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A Methodological Systematic Review on Velocity-Based Training in Youth Athletes

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ABSTRACT

Velocity-Based Training (VBT) supports resistance training (RT) load prescription and monitors changes in neuromuscular function, particularly fatigue. Youth athletes (<20 years) experience various stressors affecting their neurological state and performance. Maturation impacts movement variability, suggesting VBT could offer a more objective monitoring method. This review evaluates VBT methodologies in youth athletes and addresses misconceptions, providing practice recommendations. A systematic review following PRISMA guidelines included a search of PubMed, Scopus, and SPORTDiscus. Studies were screened for eligibility with Covidence systematic review software, requiring original research, English full-text articles, and publication before March 2024, focusing on VBT in youth athletes. Out of 3,363 studies identified, 23 met the inclusion criteria. Findings show that visual feedback on velocity during RT enhances performance, motivation, and competitiveness among older youth athletes. The two-point load-velocity profile (LVP) method and group mean velocity-based one repetition maximum (1RM) were found to be more time-efficient and less fatiguing than the multiple-loads method for estimating 1RM, though they reduced prediction accuracy (differences between predicted and actual 1RM ranged from 4.7 ± 11.7 kg). This review highlights the need for further research to validate VBT feedback, refine 1RM prediction methods, and assess velocity loss thresholds in younger athletes.

Keywords: Feedback; Load velocity profiling; 1RM prediction; Adolescents; Resistance training.

INTRODUCTION

It is well established that athletes require resistance training (RT) for the development of strength [118, 119, 125], power [59, 77], speed [16, 31, 59], and lean body mass [76, 79]. Therefore, one of the primary goals of a strength and conditioning program should be to enhance sports performance [53], while reducing the likelihood of injury through the development of these physical attributes [63]. Traditionally, to develop these qualities coaches will utilize percentage-based training (i.e., percentage of 1 repetition maximum (%1RM)) to prescribe training loads relative to an individual's maximal ability [9, 78, 136]. The value of the one repetition maximum (1RM) represents the maximal load (mass) that the athlete can lift for no more than one single concentric dynamic action with good form [9, 55]. Coaches then use this relative load to assign a specific number of sets and repetitions to target various physical qualities in line with the training goal for the purpose of improving sporting performance [9, 55].

Recent evidence suggests that maximal strength exhibits considerable stability [55, 57, 58, 122], challenging one of the foundational premises of Velocity-Based Training (VBT)—the necessity to adjust for day-to-day fluctuations in athletic performance [56]. This stability implies a diminished need for frequent 1RM reassessments, particularly among adult athletes or those with established strength levels [55]. However, the landscape shifts when considering youth athletes, who undergo rapid physiological and neuromuscular transformations due to growth [91, 110]. This demographic, characterized by "motor awkwardness" [2, 27], and faster adaptations to RT [96], may potentially benefit from more frequent strength level reassessments, whether direct or predictive.

While the argument for VBT, predicated on the presumed volatility of maximal strength, may waver under scrutiny, VBT still harbors potential, especially for the developmental youth athlete. This methodology, when applied with an understanding of its limitations and the unique context of growth and maturation, can be a valuable instrument in individualizing and managing the development of youth athletes. It is also well established that the number of repetitions that can be performed with a proportion of 1RM differs between athletes with varied relative strength and training experience, and thus, assigning the same set and repetition scheme for all athletes may induce different levels of effort and fatigue [9, 54, 108, 125]. Therefore, the traditional paradigm of RT requires a shift towards more objective, and individualized methods of prescribing training loads in youth, such as the strategic use of velocity, for the purpose of enhancing sports performance in young and maturing athletes [53, 125].

It can be reasonably acknowledged that one of the main aims of RT for athletic performance should be to enhance relative force production capacity, and thus ultimately enhancing acceleration and movement velocity against any absolute load, particularly the load encountered during competitive events [53]. This focus acknowledges that relative force is a critical determinant of acceleration, whereas the duration of force application, or relative impulse, dictates the resultant velocity [22, 41, 85, 87, 115]. Given the time-constrained nature of athletic tasks, enhancing sports performance through RT seems to necessitate increasing the force component of impulse rather than extending the duration of force application [41, 62, 85, 115]. This approach aligns with the biomechanical principle that for any given movement, especially those pertinent to competitive events, the enhancement of impulse should predominantly come from an increase in force to optimize acceleration and velocity against specific loads encountered in sport [53]. These assertions are grounded in the principle that executing a RT exercise with maximal intended velocity can effectively translate into the same action during competition [15, 53]. González-Badillo et al. [53] suggest that in most sports, excluding powerlifting, competitive performance often relies on an athlete's ability to move or displace their body (or the body with a sport-specific external implement) at maximal intended velocity during various actions such as running, jumping, lifting, throwing, hitting, cycling, swimming, paddling, pushing or pulling opponents, and numerous other specific actions executed in both individual and team sports. Therefore, if the main objective of RT for athletic performance is to enhance an athlete's ability to accelerate against any absolute load rapidly and forcefully by applying maximal intent, thereby enhancing movement velocity as an outcome, then it would logically follow that the velocity of a training exercise be objectively monitored. In lifts where the movement begins and ends at zero velocity (0 $m.s^{-1}$), such as the bench press or squat, the mean force is influenced primarily by the load, but it also depends significantly on movement velocity, acceleration, and time under tension [53]. Even with a constant external load, variations in how force is applied throughout the lift can alter acceleration and velocity profiles, thereby impacting overall power output. Specifically, applying a greater net force during the concentric phase increases acceleration, resulting in a higher movement velocity, assuming displacement remains constant. This enhanced velocity subsequently contributes to greater power output and overall impulse [53]. Therefore, it is imperative for S&C coaches to clearly understand the objectives of their RT programs, and the mechanisms that govern the adaptations required for enhancing athletic performance in competition.

The underlying mechanisms which govern the adaptations associated with training the physical qualities of strength and power, which also contribute to increased movement velocity, can be defined into three categories – mechanical/neural stimuli (e.g., forces, contraction duration, impulse, work and muscle action) [25], metabolic stimuli (e.g., lactate/lactic acid) [24], and hormonal stimuli (e.g., testosterone, growth hormone, insulin, insulin-like growth factor 1, and cortisol) [26]. It is proposed that all these mechanisms are heavily influenced by the individual's ability to provide maximal intended movement velocity during RT, independent of the load lifted [51, 100, 126]. Maximal strength and power adaptations have been shown to be directly affected by maximal-intended concentric movement velocity during RT movements utilizing barbells, which can enhance rate coding and rate of force development (RFD) [34]. These attributes can be optimized through RT movements executed with maximal intended concentric movement velocity; in simple terms this is when the athlete provides maximal effort to move the load as fast as possible during the concentric phase of a RT movement [28, 34, 100]. While there are other forms of RT that utilize the same maximal intent of movement, such as plyometrics, which involve rapid force production that can improve RFD [14, 89, 105], maximal-intended movement velocity during barbell/weighted RT movements plays a major role in optimizing RFD [37, 52, 95, 100, 101]. This is because moving a load with maximal intent to accelerate as fast as possible enhances the ability of the nervous system to recruit and synchronize motor units to produce force rapidly (rate coding) [1, 30]. Therefore, it is critical to monitor and track velocity during RT sessions to ensure maximal-intended movement velocity is being applied by the athlete. Fortunately, advancements in recent velocity monitoring technologies have made this possible, providing S&C coaches access to velocity metrics as an objectively measurable outcome they can assess and monitor during RT exercises [127].

VBT was developed to provide objective data to support the prescription (i.e., loads, sets, or repetitions) of RT [12, 70, 130] and monitoring of neuromuscular fatigue [113]. To date, approximately nine uses of VBT have been identified for application in the training of athletes [125]. These nine methods can be summarized into the following VBT methods of application, of which this review focuses on, namely feedback, load velocity profiling (LVP), 1RM estimation, and the use of velocity loss thresholds and cutoffs. These approaches represent the forefront of VBT's contribution to enhancing athletic performance through informed training practices. However, these methods are not without their limitations, for example when analyzing the current body of scientific literature on velocity based 1RM predictions, it is evident that what was once purported as a theoretically promising method to estimate 1RM on a daily basis, is still not practically feasible due to consistent overestimation of loads across the various estimation methods [56]. Additionally, the use of some velocity loss thresholds (i.e. 5%, and 10%) may exceed the typical measurement error of some velocity monitoring devices or specific exercise used, and thus make them redundant [72, 127]. Some methods, including feedback [129, 131, 133, 134] and monitoring performance through LVP [56] show promise and utility. However, S&C coaches still require substantiated evidence to navigate the practical application of VBT methods with their athletes effectively.

The maturation process of youth athletes (less than 20 years of age) is a complex process that involves multiple internal (biological, mental) and external (social, environmental) stressors that can affect their neurological state and athletic performance [91, 110]. During this period, the load required to achieve a target velocity or velocity zone during RT may fluctuate due to changes in relative strength [91]. Maturation-specific changes, such as those affecting muscle cross-sectional area and fascicle length, can impact force production characteristics and therefore velocity, and power output [92]. These changes may have the greatest impact on force production during rapid growth periods, of which may result in temporary disruptions in motor coordination [2, 27]. Biomechanically, the length-tension relationship in youth athletes is different from that of adults, as younger athletes exhibit higher force at longer muscle lengths [88]. Furthermore, younger athletes have exhibited lower levels of velocity at all relative levels of force compared to adults, with velocity decreasing more gradually as force increases, however this was reported in studies using various forms of dynamometry for measurement and not in free weight RT [7, 124]. Because of these differences, applying the same training assumptions used for adults to youth athletes may be inappropriate. S&C coaches have a crucial role in considering the substantial maturation-related changes and movement variability in youth athletes, to guarantee the effectiveness of their training [23, 86]. VBT offers a promising solution by providing objective, quantifiable data that allow for targeted, individualized adjustments to training—potentially enhancing performance and reducing injury risks during critical developmental periods [125].

While VBT has been well-studied in male adults [8, 71, 125], most athletes globally are youth, making it crucial to validate VBT's efficacy in this population [33, 64, 116, 132]. The Authors believe that S&C coaches may be hesitant to implement VBT for youth athletes due to:

1. Concerns about the validity and reliability of VBT methods versus percentage-based training.
2. A lack of focused research on the application of VBT methods in youth athletes, with most

existing studies centered on adult males.
3. Misconceptions that youth athletes' limited technical skills preclude effective VBT use.
4. Concerns about the validity and reliability of technological devices used for monitoring resistance training.
5. Budget constraints in acquiring high-quality VBT devices, especially in multi-athlete settings.

This review primarily addresses concerns 1–4 by assessing current VBT methodologies in youth. Although financial and technological limitations (concern 5) are acknowledged, they fall outside the scope of this review. Ultimately, this analysis aims to identify gaps in current knowledge and guide future research directions for VBT in youth athletic development.

