Effects of velocity-based training vs. alternative resistance training on changes in strength, power and sprint speed: a systematic review, meta-analysis and quality of evidence appraisal

Supplementary materials:
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ABSTRACT

Background: Velocity-based training (VBT) may be an effective method for monitoring resistance training load because it accounts for daily changes in an individual's physical performance capabilities. However, the current evidence comparing VBT to alternative resistance training methods is dominated by small individual studies reporting mixed results. A systematic review is required to increase precision, explore heterogeneity, and inform directions for future research.

Objectives: To evaluate the effectiveness of regulating resistance training based on objective velocity feedback, compared to alternative resistance training methods that do not use velocity feedback (such as percentage of one repetition maximum, rating of perceived exertion, or repetitions in reserve), on changes in muscle strength, power, and sprint speed.

Data sources: Systematic searches of PubMed, Embase, SportDiscus, CINAHL, Cochrane Central, ClinicalTrials.gov, ISRCTN, and SportRxiv, and citation searching until June 2021.
Study eligibility criteria: Eligible studies included randomised trials that assessed muscle strength, power, or sprint speed in healthy participants before and after a VBT intervention and an alternative resistance training intervention lasting at least four weeks.
Appraisal and synthesis: Standardised mean differences (SMDs) were pooled using a random effects model with a multi-level structure. Risk of bias was assessed with the Risk of Bias 2 (RoB 2) tool and the quality of evidence was evaluated using the Grading of Recommendation, Assessment, Development, and Evaluation (GRADE) approach.
Results: Four trials met the eligibility criteria, comprising 27 effect estimates and 88 participants. The main analyses showed trivial differences and imprecise interval estimates for effects on muscle strength (SMD 0.06, 95% CI -0.51 to 0.64; I^2 = 42.9%; 10 effects from 4 studies; low quality evidence), power (SMD 0.11, 95% CI -0.28 to 0.49; I^2 = 13.5%; 10 effects from 3 studies; low quality evidence), and sprint speed (SMD -0.10, 95% -0.72 to 0.53; I^2 = 30.0%; 7 effects from 2 studies; very low quality evidence). The results were robust to various sensitivity analyses.
Conclusion: The current evidence does not support the use of objective velocity feedback over alternative methods of regulating resistance training load to elicit improvements in muscle strength, power, or sprint speed. Further well-designed trials with larger samples are required to increase the precision of the effect estimates and overall quality of evidence.
Registration: The review was preregistered on the Open Science Framework (https://osf.io/pz9fs).

INTRODUCTION

Regular resistance training provides a stimulus for improvements in muscle strength and power [1, 2]. These adaptations are typically considered beneficial for sports performance [3], and resistance training is often an integral component of long-term athlete development programmes [4, 5]. Muscle strength and power are also associated with better health outcomes in non-athlete populations, including reduced all-cause mortality and higher physical function [6, 7]. Indeed, the World Health Organisation recommend that healthy adults and those with chronic health conditions undertake muscle-strengthening activities, such as resistance exercise, on at least two days per week [8].

Resistance training load is an important variable in resistance training programmes [9]. The most common method of prescribing resistance training load is to use a percentage of one repetition maximum (%1RM) combined with a predetermined number of repetitions. Whilst this approach has been shown to improve muscle function in athlete and non-athlete populations [1, 10–14], it does not account for daily changes in an individual's physical performance capabilities [15].

Maximal strength can fluctuate on a day-to-day basis due to fatigue, inadequate sleep, or other life-related stressors [16]. Strength can also change throughout the training block due to (mal)adaptation [17]. In addition, the ability to complete repetitions at a given %1RM varies considerably between individuals [18]. As a consequence, prescribing resistance training load based on %1RM may lead to a suboptimal training stimulus.

Alternative resistance training strategies exist that account for an individual's perceived performance capabilities on a given day [19]. For example, training to task failure allows the number of repetitions to vary with acute performance capability. A similar approach is to perform repetitions within a set until reaching a target number of repetitions away from perceived task failure, known as repetitions in reserve (RIR) [20]. Moreover, load can be adjusted according to a rating of perceived exertion (RPE) associated with a fixed number of repetitions [21]. These methods are simple to implement, do not require the use of technology, and can be used in large group settings. However, they rely on an individual's ability to predict proximity to task failure, which can be inaccurate [22].

Velocity-based training (VBT) uses instantaneous velocity feedback to objectively monitor and adjust resistance training load [23]. Whilst various methods exist within the VBT paradigm [24], the two main approaches include velocity zones and velocity loss thresholds. Velocity zones involve performing repetitions at a concentric velocity that falls within a pre-defined threshold (e.g. 0.60-0.70 $m \cdot s^{-1}$). The velocity zones can be generic (i.e. all individuals lift within the same velocity zone) or derived from an individual's load-velocity profile. Velocity loss thresholds involve performing repetitions within a set until repetition velocity drops below a pre-specified cut-off (e.g. 20% velocity loss threshold) [25]. Because movement velocity and barbell load are is inversely related [26, 27], changes in velocity attained against a given load are indicative of changes in an individual's performance capabilities. Indeed, a decline in barbell velocity is representative of neuromuscular fatigue [28], whereas greater velocity attained against a given absolute load indicates enhanced muscle strength [26]. Thus, VBT can be used to objectively manipulate resistance training load according to an individual's current physiological state.

Several papers have published guidelines on how to implement VBT [24, 25, 29]. These guidelines are largely based on the notion that, by objectively accounting for daily changes in performance capabilities, VBT may lead to superior (or different) physiological adaptations compared with alternative resistance training methods [24, 25, 29]. However, this supposition does not seem to be supported by empirical evidence. Individual studies directly comparing VBT to alternative resistance training methods have reported mixed and imprecise results [23, 30, 31], which may be due to sampling errors associated with the small sample sizes. Pooling the results of small individual studies is crucial to increase precision and the chance of detecting an

effect, if an effect exists. Such information can then be used to inform guidelines on resistance training prescription. Synthesizing the evidence-base is also necessary to explore heterogeneity, identify gaps in knowledge, and inform directions for future research. Therefore, we systematically reviewed, meta-analysed and appraised the quality of evidence regarding the effects of VBT vs. alternative resistance training methods on changes in strength, power and sprint speed.

METHODS

This systematic review was prospectively registered Open Science Framework (OSF) [32] and followed guidelines by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [33] and Cochrane Handbook [34]. Deviations to the original protocol are described and justified in Online Resource 1.

Search strategy

Two authors (AH and LP) independently searched PubMed, Embase, SportDiscus, CINAHL and Cochrane Central Register of Controlled Trials (CENTRAL) electronic databases from inception to 1st June 2021. We also searched the ClinicalTrials.gov, International Standard Randomised Controlled Trial Number (ISRCTN), and SportRxiv databases to identify any ongoing or unpublished trials. Standard Boolean operators (AND, OR) were used to concatenate the search terms. The search string used in five electronic databases is displayed in Table 1, and searches used in all other databases are presented in Online Resource 2. We also manually searched the reference lists and forward citations of included studies and relevant reviews to identify potentially eligible studies.

