.304 m·s ⁻¹ ; MD: 0.187 m·s ⁻¹		
					Time to maximum velocity	RMSE: 0.046s; MD: 0.024s		
Speed4Lifts	T-Force	S/M Back Squat	25–95 kg	Peak velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.60%; ICC: 0.997			
				Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.09%; ICC: 0.995 r: 0.9936; SEE: 0.032 m·s ⁻¹			
				Peak velocity	SEM: 0.06 m·s ⁻¹ ; CV: 4.94%; ICC: 0.995			
		S/M Bench Press	25–95 kg	Mean propulsive velocity	SEM: 0.02 m·s ⁻¹ ; CV: 2.72%; ICC: 0.999 r: 0.9985; SEE: 0.024 m·s ⁻¹			
				Mean velocity	ICC: 0.977			
				Mean velocity				
McGrath et al. [58]	Tendo	3D Motion Camera Eagle Motion Camera	F/W Bench Press	40% IRM	Mean velocity	SEE: 0.019 m·s ⁻¹ ; RMSE: 0.025 m·s ⁻¹		
					Peak velocity	SEE: 0.024 m·s ⁻¹ ; RMSE: 0.035 m·s ⁻¹		
					Mean velocity	SEE: 0.014 m·s ⁻¹ ; RMSE: 0.017 m·s ⁻¹		
			Combined Load	30–100% IRM	Peak velocity	SEE: 0.030 m·s ⁻¹ ; RMSE: 0.041 m·s ⁻¹		
					Mean velocity	SEE: 0.017 m·s ⁻¹ ; RMSE: 0.021 m·s ⁻¹		
					Peak velocity	SEE: 0.029 m·s ⁻¹ ; RMSE: 0.029 m·s ⁻¹		
	GymAware	Vicon	F/W Back Squat	30–100% IRM	Mean velocity	SEE: 0.022 m·s ⁻¹ ; RMSE: 0.043 m·s ⁻¹		
					Peak velocity	SEE: 0.073 m·s ⁻¹ ; RMSE: 0.104 m·s ⁻¹		
					Mean velocity	SEE: 0.019 m·s ⁻¹ ; RMSE: 0.022 m·s ⁻¹		
			F/W Bench Press	30–100% IRM	Mean velocity	SEE: 0.100 m·s ⁻¹ ; RMSE: 0.162 m·s ⁻¹		
					Peak velocity	SEE: 0.018 m·s ⁻¹ ; RMSE: 0.035 m·s ⁻¹		
					Mean velocity	SEE: 0.084 m·s ⁻¹ ; RMSE: 0.182 m·s ⁻¹		
FiroDyne (Fitronic)	Vicon	S/M Bench Press	55–85% IRM	Mean velocity	Bias: -0.01 ± 0.03 m·s ⁻¹			
				Mean velocity	Bias: -0.03 ± 0.03 m·s ⁻¹			
				Mean velocity	Bias: -0.04 ± 0.02 m·s ⁻¹			
		F/W Deadlift	30–100% IRM	Mean velocity				
				Peak velocity				
				Mean velocity				
Perez-Castilla et al. [10]	T-Force	OptiTrack	S/M Bench Press	55–85% IRM	Mean velocity			
					Mean velocity			
					Mean velocity			
			ChronoJump	OptiTrack	S/M Bench Press	55–85% IRM	Mean velocity	
							Mean velocity	
							Mean velocity	
	Speed4Lift	OptiTrack	S/M Bench Press	55–85% IRM	Mean velocity			
					Mean velocity			
					Mean velocity			
			Speed4Lift	OptiTrack	S/M Bench Press	55–85% IRM	Mean velocity	
							Mean velocity	
							Mean velocity	

Table 4 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings				
Thompson et al. [24]	GymAware	12 Camera Raptor 3D Motion Capture	F/W Back Squat	40% IRM	Mean velocity	$R^2: 0.95$; LoA: $-0.02 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.97$; LoA: $0.01 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$				
				50% IRM	Mean velocity	$R^2: 0.95$; LoA: $-0.01 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.98$; LoA: $0.01 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$				
				60% IRM	Mean velocity	$R^2: 0.98$; LoA: $-0.02 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.99$; LoA: $0.01 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$				
				70% IRM	Mean velocity	$R^2: 0.97$; LoA: $-0.01 \pm 0.03 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.99$; LoA: $0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$				
				80% IRM	Mean velocity	$R^2: 0.99$; LoA: $-0.01 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.99$; LoA: $0.02 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$				
				90% IRM	Mean velocity	$R^2: 0.99$; LoA: $-0.01 \pm 0.01 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.96$; LoA: $0.02 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$				
				100% IRM	Mean velocity	$R^2: 0.97$; LoA: $-0.02 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$				
					Peak velocity	$R^2: 0.97$; LoA: $0.01 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$				
				Power Clean				Full	Mean velocity	$R^2: 0.99$; LoA: $-0.01 \pm 0.03 \text{ m}\cdot\text{s}^{-1}$
									Peak velocity	$R^2: 0.99$; LoA: $0.01 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$
								40% IRM	Mean velocity	$R^2: 0.93$; LoA: $-0.03 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$
									Peak velocity	$R^2: 0.91$; LoA: $-0.01 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$
								50% IRM	Mean velocity	$R^2: 0.95$; LoA: $-0.03 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
									Peak velocity	$R^2: 0.93$; LoA: $-0.01 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$
60% IRM	Mean velocity	$R^2: 0.95$; LoA: $-0.03 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.95$; LoA: $-0.01 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$								
70% IRM	Mean velocity	$R^2: 0.78$; LoA: $-0.02 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.95$; LoA: $0.00 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$								
80% IRM	Mean velocity	$R^2: 0.86$; LoA: $-0.02 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.91$; LoA: $0.00 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$								
90% IRM	Mean velocity	$R^2: 0.42$; LoA: $0.00 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.86$; LoA: $0.01 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$								
100% IRM	Mean velocity	$R^2: 0.64$; LoA: $-0.01 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.86$; LoA: $0.08 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$								
Full	Mean velocity	$R^2: 0.94$; LoA: $-0.02 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$								
	Peak velocity	$R^2: 0.96$; LoA: $0.00 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$								

IRM one repetition maximum, SEE standard error of the estimate, MV mean concentric velocity, T-Force T-force linear velocity transducer, GymAware GymAware PowerTool, CV coefficient of variation, RMSE root mean square of the estimate, TEE typical error of the estimate, S/M Smith machine, F/W free weight, MD mean difference, r Pearson's correlation coefficient, ICC intraclass correlation coefficient, SEM standard error of measurement, CMJ countermovement jump, ES effect size, ROM range of motion, ECC eccentric, CON concentric, LoA limits of agreement

accelerometer devices tends to range from 10 to 20% across exercises, with lighter relative loads (i.e., faster velocities) tending to have less error [8, 47]. Furthermore, monitoring mean velocity with heavy loads (i.e., > 90% of 1RM) may be extremely inaccurate (i.e., CV = 27–35%) which may be related to the detection of different phases of each movement [8, 47, 60, 63]. This may be an issue for practitioners as mean concentric velocity is often advised for monitoring resistance training adaptations in non-ballistic exercises (e.g., squats, bench press) [64–66]. Considering these findings, accelerometers may best be used for the provision of feedback to enhance motivation and competitiveness during ballistic, high-velocity exercises [67]. However, accelerometers should not be used to track changes in performance (e.g., assessment of velocity against a fixed absolute load) nor to prescribe the loads or the volume of training sets when using velocity loss thresholds.

Of the studies that involved devices that were not accelerometer or linear transducers and assessed validity (Tables 6, 7), only three utilised a true gold-standard criterion [22, 24, 68]. When compared against a high-speed 3D motion-capture set-up, the Velwin opto-electronic device has demonstrated acceptable validity for both mean and peak velocity (CV = 6.5–7.5%); however, proportional bias in peak velocity may be present [68]. The optic laser Flex device has demonstrated acceptable validity for mean velocity during both free-weight squat and bench-press exercises across a range of loads (i.e., 20–100% 1RM) [22]. While there are small increases in variability at the lightest loads (i.e., 20% 1RM), between 40 and 100% of 1RM the typical error is approximately $0.02 \text{ m}\cdot\text{s}^{-1}$. It should be noted, though, that currently only mean velocity has been validated for the Flex, and other variables (e.g., peak velocity) still need to be compared against a gold-standard measure as these outputs may be most relevant to the lightest loads (e.g., 20% 1RM). Finally, with the increasing interest in monitoring resistance training performance, mobile phone apps have also become available [10, 24, 36, 69, 70]. While there is conflicting evidence [24, 36, 51, 70], it appears that substantial bias and error can be introduced when different devices and/or users implement these measuring tools [23]. Thus, practitioners should ensure thorough familiarisation and standardised protocols when using these applications.

4.2 Reliability

A number of studies have investigated the reliability of linear transducers [10, 26, 36, 52] (Table 8). To date, the T-Force has had six separate studies investigate some aspect of reliability [10, 36, 54, 61, 71, 72]. Specifically, Courel-Ibañez et al. [36] have recently demonstrated the

inter-device (i.e., two devices of the same manufacturer) reliability of mean, mean propulsive, and peak velocity, and shown the extremely low error (e.g., mean velocity CV = 1.0–2.1%) when completing the Smith machine bench press, squat, and the prone row. With respect to the intra-device (i.e., the same unit assessed across multiple repetitions), the study by Courel-Ibañez [36] demonstrated a slightly greater, but still relatively small, level of variability (i.e., mean velocity CV = 1.9–3.0%) within the same exercises. Furthermore, the authors presented findings to suggest that the Chronojump LPT exhibited slightly increased inter-device and intra-device error than the T-Force, with mean velocity variability ranging from 3.3 to 4.7% and 3.9 to 5.2%, respectively [36]. It should be acknowledged that the slightly greater intra-device variability values reported in this review may be due to the introduction of biological variation across repetitions (i.e., the ability of a human to perfectly replicate two repetitions with the exact same physical output). Furthermore, it is reasonable to suggest that these reliability outcomes may be negatively impacted when exercises are taken outside of a 2D plane (i.e., a Smith machine). During free-weight exercises, the within-device reliability of the GymAware PowerTool has been shown to be of a high standard [48, 52]. During the free-weight back squat, typical errors of $0.03\text{--}0.05 \text{ m}\cdot\text{s}^{-1}$ across loads of 20–90% of 1RM have been shown. However, this variability may be artificially inflated due to the time between testing occasions (i.e., 7 days) and the normal fluctuations in human performance [48]. Future research is still required to assess the inter-device reliability of this device.

While the accuracy of accelerometers during resistance training appears to be questionable, some accelerometer devices may have greater intra-device reproducibility [29] (Table 9). When placed on the bar, Push 2.0 has demonstrated acceptable reliability of both mean and peak velocity within the bench press at 60% and 90% of 1RM [29]. Furthermore, Hughes et al. [52] have shown conflicting reliability for this device during the Smith machine and free-weight squat, bench press, overhead press, and prone row when placed on either the bar or arm. Contrasting this, Beckham et al. [28] demonstrated that the Bar Sensei achieved both poor accuracy and poor reliability for mean and peak velocity measures during the free-weight barbell back squat. However, these values may have been inflated due to the period of time between testing occasions (i.e., 3–7 days) and the potential for biological variation to influence reliability outcomes [22]. Finally, the Beast Sensor has demonstrated extremely large variability (CV 24–55%) and systematic error at intensities of 45–85% of 1RM in a Smith machine back squat [10]. While a previous study has suggested that it demonstrates satisfactory reliability [69], the statistical approach has recently been

Table 5 Summary of studies that investigated the validity of accelerometer devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings				
Abbott et al. [59]	Bar Sensei	Vicon (Nexus 1.8.5)	F/W Back Squat	20%IRM	Peak velocity	SEE: 0.06 m·s ⁻¹				
					Mean velocity	SEE: 0.05 m·s ⁻¹				
				30%IRM	Mean propulsive velocity	SEE: 0.11 m·s ⁻¹				
					Peak velocity	SEE: 0.05 m·s ⁻¹				
				40%IRM	Mean velocity	SEE: 0.04 m·s ⁻¹				
					Mean propulsive velocity	SEE: 0.08 m·s ⁻¹				
				50%IRM	Peak velocity	SEE: 0.05 m·s ⁻¹				
					Mean velocity	SEE: 0.05 m·s ⁻¹				
				60%IRM	Mean propulsive velocity	SEE: 0.07 m·s ⁻¹				
					Peak velocity	SEE: 0.06 m·s ⁻¹				
				70%IRM	Mean velocity	SEE: 0.05 m·s ⁻¹				
					Mean propulsive velocity	SEE: 0.10 m·s ⁻¹				
				80%IRM	Peak velocity	SEE: 0.09 m·s ⁻¹				
					Mean velocity	SEE: 0.04 m·s ⁻¹				
				90%IRM	Mean propulsive velocity	SEE: 0.06 m·s ⁻¹				
					Peak velocity	SEE: 0.14 m·s ⁻¹				
				100%IRM	Mean velocity	SEE: 0.04 m·s ⁻¹				
					Mean propulsive velocity	SEE: 0.07 m·s ⁻¹				
				Balsalobre-Fernández et al. [62]	Push Band	T-Force	S/M Back Squat	20–70 kg	Peak velocity	r: 0.91; SEE: 0.1 m·s ⁻¹ ; MD: - 0.07 ± 0.1 m·s ⁻¹
									Mean velocity	r: 0.86; SEE: 0.08 m·s ⁻¹ ; MD: 0.11 ± 0.1 m·s ⁻¹
50–95%IRM	Mean velocity	Bias: 0.03 ± 0.06 m·s ⁻¹ ; SEE: 0.06 m·s ⁻¹								
	Mean velocity	Bias: 0.009 ± 0.04 m·s ⁻¹ ; SEE: 0.04 m·s ⁻¹								
50–95%IRM	Mean velocity	Bias: 0.06 ± 0.07 m·s ⁻¹ ; SEE: 0.07 m·s ⁻¹								
	Mean velocity	Bias: - 0.003 ± 0.05 m·s ⁻¹ ; SEE: 0.05 m·s ⁻¹								
50–95%IRM	Mean velocity	Bias: 0.04 ± 0.05 m·s ⁻¹ ; SEE: 0.05 m·s ⁻¹								
	Mean velocity	Bias: 0.03 ± 0.05 m·s ⁻¹ ; SEE: 0.04 m·s ⁻¹								
Balsalobre-Fernández et al. [69]	Beast Sensor (wrist)	SmartCoach Power Encoder	F/W Back Squat					50–95%IRM	SEE: 0.03 m·s ⁻¹	
								50–95%IRM	SEE: 0.03 m·s ⁻¹	
				50–95%IRM	SEE: 0.03 m·s ⁻¹					
				50–95%IRM	SEE: 0.03 m·s ⁻¹					
Beast Sensor (barbell)	SmartCoach Power Encoder	F/W Back Squat	50–95%IRM	SEE: 0.03 m·s ⁻¹						
			50–95%IRM	SEE: 0.03 m·s ⁻¹						
			50–95%IRM	SEE: 0.03 m·s ⁻¹						
			50–95%IRM	SEE: 0.03 m·s ⁻¹						

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/ load	Variable measured	Findings				
Banyard et al. [8]	Push Band	4 x Celesco PT5A-250 LPT & 1 x AMTI BP6001200 Force Plate	F/W Back Squat	20%IRM	Mean velocity	$r: 0.86$; CV: 6.9%; ES: 0.24; SEE: 0.08 $\text{m}\cdot\text{s}^{-1}$				
					Peak velocity	$r: 0.80$; CV: 8.1%; ES: 0.03; SEE: 0.16 $\text{m}\cdot\text{s}^{-1}$				
					Mean force	$r: 0.91$; CV: 6.1%; ES: 2.29; SEE: 63.9N				
									Peak force	$r: 0.98$; CV: 4%; ES: 0.04; SEE: 79.75N
								Mean power	$r: 0.89$; CV: 9.6%; ES: 0.28; SEE: 122.22W	
								Peak power	$r: 0.87$; CV: 11.9%; ES: - 0.29; SEE: 299.89W	
					40%IRM	Mean velocity	$r: 0.80$; CV: 8.2%; ES: 0.18; SEE: 0.08 $\text{m}\cdot\text{s}^{-1}$			
				Peak velocity		$r: 0.76$; CV: 9.6%; ES: - 0.16; SEE: 0.15 $\text{m}\cdot\text{s}^{-1}$				
				Mean force		$r: 0.96$; CV: 5%; ES: 1.41; SEE: 70.29N; $r: 0.98$; CV: 4.7%; ES: 0.04; SEE: 109.92N				
								Peak force	$r: 0.82$; CV: 10.9%; ES: - 0.35; SEE: 145.92W	
								Mean power	$r: 0.81$; CV: 14.2%; ES: - 0.5; SEE: 364.36W	
					60%IRM	Mean velocity	$r: 0.76$; CV: 8.4%; ES: 0.49; SEE: 0.06 $\text{m}\cdot\text{s}^{-1}$			
				Peak velocity		$r: 0.74$; CV: 10%; ES: - 0.22; SEE: 0.13 $\text{m}\cdot\text{s}^{-1}$				
				Mean force		$r: 0.96$; CV: 5%; ES: 1.2; SEE: 87.53N				
								Peak force	$r: 0.97$; CV: 5%; ES: 0.09; SEE: 117.37N	
								Mean power	$r: 0.79$; CV: 13.1%; ES: - 0.36; SEE: 163.11W	
								Peak power	$r: 0.79$; CV: 15.8%; ES: - 0.33; SEE: 383.25W	
					80%IRM	Mean velocity	$r: 0.73$; CV: 10.7%; ES: 0.54; SEE: 0.05 $\text{m}\cdot\text{s}^{-1}$			
				Peak velocity		$r: 0.68$; CV: 13.2%; ES: - 0.29; SEE: 0.14 $\text{m}\cdot\text{s}^{-1}$				
				Mean force		$r: 0.97$; CV: 4.9%; ES: 0.83; SEE: 102.78N				
								Peak force	$r: 0.98$; CV: 4.2%; ES: 0.07; SEE: 103.68N	
								Mean power	$r: 0.78$; CV: 14.2%; ES: - 0.09; SEE: 126.79W	
								Peak power	$r: 0.78$; CV: 18.7%; ES: - 0.5; SEE: 402.16W	
	90%IRM	Mean velocity	$r: 0.65$; CV: 11.8%; ES: 0.69; SEE: 0.04 $\text{m}\cdot\text{s}^{-1}$							
Peak velocity		$r: 0.65$; CV: 12.9%; ES: - 0.52; SEE: 0.12 $\text{m}\cdot\text{s}^{-1}$								
Mean force		$r: 0.98$; CV: 3.4%; ES: 0.65; SEE: 77.28N								
				Peak force	$r: 0.97$; CV: 4.9%; ES: 0.13; SEE: 135.34N					
				Mean power	$r: 0.67$; CV: 22.7%; ES: 0.35; SEE: 163.23W					
				Peak power	$r: 0.81$; CV: 17.1%; ES: - 0.41; SEE: 346.51W					