METHODS

Search Strategy

A comprehensive search strategy was implemented following PRISMA guidelines for systematic reviews [93]. The academic databases PubMed, Scopus, and SPORTDiscus were systematically searched in March 2024 to identify peer-reviewed original research studies on the application of VBT methods in youth athletes. The search was guided by the PICO strategy [135], and utilized pre-determined search terms, keywords, and Boolean operators (AND/OR). The search results were extracted and imported into a reference manager (*EndNote 20.4.1, Clarivate Analytics, Philadelphia, PA, USA*) and analyzed for relevance to the scope of this systematic review. The specific search strategies for each database are presented in Table 1. In addition to the electronic searches, the reference lists of the included full text articles were screened with publications that met the inclusion criteria included in the review.

Study Selection & Data Extraction

All articles were screened using pre-determined eligibility criteria to ensure the inclusion of relevant studies. These criteria required that the studies be original research investigations published in English prior to February 2024. Additionally, the studies had to focus on outcomes related to any VBT method, including feedback, 1RM prediction/estimation, load velocity profiling, velocity loss, and velocity-based resistance training prescription and intervention. The research subjects in these studies had to be youth athletes under 20 years of age. This comprehensive screening process was designed to ensure that only relevant studies meeting all specified criteria were included in the review. The screening process was conducted independently by two reviewers (YW, RC) to minimize potential biases, and conflicts were resolved through discussion or by consulting a third reviewer (SL).

The data extraction was conducted by two independent reviewers (YW, SL) using Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia). This software facilitated the removal of duplicates and extraction of relevant information from the included studies. The extracted data covered a range of variables across different VBT methods. General study information included authors, publication year, study title, study design (e.g., randomized controlled trial, observational study), and participant details (sample size, age, sex, training background). For feedback studies, we recorded device information (type and name, e.g., linear position transducer, GymAware), specific exercises (e.g., back squat, jump squat), feedback characteristics (frequency and mode), and measured variables (peak concentric velocity, peak concentric power, motivation, competitiveness). We extracted means and standard deviations for no feedback and feedback conditions, and calculated Hedges' g effect sizes from the available data. There was no need to convert standard errors or digitize graphical data. For 1RM prediction studies, we documented the device used (e.g., linear position transducer, 2D motion analysis), specific exercises (e.g., supine leg press, push up), 1RM prediction methods (e.g., velocity at 100% 1RM), and reported outcomes (prediction accuracy, correlations, absolute errors). Means and standard deviations were also extracted for 1RM and velocity values. In LVP studies, we recorded device information (type and name), specific exercises (e.g., bench press, back squat), participant age (mean ± SD), loading schemes (percentages of 1RM, absolute loads), repetitions at each load, and rest periods. Velocity measurements across different loads, including means and standard deviations, were extracted. For velocity cutoff/threshold studies, we extracted specific exercises (e.g., back squat, bench press), device information (type and name), participant demographics, specific velocity thresholds (e.g., ≤10% velocity loss), device-specific measurement errors (e.g., coefficient of variation), and performance outcomes post-intervention. In intervention studies, we described the VBT methods used (e.g., velocity loss thresholds), device information (type and name, e.g., linear position transducer, T-Force), specific exercises (e.g., back squat, jump squat), participant characteristics (age, sex, training age, group assignment), duration of the intervention, and training phases. Reported outcomes included changes in maximum dynamic strength (1RM), muscle power, jumping, and sprinting performance, with means, standard deviations, and significance levels extracted.

Quality Assessment Tool

To assess the quality of each study included in this review, a modified version of the Downs and Black checklist was used to better suit the nature of studies included [32] using Covidence software (Veritas Health Innovation, Melbourne, Australia) (Table 2). This checklist was validated for reporting the quality of observational study designs and has been previously used in sport science systematic reviews [69, 127]. However, not all checklist criteria were applicable to the studies included in this review. Nine of the 27 criteria were used to assess the VBT methodology studies. The modified Downs and Black questions can be found in the electronic supplementary material (*see Table 1 in supplementary material, detailing the modified Downs and Black questions*). The reporting quality was scored on a scale using 0 (unable to determine or no) or 1 (yes). A total score of 9 indicated the highest reporting quality with scores above 6 considered "good", scores of 4-6 considered "moderate", and scores below 4 considered "poor".

RESULTS

Identification of Studies

The systematic search retrieved 3,363 documents (Fig. 1). After removing duplicates, the titles, and abstracts of the remaining 3,256 documents were screened for eligibility, with 21 studies included from the original search and an additional 2 studies included from the references list of the included studies, resulting in a total of 23 studies included.

Reporting Quality

The reporting quality of the studies investigating velocity-based training methodologies was generally high, resulting in an overall score of 8.17 ± 0.83 (mean ± standard deviation) (Table 2). Of the 23 studies, nine reported a perfect score of 9 while no studies showed poor reporting quality with a score of less than 4. However, 8 studies failed to provide full details of the technological device in accordance with item 3 of the checklist, and 2 studies did not report contextually relevant statistics according to item 10.

Study Characteristics

A total of 23 studies applied VBT methods to youth athletes. Of the 23 studies, five studies (Table 3) investigated the use of velocity-based feedback of which all utilized a linear position transducer (LPT) device and provided visual feedback at the end of each repetition. Six studies utilized 1RM predictions using either an LPT or 2D motion analysis device (Table 4). Nine studies used either the two-point or multiple loads method to develop an LVP while two studies conducted an optimal power assessment (Table 5). To measure the LVP, seven studies used an LPT, with three of these studies utilizing the T-Force system, three utilizing the GymAware system, and one each using the SmartCoach, ChronoJump System, and Celesco Model PT9510-0150-112-1310. Only one study used a 2D motion analysis system, the Kinovea software via a Redmi Note 8, for this purpose. Table 6 provides a comprehensive summary of the various LVP protocols employed in each study. Only one study [73] was identified that used a relative velocity loss threshold among youth athletes (aged 16 ± 0.5 years) (Table 7). The study by Kalmus et al. [73] used the Speed4Lifts LPT to examine the short-term effects of a 10% VL threshold on explosive performance in two RT sessions consisting of 4 sets of 5 repetitions at 70% 1RM with 2 minutes of rest for the free weight back squat, bench press, and hip thrust. Only one study [84] used VBT for a performance enhancing intervention (Table 8). No studies were identified as using accelerometers, 3D motion analysis, or optical devices to support the application of VBT in youth athletes.

Table 1. Search terms and key words utilized in each database. Searches were combined using the BOOLEAN operator "AND".

Database:	PubMed	
Search 1	Search 2	Search 3
(("velocit*"[Title/Abstract] OR "Power"[Title/Abstract] OR "Plyometric"[Title/Abstract] OR "Speed"[Title/Abstract] OR "Ballistic"[Title/Abstract] OR "Tempo"[Title/Abstract] OR "Force"[Title/Abstract] OR "accelerat*"[Title/Abstract] OR "Linear Position Transducer"[Title/Abstract] OR "Accelerometer"[Title/Abstract] OR "Motion Capture"[Title/Abstract] OR "Velocity Based Training"[Title/Abstract] OR "VBT"[Title/Abstract] OR "Load Velocity Profiling"[Title/Abstract] OR "Load Velocity"[Title/Abstract] OR "1RM Prediction"[Title/Abstract] OR "1rm prediction equation*"[Title/Abstract] OR "Velocity Cutoff"[Title/Abstract] OR "velocity loss threshold*"[Title/Abstract] OR "velocity threshold*"[Title/Abstract] OR "velocity band*"[Title/Abstract] OR "velocity zone*"[Title/Abstract] OR "Peak Velocity"[Title/Abstract] OR "Mean Propulsive Velocity"[Title/Abstract] OR "Barbell Speed"[Title/Abstract] OR "Barbell Velocity"[Title/Abstract] OR "Barbell Displacement"[Title/Abstract] OR "Velocity Tracking"[Title/Abstract] OR "Velocity Monitoring"[Title/Abstract] OR "Velocity Profiling" [Title/Abstract])	("Exercise"[MeSH Terms] OR "resistance train*"[Title/Abstract] OR "strength train*"[Title/Abstract] OR "exercis*"[Title/Abstract])	("Youth"[Title/Abstract] OR "adolescen*"[Title/Abstract]))

Database:	Scopus	
Search 1	Search 2	Search 3
"Velocity based" Training	"Resistance Training" OR Strength	Youth OR Children OR Adolescen* OR Teen

Database:	SPORTDiscus		
Search 1	Search 2	Search 3	Search 4
Velocity Based Training	Athletes	Resistance Training OR Strength Training OR Weight Training OR Resistance Exercise	Youth OR Adolescents OR Young People OR Teen OR Young Adults OR Children

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

Study	Items assessed using modified Downs and Black checklist									
	Reporting					Internal Validity				Total
	1	2	3	6	7	10	16	18	20	
Alonso-Aubin et al. [3]	1	1	1	1	1	1	1	1	1	9
Amara et al. [5]	1	1	1	1	1	1	1	1	0	8
Arede et al. [6]	1	1	0	1	1	1	1	1	1	8
Bautista et al. [13]	1	1	1	1	1	1	1	1	1	9
Caven et al. [18]	1	1	1	1	1	1	1	1	1	9
Cetin and Isik [19]	1	1	1	1	1	1	1	0	0	7
Fernandez Ortega et al. [38]	1	1	0	1	1	1	1	1	1	8
Franco-Márquez et al. [39]	1	1	0	1	1	1	1	1	1	8
García-Ramos et al. [47]	1	1	1	1	1	1	1	1	1	9
GonzÁLez-Badillo et al. [50]	1	1	1	1	1	1	1	1	1	9
Kalmus et al. [73]	1	1	0	1	0	1	1	1	1	7
Loturco et al. [84]	1	1	1	1	1	0	1	1	1	8
Meylan et al. [92]	1	1	1	1	1	1	1	1	1	9
Oberhofer et al. [98]	1	1	1	1	1	1	1	0	0	7
Orange et al. [99]	1	1	1	1	0	0	1	0	1	6
Rodríguez-Rosell et al. [107]	1	1	0	1	1	1	1	1	1	8
Stern et al. [117]	1	1	0	1	1	1	1	1	1	8
Tillaar et al. [121]	1	1	0	1	1	1	1	1	1	8
Watson et al. [123]	1	1	1	1	1	1	1	1	1	9
Weakley et al. [129]	1	1	1	1	1	1	1	0	1	8
Weakley et al. [131]	1	1	1	1	1	1	1	1	1	9
Wilson et al. [134]	1	1	1	1	1	1	1	1	1	9
Wilson et al. [133]	1	1	0	1	1	1	1	1	1	8

Table 3. Summary of velocity-based training feedback studies.