Inclusion criteria

Original research articles were included if they met the following inclusion criteria: (1) the study was a prospective randomised trial (2) full-text was available in English language, (3) participants were healthy and aged ≥16 years, (4) participants were randomly allocated to a VBT intervention or a comparison resistance training intervention using a between-group design, or contralateral limbs were randomised in parallel to the interventions using a within-group design, (5) the VBT intervention used a measurement tool to objectively monitor movement velocity such as high-speed video capture, linear position/velocity transducer, inertial measurement unit, or laser optic device, (6) the interventions lasted at least four weeks, (7) a measure of muscle strength, muscle power, or sprint speed was assessed before and after the intervention. Studies were excluded if: (1) they used a quasi-experimental, crossover, or observational design, (2) participants were recruited on the basis of any medical condition, or (3) the article has been

retracted. In line with Cochrane guidelines, quasi-experimental trials were excluded because it is feasible to conduct randomised trials to answer the questions being addressed by this review [35]. Crossover trials were also considered inappropriate due to the likelihood of a carry-over effect [36] (for example, muscle strength is maintained >6 months after resistance training cessation [37]). However, quasi-experimental and cross-over trials were included in a sensitivity analysis (see Statistical Analysis section).

Table 1. Search terms used in PubMed, EMBASE, Cochrane CENTRAL, SPORTDiscus, and CINAHL

[All fields] "velocity-based training" OR "velocity training" OR "load velocity profile*" OR "velocity loss" OR VBT OR autoregulation
AND
[All fields] "resistance training" OR "strength training" OR "weight training" OR weightlifting
AND
All fields] "one repetition maximum" OR 1RM OR isometric OR isokinetic OR speed OR sprint OR jump OR power

We broadly defined resistance training as a sequence of dynamic strength exercises that utilised concentric and/or eccentric muscle contractions [1]. We defined VBT as a resistance training intervention that used velocity feedback to manipulate resistance training load or the number of repetitions/sets performed in at least one resistance exercise. The comparison resistance training intervention was defined as an intervention that did not use velocity feedback to manipulate resistance training load/volume, but instead informed resistance training prescription based on one of the following methods: (1) %1RM, with the 1RM assessed at baseline (2) RPE, (3) RIR, or (4) task failure (i.e., repetition maximum zones or repetition-failure).

Outcomes

Outcomes included measures of maximal strength, power, and sprint speed and were continuous variables. Maximal strength outcomes included mass lifted in dynamic 1RM tests in the upper- or lower-body (e.g. back squat, bench press), or force achieved in isometric assessments (e.g. mid-thigh pull, squat, knee extension). Muscle power outcomes included power or velocity obtained in the concentric phase of a resistance exercise (e.g. back squat). Muscle power outcomes also included power produced or height achieved in a countermovement or depth jump. Sprint speed included a timed maximal sprint between 5 and 100 m in distance.

Study selection

After the literature searches were completed, studies were collected into a single list in a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA). Two authors (AH and LP) independently removed duplicates and screened the titles and abstracts to identify potentially eligible studies. Full-texts were obtained for all studies that appeared relevant or where there was any uncertainty. Two authors (AH and LP) then independently examined each full-text manuscript against the eligibility criteria. Any disagreements were resolved through discussion and consultation with a third author (STO). If it was necessary to clarify aspects of the study in relation to the eligibility criteria, or retrieve a full-text manuscript, we contacted corresponding authors on at least two occasions within a one-month period.

Data extraction

Data items extracted from each eligible study included: (1) authors, (2) title and year of publication, (3) sample size, (4) participant characteristics, (5) details of the VBT intervention, (6) details of the comparison intervention, (7) details of the outcome measures, (8) details of retention rates and intervention adherence, and (9) baseline, follow-up, and change score data for each outcome measure (mean and SD). If SDs weren't reported, we collected other relevant data that can be converted to an SD, such as 95% confidence intervals (CIs) or *p*-values.

Risk of bias

The Cochrane risk of bias tool for randomized trials (RoB 2) was used to judge the risk of bias for each included outcome within each study [38]. RoB 2 comprises five domains and a series of signalling questions relating to the: 1) randomisation process, 2) deviations from intended interventions, 3) missing outcome data, 4) measurement of the outcome, and 5) selection of the reported result. Judgements for each domain and the overall risk of bias are expressed as 'low', 'high', or 'some concerns'. An overall bias judgment was taken as the least favourable assessment across all the domains [38]. Judgements were made independently by two authors (TJ and OJ), with any disagreements resolved by discussion and consensus with a third author (STO).

When a meta-analysis included 10 or more effect sizes, risk of bias due to missing results in a synthesis was explored with Egger's test of the intercept [39] and by visually inspecting a funnel plot of the effect estimates plotted against their corresponding sampling variance.

Quality of evidence

We rated the quality of evidence for each outcome using the Grading of Recommendation, Assessment, Development, and Evaluation (GRADE) approach [40]. GRADE has four levels of

evidence: very low, low, moderate and high. Randomised trials start with a 'high quality' rating, and we downgraded the certainty evidence for each outcome based on the following factors: 1) risk of bias, 2) inconsistency of results, 3) indirectness of evidence, 4) imprecision of results, and 5) publication bias [41]. The evidence was downgraded by one level if we judged that there was a *serious limitation* or by two levels if we judged there to be a *very serious limitation.* Criteria for downgrading the evidence were decided *a priori* [32]. Two review authors (STO and JS) independently graded the certainty of evidence, with any discrepancies resolved through consensus. An overall GRADE certainty rating was applied to the body of evidence by taking the lowest certainty of evidence from all of the outcomes [42].

Statistical analysis

All studies included in the review are narratively synthesized. Where two or more trials reported the same outcome, we performed a meta-analysis of standardised mean differences (SMDs) between conditions. SMDs were calculated by dividing the mean difference (MD) by the pooled SD at baseline, where the MD was calculated as the mean pre-post change in the VBT group minus the mean pre-post change in the comparison group [43]. Hedges' *g* correction was applied to the SMD to adjust for sample bias. Qualitative descriptors used to interpret the strength of the SMDs were based on Cohen's (1998) thresholds (±): trivial (< 0.2), small (0.2 to 0.49), moderate (0.5 to 0.79), and large (≥ 0.8) [44]. For the purposes of interpretation, the interval estimate around an SMD was considered precise if its width was less than 0.5 SMDs. An arbitrary threshold of 0.5 SMDs was chosen to indicate (im)precision because this magnitude is able to span adjacent effect size thresholds according to Cohen's criteria [44].

As supplementary analyses, we performed a meta-analysis of MDs when the original units of measurement were available from two or more studies. Moreover, we determined pre-post effects of VBT and comparison groups by performing a meta-analysis on the standardised mean changes (SMCs), which were calculated by dividing the mean pre-post change by the SD of the change score (SD_{diff}) in each condition. We then converted the SMC to a percentage and reported the common language effect size (CLES), which expresses the probability of a randomly selected individual undergoing an improvement from pre- to post-intervention [45]. If a study did not report the SD_{diff} and it could not be retrieved from the corresponding author, it was estimated using SDs at baseline and post-intervention in addition to the pre-post correlation coefficient [46]. The pre-post correlation was assumed to be 0.7 in line with guidelines by Rosenthal [47] and with previous meta-analyses [1, 48, 49].

Meta-analyses were performed with a random effects model using the restricted maximum likelihood method to estimate between-study variance. CIs and test statistics were calculated via

a t-distribution using the Hartung-Knapp-Sidik-Jonkman (HKSJ) approach. The HKSJ approach for random effects meta-analysis results in superior error rates compared with the standard DerSimonian-Laird (DL) method when the number of included studies is small [50]. Studies were weighted according to the inverse of the sampling variance. When a meta-analysis included more than one outcome measure from the same study, effect estimates were nested within studies using a multi-level structure to account for correlated effects [51].