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/ load	Variable measured	Findings
Beckham et al. [28]	Bar Senci	GymAware	F/W Back Squat	100%IRM	Mean velocity	$r: 0.33$; CV: 27.2%; ES: 1.62; SEE: 0.05 m·s ⁻¹
					Peak velocity	$r: 0.49$; CV: 18.4%; ES: - 0.13; SEE: 0.13 m·s ⁻¹
					Mean force	$r: 0.97$; CV: 5%; ES: 0.52; SEE: 115.17N
					Peak force	$r: 0.92$; CV: 8.3%; ES: 0.26; SEE: 213.05N
					Mean power	$r: 0.32$; CV: 38.3%; ES: 1.23; SEE: 162.09W
					Peak power	$r: 0.66$; CV: 18.7%; ES: - 0.18; SEE: 319.13W
					Mean velocity	ICC: 0.482; MD: - 0.106 m·s ⁻¹
					Peak velocity	ICC: 0.555; MD: 0.009 m·s ⁻¹
					Mean velocity	ICC: 0.303; MD: - 0.094 m·s ⁻¹
					Peak velocity	ICC: 0.362; MD: - 0.037 m·s ⁻¹
Chery & Ruf [60]	PUSH Band	GymAware	F/W Deadlift	75%IRM	Mean velocity	ICC: 0.329; MD: - 0.081 m·s ⁻¹
					Peak velocity	ICC: 0.361; MD: - 0.099 m·s ⁻¹
					Mean velocity	CV: 11.21%; MD: 0.05 m·s ⁻¹ ; CV: 10.63%; MD: 0.12 m·s ⁻¹
					Peak velocity	CV: 17.51%; MD: - 0.10 m·s ⁻¹
					Mean velocity	CV: 15.23%; MD: - 0.16 m·s ⁻¹
					Peak velocity	CV: 9.51%; MD: 0.02 m·s ⁻¹
					Mean velocity	CV: 10.34%; MD: 0.02 m·s ⁻¹
					Peak velocity	CV: 16.02%; MD: 0.13 m·s ⁻¹ ; CV: 11.76%; MD: 0.18 m·s ⁻¹
					Mean velocity	CV: 14.23%; MD: 0.10 m·s ⁻¹
					Peak velocity	CV: 8.15%; MD: 0.12 m·s ⁻¹
Comstock et al. [48]	Myotest	Ballistic Measurement System force plate and Celesco linear transducer	S/M Bench Press	100%IRM	Mean velocity	CV: 35.00%; MD: 0.08 m·s ⁻¹
					Peak velocity	CV: 33.34%; MD: 0.13 m·s ⁻¹
					Mean velocity	CV: 22.69%; MD: 0.05 m·s ⁻¹
					Peak velocity	CV: 20.35%; MD: 0.07 m·s ⁻¹
					Peak force	$R^2: 0.92$
					Peak power	$R^2: 0.92$
					Peak force	$R^2: 0.97$
					Peak power	$R^2: 0.82$
					Mean velocity	SEM: 0.13 m·s ⁻¹ ; CV: 18.3%; ICC: 0.928
					Peak velocity	SEM: 0.23 m·s ⁻¹ ; CV: 17.1%; ICC: 0.937
Couriel-Ibanez et al. [36]	Push Band	T-Force	S/M Squat Jump	20-80 kg	Mean velocity	SEM: 0.07 m·s ⁻¹ ; CV: 8.8%; ICC: 0.941
					Peak velocity	SEM: 0.10 m·s ⁻¹ ; CV: 6.4%; ICC: 0.952
					Mean velocity	
					Peak velocity	
Comstock et al. [48]	Myotest	Ballistic Measurement System force plate and Celesco linear transducer	S/M Bench Press	100%IRM	Mean velocity	SEM: 0.13 m·s ⁻¹ ; CV: 18.3%; ICC: 0.928
					Peak velocity	SEM: 0.23 m·s ⁻¹ ; CV: 17.1%; ICC: 0.937
					Mean velocity	SEM: 0.07 m·s ⁻¹ ; CV: 8.8%; ICC: 0.941
					Peak velocity	SEM: 0.10 m·s ⁻¹ ; CV: 6.4%; ICC: 0.952

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Crewther et al. [50]	MyoTest	Force Plate	F/W Loaded squat jump	20 kg	Peak force	$r: 0.87$; bias: $171 \pm 336\text{N}$
					Peak power	$r: 0.66$; bias: $141 \pm 896\text{W}$
				40 kg	Peak force	$r: 0.89$; bias: $73 \pm 256\text{N}$
					Peak power	$r: 0.88$; bias: $-180 \pm 593\text{W}$
				60 kg	Peak force	$r: 0.95$; bias: $32 \pm 196\text{N}$
					Peak power	$r: 0.82$; bias: $-112 \pm 610\text{W}$
				80 kg	Peak force	$r: 0.97$; bias: $7 \pm 219\text{N}$
					Peak power	$r: 0.90$; bias: $23 \pm 400\text{W}$
				10–100%IRM	Mean velocity	Bias: $0.02 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$
					Mean propulsive velocity	Bias: $0.06 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$
Garcia-Pinillos et al. [61]	WIMU System	T-Force	S/M Concentric-Only Half ROM Back Squat	10% IRM	Maximum velocity	Bias: $0.16 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$r: 0.865$
					Mean propulsive velocity	$r: 0.898$
				20% IRM	Maximum velocity	$r: 0.971$
					Mean velocity	$r: 0.520$
					Mean propulsive velocity	$r: 0.398$
				30% IRM	Maximum velocity	$r: 0.773$
					Mean velocity	$r: 0.696$
					Mean propulsive velocity	$r: 0.813$
				40% IRM	Maximum velocity	$r: 0.196$
	Mean velocity	$r: 0.877$				
	Mean propulsive velocity	$r: 0.882$				
50% IRM	Maximum velocity	$r: 0.842$				
	Mean velocity	$r: 0.760$				
	Mean propulsive velocity	$r: 0.823$				
60% IRM	Maximum velocity	$r: 0.908$				
	Mean velocity	$r: 0.646$				
	Mean propulsive velocity	$r: 0.645$				
	Maximum velocity	$r: 0.729$				

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings		
Hughes et al. [52]	PUSH Band 2.0 (body)	CymAware	F/W Back Squat	70% IRM	Mean velocity	$r: 0.419$		
					Mean propulsive velocity	$r: 0.628$		
					Maximum velocity	$r: 0.819$		
			F/W Bench Pull	80% IRM	Mean velocity	$r: 0.662$		
					Mean propulsive velocity	$r: 0.632$		
					Maximum velocity	$r: 0.498$		
			F/W OH Press	90% IRM	Mean velocity	$r: 0.739$		
					Mean propulsive velocity	$r: 0.717$		
					Maximum velocity	$r: 0.742$		
			S/M Back Squat	100% IRM	Mean velocity	$r: 0.687$		
					Mean propulsive velocity	$r: 0.685$		
					Maximum velocity	$r: 0.861$		
			PUSH Band 2.0 (bar)	CymAware	F/W Back Squat	30–90% IRM	Mean velocity	$r: 0.99$
							Mean velocity	$r: 0.99$
							Mean velocity	$r: 0.98$
S/M Bench Press	30–90% IRM	Mean velocity			$r: 0.99$			
		Mean velocity			$r: 0.99$			
		Mean velocity			$r: 0.99$			
S/M OH Press	30–90% IRM	Mean velocity			$r: 0.97$			
		Mean velocity			$r: 0.99$			
		Mean velocity			$r: 0.96$			
F/W Bench Press	60% IRM	Mean velocity	$r: 0.97$					
		Mean velocity	$r: 0.98$					
		Mean velocity	$r: 0.96$					
F/W Bench Press	90% IRM	Peak velocity	MD: $-0.039 \text{ m}\cdot\text{s}^{-1}$; LPR: 0.907					
		Mean velocity	MD: $-0.065 \text{ m}\cdot\text{s}^{-1}$; LPR: 0.797					
		Peak velocity	MD: $-0.063 \text{ m}\cdot\text{s}^{-1}$; LPR: 1.110					
F/W Bench Press	90% IRM	Mean velocity	MD: $-0.038 \text{ m}\cdot\text{s}^{-1}$; LPR: 0.816					
		Mean velocity						
		Mean velocity						

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/ load	Variable measured	Findings
Lorenzetti et al. [54]	MyoTest	Vicon	F/W Ballistic Squat	25 kg	Mean velocity Maximum velocity Time to maximum velocity	RMSE: 0.233 m·s ⁻¹ ; MD: 0.149 m·s ⁻¹ RMSE: 0.418 m·s ⁻¹ ; MD: 0.278 m·s ⁻¹ RMSE: 0.054s; MD: - 0.034s
Garcia-Mateo [63]	RehaGait (bar)RehaGait (body)	MyLift via iPhone 6 iOS 9.3.2MyLift via iPhone 6 iOS 9.3.2	F/W Squat with arms extended F/W Squat with arms extended	<1 kg <1 kg	Mean velocity Mean velocity	MD ± SD: 0.364 ± 0.069 m·s ⁻¹ MD ± SD: 0.318 ± 0.08 m·s ⁻¹
McGrath et al. [58]	PUSH Band	3D Motion Camera Eagle Motion Camera	F/W Bench Press	40% IRM 80% IRM Combined Load	Mean velocity mean velocity Mean velocity	Mean ± SD: 0.746 ± 0.124 m·s ⁻¹ ; CV: 16.62% Mean ± SD: 0.322 ± 0.124 m·s ⁻¹ ; CV: 38.50% Mean ± SD: 0.510 ± 0.244 m·s ⁻¹ ; CV: 47.83%; ICC: 0.923
Mitter et al. [9]	Beast Sensor	Vicon	F/W Back Squat	30–100% IRM	Peak velocity	SEE: 0.176 m·s ⁻¹ ; RMSE: 0.320 m·s ⁻¹ ; SEE: 0.116 m·s ⁻¹ ; RMSE: 0.177 m·s ⁻¹
			F/W Bench Press	30–100% IRM	Mean velocity Peak velocity	SEE: 0.113 m·s ⁻¹ ; RMSE: 0.134 m·s ⁻¹ SEE: 0.084 m·s ⁻¹ ; RMSE: 0.098 m·s ⁻¹
			F/W Deadlift	30–100% IRM	Mean velocity Peak velocity	SEE: 0.147 m·s ⁻¹ ; RMSE: 0.361 m·s ⁻¹ SEE: 0.105 m·s ⁻¹ ; RMSE: 0.200 m·s ⁻¹
	PUSH Band	Vicon	F/W Back Squat	30–100% IRM	Peak velocity	SEE: 0.137 m·s ⁻¹ ; RMSE: 0.229 m·s ⁻¹ SEE: 0.078 m·s ⁻¹ ; RMSE: 0.147 m·s ⁻¹
			F/W Bench Press	30–100% IRM	Peak velocity	SEE: 0.113 m·s ⁻¹ ; RMSE: 0.121 m·s ⁻¹
			F/W Deadlift	30–100% IRM	Mean velocity Peak velocity	SEE: 0.065 m·s ⁻¹ ; RMSE: 0.101 m·s ⁻¹ SEE: 0.183 m·s ⁻¹ ; RMSE: 0.235 m·s ⁻¹
Muyor et al [38]	WIMU	T-Force	S/M Back Squat	40% IRM 80% IRM	Mean velocity Mean velocity (con) Mean velocity (ecc) Mean velocity (con) Mean velocity (ecc)	SEE: 0.105 m·s ⁻¹ ; RMSE: 0.136 m·s ⁻¹ ES: 0.34d; SEM: 0.003 m·s ⁻¹ ; ICC: 0.970 ES: 0.21d; SEM: 0.007 m·s ⁻¹ ; ICC: 0.971 ES: 0.25d; SEM: 0.003 m·s ⁻¹ ; ICC: 0.976 ES: 0.44d; SEM: 0.005 m·s ⁻¹ ; ICC: 0.953

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Orange et al. [47]	PUSH Band PUSH Band	GymAware	F/W Back Squat	20%IRM	Mean velocity	Standardised mean bias: 0.61 m·s ⁻¹ ; r:0.80
					Peak velocity	Standardised mean bias: 0.53 m·s ⁻¹ ; r:0.80
				40%IRM	Mean power	Standardised mean bias: 0.51W; r:0.91
					Peak power	Standardised mean bias: 1.20W; r:0.90
				60%IRM	Mean velocity	Standardised mean bias: 1.17 m·s ⁻¹ ; r: 0.72
					Peak velocity	Standardised mean bias: 1.20 m·s ⁻¹ ; r:0.70
				80%IRM	Mean power	Standardised mean bias: 1.10W; r:0.77
					Peak power	Standardised mean bias: 1.01W; r:0.88
				90%IRM	Mean velocity	Standardised mean bias: 1.41 m·s ⁻¹ ; r: 0.78
					Peak velocity	Standardised mean bias: 1.58 m·s ⁻¹ ; r:0.68
				20%IRM	Mean power	Standardised mean bias: 1.73W; r:0.76
					Peak power	Standardised mean bias: 1.39W; r:0.77
				40%IRM	Mean velocity	Standardised mean bias: 2.23 m·s ⁻¹ ; r: 0.79
					Peak velocity	Standardised mean bias: 2.23 m·s ⁻¹ ; r:0.84
				60%IRM	Mean power	Standardised mean bias: 2.24W; r:0.76
					Peak power	Standardised mean bias: 1.43W; r:0.85
80%IRM	Mean velocity	Standardised mean bias: 2.61 m·s ⁻¹ ; r:0.66				
	Peak velocity	Standardised mean bias: 2.74 m·s ⁻¹ ; r:0.41				
90%IRM	Mean power	Standardised mean bias: 2.08W; r:0.67				
	Peak power	Standardised mean bias: 1.59W; r:0.59				
20%IRM	Mean velocity	Standardised mean bias: 1.06 m·s ⁻¹ ; r: 0.30				
	Peak velocity	Standardised mean bias: 0.55 m·s ⁻¹ ; r:0.44				
40%IRM	Mean power	Standardised mean bias: 0.35W; r:0.50				
	Peak power	Standardised mean bias: 0.74W; r:0.66				
60%IRM	Mean velocity	Standardised mean bias: 0.68 m·s ⁻¹ ; r: 0.85				
	Peak velocity	Standardised mean bias: 0.37 m·s ⁻¹ ; r:0.73				
80%IRM	Mean power	Standardised mean bias: 0.31W; r:0.88				
	Peak power	Standardised mean bias: 0.73W; r:0.59				
90%IRM	Mean velocity	Standardised mean bias: 0.55 m·s ⁻¹ ; r: 0.59				
	Peak velocity	Standardised mean bias: 0.18 m·s ⁻¹ ; r:0.52				
20%IRM	Mean power	Standardised mean bias: 0.00W; r:0.68				
	Peak power	Standardised mean bias: 0.70W; r:0.62				
40%IRM	Mean velocity	Standardised mean bias: 1.03 m·s ⁻¹ ; r: 0.73				
	Peak velocity	Standardised mean bias: 0.00 m·s ⁻¹ ; r: 0.50				
60%IRM	Mean power	Standardised mean bias: 0.64W; r:0.76				
	Peak power	Standardised mean bias: 0.88W; r:0.46				
80%IRM	Mean velocity	Standardised mean bias: 1.12 m·s ⁻¹ ; r: 0.44				
	Peak velocity	Standardised mean bias: 0.10 m·s ⁻¹ ; r: 0.45				
90%IRM	Mean power	Standardised mean bias: 0.60W; r:0.48				
	Peak power	Standardised mean bias: 0.48W; r:0.49				

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Perez-Castilla et al. [10]	PUSH Band Beast sensor	OptiTrack	S/M Bench Press	55–85%IRM	Mean velocity	Bias: $0.10 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$
Pino-Ortega et al. [66]	WIMU	OptiTrack	S/M Bench Press	55–85%IRM	Mean velocity	Bias: $0.05 \pm 0.21 \text{ m}\cdot\text{s}^{-1}$
		GymAware	Leg Extension Machine	30–90 kg	Mean linear velocity	R^2 : 0.9995; Bias: $0.011 \pm 0.006 \text{ m}\cdot\text{s}^{-1}$; LoA: -0.024 to $0.01 \text{ m}\cdot\text{s}^{-1}$
Sato et al. [37]	PUSH Band	Vicon (Nexus 1.8.5)	DB Biceps Curl	4.54–6.82 kg	Mean velocity	TE: $0.060 \text{ m}\cdot\text{s}^{-1}$; RTE: 7.2%; r : 0.883
Thompson et al. [24]	PUSH Band (body) PUSH Band (bar) Bar Sensei Beast Sensor	12 Camera raptor 3D motion capture	DB Shoulder Press	4.54–6.82 kg	Peak velocity	TE: $0.105 \text{ m}\cdot\text{s}^{-1}$; RTE: 6.5%; r : 0.923
			F/W Back Squat	40%IRM	Mean velocity	TE: $0.090 \text{ m}\cdot\text{s}^{-1}$; RTE: 12.6%; r : 0.864
				40%IRM	Peak velocity	TE: $0.163 \text{ m}\cdot\text{s}^{-1}$; RTE: 14.0%; r : 0.801
				50%IRM	Mean velocity	R^2 : 0.92; LoA: $0.00 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Peak velocity	R^2 : 0.94; LoA: $0.09 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Mean velocity	R^2 : 0.96; LoA: $0.00 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Peak velocity	R^2 : 0.76; LoA: $0.09 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Mean velocity	R^2 : 0.95; LoA: $0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Peak velocity	R^2 : 0.45; LoA: $0.12 \pm 0.33 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	R^2 : 0.88; LoA: $0.02 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Peak velocity	R^2 : 0.60; LoA: $0.11 \pm 0.29 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Mean velocity	R^2 : 0.92; LoA: $0.00 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$
	90%IRM	Peak velocity	R^2 : 0.37; LoA: $0.13 \pm 0.44 \text{ m}\cdot\text{s}^{-1}$			
	100%IRM	Mean velocity	R^2 : 0.79; LoA: $0.00 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$			
	100%IRM	Peak velocity	R^2 : 0.53; LoA: $0.15 \pm 0.30 \text{ m}\cdot\text{s}^{-1}$			
	Full	Mean velocity	R^2 : 0.58; LoA: $-0.07 \pm 0.10 \text{ m}\cdot\text{s}^{-1}$			
	Full	Peak velocity	R^2 : 0.48; LoA: $0.12 \pm 0.35 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.97; LoA: $-0.01 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.80; LoA: $0.12 \pm 0.30 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.38; LoA: $0.07 \pm 0.24 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.27; LoA: $0.61 \pm 0.40 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.50; LoA: $0.07 \pm 0.23 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.43; LoA: $0.60 \pm 0.38 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.50; LoA: $0.07 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.24; LoA: $0.56 \pm 0.42 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.66; LoA: $0.07 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.43; LoA: $0.59 \pm 0.32 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.54; LoA: $0.07 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.27; LoA: $0.58 \pm 0.36 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.61; LoA: $0.10 \pm 0.19 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.60; LoA: $0.62 \pm 0.24 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.34; LoA: $0.09 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.66; LoA: $0.59 \pm 0.17 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Mean velocity	R^2 : 0.72; LoA: $0.08 \pm 0.19 \text{ m}\cdot\text{s}^{-1}$			
	Power clean	Peak velocity	R^2 : 0.65; LoA: $0.59 \pm 0.32 \text{ m}\cdot\text{s}^{-1}$			