Study	Sample Size	Device Type	Device Name	Exercise	Frequency	Mode	Variables Measured	No Feedback	Feedback	Effect Sizes (Hedges' g)
Weakley et al. [129]	11	Linear Position Transducer	GymAware	Jump Squat	Post-Repetition	Visual	Peak concentric velocity, Peak concentric power, Motivation, and Competitiveness	2.24 ± 0.07 m.s^{-1}, 1900 ± 103 W, 4.63 ± 0.45, 4.02 ± 0.53	.47 ± 0.04 m.s^{-1}, 2231 ± 64 W, 8.00 ± 0.76, 7.72 ± 0.36	4.03, 3.86, 5.39, 8.16
Weakley et al. [131]	15	Linear Position Transducer	GymAware	Back Squat	Post-Repetition	Visual	Mean concentric velocity, Motivation (change), Competitiveness, and Perceived global workload	0.65 ± 0.05 m.s^{-1}, -0.57 ± 0.58, 5.90 ± 1.18, 5.97 ± 0.66	.70 ± 0.04 m.s^{-1}, 0.13 ± 0.39, 8.63 ± 0.38, 6.59 ± 0.63	1.07, 1.38, 3.03, 0.94
Wilson et al. [133]	11	Linear Position Transducer	GymAware	Jump Squat	Post-Repetition	Visual	Peak concentric velocity, Peak concentric power, Motivation, and Competitiveness	2.24 ± 0.07 m.s^{-1}, 1900 ± 103 W, 4.63 ± 0.45, 4.02 ± 0.53	2.47 ± 0.04 m.s^{-1}, 2231 ± 64 W, 8.00 ± 0.76, 7.72 ± 0.36	4.03, 3.86, 5.39, 8.16
Wilson et al. [134]	15	Linear Position Transducer	GymAware	Back Squat	Post-Repetition	Visual	Mean concentric velocity, Competitiveness, Mental demand, Physical demand, Temporal demand, Performance demand, Effort, Frustration, Global workload, Motivation (change), Hedonic tone (change), Energetic arousal (change), Tense arousal (change), Anger/frustration (change)	0.65 ± 0.05 m.s^{-1}, 5.90 ± 1.18, 6.13 ± 1.30, 5.40 ± 0.91, 6.27 ± 1.16, 6.07 ± 0.70, 7.33 ± 0.82, 4.60 ± 1.18, 5.97 ± 0.66, -0.57 ± 0.58, -0.26 ± 0.39, -0.06 ± 0.13, 0.00 ± 0.22, 0.08 ± 0.18	0.70 ± 0.04 m.s^{-1}, 8.63 ± 0.38, 7.87 ± 0.92, 7.13 ± 0.99, 7.40 ± 1.45, 7.47 ± 1.30, 8.07 ± 0.80, 1.60 ± 1.12, 6.59 ± 0.63, 0.13 ± 0.39, 0.03 ± 0.20, 0.07 ± 0.23, -0.09 ± 0.28, 0.05 ± 0.23	1.07, 3.03, 1.50, 1.77, 0.84, 1.30, 0.89, -2.54, 0.94, 1.38, 0.91, 0.68, -0.35, -0.14
Kalmus et al. [73]		Linear Position Transducer	Speed4Lifts	Back Squat, Bench Press, and Hip Thrust	Post-Repetition	Verbal	No Feedback Associated Variables	-	-	Did not report statistical outcomes related to feedback.

Note: Hedges' g values are interpreted as follows: ≤0.2 = small effect, >0.2 to <0.5 = medium effect, ≥0.5 = large effect.

Table 4. Summary of velocity-based training one repetition maximum prediction studies.

Study	Device Type	Device Name	Exercise	Prediction Method	Reported Outcomes
Meylan et al. [92]	Linear Position Transducer	Celesco (Model PT9510-0150-112-1310)	Supine Leg Press (squat)	Velocity at 100% 1RM (0.23 m.s^{-1})	5% (confidence limits [CL]: 9.5 - 0.2%) underestimation of the actual 1RM (118.5 ± 27.3 kg) when compared to predicted 1RM using a MVT of 0.23 m·s^{-1} (112.1 ± 23.0 kg). A strong correlation of r = 0.94 (CL: 0.80 - 0.98) between the two measures were reported.
Amara et al. [5]	2D Motion Analysis	Kinovea via Redmi Note 8 camera	Push Up	Velocity at 100% 1RM (0.18 m.s^{-1})	Did not report 1RM prediction / comparison specific statistics.
Caven et al. [18]	Linear Position Transducer	GymAware	Bench Press & Back Squat	Velocity at 100% 1RM (individual and group)	All prediction methods found very large to nearly perfect correlations with respect to the actual 1RM (r range = 0.76 to 0.97), and absolute errors ranging from 2.1 to 3.8 kg for the bench press and 4.9 to 9.7 kg for the squat.
Franco-Márquez et al. [39]	Linear Position Transducer	T-Force	Smith Machine Squat	V1 Load (1.00 m.s^{-1})	Did not report 1RM prediction / comparison specific statistics.
Rodríguez-Rosell et al. [107]	Linear Position Transducer	T-Force	Smith Machine Squat	V1 Load (1.00 m.s^{-1})	Did not report 1RM prediction / comparison specific statistics.
Cetin and Isik [19]	2D Motion Analysis	Mylift Application (Previously PowerLift)	Back Squat & Conventional Deadlift	Device Based Prediction (two submaximal loads at 75% and 85% of 1RM)	Coefficients of determination (R^2 = 0.99 for both exercises) when using two submaximal loads at 75% and 85% 1RM.

Abbreviations: MVT: Minimal Velocity Threshold

Table 5. Summary of methods and protocols used to develop a load velocity profile.

Study	Type of Device	Device Name	Exercise	Subject Age in Years (mean ± SD)	Method Used	Loading Scheme	Repetitions	Rest Period
Meylan et al. [92]	Linear Position Transducer	Celesco Model PT9510-0150-112-1310	Supine Leg Press (squat)	13.1 ± 1.1	Multiple Loads	80%, 100%, 120%, 140%, and 160% body mass	3 rep's at all loads	30 second's intra-set & 2 minutes b/w sets
Alonso-Aubin et al. [3]	Linear Position Transducer	T-Force	Bench Press & Back Squat	14.48 ± 1.31	Multiple Loads	Squat: 40%, 50%, 60%, 70%, 80% 1RM Bench Press: 50%, 60%, 70%, 80% 1RM	2 sets of 5 rep's	3 minutes b/w sets
Amara et al. [72]	2D Motion Analysis	Kinovea via	Push Up	16.46 ± 0.59	Multiple Loads	Body Mass, 10 kg, 20 kg, 30 kg weight vest	3 rep's at each load	3-5 minutes b/w sets

Study	Type of Device	Device Name	Exercise	Subject Age in Years (mean ± SD)	Method Used	Loading Scheme	Repetitions	Rest Period
Arede et al. [6]	Redmi Note 8	SmartCoach	Bench Press & Back Squat	15.2 ± 1.1	Multiple Loads	Back Squat: 20 kg + 10 kg until MPV < 0.99 $m.s^{-1}$ Bench Press: < 0.5 $m.s^{-1}$ then + 2.5-5 kg until 1RM	4 rep's at 20–30 kg 3 rep's at 40–70 kg 2 rep's at 80 kg (approx. 20-90% 1RM) 3 reps for the lighter loads (BS = MPV > 1.0 $m.s^{-1}$; BP = MPV > 0.97 $m.s^{-1}$) 2 reps for medium loads (BS = 0.57 $m.s^{-1}$ ≤ MPV ≤ 0.99 $m.s^{-1}$; BP = 0.50 $m.s^{-1}$ ≤ MPV ≤ 0.97 $m.s^{-1}$) 1 reps for heaviest loads (BS = MPV < 0.57 $m.s^{-1}$; BP = MPV < 0.50 $m.s^{-1}$)	3 minutes for lighter and medium loads 5 minutes for the heaviest loads
Bautista et al. [13]	Linear Position Transducer	T-Force	Bench Press	18 ± 1	Multiple Loads	20 kg, 30 kg, 40 kg, 50 kg, 60 kg, 70 kg, and 80 kg	4 rep's at 20–30 kg 3 rep's at 40–70 kg 2 rep's at 80 kg (approx. 20-90% 1RM)	3-minutes for trials > 0.7 m.s-1 5 minutes < 0.7 $m.s^{-1}$
Caven et al. [18]	Linear Position Transducer	GymAware	Bench Press & Back Squat	17.8 ± 1.3	Multiple Loads & Two Loads	Multiple Loads Method: Bench Press 40%, 45%, 55%, 60%, 70%, 80%, 85%, and 90% 1RM Back Squat 20%, 30%, 45%, 55%, 65%, 75%, 85%, and 90% 1RM Two Loads Method: 40% and 90% 1RM	2 rep's for trials > 0.6 $m.s^{-1}$ 1 rep' for trials ≤ 0.6 $m.s^{-1}$	15 second's intra-set & 5 minutes b/w sets
García-Ramos et al. [47]	Linear Position Transducer	T-Force	Prone Bench Pull	20.6 ± 2.7 years [range: 16–25 years]	Multiple Loads	40% and 90% 1RM		

Study	Type of Device	Device Name	Exercise	Subject Age in Years (mean ± SD)	Method Used	Loading Scheme	Repetitions	Rest Period
Orange et al. [99]	Linear Position Transducer	GymAware	Back Squat	Under 19s	Multiple Loads	20 kg + 10 kg until the mean velocity (MV) fell below 0.80 m/s (approximately 70% of 1RM). Then + 1-5 kg until 100% 1RM	3 rep's for (MV > 1.10 m/s) 2 rep's for	10 second's intra-set & 5 minutes b/w sets
Watson et al. [123]	Linear Position Transducer	ChronoJump	Back Squat, Jump Squat, Bench Press, and Bench Throw	Males 15.3 ± 1.3 Females 15.0 ± 1.0	Multiple Loads	40%, 60%, 80%, and 90% 1RM	3 rep's at 40 & 60% 2 rep's at 80% 1 rep' at 90%	30 second's intra-set & 2 minutes b/w sets

Table 6. Summary of Studies using a Velocity Cutoff/Threshold via Device

Study	Exercise	Device Type	Device Name	Population	Velocity Cutoff	Measurement Error of Device	Group or Individual	Reported Outcomes
Kalmus et al. [73]	Back Squat, Bench Press, and Hip Thrust	Linear Position Transducer	Speed4Lifts	Adolescent Basketball Players Aged 16 ± 0.5 years	≤10%	coefficient of variation of 2.61%	Individual	Increases of CMJ post 6 h (VC: +6.7%; RTF: +2.4%) and MBT post 24 h (VC: +4.6%; RTF: +4.2%) were observed after both VC and RTF. Only VC potentiated CMJ after 24 h (+2.0 ± 2.3%). No other changes or differences between protocols were observed

Abbreviations: CMJ: Countermovement Jump, VC: Velocity-controlled, RTF: Repetition to failure, MBT: Medicine ball toss

Table 7. Summary of velocity-based training intervention studies.