Statistical heterogeneity between studies was evaluated with tau-squared (τ^2) and the Chi-squared test (χ^2), and the proportion of variability in effect estimates due to heterogeneity rather than sampling error was estimated using the I^2 statistic. Thresholds for the interpretation of I^2 were in line with Cochrane recommendations: 0-40% ('might not be important'), 30-60% ('may represent moderate heterogeneity'), 50-90% ('may represent substantial heterogeneity'), and 75-100% ('considerable heterogeneity') [52]. The importance of the observed I^2 value was interpreted alongside its 95% CI and the *p*-value from the χ^2 test [52].

When a meta-analysis included 10 or more effect estimates, and there was evidence of at least moderate heterogeneity, we performed meta-regressions to explore sources of heterogeneity. Covariates included: (1) mean age of participants (continuous variable), (2) whether the interventions involved weekly fluctuations in training load (i.e. periodisation; yes vs. no), and (3) the number of resistance exercises in the VBT intervention that were manipulated using velocity feedback (≤1 vs. >1 exercise). An additional meta-regression for strength outcomes included the muscle group tested (lower-body vs upper-body). Apart from age, meta-regressions were not specified in the pre-registered protocol and were exploratory.

We performed various sensitivity analyses on the main meta-analysis models to examine whether decisions made in the review process influenced the overall findings. Sensitivity analyses included: (1) computing test statistics and 95% CIs based on a normal (z) distribution rather than a t-distribution, (2) including quasi-experimental and crossover studies in the meta-analyses, and (3) using SD_{diff} to calculate effect estimates rather than the SD at baseline. We also examined meta-analyses for influential cases by calculating Cook's distance and hat values [53]. Cook's distance values of greater than $\frac{4}{k}$ or hat values of more than $3\frac{1}{k}$ were considered influential cases, where k is the number of observations in the model. We then performed a Leave-One-Out sensitivity analysis to assess whether removing an individual effect estimate from a meta-analysis influenced the model parameters.

Statistical analyses were conducted using package metafor in R version 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was set at $p<0.05$. Data are presented as point estimates with their corresponding 95% CIs. Effects in the positive direction

favour the VBT condition whereas effects in a negative direction favour the comparison interventions. One author (STO) performed the statistical analyses, with another author (JS) checking the code and reproducing the results. The search results, dataset, and code are available on OSF [54].

Results

Study identification and selection

A total of 572 records were identified through the database searches, of which 317 were duplicates (Figure 1). One additional record was identified through forward citation tracing. After deduplication and screening of 256 abstracts, 22 full-texts were assessed for eligibility. A total of four trials met the eligibility criteria and were included in this review and meta-analysis.

Study characteristics

An overview of the included studies is presented in Table 2. Two out of the four studies were based in the UK [23, 55], with one study based in Germany [31], and one study based in Spain [30]. All studies recruited participants with at least two years of resistance training experience. Three out of the four studies exclusively recruited males, whereas one study recruited males and females [31]. Two studies recruited sports players that were engaged in sports-specific training alongside the resistance training interventions [23, 31]. The median sample size was 23 (range: 16 to 27). Only one study intervention used individual velocity zones to manipulate resistance training [23]; one study used general velocity zones [30], one study used velocity loss thresholds [31], and one study combined general velocity zones with velocity loss thresholds [55]. Studies used either a linear position transducer or linear velocity transducer to monitor barbell velocity. The comparison intervention in all studies involved using a %1RM to prescribe resistance training load, and one of the interventions combined %1RM prescription with repetition failure [31]. All interventions involved two exercise sessions per week and lasted between six and eight weeks.

'Near misses'

Three studies were judged to be meet many, but not all, of the eligibility criteria (i.e. 'near misses') [56–58]. Justifications for excluding these studies are presented in Online Resource 3.

Risk of bias

We evaluated the risk of bias for all outcomes included in the review (strength, power, and sprint speed). The principal risk of bias assessment is based on muscle strength because this was assessed in all included trials, although bias assessments for other outcomes are presented in

Online Resource 4. Three trials were judged to raise some concerns overall, and one trial was judged to have a high overall risk of bias. Common concerns were bias due to the randomisation process, measurement of the outcome, and selection of the reported result. Judgements for each study in each RoB2 domain are illustrated in Figure 2, and justifications are available on OSF [54].