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
		12 Camera raptor 3D motion capture	F/W Back Squat	40%IRM	Mean velocity	$R^2: 0.69$; LoA: $-0.08 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.91$; LoA: $0.02 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Mean velocity	$R^2: 0.95$; LoA: $-0.06 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.89$; LoA: $0.07 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Mean velocity	$R^2: 0.83$; LoA: $-0.07 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.84$; LoA: $0.06 \pm 0.17 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Mean velocity	$R^2: 0.84$; LoA: $-0.07 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.80$; LoA: $0.09 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	$R^2: 0.87$; LoA: $-0.07 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.60$; LoA: $0.08 \pm 0.28 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Mean velocity	$R^2: 0.92$; LoA: $-0.07 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.56$; LoA: $0.08 \pm 0.29 \text{ m}\cdot\text{s}^{-1}$
				100%IRM	Mean velocity	$R^2: 0.39$; LoA: $0.10 \pm 0.13 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.41$; LoA: $0.01 \pm 0.36 \text{ m}\cdot\text{s}^{-1}$
				Full	Mean velocity	$R^2: 0.97$; LoA: $-0.07 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.86$; LoA: $0.06 \pm 0.23 \text{ m}\cdot\text{s}^{-1}$
				40%IRM	Mean velocity	$R^2: 0.62$; LoA: $0.22 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.59$; LoA: $0.35 \pm 0.43 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Mean velocity	$R^2: 0.54$; LoA: $0.22 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.11$; LoA: $0.36 \pm 0.62 \text{ m}\cdot\text{s}^{-1}$
60%IRM	Mean velocity	$R^2: 0.50$; LoA: $0.22 \pm 0.15 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.68$; LoA: $0.35 \pm 0.26 \text{ m}\cdot\text{s}^{-1}$				
70%IRM	Mean velocity	$R^2: 0.24$; LoA: $0.16 \pm 0.26 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.08$; LoA: $0.31 \pm 0.74 \text{ m}\cdot\text{s}^{-1}$				
80%IRM	Mean velocity	$R^2: 0.35$; LoA: $0.14 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.06$; LoA: $0.30 \pm 0.64 \text{ m}\cdot\text{s}^{-1}$				
90%IRM	Mean velocity	$R^2: 0.41$; LoA: $0.19 \pm 0.15 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.26$; LoA: $0.46 \pm 0.35 \text{ m}\cdot\text{s}^{-1}$				
100%IRM	Mean velocity	$R^2: 0.23$; LoA: $0.14 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.60$; LoA: $0.35 \pm 0.23 \text{ m}\cdot\text{s}^{-1}$				
Full	Mean velocity	$R^2: 0.62$; LoA: $0.18 \pm 0.20 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.48$; LoA: $0.35 \pm 0.49 \text{ m}\cdot\text{s}^{-1}$				
40%IRM	Mean velocity	$R^2: 0.82$; LoA: $0.07 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.96$; LoA: $0.03 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$				
50%IRM	Mean velocity	$R^2: 0.75$; LoA: $0.05 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$				
	Peak velocity	$R^2: 0.93$; LoA: $0.07 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$				

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
			Power clean	60%IRM	Mean velocity	$R^2: 0.67$; LoA: $0.04 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Peak velocity	$R^2: 0.82$; LoA: $0.12 \pm 0.17 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	$R^2: 0.86$; LoA: $0.04 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Peak velocity	$R^2: 0.66$; LoA: $0.19 \pm 0.25 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	$R^2: 0.66$; LoA: $0.05 \pm 0.11 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Peak velocity	$R^2: 0.52$; LoA: $0.31 \pm 0.33 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Mean velocity	$R^2: 0.23$; LoA: $0.01 \pm 0.21 \text{ m}\cdot\text{s}^{-1}$
				100%IRM	Peak velocity	$R^2: 0.10$; LoA: $0.31 \pm 0.33 \text{ m}\cdot\text{s}^{-1}$
				100%IRM	Mean velocity	$R^2: 0.01$; LoA: $-0.05 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				Full	Peak velocity	$R^2: 0.02$; LoA: $0.24 \pm 0.49 \text{ m}\cdot\text{s}^{-1}$
				Full	Mean velocity	$R^2: 0.87$; LoA: $0.03 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$
				40%IRM	Peak velocity	$R^2: 0.80$; LoA: $0.18 \pm 0.37 \text{ m}\cdot\text{s}^{-1}$
				40%IRM	Mean velocity	$R^2: 0.82$; LoA: $-0.13 \pm 0.14 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Peak velocity	$R^2: 0.47$; LoA: $-0.36 \pm 0.38 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Mean velocity	$R^2: 0.82$; LoA: $-0.08 \pm 0.15 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Peak velocity	$R^2: 0.22$; LoA: $-0.25 \pm 0.49 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Mean velocity	$R^2: 0.73$; LoA: $-0.10 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Peak velocity	$R^2: 0.61$; LoA: $-0.20 \pm 0.35 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Mean velocity	$R^2: 0.04$; LoA: $-0.02 \pm 0.34 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Peak velocity	$R^2: 0.50$; LoA: $-0.15 \pm 0.38 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	$R^2: 0.07$; LoA: $0.01 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Peak velocity	$R^2: 0.69$; LoA: $-0.12 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$
				90%IRM	Mean velocity	$R^2: 0.18$; LoA: $0.02 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$
				100%IRM	Peak velocity	$R^2: 0.84$; LoA: $-0.04 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				100%IRM	Mean velocity	$R^2: 0.02$; LoA: $0.01 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.57$; LoA: $-0.05 \pm 0.27 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.73$; LoA: $-0.04 \pm 0.25 \text{ m}\cdot\text{s}^{-1}$
				Full	Peak velocity	$R^2: 0.74$; LoA: $-0.17 \pm 0.39 \text{ m}\cdot\text{s}^{-1}$
				40%IRM	Mean velocity	$R^2: 0.64$; LoA: $-0.01 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Peak velocity	$R^2: 0.10$; LoA: $-0.05 \pm 0.50 \text{ m}\cdot\text{s}^{-1}$
				50%IRM	Mean velocity	$R^2: 0.71$; LoA: $0.04 \pm 0.13 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Peak velocity	$R^2: 0.12$; LoA: $-0.04 \pm 0.43 \text{ m}\cdot\text{s}^{-1}$
				60%IRM	Mean velocity	$R^2: 0.49$; LoA: $0.08 \pm 0.21 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Peak velocity	$R^2: 0.00$; LoA: $0.02 \pm 0.53 \text{ m}\cdot\text{s}^{-1}$
				70%IRM	Mean velocity	$R^2: 0.46$; LoA: $0.11 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Peak velocity	$R^2: 0.00$; LoA: $0.01 \pm 0.56 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Mean velocity	$R^2: 0.58$; LoA: $0.16 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$
				80%IRM	Peak velocity	$R^2: 0.02$; LoA: $0.04 \pm 0.44 \text{ m}\cdot\text{s}^{-1}$

Table 5 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
van den Tillaar and Ball [11]	PUSH Band	ET-Enc-02 Ergoest linear encoder	F/W Bench Press	50%IRM, + 10 to 30 kg	Mean velocity	$R^2: 0.12$; LoA: $0.10 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.58$; LoA: $0.22 \pm 0.28 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.20$; LoA: $-0.09 \pm 0.26 \text{ m}\cdot\text{s}^{-1}$
					Peak velocity	$R^2: 0.15$; LoA: $0.25 \pm 0.52 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.80$; LoA: $0.06 \pm 0.24 \text{ m}\cdot\text{s}^{-1}$
	Push-Up			Body Weight, 10–30 kg vests	Peak velocity	$R^2: 0.57$; LoA: $0.06 \pm 0.51 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	Bias: $0.11 \text{ m}\cdot\text{s}^{-1}$; SEE: $0.17 \text{ m}\cdot\text{s}^{-1}$; $r: 0.62$
					Mean peak velocity	Bias: $0.22 \text{ m}\cdot\text{s}^{-1}$; SEE: $0.33 \text{ m}\cdot\text{s}^{-1}$; $r: 0.49$
					Mean velocity	Bias: $0.12 \text{ m}\cdot\text{s}^{-1}$; SEE: $0.16 \text{ m}\cdot\text{s}^{-1}$; $r: 0.70$
					Mean peak velocity	Bias: $0.15 \text{ m}\cdot\text{s}^{-1}$; SEE: $0.34 \text{ m}\cdot\text{s}^{-1}$; $r: 0.46$

IRM one repetition maximum, SEE standard error of the estimate, MV mean concentric velocity, T-Force T-force linear velocity transducer, GymAware GymAware PowerTool, CV coefficient of variation, RMSE root mean square of the estimate, LPR least products regression, TEE typical error of the estimate, SM Smith machine, F/W free weight, MD mean difference, r Pearson's correlation coefficient, ICC intraclass correlation coefficient, SEM standard error of measurement, CMJ countermovement jump, ES effect size, ROM range of motion, RTE relative typical error, OH overhead, DB dumbbell

questioned due to the pooling of repeated measures from a range of different intensities and consequently violating the assumption of independence [28]. Naturally, this may help to explain the contrasting results for this device and the high reliability correlation values previously reported [69].

Recent work by Perez-Castilla et al. [10] has compared seven commercially available devices in the Smith machine bench press across a range of loads (i.e., 45–85% of 1RM). Of these, the Speed4Lifts linear position transducer was found to demonstrate the greatest intra-device reliability (CV = 2.39–3.92%). This was closely followed by the Velwin, PowerLift, T-Force, and Chronojump that all demonstrated similar levels of reliability (CV = ~ 3–6%) [10]. The authors reported that, outside of Speed4Lifts linear position transducer, all other devices demonstrated substantial heteroscedasticity when compared to a high-speed 3D motion-capture system. However, caution is required when interpreting these outcomes as the influence of between-day biological variation was not separated from the true technological error of the devices. Nevertheless, it should be noted that similar (CV = ~ 4–8%) within-device reproducibility was observed for the Velwin and Powerlift when procedures were completed within-day [36] (Tables 10, 11). To the authors' knowledge, the only study to separate these forms of variation when assessing within-device reliability is the recent work by Weakley et al. [22] on the optic laser FLEX device. This study investigated the reliability across a prolonged time (i.e., 21 days between testing occasions) with the use of a purposely designed calibrated rig. Mean velocity demonstrated an overall within-device typical error of ~ 4% with velocities ranging from 0.09 to 0.99 m·s⁻¹. Additionally, this study demonstrated inter-device variance with both technological and biological variation accounted for. The authors concluded that the optic laser FLEX device exhibited acceptable inter-device reliability, suggesting that these devices can be used interchangeably (e.g., within a team environment where multiple barbells are set up). However, it should be noted that additional metrics (e.g., peak velocity) have recently been released by the manufacturers, and future research should be completed to assess these outputs.

While this review has considered a range of commercially available devices for the monitoring of resistance training, there are still several aspects that need further investigation. First, it should be acknowledged that the accuracy of these devices has been tested within a limited number of exercises (e.g., squat, bench press). Furthermore, a number of these studies have been done within a Smith machine which is expected to increase the reliability of the outputs. However, strength and conditioning practitioners often utilise a wide range of exercises and these are often done with free weights [73–76]. Additionally,

Table 6 Summary of studies that investigated the validity of mobile phone and tablet applications used to measure kinetic and kinematic variables during resistance training

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Balsalobre-Fernández et al. [69]	PowerLift (v4.0 iOS)	SmartCoach Power Encoder	F/W Back Squat	50–95%IRM	Mean velocity	Bias: $-0.005 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$ SEE: $0.04 \text{ m}\cdot\text{s}^{-1}$
			F/W Bench Press	50–95%IRM	Mean velocity	Bias: $-0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$ SEE: $0.05 \text{ m}\cdot\text{s}^{-1}$
			F/W Hip-Thrust	50–95%IRM	Mean velocity	Bias: $0.02 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$ SEE: $0.03 \text{ m}\cdot\text{s}^{-1}$
Balsalobre-Fernández et al. [70]	PowerLift (v2.8 iOS)	SmartCoach Power Encoder	F/W Bench Press	75–100%IRM	Mean velocity	$r: 0.94$; SEE: $0.028 \text{ m}\cdot\text{s}^{-1}$; ICC: 0.965 MD: $0.008 \pm 0.03 \text{ m}\cdot\text{s}^{-1}$
Courel-Ibanez et al. [36]	PowerLift (v4.0 iOS)	T-Force	S/M Bench Press	20–80 kg	Mean velocity	SEM: $0.09 \text{ m}\cdot\text{s}^{-1}$; CV: 11.7% ; ICC: 0.966
			S/M Back Squat	20–80 kg	Mean velocity	SEM: $0.06 \text{ m}\cdot\text{s}^{-1}$; CV: 7.6% ; ICC: 0.955
de Sá et al. [80]	iLoad App (v 1.0)	Chronojump	S/M Half ROM Back Squat	10RM	Mean velocity	Bias \pm random error: $-0.022 \pm 0.034 \text{ m}\cdot\text{s}^{-1}$
				10RM	Total work	ES: -0.21 (-0.39 , -0.04); $r: 0.948$
					Peak velocity	Bias \pm random error: $0.706 \pm 3.391 \text{ kJ}$ ES: 0.04 (-0.07 , 0.16); $r: 0.977$
Martinez-Cava et al. [51]	My Lift (v8.1 iOS)	T-Force	S/M Back Squat	25–95 kg	Peak velocity	SEM: $0.12 \text{ m}\cdot\text{s}^{-1}$; CV: 7.59% ; ICC: 0.937
			S/M Bench Press	25–95 kg	Peak velocity	SEM: $0.10 \text{ m}\cdot\text{s}^{-1}$; CV: 7.04% ; ICC: 0.991
Perez-Castilla et al. [10]	PowerLift (v.6.0.1 iOS)	OptiTrack	S/M Bench Press	55–85%IRM	Mean velocity	Bias: $-0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
Sanchez-Pay et al. [23]	Kinovea (v0.8.15) via Samsung S6	T-Force	S/M Bench Press	All loads	Mean velocity	Bias: $0.10 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$; $r: 0.997$
					Distance	Bias: $1.07 \pm 0.65 \text{ cm}$; $r: 0.996$
					Time	Bias: $-61.6 \pm 36.1 \text{ ms}$; $r: 0.998$
				High Loads ($MV < 0.80 \text{ m}\cdot\text{s}^{-1}$)	Mean velocity	Bias: $0.06 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$; $r: 0.986$
					Distance	Bias: $-0.95 \pm 0.69 \text{ cm}$; $r: 0.992$
					Time	Bias: $-76.6 \pm 41.3 \text{ ms}$; $r: 0.997$
				Low Loads ($MV > 0.80 \text{ m}\cdot\text{s}^{-1}$)	Mean velocity	Bias: $0.14 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$; $r: 0.985$
					Distance	Bias: $1.21 \pm 0.59 \text{ cm}$; $r: 0.996$
					Time	Bias: $-44.2 \pm 17.2 \text{ ms}$; $r: 0.978$
				All Loads	Mean velocity	Bias: $0.09 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$; $r: 0.996$
					Distance	Bias: $1.24 \pm 0.45 \text{ cm}$; $r: 0.998$
					Time	Bias: $-57.4 \pm 33.4 \text{ ms}$; $r: 0.998$
				High Loads ($MV < 0.80 \text{ m}\cdot\text{s}^{-1}$)	Mean velocity	Bias: $0.06 \pm 0.03 \text{ m}\cdot\text{s}^{-1}$; $r: 0.994$
					Distance	Bias: $1.21 \pm 0.47 \text{ cm}$; $r: 0.995$
					Time	Bias: $-74.3 \pm 34.5 \text{ ms}$; $r: 0.998$