Study	VBT Method	Device Type	Device Name	Exercise	Partici-pants (n)	Age	Sex	Training Age	Group or Individual	Intervention Duration	Reported Outcomes
Loturco et al. [84]	Load Velocity Profiling	Linear Position Trans-ducer	T-Force	Back Squat & Jump Squat	32	Velocity Group (n = 16) Age: 19.18 ± 0.72 years Intensity Group (n = 16) Age: 19.11 ± 0.7 years	Males	RT expe-rience not reported	Individual	6 weeks total 3-week strength phase & 3-week pow-er phase	Maximum dynamic strength (1RM) was evaluated before (B), at midpoint (i.e., after3 weeks; T1), and after 6 weeks (T2) of preseason strength/power training. Muscle power, jumping, and sprinting performance were evaluated at B and T2. Similar 1RM gains were observed in both groups at T1 (VEL: 9.2%; INT: 11.0%) and T2 (VEL:19.8%; INT: 22.1%). The 2 groups also presented significant ($p < 0.05$) improvements (within-group comparisons) in all of the variables. No between-group differences were detected. Mean power in the back squat (VEL: 18.5%; INT: 20.4%) and mean propulsive power in the jump squat (VEL: 29.1%; INT: 31.0%) were similarly improved at T2. The 10-m sprint (VEL: 24.3%; INT: 21.6%), jump squat (VEL: 7.1%; INT: 4.5%), and counter-movement jump (VEL: 6.7%; INT: 6.9%) were also improved in both groups at T2. The 30-m sprint time (VEL: 20.8%; INT: 20.1%) did not significantly improve for both groups.

Abbreviations: VBT: Velocity-based training, 1RM: One-repetition maximum, INT: Intensity Group, VEL: Velocity Group, B: Baseline, T1: Trial 2, T2: Trial 2.

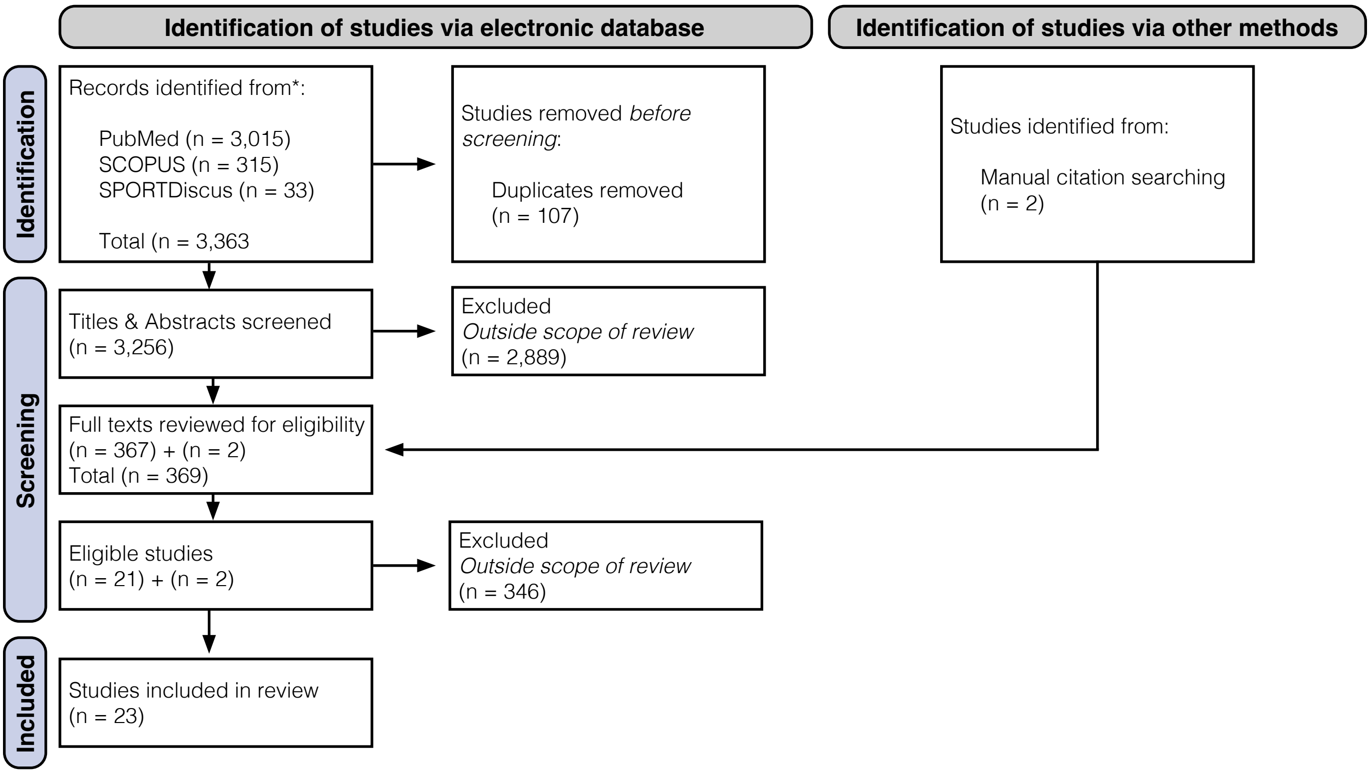

Figure 1. PRISMA flow diagram of study selection process for eligible studies included in review.

Feedback Results

Table 3 details the feedback studies identified by this review. Wilson et al. [134] showed that the average velocity in the feedback condition was significantly greater ($p < 0.001$) compared to the no-feedback condition, along with a significant interaction effect between condition and repetitions. Global workload was also found to be higher in the feedback condition. In a subsequent study, Wilson et al. [133] showed that peak velocity was significantly higher ($p < 0.001$) in the feedback condition compared to the no-feedback condition. Also, the results of this study showed that motivation and task competitiveness were increased in the feedback condition compared to the no-feedback condition.

Similarly, Weakley et al. [129] reported that providing feedback on velocity significantly improved performance, motivation, and competitiveness in adolescent females. This was demonstrated by a significant increase ($p < 0.001$) in mean peak concentric velocity and power in the group that received feedback. A second study by Weakley et al. [131] in adolescent males showed that there were large effects (Hedges' $g = 1.07$, where ≥ 0.5 indicates a large effect) in mean concentric velocity between the feedback and control conditions (Table 3). Kalmus et al. [73] utilized visual velocity feedback at the end of each repetition but did not report any statistics or outcomes related to the use of feedback.

1RM Estimation Results

This review identified six studies that applied 1RM prediction methods among youth athletes (Table 4). The studies employed various devices for measuring velocity, including LPT's, 2D motion analysis systems, and software programs. Three studies utilized the velocity at one repetition maximum (V1RM) method for the estimation of 1RM in youth athletes (Table 4). Caven et al. [18] estimated the 1RM at both the group and individual levels by utilizing the load-velocity relationship through two methods: the multiple-point method (with 8 loads) and the two-point method (with 2 loads). The group V1RM values used to estimate 1RM for bench press was 0.22 m·s^{-1} and 0.36 m·s^{-1} for the squat. For the 1RM prediction from the individual V1RM, each participant's V1RM ranged from 0.10-0.32 m·s^{-1} and 0.24-0.47 m·s^{-1} for bench press and squat, respectively. Caven et al. [18] reported that for bench press and squat, all prediction methods found very large to nearly perfect correlations with respect to the actual 1RM ($r = 0.76$ to 0.97), and absolute errors ranging from 2.1-3.8 kg (5.4-9.9%) for the bench press and 4.9-9.7 kg (5.7-11.2%) for the squat.

Meylan et al. [92] also used a V1RM and aimed to quantify the inter-session reliability of force-velocity-power profiling and estimated maximal strength for a supine squat in youth. Using a Celesco (Model PT9510-0150-112-1310) LPT 1RM was estimated via the load-velocity relationship using a minimal velocity threshold (MVT) of 0.23 $m.s^{-1}$ which was adapted from adult male studies [60, 67]. Meylan et al. [92] found a 5% underestimation of the actual 1RM (118.5 ± 27.3 kg) when compared to the predicted 1RM using a MVT of 0.23 $m·s^{-1}$ (112.1 ± 23.0 kg). A strong correlation of r = 0.94 (CL: 0.80 - 0.98) between the two measures was reported [92]. Amara et al. [5] used 2D motion analysis in the form of a Redmi Note 8 camera and analyzed the video using the Kinovea software to investigate the relationship between swimming performance, biomechanical variables, and the predicted 1-RM push-up in competitive swimmers. After establishing the load-velocity relationship for each participant Amara then calculated the predicted 1RM push-up using the following formula y = a × x + b. Amara et al. [5] set the variable x at 0.18 $m·s^{-1}$, which indicated the minimum mean propulsive velocity (MPV) at which 1RM was theoretically achievable (V1RM), established from González-Badillo et al. [49]. Additionally, the coefficient of x (a) and y-intercept (b) were individualized for each participant. No statistics in relation to the 1RM estimation accuracy or reliability were reported.

Rodríguez-Rosell et al. [107] and Franco-Márquez et al. [39] used the T-Force LPT system to complete an incremental loading test on the Smith machine squat to identify the load at which each subject attained an MPV of ~1.00 $m·s^{-1}$ (range 0.96–1.04 $m·s^{-1}$). From this both studies utilized the adapted formula from Sánchez-Medina et al. [114] (100 × Load/–2.185 × MPV2 – 61.53 × MPV + 122.5) which previously reported an R^2 of 0.96 and SEE of 5.5% when inputting the MPV with the last load (kg) of the incremental test to estimate the 1RM. No statistics about the 1RM estimation accuracy or reliability were reported in either study.

Cetin and Isik [19] aimed to determine the validity and reliability of the My Lift application to estimate the 1RM load for conventional deadlift and barbell back squat exercises. My Lift estimated 1RM data was obtained by marking the starting and ending frames of the exercises and then loading range of motion (ROM) (cm) of the exercises and the lifted loads (kg) to the application [19]. The My Lift application (app) reported a high degree of accuracy in estimating 1RM for deadlift and barbell back squat exercises, supported by coefficients of determination (R^2 = 0.99 for both exercises) when using two submaximal loads at 75% and 85% 1RM. The results indicate a strong correlation between the app's estimations and actual 1RM values.