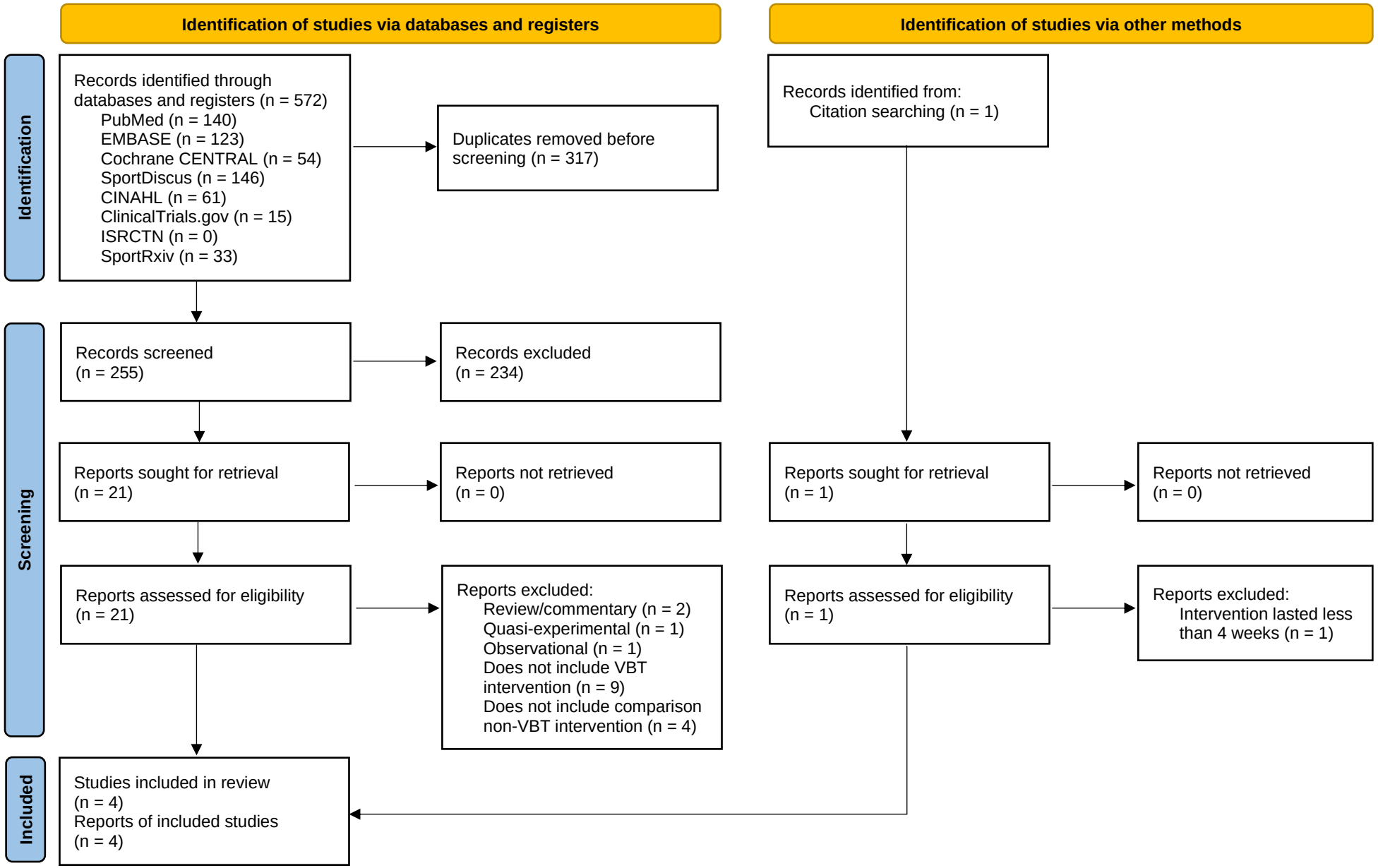

Figure 1. PRISMA flow diagram of systematic search and included studies

Table 2. Description of included studies

Study	Participants	Country	VBT intervention	Comparison intervention	Velocity monitoring tool	Frequency/ duration	Adherence	Outcomes included in the review		
								Strength	Power	Speed
Orange et al. [23]	**N =** VBT: 12, C: 15 **Sex =** M **Age =** 17±1 **RT experience =** 2 yr	UK	**Type:** Individual velocity zones **Exercise(s):** Back squat **Load:** MV @ 60 & 80% 1RM **Reps x sets:** 5 x 4 **Intended velocity:** Max **Inter-set rest:** 2-3 min	**Type:** %1RM **Exercise(s):** Back squat **Load:** 60 & 80% 1RM **Reps x sets:** 5 x 4 **Intended velocity:** Max **Inter-set rest:** 2-3 min	LPT	2x/week for 7 weeks	VBT: 90% C: 86%	Back squat 1RM	CMJ height DJ height Back squat MV @40-90% 1RM	5-30 m sprint time

Dorrell et al. [55]	**N =** VBT: 8, C = 8 **Sex =** M **Age =** 23±5 **RT experience =** 2 yr	UK	**Type:** General velocity zones & 20% VL thresholds **Exercise(s):** Back squat, bench press, OHP, deadlift **Load:** MV @ 70-95% 1RM **Reps x sets:** 2-8 x 3 **Intended velocity:** Max **Inter-set rest:** NR	**Type:** %1RM **Exercise(s):** Back squat, bench press, OHP, deadlift **Load:** 70-95% 1RM **Reps x sets:** 2-8 x 3 **Intended velocity:** Max **Inter-set rest:** NR	LPT	2x/week for 6 weeks	VBT: 100% C: 100%	Back squat, bench press, OHP, & deadlift 1RM	CMJ height
Held et al. [31]	**N =** VBT: 11, C = 10 **Sex** = M & F **Age =** 20±2	Germany	**Type:** 10% VL thresholds **Exercise(s):** Power	**Type:** %1RM & RF **Exercise(s):** Power clean, squat, bench	LPT	2x/week for 8 weeks	NR	Squat, deadlift, bench row, & bench	

	RT experience = 2 yr		clean, squat, bench row, deadlift, bench press **Load:** 80% 1RM **Reps x sets:** 4 sets (variable reps) **Intended velocity:** Max **Inter-set rest:** 2-3 min	row, deadlift, bench press **Load:** ~80% 1RM **Reps x sets:** 4 sets (variable reps) **Intended velocity:** Max **Inter-set rest:** 2-3 min				press 1RM		
Jiménez-Reyes et al. [30]	N = VBT: 13, C = 11 Sex = M Age = 23±4 RT experience = 2 yr	Spain	**Type:** General velocity zones **Exercise(s):** Smith machine squat	**Type:** %1RM **Exercise(s):** squat **Load:** 50-80 %1RM **Reps x sets:** 2-8 x 3-4	LVT	2x/week for 8 weeks	NR	Smith machine squat 1RM	CMJ height Smith machine squat MPV	10-20 m sprint time

	Load: MV @ 50-80 %1RM **Reps x sets:** 2-8 x 3-4 **Intended velocity:** Max **Inter-set rest:** 4 min	**Intended velocity:** Max **Inter-set rest:** 4 min

C = comparison intervention; CMJ = countermovement jump; DJ = drop jump; LPT = linear position transducer; LVP = linear velocity transducer; MV = mean velocity; MPV = mean propulsive velocity; N = sample size analysed; OHP = overhead press; RF = repetition failure; RT = resistance training; UK = United Kingdom; VBT = percentage-based training; VL = velocity loss.

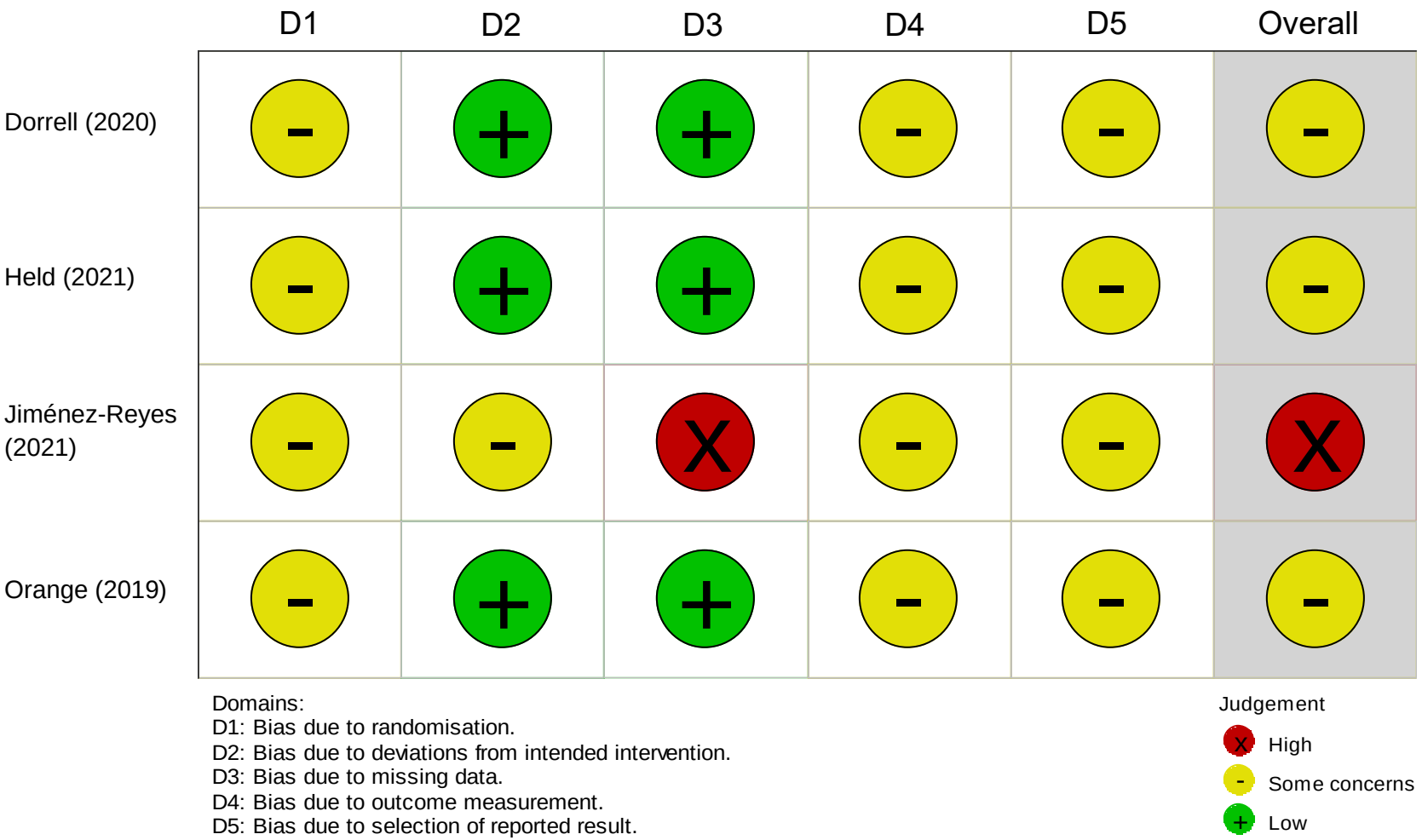

Figure 2. Risk of bias judgements for strength outcomes in each included study, using the revised Cochrane risk of bias tool for randomised trials (RoB 2)