Table 6 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings				
Kinovea (v0.8.15) via iPhone X		T-Force	S/M Bench Press	Low Loads (MV > 0.80 m.s ⁻¹)	Mean velocity	Bias: 0.13 ± 0.06 m.s ⁻¹ ; r: 0.981				
					Distance	Bias: 1.38 ± 0.39 cm; r: 0.997				
					Time	Bias: - 37.6 ± 18.0 ms; r: 0.975				
				All Loads	Mean velocity	Bias: 0.11 ± 0.08 m.s ⁻¹ ; r: 0.994				
					Distance	Bias: 1.34 ± 0.75 cm; r: 0.993				
					Time	Bias: - 69.5 ± 34.8 ms; r: 0.998				
				High Loads (MV < 0.80 m.s ⁻¹)	Mean velocity	Bias: 0.07 ± 0.04 m.s ⁻¹ ; r: 0.995				
					Distance	Bias: 1.29 ± 0.81 cm; r: 0.986				
					Time	Bias: - 85.6 ± 41.3 ms; r: 0.998				
				Kinovea (v0.8.15) via Casio FH20		T-Force	S/M Bench Press	Low Loads (MV > 0.80 m.s ⁻¹)	Mean velocity	Bias: 0.17 ± 0.09 m.s ⁻¹ ; r: 0.977
									Distance	Bias: 1.40 ± 0.68 cm; r: 0.993
									Time	Bias: - 50.4 ± 22.0 ms; r: 0.961
All Loads	Mean velocity	Bias: 0.14 ± 0.09 m.s ⁻¹ ; r: 0.992								
	Distance	Bias: 2.48 ± 0.87 cm; r: 0.990								
	Time	Bias: - 69.5 ± 40.7 ms; r: 0.997								
High Loads (MV < 0.80 m.s ⁻¹)	Mean velocity	Bias: 0.08 ± 0.05 m.s ⁻¹ ; r: 0.990								
	Distance	Bias: 2.36 ± 0.91 cm; r: 0.984								
	Time	Bias: - 83.4 ± 44.3 ms; r: 0.996								
Kinovea (v0.8.15) via Digital Video Camera (50Hz)		T-Force	S/M Bench Press					Low Loads (MV > 0.80 m.s ⁻¹)	Mean velocity	Bias: 0.20 ± 0.09 m.s ⁻¹ ; r: 0.963
									Distance	Bias: 2.62 ± 0.81 cm; r: 0.989
									Time	Bias: - 53.2 ± 28.9 ms; r: 0.932
				20 kg	Mean propulsive velocity	Bias: - 0.43 m.s ⁻¹				
					Maximal velocity	Bias: - 0.57 m.s ⁻¹				
					Mean propulsive velocity	Bias: - 0.41 m.s ⁻¹				
				30 kg	Maximal velocity	Bias: - 0.59 m.s ⁻¹				
					Mean propulsive velocity	Bias: - 0.30 m.s ⁻¹				
					Maximal velocity	Bias: - 0.42 m.s ⁻¹				
				40 kg	Mean propulsive velocity	Bias: - 0.23 m.s ⁻¹				
					Maximal velocity	Bias: - 0.36 m.s ⁻¹				
					Mean propulsive velocity	Bias: - 0.16 m.s ⁻¹				
50 kg	Maximal velocity	Bias: - 0.28 m.s ⁻¹								
	Mean propulsive velocity									
	Maximal velocity									
60 kg	Maximal velocity									
	Mean propulsive velocity									
	Maximal velocity									

Table 6 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Thompson et al. [24]	MyLift (PowerLift at the time of data collection)	12 Camera raptor 3D motion capture	F/W Back Squat	70 kg	Mean propulsive velocity	Bias: $-0.14 \text{ m}\cdot\text{s}^{-1}$
					Maximal velocity	Bias: $-0.28 \text{ m}\cdot\text{s}^{-1}$
				80 kg	Mean propulsive velocity	Bias: $-0.16 \text{ m}\cdot\text{s}^{-1}$
					Maximal velocity	Bias: $-0.23 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.96$; LoA: $0.02 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.94$; LoA: $0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.88$; LoA: $0.01 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.95$; LoA: $0.01 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.93$; LoA: $0.00 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$
					Mean velocity	$R^2: 0.92$; LoA: $0.00 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$
Mean velocity	$R^2: 0.85$; LoA: $0.00 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$					
Mean velocity	$R^2: 0.99$; LoA: $0.01 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$					

IRM one repetition maximum, *MV* mean concentric velocity, *CV* coefficient of variation, *T-Force* T-force linear velocity transducer, *S/M* Smith machine, *F/W* free weight, *r* Pearson's correlation coefficient, *ES* effect size, *ROM* range of motion, *RE* random error, *SEE* standard error of the estimate, *SEM* standard error of the measurement

some exercises that have greater horizontal displacement (e.g., Olympic weightlifting movements) have had minimal investigation. Therefore, future research is required for the validation of current technology using a wider range of exercises that include weightlifting movements and their derivatives. Second, future research must consider the influence of biological variation when assessing the reliability of measurement devices. To date, all but one reliability study [22] have disregarded this consideration during within-device analysis, despite it being widely acknowledged that human performances fluctuate within-session and between-days. Thus, most of the within-device reliability research may mistakenly report reproducibility errors that are unrelated to the device. Finally, it is important to acknowledge the wide range of statistical approaches that have been used within the literature and that erroneous conclusions of validity and reliability may be drawn from an individual statistical value. For example, alone, correlations characterise the relationship between two outcomes, but they are incapable of describing any systematic bias that may exist. This has implications for concluding whether a device is truly accurate or reliable. Additionally, when interpreting error of individual devices, this should be put into context in relation to practical criteria or acceptable levels of disagreement. Thus, when quantifying the validity and reliability of these technologies, researchers are strongly advised to consider using a number of analyses that provide information about the level of agreement and the magnitude of errors that are associated with each device and compare these to appropriate criteria.

5 Conclusions

The current review provides the reliability and validity of a range of different devices which are commercially available for the monitoring and prescription of resistance training. Generally, linear transducers have shown the greatest accuracy with mean concentric velocity the most assessed outcome. However, to date, only the GymAware [9, 25, 26, 54], T-Force [54], Open Barbell System [53], Tendo Fitrodyne [53, 54, 58], and Fitrodyne (Fitronic) [9] have been directly compared to a 'true' gold-standard 3D high-speed motion-capture system set-up during free-weight resistance training. When these devices have been directly compared to each other during free-weight exercises [9, 53, 54], it appears that the GymAware provides the greatest accuracy. This accuracy may be due to the device's ability to account for horizontal displacement and variable rate sampling which is distinct to this device. Additionally, the T-Force demonstrates acceptable accuracy when exercise is performed within the Smith machine.

Table 7 Summary of studies that investigated the validity of optic devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
Courel-Ibanez et al. [36]	Velowin	T-Force	S/M Bench Press	20–80 kg	Mean velocity	SEM: 0.02 m·s ⁻¹ ; CV: 3.1%; ICC: 0.998
					Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.5%; ICC: 0.997
					Peak velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.7%; ICC: 0.999
					Mean velocity	SEM: 0.03 m·s ⁻¹ ; CV: 4.4%; ICC: 0.992
Garcia-Ramos et al. [71]	Velowin	T-Force	S/M Prone Bench Pull	20–80 kg	Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.6%; ICC: 0.992
					Peak velocity	SEM: 0.04 m·s ⁻¹ ; CV: 2.3%; ICC: 0.993
					Mean velocity	SEM: 0.09 m·s ⁻¹ ; CV: 8.1%; ICC: 0.967
					Mean propulsive velocity	SEM: 0.25 m·s ⁻¹ ; CV: 8.1%; ICC: 0.967
Laza-Cagigas et al. [68]	Velowin	T-Force	F/W Back Squat	20–70 kg	Peak velocity	SEM: 0.03 m·s ⁻¹ ; CV: 1.9%; ICC: 0.999
					Mean velocity	Bias: 0.02 ± 0.05 m·s ⁻¹ ; SEE: 0.040 m·s ⁻¹
					Mean propulsive velocity	Bias: 0.02 ± 0.06 m·s ⁻¹ ; SEE: 0.055 m·s ⁻¹
					Maximum velocity	Bias: - 0.09 ± 0.06 m·s ⁻¹ ; SEE: 0.057 m·s ⁻¹
Peña Garcia-Orea et al. [82]	Velowin	T-Force	S/M Squat	20–70 kg	Displacement	RMSE: 3.73 cm; CV: 6.6%; ICC: 0.84
					Mean velocity	RMSE: 0.06 m·s ⁻¹ ; CV: 7.3%; ICC: 0.97
					Peak velocity	RMSE: 0.09 m·s ⁻¹ ; CV: 6.5%; ICC: 0.96
					Mean force	RMSE: 43N; CV: 3.6%; ICC: 0.99
Peña Garcia-Orea et al. [72]	Velowin	T-Force	Loaded CMJ	3.5–43.5 kg	Peak force	RMSE: 100N; CV: 5.2%; ICC: 0.98
					Mean power	RMSE: 73W; CV: 8.2%; ICC: 0.92
					Peak power	RMSE: 160W; CV: 8.3%; ICC: 0.85
					Mean velocity	No significant differences were found between the variances of the two devices
Perez-Castilla et al. [10]	Velowin	OptiTrack	S/M Bench Press	55–85%1RM	Mean propulsive velocity	No significant differences were found between the variances of the two devices
					Peak velocity	Bias: - 0.05 ± 0.03 m·s ⁻¹
Weakley et al. [22]	FLEX	Vicon	F/W Back Squat	20%1RM	Mean velocity	Bias: 0.00 ± 0.01 m·s ⁻¹ ; TEE: 0.06 ± 0.02 m·s ⁻¹ ; r: 0.97 ± 0.03

Table 7 (continued)

Study	Device	Criterion	Exercise	Intensity/load	Variable measured	Findings
				40%IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.008 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.01
				60%IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.008 \text{ m}\cdot\text{s}^{-1}$; r : 0.97 ± 0.03
				80%IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.004 \text{ m}\cdot\text{s}^{-1}$; r : 0.95 ± 0.05
				$\geq 90\%$ IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.004 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.01
				Overall	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.03 \pm 0.004 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.00
			F/W Bench Press	20%IRM	Mean velocity	Bias: $-0.01 \pm 0.03 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.08 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$; r : 0.97 ± 0.04
				40%IRM	Mean velocity	Bias: $-0.02 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.04 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.02
				60%IRM	Mean velocity	Bias: $0.00 \pm 0.01 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$; r : 0.98 ± 0.02
				80%IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.01 \pm 0.005 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.01
				$\geq 90\%$ IRM	Mean velocity	Bias: $0.00 \pm 0.00 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.02 \pm 0.005 \text{ m}\cdot\text{s}^{-1}$; r : 0.98 ± 0.01
				Overall	Mean velocity	Bias: $-0.01 \pm 0.01 \text{ m}\cdot\text{s}^{-1}$; TEE: $0.04 \pm 0.005 \text{ m}\cdot\text{s}^{-1}$; r : 0.99 ± 0.00

IRM one repetition maximum, SEE standard error of the estimate, T-force T-force linear velocity transducer, CV coefficient of variation, RMSE root mean square of the estimate, TEE typical error of the estimate, S/M Smith machine, F/W free weight, r Pearson's correlation coefficient, ICC intraclass correlation coefficient, SEM standard error of measurement, CMJ counter-movement jump

Table 8 Summary of studies that investigated the reliability of linear transducer devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Balsalobre-Fernández et al. [62]	T-Force	Intra-device	S/M Back Squat	20–70 kg	Peak velocity	CV: $4.2 \pm 2.5\%$; ICC: 0.988; r : 0.975
Balsalobre-Fernández et al. [69]	SmartCoach	Intra-device	F/W Back Squat	50–95%IRM	Mean velocity	CV: $3.9 \pm 2.4\%$; ICC: 0.989; r : 0.989
Beckham et al. [28]	GymAware	Intra-device	F/W Bench Press	50–95%IRM	Mean velocity	ICC: 0.981
			F/W Hip Thrust	50–95%IRM	Mean velocity	ICC: 0.966
			F/W Back Squat	45%IRM	Mean velocity	ICC: 0.774
				60%IRM	Peak velocity	ICC: 0.793
				75%IRM	Mean velocity	ICC: 0.752
Boehringer and Whyte [77]	1080Q	Intra-device	S/M Bench Press	30–80%IRM	Peak velocity	ICC: 0.775
				30%IRM	Mean velocity	ICC: 0.651
				40%IRM	Peak velocity	ICC: 0.761
				30–80%IRM	Mean velocity	MD: $0.004 \text{ m}\cdot\text{s}^{-1}$; CV: 7.0%; ICC: 0.97
				30%IRM	Mean velocity	MD: $-0.003 \text{ m}\cdot\text{s}^{-1}$; CV: 4.5%; ICC: 0.64
				40%IRM	Mean velocity	MD: $0.001 \text{ m}\cdot\text{s}^{-1}$; CV: 3.7; ICC: 0.82
				50%IRM	Mean velocity	MD: $0.010 \text{ m}\cdot\text{s}^{-1}$; CV: 5.7; ICC: 0.53
				60%IRM	Mean velocity	MD: $0.017 \text{ m}\cdot\text{s}^{-1}$; CV: 6.5; ICC: 0.45
				70%IRM	Mean velocity	MD: $0.000 \text{ m}\cdot\text{s}^{-1}$; CV: 7.6; ICC: 0.63
				80%IRM	Mean velocity	MD: $-0.003 \text{ m}\cdot\text{s}^{-1}$; CV: 11.0; ICC: 0.69
				30–80%IRM	Mean force	MD: -0.3N ; CV: 1.7%; ICC: 1.00
				30%IRM	Mean force	MD: -4.1N ; CV: 2.0%; ICC: 0.93
				40%IRM	Mean force	MD: -0.9N ; CV: 1.9%; ICC: 0.98
	50%IRM	Mean force	MD: 3.4N ; CV: 2.3%; ICC: 0.96			
	60%IRM	Mean force	MD: 3.2N ; CV: 1.7%; ICC: 0.98			
	70%IRM	Mean force	MD: -4.8N ; CV: 1.1%; ICC: 0.99			
	80%IRM	Mean force	MD: -0.9N ; CV: 0.9%; ICC: 0.99			
	30–80%IRM	Mean power	MD: 3.4W ; CV: 8.0%; ICC: 0.90			
	30%IRM	Mean power	MD: -4.1W ; CV: 6.7%; ICC: 0.73			
	40%IRM	Mean power	MD: -1.6W ; CV: 5.1%; ICC: 0.91			
	50%IRM	Mean power	MD: 8.1W ; CV: 7.3%; ICC: 0.79			
	60%IRM	Mean power	MD: 14.8W ; CV: 7.6%; ICC: 0.74			
	70%IRM	Mean power	MD: -0.4W ; CV: 8.3%; ICC: 0.73			
	80%IRM	Mean power	MD: -1.1W ; CV: 11.4%; ICC: 0.65			

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Courtel-Ibanez et al. [36]	T-Force	Inter-device	S/M Bench Press	30–80%IRM	Peak velocity	MD: 0.002 m·s ⁻¹ ; CV: 6.3%; ICC: 0.97
				30%IRM	MD: 0.002 m·s ⁻¹ ; CV: 4.1%; ICC: 0.61	
				40%IRM	MD: 0.001 m·s ⁻¹ ; CV: 3.6%; ICC: 0.84	
				50%IRM	MD: 0.008 m·s ⁻¹ ; CV: 5.0%; ICC: 0.68	
				60%IRM	MD: 0.000 m·s ⁻¹ ; CV: 5.0%; ICC: 0.75	
				70%IRM	MD: 0.004 m·s ⁻¹ ; CV: 8.2%; ICC: 0.58	
				80%IRM	MD: - 0.001 m·s ⁻¹ ; CV: 9.5%; ICC: 0.80	
				30–80%IRM	MD: - 2.6N; CV: 4.4%; ICC: 0.94	
				30%IRM	MD: - 20.9N; CV: 7.0%; ICC: 0.51	
				40%IRM	MD: - 4.9N; CV: 3.5%; ICC: 0.90	
				50%IRM	MD: 7.4N; CV: 4.9%; ICC: 0.79	
				60%IRM	MD: 1.3N; CV: 4.2%; ICC: 0.80	
				70%IRM	MD: 0.4N; CV: 4.3%; ICC: 0.78	
				80%IRM	MD: - 9.4N; CV: 3.7%; ICC: 0.87	
				30–80%IRM	MD: 2.0W; CV: 7.4%; ICC: 0.91	
				30%IRM	MD: 2.4W; CV: 6.1%; ICC: 0.79	
				40%IRM	MD: - 2.2W; CV: 5.1%; ICC: 0.92	
				50%IRM	MD: 6.9W; CV: 7.0%; ICC: 0.85	
				60%IRM	MD: 1.3W; CV: 6.1%; ICC: 0.88	
				70%IRM	MD: 1.6W; CV: 8.9%; ICC: 0.77	
80%IRM	MD: 2.5W; CV: 10.2%; ICC: 0.79					
20–80 kg	Mean velocity	SEM: 0.01 m·s ⁻¹ ; CV: 1.4%; ICC: 1.000				
	Mean propulsive velocity	SEM: 0.01 m·s ⁻¹ ; CV: 1.3%; ICC: 1.000				
	Peak velocity	SEM: 0.01 m·s ⁻¹ ; CV: 0.6%; ICC: 1.000				
	Mean velocity	SEM: 0.01 m·s ⁻¹ ; CV: 1.0%; ICC: 0.999				
	Mean propulsive velocity	SEM: 0.01 m·s ⁻¹ ; CV: 1.1%; ICC: 0.999				
	Peak velocity	SEM: 0.01 m·s ⁻¹ ; CV: 0.8%; ICC: 0.999				
	Mean velocity	SEM: 0.02 m·s ⁻¹ ; CV: 2.1%; ICC: 0.998				
	Mean propulsive velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.9%; ICC: 0.998				
	Peak velocity	SEM: 0.01 m·s ⁻¹ ; CV: 0.8%; ICC: 1.000				
	Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 4.7%; ICC: 0.995				
	Mean propulsive velocity	SEM: 0.04 m·s ⁻¹ ; CV: 5.2%; ICC: 0.995				
	Peak velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.4%; ICC: 1.000				
	Mean velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.6%; ICC: 0.991				
	Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.9%; ICC: 0.991				
Chronojump	Inter-device	Inter-device	S/M Bench Press	20–80 kg	Peak velocity	SEM: 0.01 m·s ⁻¹ ; CV: 0.8%; ICC: 1.000
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 4.7%; ICC: 0.995
					Mean propulsive velocity	SEM: 0.04 m·s ⁻¹ ; CV: 5.2%; ICC: 0.995
	Peak velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.4%; ICC: 1.000				
	Mean velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.6%; ICC: 0.991				
	Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.9%; ICC: 0.991				