Load Velocity Profiling Results

Only one study identified in this review used both multiple loads and the 2-point method for the development of individualized LVPs [18]. For the multiple loads method participants recorded mean velocity for eight loads at approximately 40, 45, 55, 60, 70, 80, 85 and 90% 1RM for bench press and ~20, 30, 45, 55, 65, 75, 85 and 90% 1RM for squat exercise (Table 5). For the two-point method the participants recorded two distant loads at approximately 40% and 90% 1RM, with linear regression models then applied for modelling of individualized LVPs. Caven et al. [18] reported the 2-point method can accurately predict the 1RM in a quicker manner than using multiple loads (Table 4). Orange et al. [99] utilized the LVP for training prescription in a RT intervention. The LVP's were developed using the multiple loads method using mean velocity (MV) in the free-weight back squat. MV was recorded for three repetitions at 40%, three repetitions at 60%, two repetitions at 80%, and one repetition at 90% of baseline 1RM, with three minutes rest between sets (Table 5). The MVs corresponding to 60 and 80% 1RM were then used to modify the training loads in the VBT group. Orange et al. [84] showed that athletes in the VBT group exhibited significant ($p < 0.05$) enhancements in performance metrics over those in the percentage based (PBT) group. Specifically, the VBT group showed statistically significant ($p < 0.05$) improvements in mean velocity across all loads, peak power output, and the execution speed of lifts at submaximal intensities of 30%, 40%, and 50% of their 1RM, indicating better improvements in both power and speed of movement compared to the PBT group.

Meylan et al. [92] studied the reliability of force-velocity-power profiling (FVPP) and maximal strength assessment in youth athletes. The study used the multiple loads method (80%, 100%, 120%, 140%, and 160% body mass) to develop the load-velocity profile for the supine leg press exercise (Table 5). Peak and mean force, velocity, and peak displacement were collected during the ballistic supine leg press test, which was performed on three separate occasions. Power-related variables, including maximal power output and the optimal load and velocity for achieving this maximal output, were derived from the power-load and power-velocity regression curves. The variables were found to be reliable (ICC: 0.74 to 0.99), but the maximal force/velocity ratio and load at maximal power were found to be unreliable (ICC: 0.35 to 0.61).

García-Ramos et al. [47] aimed to determine the best velocity variable and regression model for assessing the load-velocity relationship during the free-weight prone bench pull exercise (Table 5). They also assessed the reliability of velocity across various 1RM percentages, comparing different velocity variables, regression models, and analyzing within- and between-subject velocity variability. García-Ramos et al. [47] found that the general and individual load-velocity relationships were highly linear (r = 0.964 - 0.973) with median values of r = 0.986 for mean velocity, r = 0.989 for MPV, and r = 0.984 for peak velocity. The reliability of velocity at different percentages of 1RM did not significantly differ between velocity variables (CV = 2.55-7.61% for mean velocity, CV = 2.84-7.72% for mean propulsive velocity, and CV = 3.50-6.03% for peak velocity) or between regression models (CV = 2.55-7.72% for linear regression and 2.73-5.25% for polynomial regression). The within-subject variability of velocity at different percentages of 1RM was lower than the between-subject variability for light-moderate loads. For the mean velocity of the 1RM trial, the within-subject CV was 6.02% while the between-subject CV was 6.60%. For peak velocity, the within-subject CV was 6.36% while the between-subject CV was 7.56%. The results of this study suggest that the individual load-mean velocity relationship should be determined with a linear regression model to accurately prescribe the relative load during the free-weight prone bench pull exercise.

Alonso-Aubin et al. [3] aimed to examine the force velocity profile (FVP) using the T-force LPT system on the squat and bench press exercises in adolescent rugby players and to analyze sex-related differences between male and female players. The subjects performed an incremental loading test (Table 5) which resulted in males possessing a higher 1RM squat performance than the females (104.26 kg vs 115.17 kg) while the females had a slightly higher 1RM bench press performance than the males (45.85 kg vs 46.97 kg). Significant sex-related differences for maximum (40%), mean (40-50%), and time to maximum velocities (40-80%) as well as time to maximum power (80%) were reported. Significant sex-related differences were also reported for power and time to maximum velocity (40-60% to 70%-80%) for the bench press exercise.

Bautista et al. [13] completed an incremental test (Table 5) during the barbell bench press exercise to assess the LVP of elite international handball players. The researchers in this study compared the use of two calculation methods, average value (Avalue) and best value (Bvalue), to assess the MPV during the exercise. They also analyzed the relationship between the individual coefficient of variation (CVind) of the incremental load protocol in the bench press exercise and the relative strength (Frel) of the players. The results showed that there were significant ($p < 0.05$) differences between the Avalue and Bvalue methods, with the Bvalue method being more effective when the CVind was less than 10% and the Avalue method being more effective when the CVind was greater than 10%. There was also an inverse relationship between Frel and CVind, with higher Frel being associated with lower CVind. The researchers concluded that the calculation method used to assess the LVP in the barbell bench press exercise has an impact on the nature of the relationship and that the Avalue method is a good choice for determining the LVP when the CVind is >10%, while the Bvalue method is a better choice when the CVind <10%.

Arede et al. [6] and Watson et al. [123] used an incremental loading test (Table 5) across multiple loads to determine the load that maximized mean propulsive power output. Despite both studies not directly assessing outcomes of the LVP, the methodological details of the incremental loading test used in their young subjects are critical. Arede et al. [6] conducted a parallel back squat (BS) and bench press (BP) incremental load tests to determine the load that maximized mean propulsive power (MPP) output (Loadopt) in young male basketball players (15.2 ± 1.1 years). Only the best repetition at each load was considered for analysis, and the MPP output showed an almost perfect individual load-power relationship (R^2 = 0.95), allowing for the determination of power output at each percentage of 1RM for each subject. Watson et al. [123] also utilized an incremental load test (Table 5) for the determination of the optimal load (OPL) for four different exercises (back squat, bench press, jump squat, and bench throw) in elite youth athletes (15.1 ± 1.1 years). The tests were conducted using progressively increasing loads until a consistent decrement in velocity was observed, with the OPL being identified as the absolute load resulting in the highest MPV. This study's aim was to investigate if giving youth athletes the choice of their RT exercise order affected motor performance and psychological outcomes. No meaningful differences between conditions (predetermined or self-selected exercise order) in power outputs ($p \geq 0.07$; ES $\leq$ 0.21), perceived fatigue ($p \geq 0.42$; ES $\leq$ 0.33) and enjoyment ($p = 0.72$; ES = 0.05) were reported, suggesting both conditions can be used when coaching youth athletes and that self-selection of exercise order in youth athletes can be a feasible and practical coaching option.

Amara et al. [5] used an incremental loading test (Table 5) for participants performing push-ups with four different loads: their own body weight, and with a 10, 20, and 30 kg weight vest. The push-ups were done using handles placed on a force plate to calculate the absolute load while the mean concentric velocity of the pushup was assessed using the Kinovea software after recording the exercise using the high-speed camera via a smart phone (Redmi Note 8, Xiaomi, Beijing, China). The researchers used the LVP for the purpose of estimating 1RM in the push up exercise in order to predict maximal upper body strength in swimmers (Table 4).

Velocity Cutoff's Results

Only one study [73] was identified that used a relative velocity loss (VL) threshold among youth athletes (aged 16 ± 0.5 years) (Table 6). The study by Kalmus et al. [73] used the Speed4Lifts LPT (device coefficient of variation of 2.61%) to examine the short-term effects of a 10% VL threshold on explosive performance in two RT sessions consisting of 4 sets of 5 repetitions at 70% 1RM with 2 minutes of rest for the free weight back squat, bench press, and hip thrust. The VL threshold group was compared to a repetition to failure group that performed 2 sets of 10 repetitions at the same load with an increased rest of 3 minutes. The results showed that both groups increased vertical jump performance after 6 hours and medicine ball toss performance after 24 hours. However, only the VL threshold group continued to enhance vertical jump performance after 24 hours. These results suggest that a low-volume RT session with a VL threshold of 10% may limit the performance decreases induced by fatigue in explosive movements such as sprinting and jumping.

VBT Interventions Results

Outside of the studies already mentioned prior, this review only identified one VBT intervention study (Table 7). Loturco et al. [84] investigated the effects of two different power training loading schemes in Brazilian elite youth soccer players (mean age: 19.18 ± 0.72 years) using the T-Force LPT system. The athletes completed three weeks of strength training followed by three weeks of power-oriented training with varied loading schemes. One group increased velocities and decreased intensities (from 60-30% 1RM) during the power phase, while another group increased training intensity (from 30-60% 1RM) and decreased movement velocity. Both groups showed significant improvements in all variables measured (1RM back squat, jump squat, countermovement jump, and 10-meter sprint time). However, no differences between groups were observed, suggesting that these variables can potentially improve with the use of varied power loading schemes using VBT.

DISCUSSION

This review identified that VBT methods have been applied in a limited number of studies involving youth athletes. The most frequently used method among these studies was load velocity profiling, which was applied in nine studies using LPT's, with the GymAware and T-Force systems being the most used devices. No studies were identified that utilized accelerometers, 3D motion analysis devices, or laser/optical devices in youth athletes. While this review sheds light on the application of VBT methods in youth athletes, several limitations have emerged that necessitate a cautious interpretation of the findings from some of the methods and highlight areas for further research. Firstly, feedback from VBT was only applied in studies involving older youth athletes, aged 17 years, and not younger groups who may exhibit different acute responses. Additionally, the more valid methods used to predict 1RM appear to overestimate it, particularly when using group-based estimates that do not account for high between-subject variability [18]. This is compounded by the inappropriate use of adult V1RM values when predicting 1RM for youth, who were shown to possess faster velocities at 1RM compared to adults [18]. The reliability and validity of velocity loss thresholds are also highly dependent on the specific devices, exercises, and demographic characteristics studied, with typical error measures indicating that smaller VL thresholds on specific devices may be redundant [70]. Moreover, load velocity profiling, while beneficial, may be impractical to conduct frequently and its reliability across various exercises in youth populations remains underexplored. These limitations collectively suggest that the current body of evidence might not fully capture the nuances that may be involved if applying VBT methods to younger athletes, pointing towards the need for more diversified and age-specific studies in the field.