Outcomes

Muscle strength

The main model on strength outcomes comprised of 10 effect estimates from 4 trials (88 participants in total). All effect estimates related to tests of 1RM strength; six effects related to lower-body strength (back squat and deadlift 1RM) and the remaining four effects assessed upper-body strength (bench press, overhead press, and bench row). The meta-analysis revealed a trivial SMD between VBT and comparison groups with an imprecise interval estimate (SMD 0.06, 95% CI -0.51 to 0.64; p=0.81; Figure 3). The total amount of heterogeneity across all levels in the model not attributable to sampling error was moderate (τ^2 = 0.16; I^2 = 42.9%; p = 0.42). Visual inspection of the funnel plot showed that the treatment effects were symmetrically distributed around the overall pooled effect size (Figure 4) and Egger's test of the intercept showed that sampling variance did not significantly mediate the overall effect (β 6.5, 95% CI -11.1 to 24.3; p=0.42).

We also performed a meta-analysis of MDs in original measurement units, which included the same effect estimates as the main model (10 effect estimates across four trials). The pooled analysis in raw units showed a non-significant difference of 0.46 kg (favouring VBT) with an imprecise interval estimate (MD 0.46 kg, 95% CI -8.3 to 9.2 kg; p=0.91).

Muscle power

The main model for power included three trials, consisting of 10 effect estimates and 67 participants. Four effect estimates from three trials related to jump height, and six effects from two trials related to velocity attained obtained in the concentric phase of a resistance exercise. The meta-analysis showed a trivial SMD between VBT and comparison groups with an imprecise interval estimate (SMD 0.11, 95% CI -0.28 to 0.49; p=0.55; Figure 5). The magnitude heterogeneity across all levels in the model not attributable to sampling error might not be important (τ^2 = 0.03; I^2 13.5%; p=0.75). Funnel plot analysis showed treatment effects were symmetrically distributed around the overall pooled effect size (Figure 4) and Egger's test of the intercept was non-significant (β 1.45, 95% CI –13.5 to 16.4; p=0.83).

To provide the pooled effect in original measurement units, we performed separate meta-analyses of MDs for jump height (4 effects across 3 trials) and barbell velocity (6 effects across 2

trials). The meta-analyses revealed a non-significant difference of 0.39 cm in jump height favouring the comparison intervention (MD -0.39 cm, 95% -3.8 to 3.0 cm; p=0.74) and a non-significant difference of 0.21 m·s^{-1} in barbell velocity favouring the VBT condition (MD 0.21 m·s^{-1}, 95% CI -0.01 to 0.06 m·s^{-1}; p=0.18).

Sprint time

The main model for sprint time comprised of two trials, involving seven effect estimates and 46 participants. Three effect estimates related to sprint times of ≤10 meters, whereas four effects related to sprint times of 20 or 30 meters. The meta-analysis revealed a trivial SMD with an imprecise interval estimate (SMD -0.10, 95% CI -0.72 to 0.53; p=0.72; Figure 6). The magnitude of heterogeneity might not be important (τ^2 = 0.08; I^2 30.0%; p=0.49). Funnel plot analysis nor Egger's test of the intercept were undertaken because the meta-analysis included less than 10 effect estimates. However, none of the individual effect estimates included in the meta-analysis reached the conventional threshold for statistical significance (i.e. p<0.05), and therefore we considered publication bias to be unlikely.

A secondary meta-analysis of MDs in original measurement units showed a point estimate of zero seconds between VBT and comparison conditions (0.00 s, 95% CI -0.04 to 0.04; p=0.94).

Meta-regressions

Meta-regressions for strength effects are presented in Table 3. Including the number of VBT exercises as a categorical covariate in the model reduced the magnitude of heterogeneity from I^2=40.9% (i.e. 'moderate') to I^2 = 13.7% (i.e. 'might not be important') and increased the point estimate in favour of VBT. All other covariates had a negligible influence on model parameters. Meta-regressions were not undertaken for muscle power or sprint speed effects because of the negligible amount of heterogeneity in the model and because the meta-analysis included less than 10 effect estimates, respectively.

Pre-post effects

Meta-analyses of pre-post effects are presented in Online Resource 5. The CLES indicates that the probability of a randomly selected individual increasing their muscle strength, power, and speed after a VBT intervention is 97%, 84% and 25%, respectively. Similarly, the probability of a

randomly selected person's muscle strength, power and sprint speed increasing after an alternative resistance training intervention is 90%, 78%, and 39%, respectively. SD_{diffs} were unavailable for three effect estimates from one study (10-20 m sprint time, squat velocity attained against loads that were moved faster than 1 $m \cdot s^{-1}$, and slower than 1 $m \cdot s^{-1}$) [30] and were therefore imputed using the baseline and post-intervention SDs and assuming a pre-post correlation of 0.7.

Quality of evidence

GRADE assessments showed that the quality of evidence for strength and power effects was low, and the quality of evidence for sprint speed effects was very low. Thus, the overall quality of evidence for the body of evidence was judged to be very low. This was mainly due to risk of bias within individual studies and low precision of estimates (i.e. small total sample size and/or wide interval estimates). A summary of findings table is presented in Table 4.

Sensitivity analyses

The sensitivity analyses did not change the results in such a way that the interval estimate excluded zero. However, including quasi-experimental and crossover trials in the meta-analyses (leading to the inclusion of two additional studies consisting of 17 effect estimates and 40 participants) reduced heterogeneity and increased the precision of the interval estimates for all outcomes (see Online Resource 6).

Influential case analyses are graphically presented in Online Resource 7. One effect estimate [30] was identified as having a strong influence on the main model for strength effects. Removing this observation reduced the magnitude of heterogeneity and increased the point estimate in favour of VBT, but the interval estimate still crossed the line of no effect. All results from the Leave-One-Out analysis are detailed in Online Resource 8.