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Dorrell et al. [26]	T-Force	Intra-device	S/M Back Squat	20–80 kg	Peak velocity	SEM: 0.03 m·s ⁻¹ ; CV: 1.8%; ICC: 0.996
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.3%; ICC: 0.995
					Mean propulsive velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.4%; ICC: 0.995
		Intra-device	S/M Prone Bench Pull S/M Bench Press	20–80 kg	Peak velocity	SEM: 0.04 m·s ⁻¹ ; CV: 2.4%; ICC: 1.00
					Mean velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.9%; ICC: 0.999
					Mean propulsive velocity	SEM: 0.02 m·s ⁻¹ ; CV: 1.8%; ICC: 0.999
	Intra-device	S/M Back Squat	20–80 kg	Peak velocity	SEM: 0.03 m·s ⁻¹ ; CV: 2.0%; ICC: 0.999	
				Mean velocity	SEM: 0.03 m·s ⁻¹ ; CV: 2.5%; ICC: 0.995	
				Mean propulsive velocity	SEM: 0.02 m·s ⁻¹ ; CV: 2.6%; ICC: 0.996	
	Chronojump	Intra-device	S/M Prone Bench Pull	20–80 kg	Peak velocity	SEM: 0.05 m·s ⁻¹ ; CV: 2.9%; ICC: 0.989
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.0%; ICC: 0.995
					Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.0%; ICC: 0.995
Peak velocity					SEM: 0.03 m·s ⁻¹ ; CV: 1.8%; ICC: 0.999	
Mean velocity					SEM: 0.04 m·s ⁻¹ ; CV: 4.3%; ICC: 0.997	
Mean propulsive velocity					SEM: 0.03 m·s ⁻¹ ; CV: 3.2%; ICC: 0.998	
GymAware	Intra-device	S/M Back Squat	20–80 kg	Peak velocity	SEM: 0.04 m·s ⁻¹ ; CV: 2.4%; ICC: 0.999	
				Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.9%; ICC: 0.990	
				Mean propulsive velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.8%; ICC: 0.991	
				Peak velocity	SEM: 0.06 m·s ⁻¹ ; CV: 3.4%; ICC: 0.985	
				Mean velocity	SEM: 0.07 m·s ⁻¹ ; CV: 5.2%; ICC: 0.990	
				Mean propulsive velocity	SEM: 0.07 m·s ⁻¹ ; CV: 5.4%; ICC: 0.987	
	Intra-device	F/W Back Squat	80%IRM	Peak velocity	SEM: 0.04 m·s ⁻¹ ; CV: 2.3%; ICC: 0.998	
				Bar displacement	Mean TE: 3.8% (3.0–5.3%)	
				Peak velocity	Mean TE: 8.1% (6.4–11.5%)	
				Mean velocity	Mean TE: 7.0% (5.6–10.0%)	
				Peak force	Mean TE: 4.3% (3.4–6.1%)	
				Mean force	Mean TE: 0.6% (0.5–0.9%)	
Intra-device	F/W Bench Press	80%IRM	Bar displacement	Mean TE: 3.0% (2.3–4.1)		
			Peak velocity	Mean TE: 6.2% (4.9–8.7)		
			Mean velocity	Mean TE: 7.4% (5.8–10.5%)		
			Bar displacement	Mean TE: 2.0% (1.6–2.7%)		
			Peak velocity	Mean TE: 8.8% (7.0–12.5%)		
			Mean velocity	Mean TE: 7.0% (5.5–9.8%)		
Intra-device	F/W Deadlift	80%IRM	Peak force	Mean TE: 3.1% (2.5–4.4%)		
			Mean force	Mean TE: 1.6% (1.3–2.2%)		

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Fernandes et al. [55]	FitroDyne (fitronic)	Intra-device (intra-day)	S/M Bench Press	20%IRM	Peak power	TE: 18.3W; CV: 4.3%
					Mean power	TE: 8.2W; CV: 3.4%
				30%IRM	Peak velocity	TE: 6.9 cm·s ⁻¹ ; CV: 3.3%
					Mean velocity	TE: 3.4 cm·s ⁻¹ ; CV: 2.9%
				40%IRM	Peak power	TE: 11.3W; CV: 2.1%
					Mean power	TE: 8.4W; CV: 2.6%
				50%IRM	Peak velocity	TE: 3.1 cm·s ⁻¹ ; CV: 1.7%
					Mean velocity	TE: 2.9 cm·s ⁻¹ ; CV: 2.7%
				60%IRM	Peak power	TE: 10.1W; CV: 1.6%
					Mean power	TE: 11.0W; CV: 2.9%
				70%IRM	Peak velocity	TE: 2.8 cm·s ⁻¹ ; CV: 1.8%
					Mean velocity	TE: 2.9 cm·s ⁻¹ ; CV: 3.1%
				80%IRM	Peak power	TE: 16.9W; CV: 2.6%
					Mean power	TE: 10.7W; CV: 2.7%
				20%IRM	Peak velocity	TE: 3.6 cm·s ⁻¹ ; CV: 2.8%
					Mean velocity	TE: 2.2 cm·s ⁻¹ ; CV: 2.8%
				30%IRM	Peak power	TE: 23.8W; CV: 4.0%
					Mean power	TE: 17.7W; CV: 4.6%
				40%IRM	Peak velocity	TE: 3.8 cm·s ⁻¹ ; CV: 3.9%
					Mean velocity	TE: 2.8 cm·s ⁻¹ ; CV: 4.4%
20%IRM	Peak power	TE: 18.6W; CV: 3.4%				
	Mean power	TE: 16.4W; CV: 4.8%				
30%IRM	Peak velocity	TE: 2.6 cm·s ⁻¹ ; CV: 3.3%				
	Mean velocity	TE: 2.2 cm·s ⁻¹ ; CV: 4.5%				
40%IRM	Peak power	TE: 53.0W; CV: 12.2%				
	Mean power	TE: 44.2W; CV: 17.1%				
20%IRM	Peak velocity	TE: 5.3 cm·s ⁻¹ ; CV: 9.7%				
	Mean velocity	TE: 4.3 cm·s ⁻¹ ; CV: 13.4%				
30%IRM	Peak power	TE: 21.8W; CV: 4.9%				
	Mean power	TE: 13.3W; CV: 5.3%				
40%IRM	Peak velocity	TE: 7.0 cm·s ⁻¹ ; CV: 4.1%				
	Mean velocity	TE: 3.9 cm·s ⁻¹ ; CV: 4.0%				
20%IRM	Peak power	TE: 34.6W; CV: 5.4%				
	Mean power	TE: 19.9W; CV: 5.6%				
30%IRM	Peak velocity	TE: 7.4 cm·s ⁻¹ ; CV: 4.5%				
	Mean velocity	TE: 4.2 cm·s ⁻¹ ; CV: 4.6%				
40%IRM	Peak power	TE: 35.2W; CV: 4.3%				
	Mean power	TE: 28.2W; CV: 6.4%				
20%IRM	Peak velocity	TE: 6.1 cm·s ⁻¹ ; CV: 4.0%				
	Mean velocity	TE: 4.8 cm·s ⁻¹ ; CV: 5.7%				

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
				50%IRM	Peak power	TE: 22.8W; CV: 2.4%
					Mean power	TE: 14.2W; CV: 2.9%
					Peak velocity	TE: 3.9 cm·s ⁻¹ ; CV: 2.7%
					Mean velocity	TE: 2.4 cm·s ⁻¹ ; CV: 3.2%
				60%IRM	Peak power	TE: 36.7W; CV: 3.5%
					Mean power	TE: 22.3W; CV: 4.1%
					Peak velocity	TE: 4.5 cm·s ⁻¹ ; CV: 3.3%
					Mean velocity	TE: 3.0 cm·s ⁻¹ ; CV: 4.3%
				70%IRM	Peak power	TE: 55.6W; CV: 4.9%
					Mean power	TE: 29.6W; CV: 5.4%
					Peak velocity	TE: 6.4 cm·s ⁻¹ ; CV: 5.2%
					Mean velocity	TE: 3.8 cm·s ⁻¹ ; CV: 6.3%
				80%IRM	Peak power	TE: 46.7W; CV: 3.9%
					Mean power	TE: 28.4W; CV: 5.5%
					Peak velocity	TE: 5.1 cm·s ⁻¹ ; CV: 4.4%
					Mean velocity	TE: 3.1 cm·s ⁻¹ ; CV: 6.4%
				20%IRM	Peak power	TE: 18.9W; CV: 5.1%
					Mean power	TE: 14.5W; CV: 6.6%
					Peak velocity	TE: 8.8 cm·s ⁻¹ ; CV: 4.4%
					Mean velocity	TE: 6.6 cm·s ⁻¹ ; CV: 5.6%
				30%IRM	Peak power	TE: 20.0W; CV: 3.8%
					Mean power	TE: 23.0W; CV: 7.4%
					Peak velocity	TE: 7.1 cm·s ⁻¹ ; CV: 3.8%
					Mean velocity	TE: 8.7 cm·s ⁻¹ ; CV: 7.9%
				40%IRM	Peak power	TE: 21.6W; CV: 3.5%
					Mean power	TE: 16.3W; CV: 4.3%
					Peak velocity	TE: 6.1 cm·s ⁻¹ ; CV: 3.7%
					Mean velocity	TE: 4.8 cm·s ⁻¹ ; CV: 4.7%
				50%IRM	Peak power	TE: 20.8W; CV: 2.9%
					Mean power	TE: 26.7W; CV: 6.1%
					Peak velocity	TE: 4.0 cm·s ⁻¹ ; CV: 2.6%
					Mean velocity	TE: 6.0 cm·s ⁻¹ ; CV: 6.4%
				60%IRM	Peak power	TE: 33.0W; CV: 4.1%
					Mean power	TE: 33.0W; CV: 6.9%
					Peak velocity	TE: 5.7 cm·s ⁻¹ ; CV: 4.0%
					Mean velocity	TE: 6.4 cm·s ⁻¹ ; CV: 7.5%
				70%IRM	Peak power	TE: 62.8W; CV: 7.8%
					Mean power	TE: 40.0W; CV: 8.2%
					Peak velocity	TE: 10.5 cm·s ⁻¹ ; CV: 8.5%
					Mean velocity	TE: 6.7 cm·s ⁻¹ ; CV: 9.0%

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Garcia-Pimillos et al. [61]	T-Force	Mean velocity Intra-device	S/M Concentric-Only Half Back Squat	80% IRM	Peak power	TE: 61.1W; CV: 7.7%
					Mean power	TE: 37.3W; CV: 7.8%
					Peak velocity	TE: 8.8 cm·s ⁻¹ ; CV: 8.3%
				10% IRM	Mean velocity	CV: 8.60%; SEM: 0.03 m·s ⁻¹
					Mean propulsive velocity	CV: 11.28%; SEM: 0.04 m·s ⁻¹
					Maximum velocity	CV: 9.18%; SEM: 0.06 m·s ⁻¹
				20% IRM	Mean velocity	CV: 6.76%; SEM: 0.02 m·s ⁻¹
					Mean propulsive velocity	CV: 8.29%; SEM: 0.03 m·s ⁻¹
					Maximum velocity	CV: 8.17%; SEM: 0.05 m·s ⁻¹
				30% IRM	Mean velocity	CV: 11.86%; SEM: 0.11 m·s ⁻¹
					Mean propulsive velocity	CV: 14.39%; SEM: 0.04 m·s ⁻¹
					Maximum velocity	CV: 7.42%; SEM: 0.04 m·s ⁻¹
				40% IRM	Mean velocity	CV: 9.95%; SEM: 0.09 m·s ⁻¹
					Mean propulsive velocity	CV: 10.87%; SEM: 0.03 m·s ⁻¹
					Maximum velocity	CV: 6.64%; SEM: 0.03 m·s ⁻¹
				50% IRM	Mean velocity	CV: 9.06%; SEM: 0.07 m·s ⁻¹
					Mean propulsive velocity	CV: 11.21%; SEM: 0.02 m·s ⁻¹
					Maximum velocity	CV: 6.49%; SEM: 0.03 m·s ⁻¹
				60% IRM	Mean velocity	CV: 9.27%; SEM: 0.02 m·s ⁻¹
					Mean propulsive velocity	CV: 13.81%; SEM: 0.03 m·s ⁻¹
Maximum velocity	CV: 6.49%; SEM: 0.03 m·s ⁻¹					
70% IRM	Mean velocity	CV: 9.91%; SEM: 0.04 m·s ⁻¹				
	Mean propulsive velocity	CV: 9.50%; SEM: 0.02 m·s ⁻¹				
	Maximum velocity	CV: 12.27%; SEM: 0.02 m·s ⁻¹				
80% IRM	Mean velocity	CV: 8.68%; SEM: 0.03 m·s ⁻¹				
	Mean propulsive velocity	CV: 9.09%; SEM: 0.02 m·s ⁻¹				
	Maximum velocity	CV: 9.07%; SEM: 0.02 m·s ⁻¹				
90% IRM	Mean velocity	CV: 5.67%; SEM: 0.02 m·s ⁻¹				
	Mean propulsive velocity	CV: 11.02%; SEM: 0.05 m·s ⁻¹				
	Maximum velocity	CV: 11.00%; SEM: 0.02 m·s ⁻¹				

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
García-Ramos et al. [71]	T-Force	Intra-device	F/W Back Squat	100% IRM	Mean velocity	CV: 16.77%; SEM: 0.02 m·s ⁻¹
					Mean propulsive velocity	CV: 17.26%; SEM: 0.02 m·s ⁻¹
				20 kg Load	Maximum velocity	CV: 9.79%; SEM: 0.02 m·s ⁻¹
					Mean velocity	SEM: 0.052 m·s ⁻¹ ; CV: 4.65%; ICC: 0.90
				40 kg Load	Mean propulsive velocity	SEM: 0.059 m·s ⁻¹ ; CV: 4.87%; ICC: 0.91
					Maximum velocity	SEM: 0.075 m·s ⁻¹ ; CV: 4.17%; ICC: 0.93
				50 kg Load	Mean velocity	SEM: 0.040 m·s ⁻¹ ; CV: 4.19%; ICC: 0.93
					Mean propulsive velocity	SEM: 0.046 m·s ⁻¹ ; CV: 4.46%; ICC: 0.92
					Maximum velocity	SEM: 0.058 m·s ⁻¹ ; CV: 3.59%; ICC: 0.95
					Mean velocity	SEM: 0.038 m·s ⁻¹ ; CV: 4.25%; ICC: 0.90
	Mean propulsive velocity	SEM: 0.047 m·s ⁻¹ ; CV: 4.83%; ICC: 0.87				
	Maximum velocity	SEM: 0.044 m·s ⁻¹ ; CV: 2.84%; ICC: 0.95				
Carmacho-Castano et al. [56]	Tendo	Intra-device	S/M Back Squat	60 kg Load	Mean velocity	SEM: 0.031 m·s ⁻¹ ; CV: 3.75%; ICC: 0.94
					Mean propulsive velocity	SEM: 0.033 m·s ⁻¹ ; CV: 3.73%; ICC: 0.95
				70 kg Load	Maximum velocity	SEM: 0.049 m·s ⁻¹ ; CV: 3.35%; ICC: 0.94
					Mean velocity	SEM: 0.036 m·s ⁻¹ ; CV: 4.84%; ICC: 0.92
				40–60 kg	Mean propulsive velocity	SEM: 0.036 m·s ⁻¹ ; CV: 4.49%; ICC: 0.93
					Maximum velocity	SEM: 0.047 m·s ⁻¹ ; CV: 3.45%; ICC: 0.95
				+ 85%IRM	Mean velocity	Bias: - 0.02 ± 0.07 m·s ⁻¹ ; CV: 8.5%
					Peak velocity	Bias: - 0.05 ± 0.13 m·s ⁻¹ ; CV: 9.6%
				40–60 kg	Mean power	Bias: - 5.45 ± 39.75W; CV: 10.9%
					Peak power	Bias: - 19.99 ± 85.78W; CV: 13.0%
+ 85%IRM	Mean velocity	Bias: 0.001 ± 0.08 m·s ⁻¹ ; CV: 9.6%				
	Peak velocity	Bias: - 0.004 ± 0.08 m·s ⁻¹ ; CV: 9.0%				
	Mean power	Bias: - 3.53 ± 27.87W; CV: 10.7%				
	Peak power	Bias: - 18.40 ± 49.35W; CV: 13.2%				
Hughes et al. [52]	GymAware	Intra-device	F/W Back Squat	30–90%IRM	Mean velocity	30%, 60%, 90%IRM ICC: 0.86, 0.78, 0.76; CV: 1.5%, 4.7%, 5.1%
					Mean velocity	ICC: 0.97, 0.80, 0.85; CV: 0.6%, 2.0%, 2.4%
					Mean velocity	ICC: 0.90, 0.92, 0.85; CV: 1.2%, 1.0%, 2.3%
					Mean velocity	ICC: 0.88, 0.83, 0.85; CV: 1.2%, 2.4%, 2.5%
				30–90%IRM	Mean velocity	ICC: 0.97, 0.80, 0.97; CV: 1.0%, 3.3%, 2.8%
					Mean velocity	ICC: 0.98, 0.94, 0.93; CV: 0.4%, 1.4%, 1.7%
					Mean velocity	ICC: 0.89, 0.98, 0.88; CV: 0.7%, 1.0%, 0.8%
					Mean velocity	ICC: 0.82, 0.86, 0.91; CV: 2.2%, 4.6%, 2.3%
					Mean velocity	
					Mean velocity	