VBT Feedback

The use of VBT as a means of providing objective feedback to athletes and coaches has gained popularity in S&C settings [125]. VBT feedback has the potential to address the limitations of qualitative only feedback by allowing coaches to provide objective, quantitative feedback to athletes [125]. VBT feedback can be provided in various formats depending on the specific technological device and its functions. While the current state of feedback literature in adult populations suggests that it has a positive impact on acute performance outcomes and adaptations [125], limited studies have explored the relationships between feedback variables and their acute effects in the youth population across different maturity stages. The youth studies in this review provide evidence of the acute effects of feedback on psychological parameters in late adolescent athletes. Additionally, the feedback studies were conducted in late adolescent athletes (aged +17 years), leaving a gap in our understanding of how younger athletes may respond to VBT feedback. Psychological readiness and cognitive development can vary significantly between younger and more mature youth athletes [120]. Personality traits could also be a significant factor in understanding fatigue tolerance in youth athletes, as in adult populations, traits like emotional stability and conscientiousness have been associated with higher levels of fatigue tolerance [17, 29]. Compared to older athletes, younger youth athletes may lack the cognitive processing skills and emotional maturity needed to effectively interpret and utilize real-time VBT feedback for enhancing movement speed and intent. Their understanding of performance metrics and what motivates them could also differ from older athletes. Therefore, the acute psychological effects of VBT feedback could potentially vary substantially between these age groups. Future research should explore the relationship between VBT feedback and psychological parameters in younger youth athletes to provide a more comprehensive understanding of how best to implement VBT feedback across different stages of youth development. Ultimately, the findings of the identified VBT feedback studies suggest that providing visual quantitative feedback on velocity after each repetition during resistance training exercises can significantly improve performance, motivation, and competitiveness in older youth athletes.

Velocity Based 1RM Prediction Methods

The development of methods to accurately predict 1RM from submaximal loads would be of great importance to S&C coaches, as it enables them to determine their athletes' maximal strength in multiple exercises without adding additional testing sessions [19, 125]. 1RM predictions, if reliable, can also be useful for competitive adolescent athletes who want to estimate their maximal dynamic strength without lifting maximal loads frequently. Movement velocity has enabled the development of methods to predict 1RM from submaximal loads [125]. The most common approaches use velocity data from submaximal loads to estimate 1RM, either through general [21, 52] or individualized load-velocity profiles (LVPs) [10, 18].

The most utilized method of 1RM prediction found by this review was the velocity at 100% 1RM (V1RM) [70], identified in three studies in this review (Table 4). It is important to note that this method should not be confused with the minimal velocity threshold (1RM MVT) method [66], as the literature often refers to the V1RM as the minimal velocity threshold (MVT) [125], which may cause confusion for some. Therefore, it is necessary to clarify the distinction between these two methods to avoid any misunderstandings. Additionally, only one study [19] reported on how the device itself estimates the 1RM, while the remaining studies used novel methods for 1RM estimation.

The term "minimal velocity threshold" is often used in literature to describe the V1RM [125]. However, it is important to differentiate it from the 1RM MVT prediction method established by Izquierdo et al. [66]. The latter proposed that the velocity obtained from the final repetition of a set performed to concentric muscular failure with different relative loads (60%, 65%, 70%, and 75% 1RM) should be defined as the MVT. This respective study found that the MVT was similar and not significantly different from the velocity at 1RM for both the Smith machine bench press and half-squat exercises. Lake et al. [80] then investigated whether the MVT, calculated as the mean propulsive velocity (MPV) and mean concentric velocity (MCV), could be used in a linear regression equation to predict 1RM for the free-weight deadlift exercise performed at 70% and 80%1RM. This procedure requires you to develop the linear regression equation from submaximal loads and input the MVT into the subsequent regression equation to obtain a predicted 1RM (Fig. 2). Lake et al. [80] found the MVT was not valid for predicting the sessional 1RM in the deadlift (underestimated 1RM by 9–15%) because the MVT for the 70% 1RM (0.28 ± 0.11 m.s^{-1}), and 80% 1RM (0.32 ± 0.12 m.s^{-1}) sets to failure were significantly different to the MPV (V1RM = 0.16 ± 0.05 m.s^{-1}) and MV (V1RM = 0.17 ± 0.05 m.s^{-1}) at 1RM.

This review did not identify any studies that used the 1RM MVT method to estimate 1RM in youth athletes. Based on the current evidence for adults, the validity of the 1RM MVT method for 1RM prediction in youth is not recommended for use in this population without future validation.

The V1RM method uses the same load–velocity regression approach as the MVT method, with the only difference being the velocity value used as the input for 1RM prediction. Instead of using an MVT derived from previous literature or testing, the V1RM method uses the actual velocity observed during a

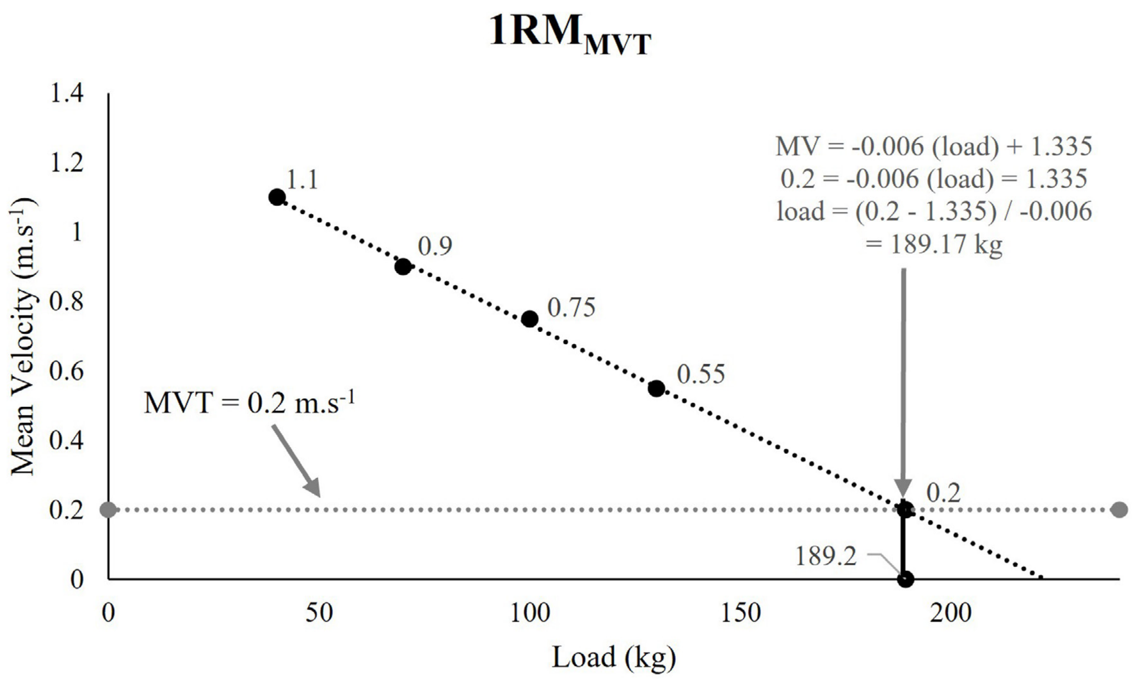

Figure 2. Minimum velocity threshold (1RM MVT) prediction method.

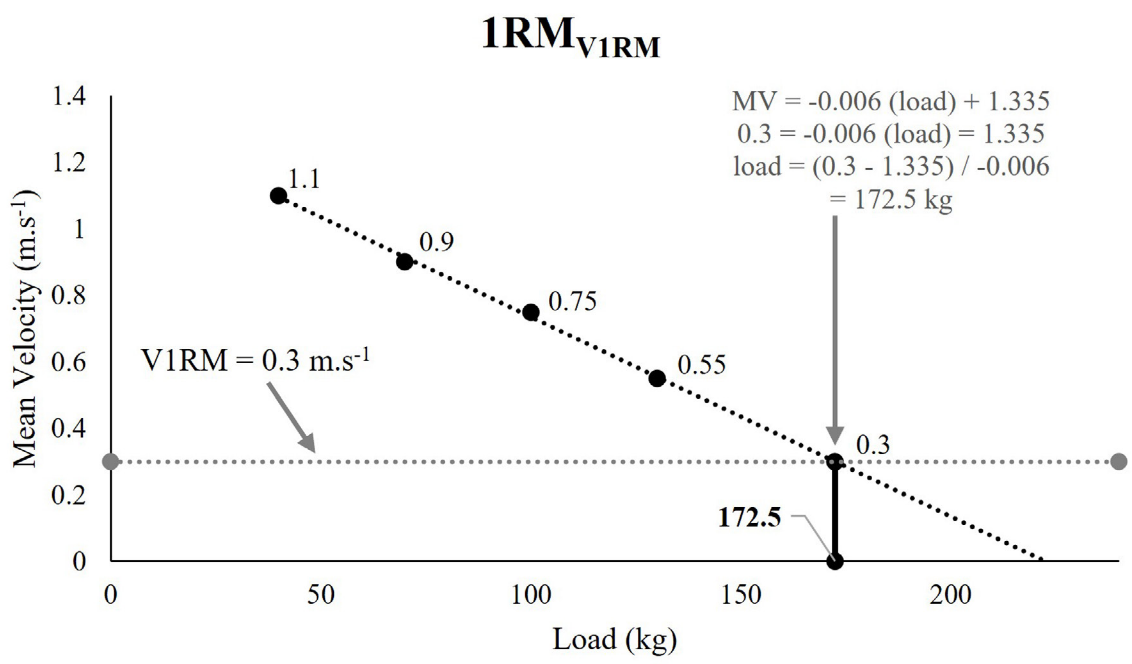

Figure 3. Minimum velocity threshold (1RM MVT) prediction method.

1RM lift (V1RM) [70]. As shown in Fig. 3, the fastest repetitions from four submaximal loads (20%, 40%, 60%, and 80% 1RM) are plotted and fitted with a linear regression line. The velocity at 1RM (V1RM), which was 0.30 $m \cdot s^{-1}$ in this example, is then entered into the regression equation to predict the 1RM load.

Previous research has shown the 1RM prediction method using V1RM was valid for accurately estimating the 1RM in the free-weight bench press, Smith machine bench press, Smith machine half-squat, and free-weight prone bench pull in adults [43, 82, 83, 125]. However, studies by Ruf et al. [112] and Banyard et al. [11] found that the V1RM method was not highly reliable for predicting sessional 1RM in the free-weight deadlift and back squat exercises due to the unstable V1RM (ICC = 0.63; CV = 15.7%; SEM = 0.03 $m \cdot s^{-1}$). Therefore, current consensus suggests the V1RM method may only be appropriate to predict 1RM in Smith machine exercises and some upper body free-weight exercises, but caution should be used when attempting to predict 1RM using this method in free-weight lower body exercises.