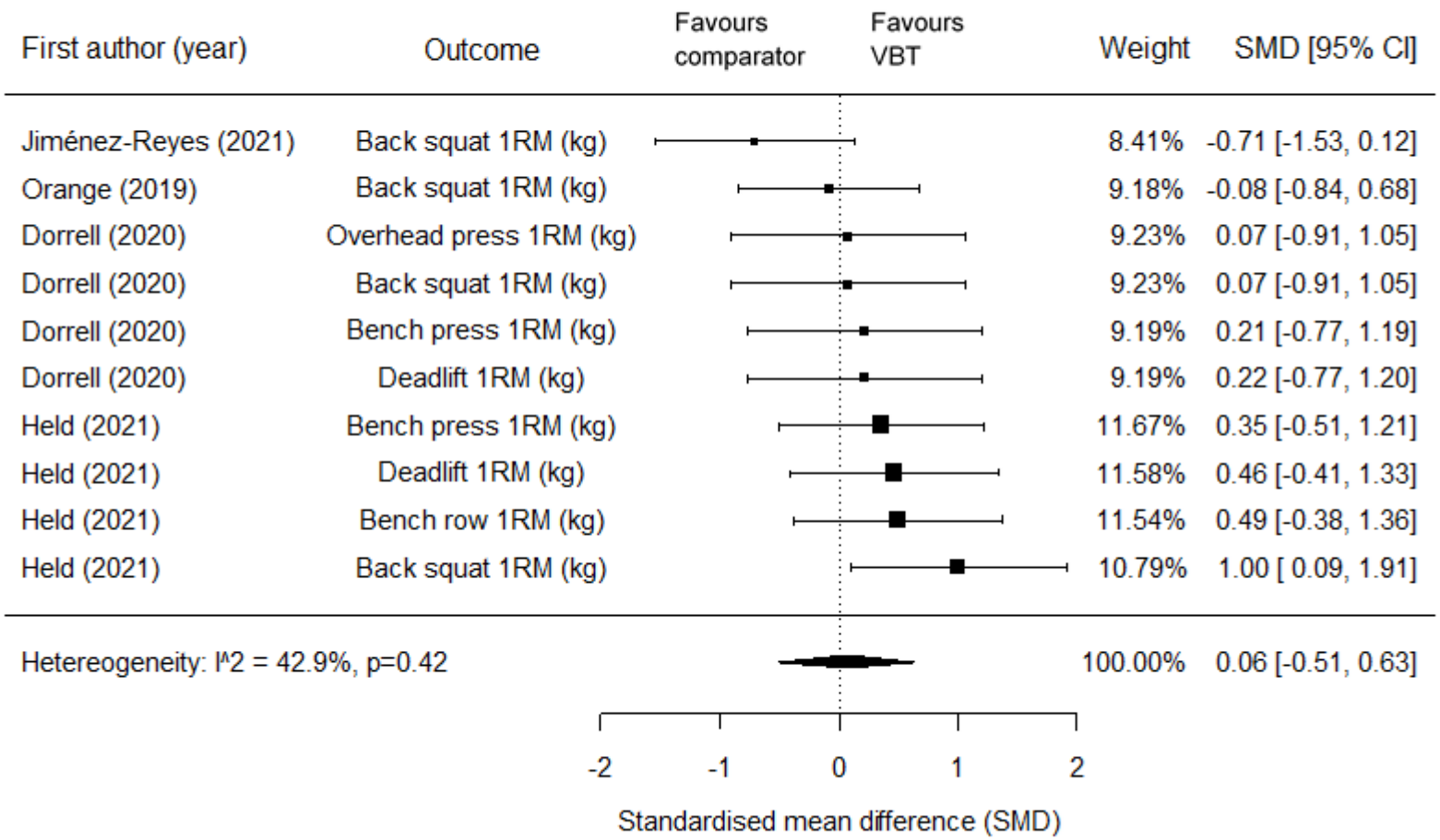

Figure 3. Forest plot of the results from a multi-level random-effects meta-analysis on muscle strength effects. Data are presented as standardised mean differences (SMDs) between velocity-based training (VBT) and comparison interventions with corresponding 95% confidence intervals (95% CIs). Effects in the positive direction favour the VBT condition whereas effects in a negative direction favour the comparison interventions.

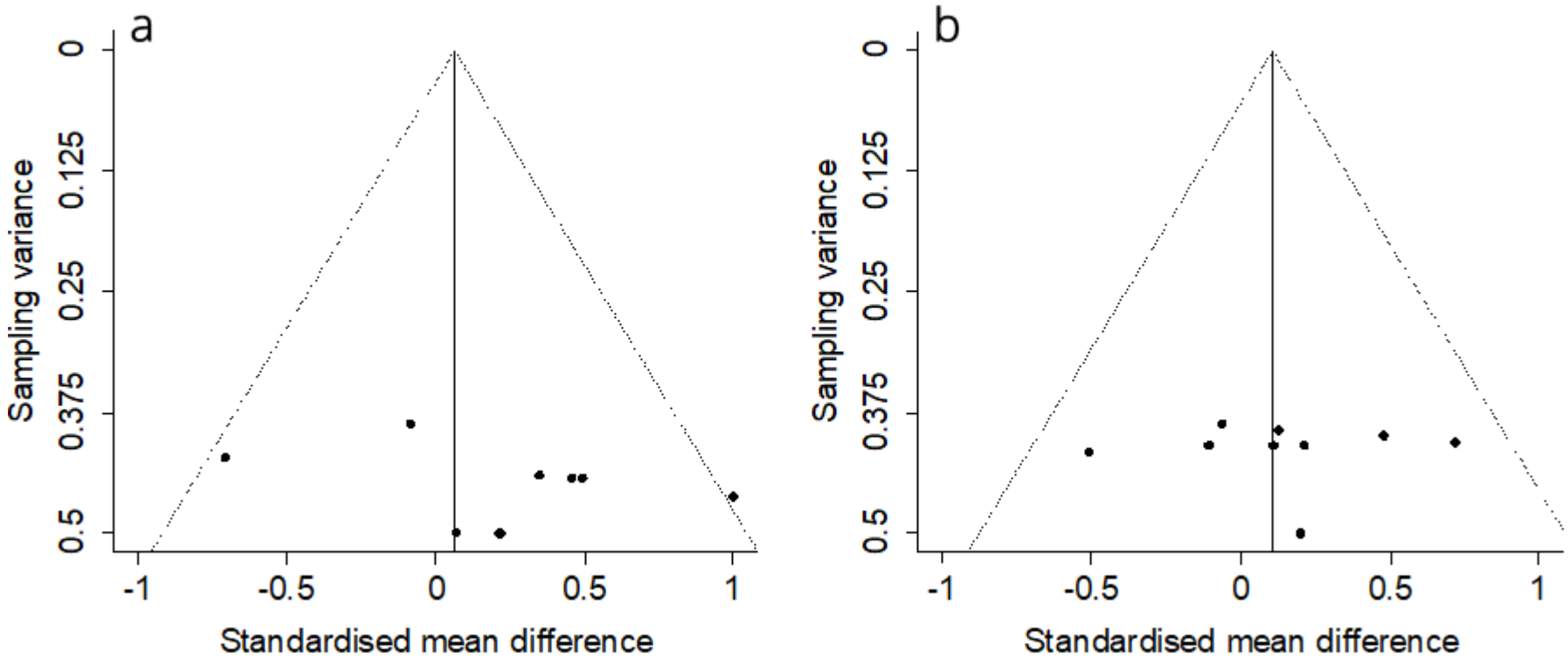

Figure 4. Funnel plot of the standardized mean differences from individual studies against the corresponding sampling variances for muscle strength (a) and muscle power (b).