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Jennings et al. [79]	FitroDyne (fitronic)	Intra-device	F/W Biceps curls F/W Squat Jump F/W Back Squat	0–90%1RM 0–90%1RM 70%1RM	Maximum power Maximum power Mean velocity Maximum velocity Time to peak velocity	Limits of Agreement: $0.11 \pm 13.60W$; ICC: 0.97 Limits of Agreement: $-17 \pm 96W$; ICC: 0.97 $r: 0.970$; RMSE: $0.070 \text{ m}\cdot\text{s}^{-1}$ $r: 0.933$; RMSE: $0.151 \text{ m}\cdot\text{s}^{-1}$ $r: 0.985$; RMSE: $0.026s$
	T-Force (v2.3)	Intra-device	F/W Ballistic Squat	25 kg	Mean velocity Maximum velocity Time to peak velocity	$r: 0.724$; RMSE: $0.167 \text{ m}\cdot\text{s}^{-1}$ $r: 0.810$; RMSE: $0.263 \text{ m}\cdot\text{s}^{-1}$ $r: 0.655$; RMSE: $0.045s$
Lorenzetti et al. [54]	Tendo (v4.1.0)	Intra-device	F/W Back Squat	70%1RM	Mean velocity Maximum velocity Time to peak velocity	$r: 0.963$; RMSE: $0.046 \text{ m}\cdot\text{s}^{-1}$ $r: 0.932$; RMSE: $0.194 \text{ m}\cdot\text{s}^{-1}$ $r: 0.985$; RMSE: $0.041s$
			F/W Ballistic Squat	25 kg	Mean velocity Maximum velocity Time to peak velocity	$r: 0.770$; RMSE: $0.157 \text{ m}\cdot\text{s}^{-1}$ $r: 0.860$; RMSE: $0.135 \text{ m}\cdot\text{s}^{-1}$ $r: 0.604$; RMSE: $0.064s$
	GymAware (v1.1.2)	Intra-device	F/W Back Squat	70%1RM	Mean velocity Maximum velocity Time to peak velocity	$r: 0.958$; RMSE: $0.064 \text{ m}\cdot\text{s}^{-1}$ $r: 0.957$; RMSE: $0.163 \text{ m}\cdot\text{s}^{-1}$ $r: 0.990$; RMSE: $0.042s$
			F/W Ballistic Squat	25 kg	Mean velocity Maximum velocity Time to peak velocity	$r: 0.783$; RMSE: $0.160 \text{ m}\cdot\text{s}^{-1}$ $r: 0.852$; RMSE: $0.304 \text{ m}\cdot\text{s}^{-1}$ $r: 0.701$; RMSE: $0.046s$
Martinez-Cava et al. [51]	T-Force	Inter-device	S/M Back Squat	25–95 kg	Peak velocity Mean propulsive velocity	SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.46% ; ICC: 1.000 ; $r: 0.9997$ SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.58% ; ICC: 1.000 ; $r: 0.9998$
			S/M Bench Press	25–95 kg	Mean velocity Peak velocity Mean propulsive velocity	SEM: $<0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.44% ; ICC: 1.000 ; $r: 0.9998$ SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.45% ; ICC: 1.000 ; $r: 0.9998$ SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.62% ; ICC: 1.000 ; $r: 0.9999$
	Speed4Lifts	Inter-device	S/M Back Squat	25–95 kg	Mean velocity Peak velocity Mean propulsive velocity	SEM: $<0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.55% ; ICC: 1.000 ; $r: 0.9999$ SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 0.86% ; ICC: 0.999 SEM: $0.01 \text{ m}\cdot\text{s}^{-1}$; CV: 1.24% ; ICC: 0.999
			S/M Bench Press	25–95 kg	Peak velocity Mean propulsive velocity	SEM: $0.02 \text{ m}\cdot\text{s}^{-1}$; CV: 1.54% ; ICC: 1.000 SEM: $0.02 \text{ m}\cdot\text{s}^{-1}$; CV: 1.80% ; ICC: 0.999
Muyor et al. [38]	Tendo	Intra-device	S/M Back Squat	40%1RM	Mean velocity (con) Mean velocity (ecc)	ES: 0.08 ; SEM: $0.007 \text{ m}\cdot\text{s}^{-1}$; CV: 2.00% ; ICC: 0.979 ES: 0.15 ; SEM: $0.009 \text{ m}\cdot\text{s}^{-1}$; CV: 3.65% ; ICC: 0.970
			80%1RM	Mean velocity (con) Mean velocity (ecc)	ES: 0.24 ; SEM: $0.013 \text{ m}\cdot\text{s}^{-1}$; CV: 4.28% ; ICC: 0.855 ES: 0.10 ; SEM: $0.011 \text{ m}\cdot\text{s}^{-1}$; CV: 4.55% ; ICC: 0.924	

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
Orange et al. [48]	GymAware	Intra-device	F/W Back Squat	20%IRM	Mean velocity	Standardised mean bias: 0.21; SEM: 0.05 m·s ⁻¹ ; ICC: 0.72
					Peak velocity	Standardised mean bias: 0.08; SEM: 0.09 m·s ⁻¹ ; ICC: 0.77
					Mean power	Standardised mean bias: 0.19; SEM: 102.5W; ICC: 0.79
					Peak power	Standardised mean bias: 0.04; SEM: 250.4W; ICC: 0.81
				40%IRM	Mean velocity	Standardised mean bias: 0.22; SEM: 0.04 m·s ⁻¹ ; ICC: 0.77
					Peak velocity	Standardised mean bias: 0.08; SEM: 0.07 m·s ⁻¹ ; ICC: 0.78
					Mean power	Standardised mean bias: 0.12; SEM: 79.6W; ICC: 0.82
					Peak power	Standardised mean bias: 0.02; SEM: 219.1W; ICC: 0.84
				60%IRM	Mean velocity	Standardised mean bias: 0.06; SEM: 0.04 m·s ⁻¹ ; ICC: 0.83
					Peak velocity	Standardised mean bias: 0.13; SEM: 0.06 m·s ⁻¹ ; ICC: 0.79
					Mean power	Standardised mean bias: 0.07; SEM: 73.0W; ICC: 0.81
					Peak power	Standardised mean bias: 0.04; SEM: 196.4W; ICC: 0.77
				80%IRM	Mean velocity	Standardised mean bias: 0.22; SEM: 0.03 m·s ⁻¹ ; ICC: 0.83
					Peak velocity	Standardised mean bias: 0.33; SEM: 0.06 m·s ⁻¹ ; ICC: 0.68
					Mean power	Standardised mean bias: 0.23; SEM: 76.7W; ICC: 0.79
					Peak power	Standardised mean bias: 0.43; SEM: 217.0W; ICC: 0.60
90%IRM	Mean velocity	Standardised mean bias: 0.11; SEM: 0.04 m·s ⁻¹ ; ICC: 0.79				
	Peak velocity	Standardised mean bias: 0.42; SEM: 0.06 m·s ⁻¹ ; ICC: 0.65				
	Mean power	Standardised mean bias: 0.20; SEM: 76.2W; ICC: 0.77				
	Peak power	Standardised mean bias: 0.50; SEM: 202.7W; ICC: 0.58				

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
			F/W Bench Press	20% IRM	Mean velocity	Standardised mean bias: 0.56; SEM: 0.09 m·s ⁻¹ ; ICC: 0.64
					Peak velocity	Standardised mean bias: 0.27; SEM: 0.13 m·s ⁻¹ ; ICC: 0.70
					Mean power	Standardised mean bias: 0.33; SEM: 52.8W; ICC: 0.81
					Peak power	Standardised mean bias: 0.14; SEM: 60.9W; ICC: 0.87
				40% IRM	Mean velocity	Standardised mean bias: 0.27; SEM: 0.05 m·s ⁻¹ ; ICC: 0.71
					Peak velocity	Standardised mean bias: 0.21; SEM: 0.06 m·s ⁻¹ ; ICC: 0.82
					Mean power	Standardised mean bias: 0.20; SEM: 27.4W; ICC: 0.91
					Peak power	Standardised mean bias: 0.16; SEM: 43.2W; ICC: 0.91
				60% IRM	Mean velocity	Standardised mean bias: 0.09; SEM: 0.04 m·s ⁻¹ ; ICC: 0.70
					Peak velocity	Standardised mean bias: 0.12; SEM: 0.05 m·s ⁻¹ ; ICC: 0.81
					Mean power	Standardised mean bias: 0.07; SEM: 27.1W; ICC: 0.89
					Peak power	Standardised mean bias: 0.16; SEM: 38.7W; ICC: 0.89
				80% IRM	Mean velocity	Standardised mean bias: 0.00; SEM: 0.04 m·s ⁻¹ ; ICC: 0.78
					Peak velocity	Standardised mean bias: 0.03; SEM: 0.06 m·s ⁻¹ ; ICC: 0.77
					Mean power	Standardised mean bias: 0.00; SEM: 28.2W; ICC: 0.83
					Peak power	Standardised mean bias: 0.06; SEM: 51.8W; ICC: 0.77
				90% IRM	Mean velocity	Standardised mean bias: 0.00; SEM: 0.03 m·s ⁻¹ ; ICC: 0.87
					Peak velocity	Standardised mean bias: 0.03; SEM: 0.07 m·s ⁻¹ ; ICC: 0.68
					Mean power	Standardised mean bias: 0.00; SEM: 29.6W; ICC: 0.85
					Peak power	Standardised mean bias: 0.06; SEM: 78.0W; ICC: 0.64

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings				
Perez-Castilla et al. [10]	T-Force	Intra-device	S/M Bench Press	45% IRM	Mean velocity	CV: 2.48%; ICC: 0.90				
				55% IRM	Mean velocity	CV: 1.82%; ICC: 0.95				
				65% IRM	Mean velocity	CV: 4.35%; ICC: 0.78				
				75% IRM	Mean velocity	CV: 4.78%; ICC: 0.77				
				85% IRM	Mean velocity	CV: 4.90%; ICC: 0.87				
				45% IRM	Mean velocity	CV: 2.31%; ICC: 0.87				
				55% IRM	Mean velocity	CV: 2.09%; ICC: 0.90				
				65% IRM	Mean velocity	CV: 6.24%; ICC: 0.72				
				75% IRM	Mean velocity	CV: 4.53%; ICC: 0.85				
				85% IRM	Mean velocity	CV: 5.65%; ICC: 0.86				
				45% IRM	Mean velocity	CV: 2.61%; ICC: 0.87				
				55% IRM	Mean velocity	CV: 2.39%; ICC: 0.84				
				65% IRM	Mean velocity	CV: 2.42%; ICC: 0.93				
				75% IRM	Mean velocity	CV: 3.92%; ICC: 0.81				
Stock et al. [78]	Tendo	Intra-device	F/W Bench Press	85% IRM	Mean velocity	CV: 3.41%; ICC: 0.94				
				10% IRM	Mean velocity	MD: 0.35 m·s ⁻¹ ; SEM: 4.2%; ICC: 0.717				
				20% IRM	Mean velocity	MD: 0.33 m·s ⁻¹ ; SEM: 5.0%; ICC: 0.572				
				30% IRM	Mean velocity	MD: 0.17 m·s ⁻¹ ; SEM: 3.1%; ICC: 0.805				
				40% IRM	Mean velocity	MD: 0.21 m·s ⁻¹ ; SEM: 4.7%; ICC: 0.669				
				50% IRM	Mean velocity	MD: 0.17 m·s ⁻¹ ; SEM: 4.6%; ICC: 0.790				
				60% IRM	Mean velocity	MD: 0.15 m·s ⁻¹ ; SEM: 4.8%; ICC: 0.785				
				70% IRM	Mean velocity	MD: 0.14 m·s ⁻¹ ; SEM: 5.8%; ICC: 0.811				
				80% IRM	Mean velocity	MD: 0.19 m·s ⁻¹ ; SEM: 10.3%; ICC: 0.714				
				90% IRM	Mean velocity	MD: 0.18 m·s ⁻¹ ; SEM: 12.6%; ICC: 0.564				
				40% IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 4.5%				
				50% IRM	Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 5.6%				
				Thompson et al. [24]	GymAware	Intra-device	F/W Back Squat	50% IRM	Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 3.4%
								60% IRM	Mean velocity	TE: 0.07 m·s ⁻¹ ; CV: 4.9%
70% IRM	Mean velocity	TE: 0.02 m·s ⁻¹ ; CV: 2.9%								
70% IRM	Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 6.0%								
70% IRM	Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 4.5%								
80% IRM	Peak velocity	TE: 0.10 m·s ⁻¹ ; CV: 8.3%								
80% IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 7.0%								
90% IRM	Peak velocity	TE: 0.09 m·s ⁻¹ ; CV: 8.6%								
90% IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 9.5%								
100% IRM	Peak velocity	TE: 0.09 m·s ⁻¹ ; CV: 12.6%								
100% IRM	Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 13.6%								
Full	Peak velocity	TE: 0.15 m·s ⁻¹ ; CV: 22.0%								
Full	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 9.8%								
Full	Peak velocity	TE: 0.10 m·s ⁻¹ ; CV: 11.3%								

Table 8 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable Measured	Findings
van den Tillaar and Ball [11]	Musclelab (Ergotest)	Intra-device	Power clean	40%IRM	Mean velocity	TE: 0.05 m·s ⁻¹ ; CV: 3.6%
					Peak velocity	TE: 0.09 m·s ⁻¹ ; CV: 3.7%
				50%IRM	Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 2.2%
					Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 3.7%
				60%IRM	Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 2.4%
					Peak velocity	TE: 0.07 m·s ⁻¹ ; CV: 3.1%
				70%IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 3.2%
					Peak velocity	TE: 0.05 m·s ⁻¹ ; CV: 2.5%
				80%IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 3.3%
					Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 3.8%
				90%IRM	Mean velocity	TE: 0.08 m·s ⁻¹ ; CV: 8.9%
					Peak velocity	TE: 0.07 m·s ⁻¹ ; CV: 3.9%
				100%IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 4.3%
					Peak velocity	TE: 0.06 m·s ⁻¹ ; CV: 4.0%
				Full	Mean velocity	TE: 0.05 m·s ⁻¹ ; CV: 4.9%
					Peak velocity	TE: 0.07 m·s ⁻¹ ; CV: 3.3%
50%IRM	F/W Bench Press	Intra-device	F/W Bench Press	Mean velocity	ICC: 0.98; CV: 6.6 ± 2.4%; r: 0.96	
				peak velocity	ICC: 0.98; CV: 6.9 ± 2.0%; r: 0.96	
+ 10 kg	F/W push-up	Intra-device	F/W push-up	mean velocity	ICC: 0.98; CV: 5.9 ± 1.7%; r: 0.95	
				peak velocity	ICC: 0.98; CV: 7.3 ± 3.0%; r: 0.95	
+ 10 kg	F/W push-up	Intra-device	F/W push-up	mean velocity	ICC: 0.98; CV: 5.9 ± 1.7%; r: 0.95	
				peak velocity	ICC: 0.98; CV: 7.3 ± 3.0%; r: 0.95	
+ 10 kg	F/W push-up	Intra-device	F/W push-up	mean velocity	ICC: 0.98; CV: 5.9 ± 1.7%; r: 0.95	
				peak velocity	ICC: 0.98; CV: 7.3 ± 3.0%; r: 0.95	
Body weight, 10–20–30 kg	F/W push-up	Intra-device	F/W push-up	mean velocity	ICC: 0.98; CV: 5.9 ± 1.7%; r: 0.95	
				peak velocity	ICC: 0.98; CV: 7.3 ± 3.0%; r: 0.95	
Vest	F/W push-up	Intra-device	F/W push-up	mean velocity	ICC: 0.98; CV: 5.9 ± 1.7%; r: 0.95	
				peak velocity	ICC: 0.98; CV: 7.3 ± 3.0%; r: 0.95	

IRM one repetition maximum, *T-Force* T-force linear velocity transducer, *GymAware* GymAware PowerTool, *Tendo* tendo weightlifting analyser, *CV* coefficient of variation, *TE* typical error, *S/M* Smith machine, *MD* mean difference, *r* Pearson's correlation coefficient, *ICC* intraclass correlation coefficient, *SEM* standard error of measurement, *OHP* overhead press, *PBP* prone bench pull, *RMSE* root-mean-square error

Table 9 Summary of studies that investigated the reliability of accelerometer devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Abbott et al. [59]	Bar Sensei	Intra-device	F/W Back Squat	20%IRM	Peak velocity	CV: 14.17%
					Mean velocity	CV: 18.97%
					Mean propulsive velocity	CV: 15.42%
				30%IRM	Peak velocity	CV: 12.44%
					Mean velocity	CV: 15.79%
					Mean propulsive velocity	CV: 15.73%
				40%IRM	Peak velocity	CV: 13.39%
					Mean velocity	CV: 17.58%
					Mean propulsive velocity	CV: 16.13%
				50%IRM	Peak velocity	CV: 15.38%
					Mean velocity	CV: 20.89%
					Mean propulsive velocity	CV: 17.98%
				60%IRM	Peak velocity	CV: 17.86%
					Mean velocity	CV: 19.24%
					Mean propulsive velocity	CV: 20.2%
70%IRM	Peak velocity	CV: 23.97%				
	Mean velocity	CV: 18.82%				
	Mean propulsive velocity	CV: 19.21%				
80%IRM	Peak velocity	CV: 31.43%				
	Mean velocity	CV: 25.51%				
	Mean propulsive velocity	CV: 25.71%				
90%IRM	Peak velocity	CV: 33.36%				
	Mean velocity	CV: 29.94%				
	Mean propulsive velocity	CV: 25.58%				
100%IRM	Peak velocity	CV: 43.77%				
	Mean velocity	CV: 43.02%				
	Mean propulsive velocity	CV: 34.59%				
Balsalobre-Fernández et al. [62]	PUSH Band	Intra-device	S/M Back Squat	20–70 kg	Peak velocity	CV: 6.0 ± 3.9%; ICC: 0.981; r: 0.952
					Mean velocity	CV: 5.0 ± 4.1%; ICC: 0.978; r: 0.956

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Balsalobre-Fernández et al. [69]	Beast Sensor (Wrist)	Intra-device	F/W Back Squat	50–95%IRM	Mean velocity	ICC: 0.975
			F/W Bench Press	50–95%IRM	Mean velocity	ICC: 0.977
			F/W Hip Thrust	50–95%IRM	Mean velocity	ICC: 0.952
			F/W Back Squat	50–95%IRM	Mean velocity	ICC: 0.979
Beckham et al. [28]	Beast Sensor (Barbell)	Intra-device	F/W Bench Press	50–95%IRM	Mean velocity	ICC: 0.981
			F/W Hip Thrust	50–95%IRM	Mean velocity	ICC: 0.958
			F/W Back Squat	45%IRM	Mean velocity	ICC: 0.419
				60%IRM	Peak velocity	ICC: 0.451
				75%IRM	Mean velocity	ICC: 0.171
					Peak velocity	ICC: 0.273
Courtel-Ibanez et al. [36]	Push Band	Intra-device	S/M Bench Press	20–80 kg	Mean velocity	ICC: 0.295
					Peak velocity	ICC: 0.349
					Mean velocity	SEM: 0.08 m·s ⁻¹ ; CV: 12.2%; ICC: 0.974
					Peak velocity	SEM: 0.18 m·s ⁻¹ ; CV: 13.7%; ICC: 0.962
					Mean velocity	SEM: 0.06 m·s ⁻¹ ; CV: 5.6%; ICC: 0.979
					Peak velocity	SEM: 0.09 m·s ⁻¹ ; CV: 5.9%; ICC: 0.944
					Mean velocity	CV: 9.02%; SEM: 0.03 m·s ⁻¹
					Mean propulsive velocity	CV: 11.69%; SEM: 0.04 m·s ⁻¹
					Maximum velocity	CV: 11.76%; SEM: 0.07 m·s ⁻¹
					Mean velocity	CV: 6.19%; SEM: 0.02 m·s ⁻¹
García-Pinillos et al. [61]	WIMU System	Intra-device	S/M Back Squat	20%IRM	Mean propulsive velocity	CV: 8.14%; SEM: 0.03 m·s ⁻¹
			S/M Concentric-Only Half Back Squat	10%IRM	Maximum velocity	CV: 8.45%; SEM: 0.05 m·s ⁻¹
				30%IRM	Mean velocity	CV: 11.77%; SEM: 0.11 m·s ⁻¹
					Mean propulsive velocity	CV: 12.44%; SEM: 0.03 m·s ⁻¹
				40%IRM	Maximum velocity	CV: 14.44%; SEM: 0.06 m·s ⁻¹
					Mean velocity	CV: 7.90%; SEM: 0.06 m·s ⁻¹
					Mean propulsive velocity	CV: 8.32%; SEM: 0.02 m·s ⁻¹
				50%IRM	Maximum velocity	CV: 7.48%; SEM: 0.03 m·s ⁻¹
					Mean velocity	CV: 7.86%; SEM: 0.06 m·s ⁻¹
					Mean propulsive velocity	CV: 8.99%; SEM: 0.02 m·s ⁻¹
				60%IRM	Maximum velocity	CV: 7.52%; SEM: 0.03 m·s ⁻¹
					Mean velocity	CV: 10.41%; SEM: 0.02 m·s ⁻¹
					Mean propulsive velocity	CV: 11.23%; SEM: 0.02 m·s ⁻¹
					Maximum velocity	CV: 13.62%; SEM: 0.05 m·s ⁻¹