Three studies utilized the V1RM estimation method for youth athletes in this review. Caven et al. [18] suggested that S&C coaches working with large groups of youth athletes may benefit from using the two-point method with a group V1RM. However, this approach may compromise accuracy, as individualized methods were reported to be more precise in predicting 1RM (difference: 3.8 ± 7.2 kg) compared to the multiple point method with group V1RM (difference: 4.7 ± 11.7 kg). This reported difference from predicted and actual 1RM will result in a potential under estimation of -7.0 kg to and over estimation of 16.4 kg in 1RM values which is not practically acceptable for coaches. The most accurate method for predicting 1RM reported by Caven et al. [75] was when the individualized multiple load method was utilized (difference: 2.7 ± 7.1 kg). Despite this being the most accurate method, it still resulted in a potential range –4.4 kg to 9.8 kg. It is important to highlight that this error surpasses those previously observed in direct 1RM measurements across various exercises among individuals with limited training experience. Specifically, errors were reported as 2.49 kg for the back squat and 1.36 kg for the power clean in one study done in male and female collegiate athletes [20], while another study noted an error of 2.9 kg for the power clean in adolescent athletes [35]. Coaches must also consider the device used and its measurement error. If the device's measurement error exceeds the absolute errors of the 1RM prediction, then logically, using that device for prediction becomes redundant. Meylan et al. [92] also found a slight underestimation in the predicted 1RM, indicating that the method may require further refinement for use in youth populations. There was a strong correlation between the estimated and actual 1RM suggesting that the method is reliable, however considering this study was done using a novel supine leg press squatting movement, its practicality is not relevant to coaches utilizing any other exercise. Amara et al. [5] did not measure actual 1RM, leaving a gap in our understanding of the precision of the estimation method in the push-up exercise. This highlights the need for future research to include a statistical comparison of both predicted and actual 1RM measures to assess the accuracy of V1RM methods in youth athletes.

The V1Load method can be used as an indirect way to estimate an individual's 1RM using the load that is recorded against a set velocity of one meter per second for the squat exercise [4, 39, 50, 107]. Sánchez-Medina et al. [114] reported a strong relationship between the load that elicited a bar velocity of ~1.00 $m.s^{-1}$ (V1LOAD) and 1RM in the full squat exercise. Researchers particularly utilize this method for prescribing training loads for safety as heavier loads may also predispose younger athletes to a higher risk of ventral flexion of the lumbar spine while squatting potentially furthering their risk for injury under high relative loads [81]. Both studies included in this review by Rodríguez-Rosell et al. [107] and Franco-Márquez et al. [39] didn't compare estimated 1RM to actual 1RM, the validity and reliability of the V1LOAD method to estimate 1RM in youth athletes is unknown and requires further investigation. Given the proposed safety benefits, future research should investigate the validity and reliability of the V1LOAD method for prescribing submaximal training loads for youth athletes in various exercises.

The study by Cetin and Isik [19] was the only study that reported on the actual 1RM estimation capabilities of a VBT measurement device. The My Lift app showed strong validity and reliability in estimating the 1RM for both deadlift and barbell back squat exercises. However, the app's requirement for precise measurement of each exercise's range of motion could pose challenges for coaches working with developing athletes. Specifically, the evolving anthropometrics of rapidly maturing youth athletes could lead to changes in the

ROM for exercises, making the app's requirements potentially problematic [6, 86, 90, 91, 109, 111].

From the identified 1RM estimation studies in this review, the V1RM method was utilized the most. Despite this, two studies [5, 92] used generalized V1RM adapted from adult studies, and both used non-conventional exercises such as a weighted push up and a supine leg press. Caven et al. [18] was the only study to compare both group mean and individual V1RM using conventional exercises (bench press and squat) in female youth athletes, and it was found that the group V1RM was on average 0.6 m.s^{-1} faster than what has been reported in adult studies [18, 125]. The reasons for this difference remain speculative and hypothetical but could be due to younger athletes possessing a higher proportion of fast twitch muscle fibers compared to adults, as well as youth athletes generally possessing less neuromuscular inhibition allowing for greater recruitment of fibers to produce greater relative forces [87]. This observed difference in V1RM compared to adults should caution coaches working with youth not to substitute generalized V1RM values obtained from adult studies when estimating 1RM. S&C coaches should be aware of the several limitations to predicting 1RM from generalized equations such as type of exercise, technique execution, sex, and the high within-subject and between-subject variability among mean velocities recorded at submaximal loads [104, 125]. The high within-subject and between-subject variability among mean velocities may be exacerbated when dealing with youth athletes due to the variable nature of maturity levels within athletes of the same age [91, 92, 109, 111]. S&C coaches working with youth athletes should be mindful when using group-based means in estimation calculations. While the study by Caven et al. [18] reported that the group V1RM prediction method produced an average bench press 1RM of 41.3 ± 9.0 kg compared to an actual mean of 38.6 ± 7.5 kg—an overall overestimation of about 7%—the method may disproportionately overestimate 1RM in lower strength athletes. For example, if an athlete with an actual bench press 1RM of 31.1 kg were assessed, the same method could overestimate their 1RM by approximately 19.9%, leading to a relative error of 24.4%. This discrepancy is critical, because if load prescriptions are based on, for instance, 80% of the predicted 1RM, the prescribed load could inadvertently represent around 95% of the athlete's actual 1RM. Such an approach is not only inaccurate but also potentially unsafe in less experienced youth, as it nearly reaches the athlete's maximum capacity. Additionally, individualized V1RM in adult studies [10, 112] have shown low reliability and within-subject and between-subject variability [11, 46, 112, 125]. As only one study in this review investigated the difference of group versus individual V1RM, more research is required to substantiate claims of which method is more accurate, reliable, and most practical for an S&C coach. Surprisingly, only one study [19] reported on the automated 1RM estimation capabilities of a VBT device. S&C coaches working with large groups could benefit from future research investigating which devices provide the most practical, valid, and reliable automated 1RM estimation capabilities.

Load Velocity Profiling Methods

The development of a load velocity profile is a key aspect of VBT and can provide several insights for the S&C coach working with youth athletes [125]. One of the key purposes of training with a LVP is the ability for the coach to distinguish between normal variation in velocity across training sessions and legitimate fluctuations in velocity that may occur from training induced adaptations [125]. Moreover, tracking LVP's in youth athletes longitudinally can provide valuable insights into their neuromuscular development during different maturational stages [92]. This information has been shown to be a critical predictor of future strength and power profiles in adulthood [40]. Two common methods used in the literature to develop LVP's include the multi-point method, which involves recording the velocity of an exercise across multiple loads, and the two-point method, which is reported as a quicker and simpler alternative which involves recording the velocity at two approximate loads of 45% and 85% 1RM [44, 45]. Few researchers have reported on the validity and reliability of the 2-point method to determine the load-velocity relationship of free weight lower body exercises [125]. Pérez-Castilla et al. [103] compared the validity and reliability of both the multiple loads and two-point method in determining various load velocity variables from the countermovement jump (CMJ) exercise. The study reported acceptable validity for the two-point method in comparison to the multiple load's method for mean velocity and MPV (ES range: -0.19 to 0.07; r range: 0.96-1.00; Concordance Correlation Coefficient (CCC) range: 0.94-0.99), but not for peak velocity (ES range: -0.54 to 0.60; r range: 0.67-0.99; CCC range: 0.55-0.98) [103]. The validation of the two-point method has been reported previously for upper body free-weight exercises such as the bench pull [43] and bench press [68]. However, further research is required to substantiate the validity and reliability of the two-point method of determining the LVP for free weight lower body exercises.

The most employed LVP method identified by this review was the multiple-load method (Table 5). The exercises used in these studies were diverse, including the bench press, bench throw, Smith machine back squat, free weight back squat, jump squat, prone bench pull, supine leg press, and loaded push up. The loading schemes (Table 5) employed in the multiple-load method varied widely, with some studies using as few as 4 loads and others as many as 8. The sets and reps used ranged from 2 to 6 sets and from as many as 5 repetitions to as few as 1 repetition for specific loads. Rest periods of 3-5 minutes were typically reported, with some studies utilizing intra-set rest between repetitions. LVPs were developed based on mean velocity and mean propulsive velocity recorded at different percentages of 1RM. Other variables, such as peak and mean force, power, velocity, and peak displacement, were also recorded. The results of these studies suggest that the multiple-load method may be more accurate in developing an LVP, but it is more time-consuming and may not be practical for coaches working with large groups. The two-point method for determining a LVP seems to be a faster, more practical alternative but at the expense of greater accuracy if used for 1RM prediction. Coaches should also choose the most appropriate velocity metric based on the specific exercise selected, such as peak velocity for explosive movements.

As mentioned previously one of the key purposes of training with a LVP is the ability for the coach to distinguish between normal variation in velocity across training sessions and legitimate fluctuations in velocity that may occur from training induced adaptions or fatigue [125]. This could be particularly advantageous for S&C coaches to make more informed decisions about adjusting training loads and exercise selection, thereby optimizing the training process [125]. No study identified by this review investigated the application of either a group or individual LVP for prescribing RT loads and assessing meaningful changes in youth athletes. Additionally, no study was identified that attempted the monitoring of LVP's in youth athletes longitudinally in order to assess the neuromuscular development occurring throughout maturation. Future studies of this nature could provide insights into how strength and neuromuscular characteristics evolve over time in this demographic. They could also help in understanding how different stages of maturation might influence the effectiveness of specific VBT protocols, thereby allowing for more individualized and age-appropriate training programs. Future research in these areas should aim to assist S&C coaches in fine-tuning RT programs to better suit the developmental stages and specific needs of youth athletes. Additionally, it could contribute to the establishment of normative VBT data for this demographic, which would be invaluable for setting performance benchmarks that are both exercise and maturation specific.

Velocity Cutoffs

The use of velocity cutoffs is a common application in VBT for the purpose of fatigue monitoring and to target a specific intensity range to acquire specific adaptations [125, 126]. Several terms related to this method can be found in the literature, some of which have similar meanings but varied application and can be confusing for readers to navigate. Table 8 attempts to define the common terminology used for velocity cutoffs for greater clarification on their definition and application. It's important to recognize that the terms starting velocities and target velocities are often used interchangeably in VBT, but they can have nuanced applications. A target velocity might be set as a specific velocity (a single value), or it can be a velocity zone or band as defined in Table 8. Additionally, during the same training session, velocity loss thresholds and cutoffs may be implemented. These are predefined limits on how much an athlete's performance can decline (velocity loss) before an intervention is made, such as ending the set or adjusting the load. This multifaceted approach allows coaches to tailor training sessions to be dynamic and responsive to acute performance.

The accumulation of repetitions during RT results in muscle fatigue and eventually exercise failure [126]. However, muscle fatigue occurs prior to exercise failure, as evidenced by reductions in maximal force, slower shortening velocity, and decreased power output [113]. The lack of specificity and precision in monitoring procedures has led to numerous assessments proposed for measuring fatigue [61]. Sanchez-Medina and González-Badillo [113] showed that the repetition velocity loss (VL) within a set can be used to monitor the neuromuscular fatigue induced by RT protocols.

It has been proposed that S&C coaches should use velocity instead of a fixed number of repetitions

Table 8. Velocity based training cutoff terminology summary.