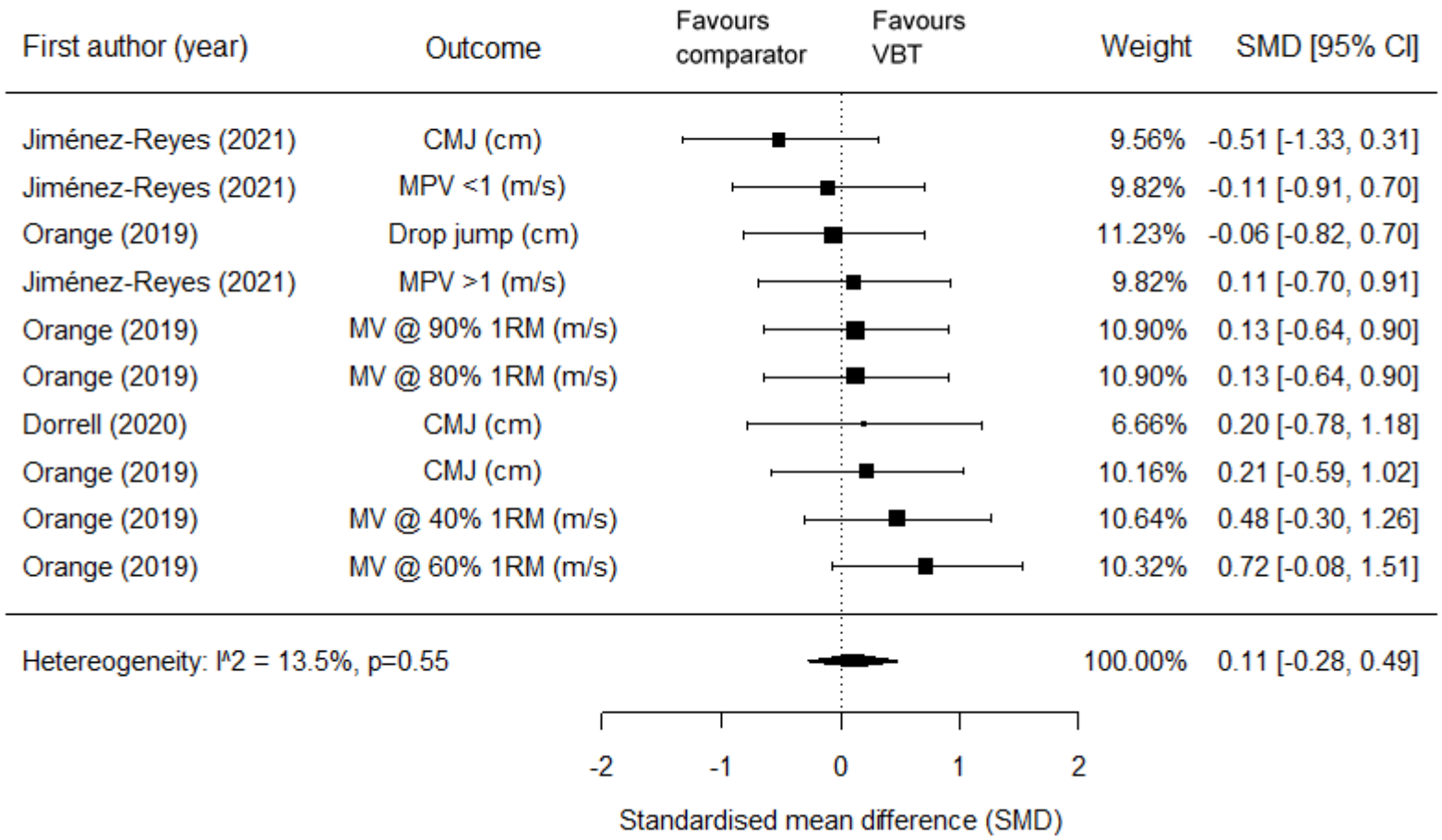

Figure 5. Forest plot of the results from a multi-level random-effects meta-analysis on muscle power effects. Data are presented as standardised mean differences (SMDs) between velocity-based training (VBT) and comparison interventions with corresponding 95% confidence intervals (95% CIs). Effects in the positive direction favour the VBT condition whereas effects in a negative direction favour the comparison interventions.

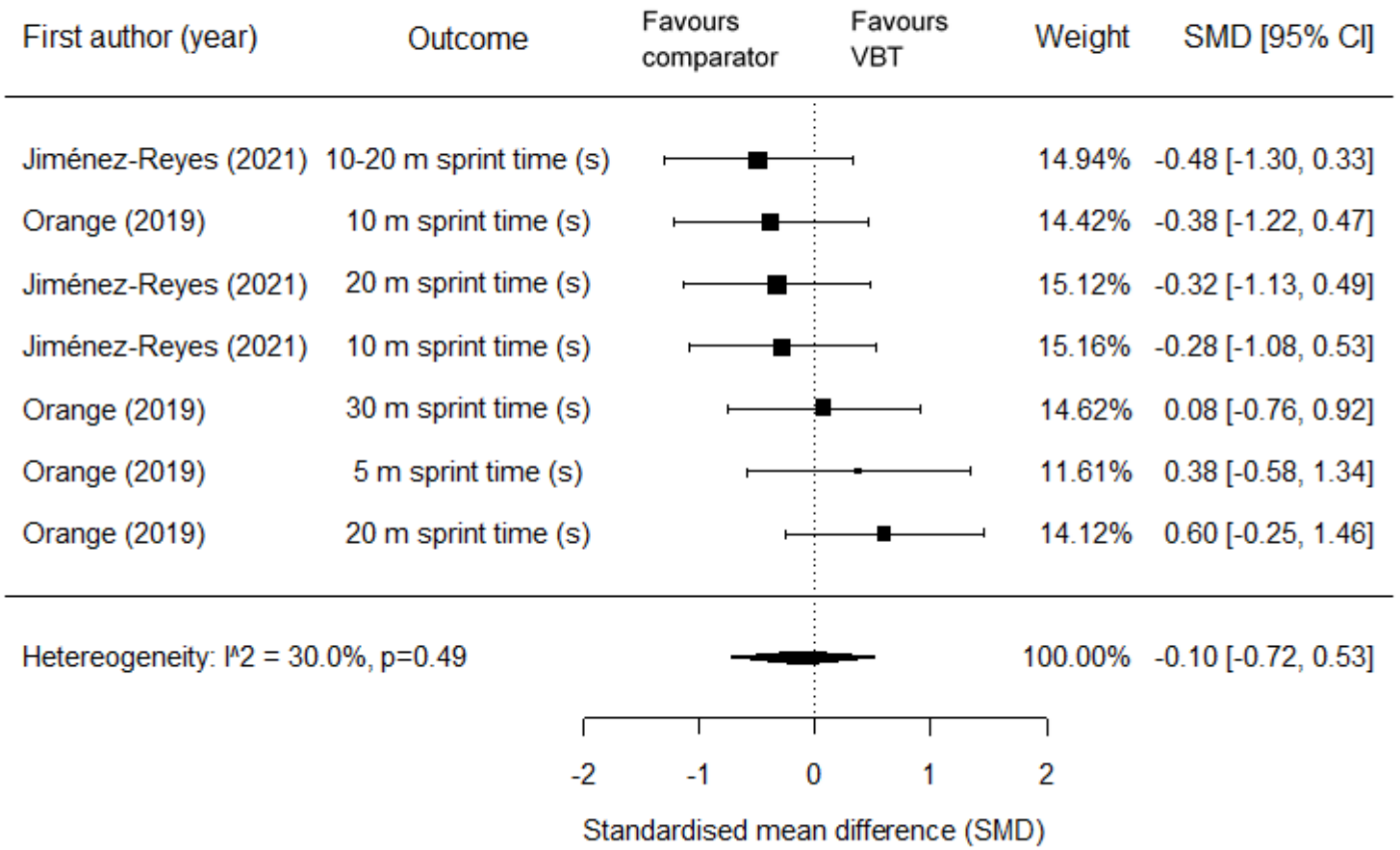

Figure 6. Forest plot of the results from a multi-level random-effects meta-analysis on sprint speed effects. Data are presented as standardised mean differences (SMDs) between velocity-based training (VBT) and comparison interventions with corresponding 95% confidence intervals (95% CIs). Effects in the positive direction favour the VBT condition whereas effects in a negative direction favour the comparison interventions.