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings				
Hughes et al. [52]	PUSH Band 2.0 (arm)	Intra-device	F/W Back Squat	70%IRM	Mean velocity	CV: 13.82%; SEM: 0.02 m·s ⁻¹				
					Mean propulsive velocity	CV: 16.75%; SEM: 0.03 m·s ⁻¹				
				80%IRM	Maximum velocity	CV: 16.80%; SEM: 0.05 m·s ⁻¹				
					Mean velocity	CV: 12.04%; SEM: 0.02 m·s ⁻¹				
					Mean propulsive velocity	CV: 13.23%; SEM: 0.02 m·s ⁻¹				
					Maximum velocity	CV: 7.18%; SEM: 0.03 m·s ⁻¹				
				90%IRM	Mean velocity	CV: 12.62%; SEM: 0.06 m·s ⁻¹				
					Mean propulsive velocity	CV: 16.47%; SEM: 0.02 m·s ⁻¹				
				100%IRM	Maximum velocity	CV: 11.77%; SEM: 0.03 m·s ⁻¹				
					Mean velocity	CV: 13.27%; SEM: 0.01 m·s ⁻¹				
								Mean propulsive velocity	CV: 14.21%; SEM: 0.01 m·s ⁻¹	
								Maximum velocity	CV: 15.66%; SEM: 0.03 m·s ⁻¹	
				Mean velocity	30%, 60%, 90%IRM ICC: 0.89, 0.86, 0.85; CV: 1.6%, 4.6%, 5.5%					
Lake et al. [29]	PUSH Band 2.0 (bar)	Intra-device	F/W Bench Press	30–90%IRM	Mean velocity	ICC: 0.94, 0.90, 0.88; CV: 0.8%, 1.6%, 2.5%				
					Mean velocity	ICC: 0.84, 0.88, 0.85; CV: 1.3%, 1.2%, 2.0%				
				30–90%IRM	Mean velocity	ICC: 0.67, 0.88, 0.75; CV: 3.3%, 3.7%, 4.2%				
					Mean velocity	ICC: 0.86, 0.94, 0.85; CV: 1.3%, 3.3%, 6.9%				
					Mean velocity	ICC: 0.83, 0.85, 0.95; CV: 1.1%, 2.4%, 4.2%				
					Mean velocity	ICC: 0.80, 0.94, 0.75; CV: 2.1%, 1.5%, 2.3%				
				30–90%IRM	Mean velocity	ICC: 0.80, 0.80, 0.75; CV: 2.1%, 5.1%, 3.2%				
					Mean velocity	ICC: 0.81, 0.80, 0.85; CV: 1.9%, 5.1%, 7.1%				
								Mean velocity	ICC: 0.84, 0.88, 0.80; CV: 1.5%, 0.7%, 3.8%	
								Mean velocity	ICC: 0.58, 0.75, 0.72; CV: 3.2%, 3.8%, 5.7%	
				Lorenzetti et al. [54]	MyoTest	Intra-device	F/W Ballistic Squat	30–90%IRM	Mean velocity	ICC: 0.87, 0.93, 0.80; CV: 1.7%, 4.6%, 6.5%
									Mean velocity	ICC: 0.88, 0.74, 0.75; CV: 1.2%, 3.5%, 3.8%
60%IRM	Peak velocity	ICC: 0.86, 0.81, 0.65; CV: 1.8%, 3.0%, 4.2%								
	Peak velocity	ICC: 0.947; CV: 4.2%								
90%IRM	Mean velocity	ICC: 0.937; CV: 5.8%								
	Peak velocity	ICC: 0.957; CV: 4.7%								
Garcia-Mateo [63]	RehaGait	Inter-device	F/W Squat with arms extended	25 kg	Mean velocity	r: 0.610				
					Maximum velocity	r: 0.552				
					Time to peak velocity	r: 0.700				
				Mean velocity	MD ± SD: 0.046 ± 0.052 m·s ⁻¹					

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Muyor et al. [38]	WIMU	Intra-device	S/M Back Squat	40%IRM	Mean velocity (com)	ES: 0.00; SEM: 0.007 m·s ⁻¹ ; CV: 2.60%; ICC: 0.976
				80%IRM	Mean velocity (ecc)	ES: 0.06; SEM: 0.013 m·s ⁻¹ ; CV: 3.79%; ICC: 0.955
					Mean velocity (com)	ES: 0.00; SEM: 0.011 m·s ⁻¹ ; CV: 3.53%; ICC: 0.905
					Mean velocity (ecc)	ES: 0.11; SEM: 0.010 m·s ⁻¹ ; CV: 4.51%; ICC: 0.924
Orange et al. [47]	PUSH Band (arm)	Intra-device	F/W Back Squat	20%IRM	Mean velocity	SEM: 0.08 m·s ⁻¹ ; ICC: 0.68
					Peak velocity	SEM: 0.12 m·s ⁻¹ ; ICC: 0.71
					Mean power	SEM: 128.3W; ICC: 0.82
					Peak power	SEM: 261.2W; ICC: 0.80
				40%IRM	Mean velocity	SEM: 0.07 m·s ⁻¹ ; ICC: 0.62
					Peak velocity	SEM: 0.18 m·s ⁻¹ ; ICC: 0.25
					Mean power	SEM: 121.5W; ICC: 0.67
					Peak power	SEM: 345.8W; ICC: 0.66
				60%IRM	Mean velocity	SEM: 0.06 m·s ⁻¹ ; ICC: 0.64
					Peak velocity	SEM: 0.11 m·s ⁻¹ ; ICC: 0.55
					Mean power	SEM: 105.9W; ICC: 0.58
					Peak power	SEM: 279.4W; ICC: 0.67
				80%IRM	Mean velocity	SEM: 0.06 m·s ⁻¹ ; ICC: 0.60
					Peak velocity	SEM: 0.11 m·s ⁻¹ ; ICC: 0.44
				90%IRM	Mean power	SEM: 129.5W; ICC: 0.37
					Peak power	SEM: 345.4W; ICC: 0.27
	Mean velocity	SEM: 0.06 m·s ⁻¹ ; ICC: 0.36				
	Peak velocity	SEM: 0.12 m·s ⁻¹ ; ICC: 0.66				
	Mean power	SEM: 117.0W; ICC: 0.41				
	Peak power	SEM: 359.5W; ICC: 0.34				
PUSH Band (arm)	PUSH Band (arm)	Intra-device	F/W Bench Press	20%IRM	Mean velocity	SEM: 0.11 m·s ⁻¹ ; ICC: 0.28
					Peak velocity	SEM: 0.21 m·s ⁻¹ ; ICC: 0.27
					Mean power	SEM: 70.6W; ICC: 0.43
					Peak power	SEM: 221.9W; ICC: 0.63
					Mean velocity	SEM: 0.08 m·s ⁻¹ ; ICC: 0.60
					Peak velocity	SEM: 0.11 m·s ⁻¹ ; ICC: 0.66
					Mean power	SEM: 33.8W; ICC: 0.83
					Peak power	SEM: 151.0W; ICC: 0.89
				60%IRM	Mean velocity	SEM: 0.08 m·s ⁻¹ ; ICC: 0.58
					Peak velocity	SEM: 0.12 m·s ⁻¹ ; ICC: 0.58
					Mean power	SEM: 51.6W; ICC: 0.69
					Peak power	SEM: 273.0W; ICC: 0.38

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Perez-Castilla et al. [10]	PUSH Band (arm)	Intra-device	F/W Bench Press	80%IRM	Mean velocity	SEM: 0.06 m·s ⁻¹ ; ICC: 0.51
					Peak velocity	SEM: 0.08 m·s ⁻¹ ; ICC: 0.47
	F/W Bench Press			90%IRM	Mean power	SEM: 51.3W; ICC: 0.58
					Peak power	SEM: 137.5W; ICC: 0.55
					Mean velocity	SEM: 0.05 m·s ⁻¹ ; ICC: 0.37
					Peak velocity	SEM: 0.10 m·s ⁻¹ ; ICC: 0.40
					Mean power	SEM: 45.7W; ICC: 0.67
					Peak power	SEM: 131.9W; ICC: 0.59
					Mean velocity	CV: 5.02%; ICC: 0.69
					Mean velocity	CV: 7.84%; ICC: 0.46
					Mean velocity	CV: 9.34%; ICC: 0.78
					Mean velocity	CV: 14.6%; ICC: 0.50
					Mean velocity	CV: 19.1%; ICC: 0.47
					Mean velocity	CV: 33.4%; ICC: 0.29
				Mean velocity	CV: 24.2%; ICC: 0.64	
				Mean velocity	CV: 35.0%; ICC: 0.30	
				Mean velocity	CV: 40.2%; ICC: 0.31	
				Mean velocity	CV: 54.9%; ICC: 0.27	
Thompson et al. [24]	PUSH Band (body)	Intra-device	F/W Back Squat	40%IRM	Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 3.5%
					Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 6.0%
					Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 4.1%
					Peak velocity	TE: 0.07 m·s ⁻¹ ; CV: 9.9%
					Mean velocity	TE: 0.02 m·s ⁻¹ ; CV: 5.4%
					Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 9.1%
					Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 5.0%
					Peak velocity	TE: 0.10 m·s ⁻¹ ; CV: 8.9%
					Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 5.2%
					Peak velocity	TE: 0.09 m·s ⁻¹ ; CV: 6.8%
				Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 15.6%	
				Peak velocity	TE: 0.09 m·s ⁻¹ ; CV: 11.0%	
				Mean velocity	TE: 0.03 m·s ⁻¹ ; CV: 14.9%	
				Peak velocity	TE: 0.15 m·s ⁻¹ ; CV: 11.4%	
				Mean velocity	TE: 0.04 m·s ⁻¹ ; CV: 10.6%	
				Peak velocity	TE: 0.10 m·s ⁻¹ ; CV: 11.3%	
				Mean velocity	TE: 0.06 m·s ⁻¹ ; CV: 4.9%	
				Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 4.9%	
				Mean velocity	TE: 0.06 m·s ⁻¹ ; CV: 5.2%	
				Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 5.2%	
				Mean velocity	TE: 0.05 m·s ⁻¹ ; CV: 4.5%	
				Peak velocity	TE: 0.08 m·s ⁻¹ ; CV: 4.5%	

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
				70%IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 7.7%
				80%IRM	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 7.7%
				80%IRM	Mean velocity	TE: 0.10 ms ⁻¹ ; CV: 10.2%
				90%IRM	Peak velocity	TE: 0.14 ms ⁻¹ ; CV: 10.2%
				90%IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 11.3%
				100%IRM	Peak velocity	TE: 0.13 ms ⁻¹ ; CV: 11.3%
				100%IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 11.4%
				Full	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 11.4%
				Full	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 8.3%
				40%IRM	Peak velocity	TE: 0.11 ms ⁻¹ ; CV: 8.3%
				40%IRM	Mean velocity	TE: 0.06 ms ⁻¹ ; CV: 5.2%
				50%IRM	Peak velocity	TE: 0.09 ms ⁻¹ ; CV: 5.7%
				50%IRM	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 9.2%
				60%IRM	Peak velocity	TE: 0.10 ms ⁻¹ ; CV: 7.5%
				60%IRM	Mean velocity	TE: 0.05 ms ⁻¹ ; CV: 5.1%
				70%IRM	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 9.4%
				70%IRM	Mean velocity	TE: 0.04 ms ⁻¹ ; CV: 5.9%
				80%IRM	Peak velocity	TE: 0.09 ms ⁻¹ ; CV: 8.3%
				80%IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 14.3%
				90%IRM	Peak velocity	TE: 0.09 ms ⁻¹ ; CV: 8.8%
				90%IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 20.3%
				100%IRM	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 14.2%
				100%IRM	Mean velocity	TE: 0.06 ms ⁻¹ ; CV: 15.4%
				Full	Peak velocity	TE: 0.09 ms ⁻¹ ; CV: 11.6%
				Full	Mean velocity	TE: 0.07 ms ⁻¹ ; CV: 14.5%
				40%IRM	Peak velocity	TE: 0.11 ms ⁻¹ ; CV: 11.0%
				40%IRM	Mean velocity	TE: 0.20 ms ⁻¹ ; CV: 21.5%
				50%IRM	Peak velocity	TE: 0.36 ms ⁻¹ ; CV: 21.5%
				50%IRM	Mean velocity	TE: 0.18 ms ⁻¹ ; CV: 19.0%
				60%IRM	Peak velocity	TE: 0.33 ms ⁻¹ ; CV: 17.9%
				60%IRM	Mean velocity	TE: 0.17 ms ⁻¹ ; CV: 18.9%
				70%IRM	Peak velocity	TE: 0.42 ms ⁻¹ ; CV: 25.4%
				70%IRM	Mean velocity	TE: 0.13 ms ⁻¹ ; CV: 14.6%
				80%IRM	Peak velocity	TE: 0.22 ms ⁻¹ ; CV: 13.4%
				80%IRM	Mean velocity	TE: 0.14 ms ⁻¹ ; CV: 16.3%
				90%IRM	Peak velocity	TE: 0.25 ms ⁻¹ ; CV: 15.6%
				90%IRM	Mean velocity	TE: 0.15 ms ⁻¹ ; CV: 18.1%
				100%IRM	Peak velocity	TE: 0.31 ms ⁻¹ ; CV: 22.2%
				100%IRM	Mean velocity	TE: 0.10 ms ⁻¹ ; CV: 13.3%
				100%IRM	Peak velocity	TE: 0.23 ms ⁻¹ ; CV: 17.5%

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Bar Sensei		Intra-device	F/W Back Squat	Full	Mean velocity	TE: 0.21 ms ⁻¹ ; CV: 18.6%
				40% IRM	Peak velocity	TE: 0.32 ms ⁻¹ ; CV: 20.5%
				50% IRM	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 9.1%
				50% IRM	Peak velocity	TE: 0.14 ms ⁻¹ ; CV: 9.4%
				50% IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 13.5%
				60% IRM	Peak velocity	TE: 0.10 ms ⁻¹ ; CV: 7.6%
				60% IRM	Mean velocity	TE: 0.07 ms ⁻¹ ; CV: 8.8%
				70% IRM	Peak velocity	TE: 0.08 ms ⁻¹ ; CV: 8.0%
				70% IRM	Mean velocity	TE: 0.07 ms ⁻¹ ; CV: 10.7% TE: 0.07 ms ⁻¹ ; CV: 10.7%
				80% IRM	Peak velocity	TE: 0.09 ms ⁻¹ ; CV: 10.2%
Beast Sensor		Intra-device	F/W Back Squat	80% IRM	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 18.3%
				90% IRM	Peak velocity	TE: 0.24 ms ⁻¹ ; CV: 35.8%
				90% IRM	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 19.1%
				100% IRM	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 18.0%
				100% IRM	Mean velocity	TE: 0.13 ms ⁻¹ ; CV: 60.5%
				Full	Peak velocity	TE: 0.12 ms ⁻¹ ; CV: 28.5%
				40% IRM	Mean velocity	TE: 0.09 ms ⁻¹ ; CV: 22.1%
				40% IRM	Peak velocity	TE: 0.13 ms ⁻¹ ; CV: 18.7%
				50% IRM	Mean velocity	TE: 0.23 ms ⁻¹ ; CV: 20.4%
				50% IRM	Peak velocity	TE: 0.20 ms ⁻¹ ; CV: 7.7%
Power Clean				50% IRM	Mean velocity	TE: 0.16 ms ⁻¹ ; CV: 13.8%
				60% IRM	Peak velocity	TE: 0.15 ms ⁻¹ ; CV: 6.5%
				60% IRM	Mean velocity	TE: 0.13 ms ⁻¹ ; CV: 12.1%
				70% IRM	Peak velocity	TE: 0.13 ms ⁻¹ ; CV: 5.8%
				70% IRM	Mean velocity	TE: 0.13 ms ⁻¹ ; CV: 11.8%
				80% IRM	Peak velocity	TE: 0.19 ms ⁻¹ ; CV: 8.8% TE: 0.19 ms ⁻¹ ; CV: 8.8%
				80% IRM	Mean velocity	8.8%
				90% IRM	Peak velocity	TE: 0.13 ms ⁻¹ ; CV: 14.9%
				90% IRM	Mean velocity	TE: 0.13 ms ⁻¹ ; CV: 6.1%
				100% IRM	Peak velocity	TE: 0.15 ms ⁻¹ ; CV: 17.7%
Power Clean				100% IRM	Peak velocity	TE: 0.14 ms ⁻¹ ; CV: 7.9%
				100% IRM	Mean velocity	TE: 0.14 ms ⁻¹ ; CV: 18.4%
				Full	Peak velocity	TE: 0.15 ms ⁻¹ ; CV: 8.5%
				40% IRM	Mean velocity	TE: 0.16 ms ⁻¹ ; CV: 15.9%
				40% IRM	Peak velocity	TE: 0.17 ms ⁻¹ ; CV: 8.7%
				50% IRM	Mean velocity	TE: 0.05 ms ⁻¹ ; CV: 20.4%
				50% IRM	Peak velocity	TE: 0.10 ms ⁻¹ ; CV: 7.7%
				50% IRM	Mean velocity	TE: 0.06 ms ⁻¹ ; CV: 13.8%
				50% IRM	Peak velocity	TE: 0.11 ms ⁻¹ ; CV: 6.5%