Literature Terminology	Definition	Example
Velocity Loss Threshold	A velocity limit calculated from the maximal attainable velocity output during a training session, which is typically determined from the initial repetition of the first training set, guiding the practitioner on when to terminate a set.	A 10% velocity loss threshold with an initial repetition speed of 0.80 $m.s^{-1}$ would require an individual to terminate the set when the repetition velocity dropped below 0.72 $m.s^{-1}$.
Arbitrary Velocity Cutoff	A predetermined velocity value used as a threshold to determine when to terminate a set of repetitions, typically chosen by the practitioner and not based on scientific evidence or objective criteria.	Practitioner decides 0.5 $m.s^{-1}$ will be the velocity cutoff for a specific exercise in a training session, meaning when this arbitrary value is reached the set is terminated.
Velocity Banding	Using predetermined upper and lower ranges of velocities to indicate the intensity of the training program.	The practitioner may decide to target an arbitrary velocity band of 0.4-0.5 $m.s^{-1}$ for slower velocities, or a velocity band of 0.8-0.9 $m.s^{-1}$ for faster velocities for a specific exercise. The load is adjusted so that the athlete stays within this band.
Velocity Zones	Predetermined ranges of velocities that are used to classify the intensity of an exercise or a training program.	The practitioner wants to prescribe a training program that focuses on speed, power, or strength, they may use velocity zones pre-defined in the literature that correspond to those specific adaptations, for example >1.3 $m.s^{-1}$ for speed focus, 0.75-1.3 $m.s^{-1}$ for power, and <0.75 $m.s^{-1}$ for strength.
Starting Velocities	A specific velocity prescribed before the session where the external load is then adjusted within guidelines to meet the desired velocity.	The athlete is prescribed a starting velocity of 0.7 $m.s^{-1}$, the load is adjusted in order to achieve the desired velocity. In the sets that follow, if the initial repetition velocity exceeds the typical error of the device (for example ± 0.06 $m.s^{-1}$), additional time is added to the existing rest period (usually 30 seconds) to achieve the same desired starting velocity for the next set. If the initial repetition velocity in the sets that follow are still outside the desired target, then the load is further adjusted by a small percentage of the 1RM such as 5%.
Target Velocity	A specific velocity prescribed before the session where the external load is then adjusted within guidelines to meet the desired velocity for a specific target repetition or set.	Similarly, this involves a pre-session prescribed velocity, focusing on either the velocity of the initial repetition or the average velocity across a set. The practitioner may select a target velocity for the first repetition (akin to starting velocity above) or as a target for the average velocity of all repetitions within a set. Based on the performance relative to this target, adjustments in the load are made to achieve the desired velocity, whether aiming to meet the velocity of the first repetition or to maintain an average across multiple repetitions.

with a given load (i.e., traditional percentage-based training) in order to provide potentially more accurate and objective monitoring of neuromuscular fatigue, as well as to target specific RT adaptations [42, 48, 94, 125, 126, 128]. Two velocity variables can be used for this purpose, the first repetition's mean velocity, which is related to relative loading magnitude and the amount of VL allowed, generally expressed as a relative percentage loss in mean velocity from the fastest repetition of each exercise set [48, 113]. When the prescribed velocity loss percentage is exceeded, the set is terminated [48]. Alternatively, arbitrary velocity cutoffs (as defined in Table 8) can be used to terminate a set of repetitions [125]. Different VL threshold percentages (i.e., 10% to 40%) have been applied in research to target specific adaptations and manipulate fatigue responses [71, 126, 128]. These thresholds have previously been reported to be effective in minimizing fatigue and maintaining or increasing average power peak or vertical velocity across a workout session [126].

A recent systematic review and meta-analysis by Jukic et al. [71] emphasized that the acute neuromuscular, metabolic, and perceptual responses to different VL thresholds depend on various factors such as the exercise, loads used, number of sets performed, and individual athlete characteristics. Additionally, Jukic et al. [71] highlighted that there are factors that can affect the consistency of VL determination, such as the device used, reference repetition, use of peak or mean velocity, and criteria for set termination, all of which should be considered when implementing VL in practice. The relative VL method can potentially provide a more accurate and objective way to monitor neuromuscular fatigue in RT compared to traditional percentage-based methods. However, the choice of exercise, the loads used, the number of sets performed, the individual athlete's characteristics, and other factors can influence the acute neuromuscular, metabolic, and perceptual responses to different VL thresholds [3, 72, 92]. For example, this means that some athletes can do a lot more reps at 80% of 1RM compared to others (i.e. 5 vs 10 reps) [125]. This heterogeneity is observed in adults due to several factors [65, 71, 72, 106] and is most likely inflated by maturation factors among youth athletes of similar ages [91, 92]. As only one study [73] was identified by this review that implemented a VL threshold, no practical recommendations can be made specifically for youth athletes. Future research is needed to further explore the impact of different velocity loss thresholds on neuromuscular, metabolic, and mechanical responses in youth athletes at different maturation stages. Additionally, the associated measurement error of the specific device and exercise used must be considered as some VL thresholds such as, 5% or 10%, may be smaller than the reported typical error and reliability associated with that device and exercise. For example, the study by Kalmus et al. [73] reported a coefficient of variation of 2.61% (Table 6) for the Speed4Lifts LPT device citing the original study by Pérez-Castilla et al. [102]. The CV of 2.61% pertains specifically to movements performed at a load of 45% 1RM in the Smith Machine bench press. Similarly, additional CVs identified across varying loads include 2.39% for 55% 1RM, 2.42% for 65% 1RM, with an upward trend observed at higher loads, where the CV reached 3.92% for 75% 1RM and 3.41% for 85% 1RM. Despite these CV's remaining below the 10% velocity loss threshold, their referenced values should only be specific to the exercise utilized and subject characteristics when assessing them (i.e. Smith Machine bench press, males/females, trained/untrained, youth/adults). Thus, this infers little certainty on whether the associated reliability of the Speed4Lifts device can in fact accurately identify 10% VL thresholds in the exercises and subjects involved in Kalmus et al. [73]. Future studies will help to provide practical recommendations for S&C coaches to effectively use the appropriate velocity loss method for specific devices and exercises when monitoring fatigue and targeting specific adaptations in this demographic.

VBT Interventions

The implementation of VBT methods except for velocity-based feedback is very limited among youth athletes (< 20 years old) [8, 125]. Despite the increasing interest in VBT as a performance-enhancing tool, there is a clear lack of research on its effects among younger populations. A recently published systematic review by Baena-Marín et al. [8] evaluated the effect of VBT programs on variables related to muscle strength (1RM), and high-speed actions such as vertical jump, and sprint performance in trained subjects. Unfortunately, only the study by Orange et al. [99] was identified in that review that was completed among youth athletes aged 17 ± 1 years. This highlights the urgent need for further research in this area to understand the effects of VBT programs on youth athletes.

Despite the positive findings from the study by Loturco et al. [84], there remains a lack of practical recommendations for S&C coaches wanting to use VBT interventions to improve performance measures in youth athletes. Further research is required to establish the most practical recommendations for applying VBT in youth athletes to enhance athletic performance. Studies assessing the implementation of VBT methods in youth athletes are currently limited, and further investigation into the performance effects of VBT on this population is needed. Until then, caution must be exercised when implementing VBT interventions in youth athletes, as practical recommendations can only be currently substantiated from adult studies.

CONCLUSION

This systematic review's main objective was to evaluate the practical application of VBT methods in the context of youth athletes. Due to the limited research specifically focused on practical applications of VBT for this demographic, this review highlights current gaps in scientific understanding through the examination of existing practices of VBT, thus serving as a call to action for future empirical studies that better inform S&C coaches utilizing VBT with youth athletes.

The secondary objective of this review was to confront the prevailing concerns (1 to 4) and hesitations regarding the implementation of VBT in youth athletes by S&C coaches. While some issues, such as the technological efficacy of velocity-monitoring devices and budgetary constraints, fall outside the scope of this review, we aim to address the following key points.

The evidence reported in this review suggests that specific VBT methods, particularly those related to feedback mechanisms, are both accurate and reliable when applied to youth athletes. However, it is important to emphasize that this reliability is not universally applicable across all VBT methods. As highlighted, some methods such as velocity cutoffs, or specific 1RM estimations, may lack sufficient empirical support.

This review emphasizes the need for youth specific VBT protocols, as current studies lack targeted guidelines for this demographic. While the studies we examined provide some insights, they do not offer specific guidelines for optimizing performance in this demographic. This gap in literature highlights a call to action for more focused research in this area. Based on the available studies identified in this review, practical recommendations tailored to this demographic are provided in the 'Practical Recommendations' section.

Contrary to the common misconception that youth athletes lack the technical skills required for VBT, many young athletes achieve a level of technical proficiency at an early age [36, 74, 97]. This is especially more prevalent given the increasing competitiveness and seriousness of youth sports [75]. The rise in competitiveness is also reflected in the growing trend of youth athletes participating in more structured training sessions [75]. In this context, we challenge the oversimplified assumption that youth athletes lack technical proficiency solely based on their age. Therefore, "training age" should serve as a more accurate benchmark for VBT implementation than chronological age. Once an athlete has demonstrated a sufficient level of technical proficiency, determined by the coach's informed judgment, VBT can be gradually incorporated into their training regimen. This balanced approach ensures that athletes not only refine their technique but also improve performance metrics, such as enhancing movement outcomes for specific loads.

Future research needs to be completed in athletes of various maturation stages to further conceptualize and summate the potential effects the application of VBT methodologies can have in youth athletes of varying maturity. Future research should also investigate the practicality of implementing these methods on both an individual and group level if possible. The aim of future studies should be to inform S&C coaches working with youth athletes of practical recommendations regarding implementation of VBT methodologies for specific monitoring and performance outcomes.

PRACTICAL APPLICATIONS

Coaches should integrate velocity-based feedback into training sessions to improve mental performance, motivation, and competitiveness. They should provide this feedback in the form of visual-kinematic outputs after each repetition to enhance acute performance through improved maximal intent. Individualized LVP methods should be utilized over generalized methods to enhance accuracy and adjust for individual variation due to factors such as maturation development among youth athletes of the same chronological age. For greater accuracy at the expense of time coaches can use the multiple point LVP method with an individualized V1RM when predicting 1RM. Also, for greater accuracy, coaches should use the multiple-point method when developing an LVP to track changes in strength. No specific recommendation can be made for loading schemes during LVP development as a wide variety have been utilized with no outstanding differences reported. Coaches also need to ensure they know the associated measurement error of the velocity monitoring device across various exercises before prescribing velocity loss thresholds, as some devices may possess a typical error greater than some velocity loss thresholds.

CONFLICTS OF INTEREST

All authors declare that they have no conflicts of interest relevant to the content of this review.

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Not Applicable

DATA AVAILABILITY STATEMENT

The data supporting this systematic review are from previously reported studies and datasets, which have been cited.

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- Conceptualization, Y.W, S.R.L,
- Methodology, Y.W, S.R.L, R.R.C
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