Table 9 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings			
van den Tillaar and Ball [11]	PUSH Band (arm)	Intra-device	F/W Bench Press	60%IRM	Mean velocity	TE: 0.08 ms ⁻¹ ; CV: 12.1%			
					Peak velocity	TE: 0.15 ms ⁻¹ ; CV: 5.8%			
				70%IRM	Mean velocity	TE: 0.12 ms ⁻¹ ; CV: 11.8%			
					Peak velocity	TE: 0.27 ms ⁻¹ ; CV: 8.8%			
				80%IRM	Mean velocity	TE: 0.22 ms ⁻¹ ; CV: 14.9%			
					Peak velocity	TE: 0.33 ms ⁻¹ ; CV: 6.1%			
				90%IRM	Mean velocity	TE: 0.21 ms ⁻¹ ; CV: 17.7%			
					Peak velocity	TE: 0.48 ms ⁻¹ ; CV: 7.9%			
				100%IRM	Mean velocity	TE: 0.15 ms ⁻¹ ; CV: 18.4%			
					Peak velocity	TE: 0.29 ms ⁻¹ ; CV: 8.5%			
				Full	Mean velocity	TE: 0.14 ms ⁻¹ ; CV: 15.9%			
					Peak velocity	TE: 0.30 ms ⁻¹ ; CV: 8.7%			
				50%IRM	Mean velocity	ICC: 0.95; CV: 12.8 ± 2.4%; r: 0.87			
					Peak velocity	ICC: 0.92; CV: 13.3 ± 2.3%; r: 0.81			
				+10 kg	Body Weight, 10–20–30 kg	Vest	F/W push-up	Mean velocity	ICC: 0.98; CV: 6.6 ± 1.3%; r: 0.95
								Peak velocity	ICC: 0.98; CV: 6.6 ± 1.3%; r: 0.94

IRM one repetition maximum, MV mean concentric velocity, CV coefficient of variation, S/M Smith machine, r Pearson’s correlation coefficient, ICC intraclass correlation coefficient, SEM standard error of measurement, OHP overhead press, RMSE root-mean-square error

Table 10 Summary of studies that investigated the reliability of mobile phone and tablet applications used to measure kinetic and kinematic variables during resistance training

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Balsalobre-Fernández et al. [69]	PowerLift (v4.0)	Intra-device	F/W Back Squat F/W Bench Press F/W Hip Thrust	50–95%IRM 50–95%IRM 50–95%IRM	Mean velocity Mean velocity Mean velocity	ICC: 0.981 ICC: 0.974 ICC: 0.961
Balsalobre-Fernández et al. [70]	PowerLift (v2.8)	Intra-observer	F/W Bench Press	75–100%IRM	Mean velocity	MD: $-0.0007 \pm 0.02 \text{ m}\cdot\text{s}^{-1}$
Courel-Ibanez et al. [36]	PowerLift App (v4.0)	Inter-device	S/M Bench Press	20–80 kg	Mean velocity	SEM: $0.08 \text{ m}\cdot\text{s}^{-1}$; CV: 10.4%; ICC: 0.973
	PowerLift App (v4.0)	Intra-device	S/M Back Squat S/M Bench Press	20–80 kg 20–80 kg	Mean velocity Mean velocity	SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 6.0%; ICC: 0.974 SEM: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 6.7%; ICC: 0.988
Martinez-Cava et al. [51]	My Lift (v8.1 iOS)	Inter-device	S/M Back Squat S/M Bench Press	20–80 kg 25–95 kg	Mean velocity Peak velocity	SEM: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 4.6%; ICC: 0.986 SEM: $0.08 \text{ m}\cdot\text{s}^{-1}$; CV: 5.79%; ICC: 0.993
Perez-Castilla et al. [10]	PowerLift (v6.0.1)	Intra-device	S/M Bench Press	25–95 kg 45%IRM	Peak velocity Mean velocity	SEM: $0.08 \text{ m}\cdot\text{s}^{-1}$; CV: 5.02%; ICC: 0.972 CV: 2.85%; ICC: 0.84
				55%IRM 65%IRM 75%IRM	Mean velocity Mean velocity Mean velocity	CV: 3.97%; ICC: 0.85 CV: 4.91%; ICC: 0.74 CV: 3.69%; ICC: 0.87
Thompson et al. [24]	MyLift (PowerLift at time of data collection)	Intra-device	F/W Back Squat	85%IRM 40%IRM 50%IRM 60%IRM 70%IRM 80%IRM 90%IRM 100%IRM	Mean velocity Mean velocity Mean velocity Mean velocity Mean velocity Mean velocity Mean velocity Mean velocity	CV: 4.97%; ICC: 0.85 TE: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 4.2% TE: $0.03 \text{ m}\cdot\text{s}^{-1}$; CV: 3.7% TE: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 5.5% TE: $0.03 \text{ m}\cdot\text{s}^{-1}$; CV: 4.9% TE: $0.04 \text{ m}\cdot\text{s}^{-1}$; CV: 6.8% TE: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 12.6% TE: $0.03 \text{ m}\cdot\text{s}^{-1}$; CV: 13.8% TE: $0.05 \text{ m}\cdot\text{s}^{-1}$; CV: 9.7%
				Full	Mean velocity	

IRM one repetition maximum, CV coefficient of variation, S/M Smith machine, MD mean difference, ICC intraclass correlation coefficient, SEM standard error of measurement, TE typical error

Table 11 Summary of studies that investigated the reliability of optic devices used to measure kinetic and kinematic variables during resistance training

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Courel-Ibanez et al. [36]	Velowin	Inter-device	S/M Bench Press	20–80 kg	Mean velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.5%; ICC: 0.997
					Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.4%; ICC: 0.997
		Intra-device	S/M Prone Bench Pull	20–80 kg	Peak velocity	SEM: 0.03 m·s ⁻¹ ; CV: 2.1%; ICC: 0.999
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.6%; ICC: 0.995
					Mean propulsive velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.5%; ICC: 0.995
					Peak velocity	SEM: 0.06 m·s ⁻¹ ; CV: 3.2%; ICC: 0.998
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 4.0%; ICC: 0.997
					Mean propulsive velocity	SEM: 0.03 m·s ⁻¹ ; CV: 3.2%; ICC: 0.998
		Intra-device	S/M Back Squat	20–80 kg	Peak velocity	SEM: 0.04 m·s ⁻¹ ; CV: 2.6%; ICC: 0.998
					Mean velocity	SEM: 0.04 m·s ⁻¹ ; CV: 3.7%; ICC: 0.988
Intra-device	S/M Prone Bench Pull	20–80 kg	Mean propulsive velocity	SEM: 0.06 m·s ⁻¹ ; CV: 4.6%; ICC: 0.987		
			Peak velocity	SEM: 0.07 m·s ⁻¹ ; CV: 3.5%; ICC: 0.983		
Peña Garcia-Orea et al. [82]	Velowin (v.1.7.232)	Intra-device	S/M Squat	20 kg	Mean velocity	SEM: 0.06 m·s ⁻¹ ; CV: 3.9%; ICC: 0.994
					Mean propulsive velocity	SEM: 0.06 m·s ⁻¹ ; CV: 3.9%; ICC: 0.994
		Intra-device	S/M Squat	20 kg	Peak velocity	SEM: 0.06 m·s ⁻¹ ; CV: 2.6%; ICC: 0.998
					Mean velocity	ICC: 0.95; CV: 3.35%; SEM: 0.225 m·s ⁻¹
					Mean propulsive velocity	ICC: 0.96; CV: 3.29%; SEM: 0.287 m·s ⁻¹
					Peak velocity	ICC: 0.95; CV: 2.89%; SEM: 0.399 m·s ⁻¹
					Mean velocity	ICC: 0.97; CV: 2.20%; SEM: 0.227 m·s ⁻¹
					Mean propulsive velocity	ICC: 0.97; CV: 2.45%; SEM: 0.284 m·s ⁻¹
		Intra-device	S/M Squat	40 kg	Peak velocity	ICC: 0.97; CV: 2.46%; SEM: 0.373 m·s ⁻¹
					Mean velocity	ICC: 0.99; CV: 2.13%; SEM: 0.248 m·s ⁻¹
Mean propulsive velocity	ICC: 0.99; CV: 2.30%; SEM: 0.306 m·s ⁻¹					
Peak velocity	ICC: 0.98; CV: 2.29%; SEM: 0.363 m·s ⁻¹					
Intra-device	S/M Squat	50 kg	Mean velocity	ICC: 0.98; CV: 2.82%; SEM: 0.276 m·s ⁻¹		
			Mean propulsive velocity	ICC: 0.99; CV: 2.98%; SEM: 0.337 m·s ⁻¹		
			Peak velocity	ICC: 0.98; CV: 2.56%; SEM: 0.362 m·s ⁻¹		
			Mean velocity	ICC: 0.99; CV: 2.46%; SEM: 0.272 m·s ⁻¹		
Intra-device	S/M Squat	60 kg	Mean propulsive velocity	ICC: 0.99; CV: 2.62%; SEM: 0.316 m·s ⁻¹		
			Peak velocity	ICC: 0.98; CV: 2.39%; SEM: 0.313 m·s ⁻¹		
Intra-device	S/M Squat	70 kg	Mean velocity	ICC: 0.99; CV: 2.55%; SEM: 0.243 m·s ⁻¹		
			Mean propulsive velocity	ICC: 0.99; CV: 2.79%; SEM: 0.280 m·s ⁻¹		
Intra-device	S/M Squat	70 kg	Peak velocity	ICC: 0.98; CV: 2.30%; SEM: 0.269 m·s ⁻¹		
			Peak velocity	ICC: 0.98; CV: 2.30%; SEM: 0.269 m·s ⁻¹		

Table 11 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Peña Garcia-Orea et al. [72]	Velowin (v1.7.232)	Intra-device	S/M Loaded Countermovement Jump	3.5 kg	Mean velocity	ICC: 0.98; CV: 2.41%; SEM: 0.0025 m·s ⁻¹
					Peak velocity	ICC: 0.98; CV: 1.77%; SEM: 0.0021 m·s ⁻¹
				13.5 kg	Mean velocity	ICC: 0.97; CV: 1.70%; SEM: 0.0021 m·s ⁻¹
					Peak velocity	ICC: 0.99; CV: 1.68%; SEM: 0.0014 m·s ⁻¹
				23.5 kg	Mean velocity	ICC: 0.95; CV: 2.56%; SEM: 0.0033 m·s ⁻¹
					Peak velocity	ICC: 0.97; CV: 2.38%; SEM: 0.0023 m·s ⁻¹
				33.5 kg	Mean velocity	ICC: 0.98; CV: 1.87%; SEM: 0.0022 m·s ⁻¹
					Peak velocity	ICC: 0.99; CV: 1.60%; SEM: 0.0018 m·s ⁻¹
				43.5 kg	Mean velocity	ICC: 0.99; CV: 2.03%; SEM: 0.0040 m·s ⁻¹
					Peak velocity	ICC: 0.99; CV: 1.57%; SEM: 0.0027 m·s ⁻¹
Garcia-Ramos et al. [71]	Velowin	Intra-device	F/W Back Squat	20 kg	Mean velocity	SEM: 0.045 m·s ⁻¹ ; CV: 4.29%; ICC: 0.91
					Mean propulsive velocity	SEM: 0.054 m·s ⁻¹ ; CV: 4.61%; ICC: 0.90
				40 kg	Maximum velocity	SEM: 0.088 m·s ⁻¹ ; CV: 4.77%; ICC: 0.92
					Mean velocity	SEM: 0.041 m·s ⁻¹ ; CV: 4.34%; ICC: 0.92
				50 kg	Mean propulsive velocity	SEM: 0.047 m·s ⁻¹ ; CV: 4.60%; ICC: 0.91
					Maximum velocity	SEM: 0.085 m·s ⁻¹ ; CV: 5.01%; ICC: 0.91
				60 kg	Mean velocity	SEM: 0.033 m·s ⁻¹ ; CV: 3.74%; ICC: 0.90
					Mean propulsive velocity	SEM: 0.043 m·s ⁻¹ ; CV: 4.50%; ICC: 0.88
				70 kg	Maximum velocity	SEM: 0.050 m·s ⁻¹ ; CV: 3.04%; ICC: 0.95
					Mean velocity	SEM: 0.039 m·s ⁻¹ ; CV: 4.75%; ICC: 0.89
85% 1RM	Mean propulsive velocity	SEM: 0.037 m·s ⁻¹ ; CV: 4.20%; ICC: 0.92				
	Maximum velocity	SEM: 0.069 m·s ⁻¹ ; CV: 4.44%; ICC: 0.91				
Perez-Castilla et al. [10]	Velowin	Intra-device	S/M Bench Press	45% 1RM	Mean velocity	SEM: 0.031 m·s ⁻¹ ; CV: 4.12%; ICC: 0.93
					Mean propulsive velocity	SEM: 0.041 m·s ⁻¹ ; CV: 5.15%; ICC: 0.90
				55% 1RM	Maximum velocity	SEM: 0.053 m·s ⁻¹ ; CV: 3.57%; ICC: 0.95
					Mean velocity	CV: 2.89%; ICC: 0.83
				65% 1RM	Mean velocity	CV: 3.27%; ICC: 0.79
					Mean velocity	CV: 3.99%; ICC: 0.83
				75% 1RM	Mean velocity	CV: 6.01%; ICC: 0.68
					Mean velocity	CV: 7.64%; ICC: 0.69

Table 11 (continued)

Study	Device	Reliability	Exercise	Intensity/load	Variable measured	Findings
Weakley et al. [22]	FLEX (technological and biological error)	Inter-device	F/W Back Squat	20–100%IRM	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.070 m·s ⁻¹ ; CV: 9.82%
			F/W Bench Press	20–100%IRM	Mean velocity	MD: 0.01 m·s ⁻¹ ; TE: 0.064 m·s ⁻¹ ; CV: 9.83%
	FLEX	Inter-device	Calibrated rig	0.53 ± 0.27 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.017 m·s ⁻¹ ; CV: 3.96%
				0.99 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.01 m·s ⁻¹ ; TE: 0.041 m·s ⁻¹ ; CV: 4.17%
				0.84 ± 0.00 m·s ⁻¹	Mean velocity	MD: - 0.01 m·s ⁻¹ ; TE: 0.06 m·s ⁻¹ ; CV: 7.10%
				0.78 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.019 m·s ⁻¹ ; CV: 2.41%
				0.71 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.016 m·s ⁻¹ ; CV: 2.28%
				0.60 ± 0.00 m·s ⁻¹	Mean velocity	MD: - 0.01 m·s ⁻¹ ; TE: 0.02 m·s ⁻¹ ; CV: 3.37%
				0.54 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.016 m·s ⁻¹ ; CV: 2.99%
				0.47 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.013 m·s ⁻¹ ; CV: 2.71%
				0.38 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.013 m·s ⁻¹ ; CV: 3.49%
				0.28 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.016 m·s ⁻¹ ; CV: 5.73%
				0.17 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.006 m·s ⁻¹ ; CV: 3.81%
				0.09 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.002 m·s ⁻¹ ; CV: 2.43%
				0.53 ± 0.27 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.016 m·s ⁻¹ ; CV: 3.77%
				0.99 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.032 m·s ⁻¹ ; CV: 3.28%
				0.84 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.01 m·s ⁻¹ ; TE: 0.043 m·s ⁻¹ ; CV: 5.11%
				0.78 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.021 m·s ⁻¹ ; CV: 2.71%
				0.71 ± 0.00 m·s ⁻¹	Mean velocity	MD: - 0.01 m·s ⁻¹ ; TE: 0.020 m·s ⁻¹ ; CV: 2.81%
				0.60 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.023 m·s ⁻¹ ; CV: 3.82%
0.54 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.017 m·s ⁻¹ ; CV: 3.19%				
0.47 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.014 m·s ⁻¹ ; CV: 3.01%				
0.38 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.013 m·s ⁻¹ ; CV: 3.42%				
0.28 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.016 m·s ⁻¹ ; CV: 5.93%				
0.17 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.006 m·s ⁻¹ ; CV: 3.64%				
0.09 ± 0.00 m·s ⁻¹	Mean velocity	MD: 0.00 m·s ⁻¹ ; TE: 0.003 m·s ⁻¹ ; CV: 2.89%				

IRM one repetition maximum, CV coefficient of variation, TE typical error, SM Smith machine, MD mean difference, ICC intraclass correlation coefficient, SEM standard error of measurement

Accelerometer devices have shown promise, but the accuracy of these devices is still questionable [29, 37, 69]. Additionally, these devices are often validated against linear transducers which may introduce additional error that impacts the assessment of accuracy for the device [36, 38, 52, 61, 70]. Of the accelerometer devices, only the Push versions 1.0 and 2.0 [29, 37] and Beast Sensor [9] have been directly compared to a gold-standard criterion during free-weight exercises. Of these three devices, the Push 2.0 may have the greatest accuracy. However, it should be acknowledged that mean velocity from this device has been questioned [29], which limits its application to resistance training as this metric is widely recommended for use during non-ballistic exercises [12, 64, 65]. Finally, of the non-linear transducer and accelerometer devices, it appears that smart phone and tablet apps may be an alternative for a quick ‘snap-shot’ of training intensity, but substantial inter-device error may exist. Therefore, unless monitoring is done by a single individual with the same device, accurate tracking of performance may be limited [23, 36]. Nevertheless, the use of optic laser devices is a promising alternative that can provide accurate, real-time feedback [22]. While further research is still warranted on additional variables (e.g., peak velocity), this provides an additional cost-effective method for monitoring resistance training.

Declarations

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Availability of data and materials All data and materials reported in this systematic review are from peer-reviewed publications. All of the extracted data are included in the manuscript and supplementary files.

Author’s contributions JW, MC, and MM conceptualized the review and criteria. JW, MM, and RJ completed the screening and data extraction of all data within this manuscript. AGR, LJ, and MM created the tables. JW, MC, AGR, LJ, and RJ completed the writing of the manuscript. All authors reviewed and refined the manuscript.

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