Table 3. Meta-regressions for muscle strength effects

Covariate	Coefficient (95% CI)	*p*-value	I^2 (χ^2 *p*-value)
Age	-0.07 (-0.35, 0.21)	0.61	53.4% (0.43)
Periodisation[a]			
No[b]	-	-	-
Yes	-0.50 (-1.7, 0.70)	0.36	45.0% (0.61)
No. of VBT exercises			
≤1 exercise[b]	-	-	-
>1 exercise	0.74 (-0.13, 1.6)	0.085	13.7% (0.85)
Muscle group tested			
Upper-body[b]	-	-	-
Lower-body	0.01 (-0.72, 0.74)	0.97	44.6% (0.36)

[a]Periodisation refers to whether the intervention involved weekly fluctuations in training load

[b]Reference category in the model

95% CI = 95% confidence interval; VBT = velocity-based training; χ^2 = Chi-squared test.

Table 4. Summary of findings and GRADE evidence profile

Summary of findings				Quality assessment					
Outcome	No. of participants (studies)	Pooled SMD (95% CI)	I^2	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Quality rating
Strength	88 (4)	0.06 (-0.51, 0.64)	42.9%	Serious limitations[a]	No serious inconsistency	No serious indirectness	Serious imprecision[b]	Undetected	⊕⊕ Low
Power	67 (3)	0.11 (-0.28, 0.49)	13.5%	Serious limitations[a]	No serious inconsistency	No serious indirectness	Serious imprecision[b]	Undetected	⊕⊕ Low
Sprint speed	46 (2)	0.10 (-0.53, 0.72)	30.0%	Serious limitations[a]	No serious inconsistency	No serious indirectness	Very serious imprecision[c]	Undetected[d]	⊕ Very low

95% CI = 95% confidence interval; GRADE = Grading of Recommendations, Assessment, Development and Evaluation; SMD = standardised mean difference.

[a]More than 50% of studies were judged to have some concerns in three or more domains in the Cochrane risk of bias tool for randomized trials (RoB 2).

[b]The total number of participants is less than the number required to have 80% statistical power to detect a standardised mean difference of 0.5 given a two-tailed p-value of 0.05 (n=128 for independent groups).

[c]The total number of participants is less than the number required to have 80% statistical power to detect a standardised mean difference of 0.8 given a two-tailed p-value of 0.05 (n=52 for independent groups).

[d]We did not perform a funnel plot or Egger's test of the intercept analysis because the meta-analysis included less than 10 effect estimates. However, none of the individual effect estimates included in the meta-analysis reached the conventional threshold for statistical significance (i.e. $p<0.05$), and therefore publication bias was considered unlikely.

Discussion

This is the first systematic review and meta-analysis to compare the effects of VBT to alternative resistance training methods on changes in muscle strength, power, and sprint speed. The main results showed no evidence of a difference between VBT and alternative methods for any outcome. Further, GRADE assessments suggest the overall body of evidence is of very low quality.

Several papers have encouraged the integration of velocity feedback into strength and conditioning programmes, highlighting the purported benefits of VBT over traditional resistance training methods [24, 25, 29]. However, our findings showed a trivial difference and an imprecise interval estimate for effects on strength. The interval estimate indicates that adjusting training load based on velocity feedback, instead of alternative resistance training methods, may lead to a moderately *positive* effect or a moderately *negative* effect on 1RM strength. The raw unit meta-analysis suggests the mean difference lies somewhere between -8.3 and 9.2 kg, reinforcing that a meaningful effect of VBT in either direction cannot be ruled out [59]. These wide range of possible effects highlight the uncertainty of the current evidence.

The meta-analysis on strength did show moderate heterogeneity, leading us to explore potential effect moderators. Including the number of VBT exercises as a covariate in the model reduced heterogeneity and increased the point estimate in favour of VBT. That is, studies that used velocity feedback to adjust training load across multiple exercises [31, 55] appeared to report larger effects in favour of VBT than studies that only used velocity feedback in one exercise [23, 30]. Studies with more VBT exercises also measured more strength outcomes, which may have led to better estimates of the effect than studies with fewer VBT exercises and outcomes. It seems intuitive that applying the VBT paradigm across several exercises would lead to greater adaptations than only applying it to one exercise, if velocity feedback is indeed beneficial for changes in strength. However, the exploratory nature of the meta-regression and the low number of included studies limit any inferences that can be made. Future research evaluating the comparative effects of VBT should consider applying velocity feedback to all (or most) prescribed exercises within a resistance training programme, at least in multi-joint exercises that have been validated with velocity measurement tools.

There is evidence that velocity feedback allows resistance exercises to be completed at faster concentric velocities than using a %1RM [23, 60], ostensibly by adjusting load according to daily readiness to train. Orange and colleagues [23] reported that VBT based on individual velocity zones increased sessional movement velocity in the back squat compared with prescribing load based on %1RM, even though the average relative load across the 7-week interventions was slightly higher in the VBT group (62% vs 60% 1RM, respectively). Faster movement velocities could theoretically translate into greater velocity-specific adaptations through reduced antagonist coactivation [61], greater early phase neural drive [62] or better coordination [63]. Notwithstanding the physiological plausibility, similar to the effect on strength, our meta-analysis showed trivial differences and imprecise interval estimates between VBT and alternative resistance training methods on changes in muscle power and sprint speed. Moreover, both models showed negligible heterogeneity over and above that attributable to sampling error, showing that, despite some differences in intervention characteristics, the effect estimate was reasonably consistent across studies.

There is some evidence that prescribing a modifiable load based on individualised velocity zones reduces concentric time under tension in the back squat compared with using a %1RM [23, 60]. Terminating a set of repetitions when concentric velocity drops below a prespecified threshold (e.g. 20%) may also reduce the overall number of repetitions performed in a given session [60, 64]. For example, Pareja-Blanco and colleagues [64] showed that performing sets of back squats with a 20% velocity loss threshold almost halved the number of repetitions performed across an 8-week intervention compared with using a 40% velocity loss threshold. A lower volume-load may be detrimental if muscle hypertrophy is the main desired outcome [64, 65], but may lead to comparable strength gains as higher-load resistance training [64, 65]. A lower resistance training volume may ensure preparedness for other aspects of training and allow for greater training frequency due to a faster recovery of neuromuscular function [66]. Thus, achieving similar strength gains as alternative resistance training methods with a lower overall training volume would be an advantage of VBT. However, the evidence base is currently too uncertain to rule of the possibility of positive or negative effects of VBT on training-related adaptations.

LIMITATIONS

The overall quality of evidence included in the review is very low. This was mostly due to the imprecision of pooled effect estimates and a risk of bias within individual studies. Common

issues relating to risk of bias included a lack of information about the randomisation process and outcome assessor blinding, and not prospectively registering the study protocol and analysis plan. In addition, the length of the interventions (six to eight weeks) may be insufficient to tease out meaningful differences between VBT and alternative resistance training methods, particularly in trained individuals. However, adaptations to resistance training typically manifest in a log-linear fashion [67], meaning longer interventions may not augment differences between conditions because trained individuals will be closer to the asymptote of adaptation over time.

Future studies may address the imprecision of effects by using larger sample sizes and/or by sharing their data in such a way that it contributes to a future meta-analysis. Our meta-analysis on strength effects included 88 participants in total, comprising 10 effect estimates from 4 studies (median of 11 participants per study arm). A meta-analysis with these parameters has 21% statistical power to detect a small effect size (SMD=0.2), assuming α=0.05 and moderate between-study heterogeneity [68]. It is likely that any differences between the effectiveness of VBT and alternative resistance training methods would be small, given that the alternative training methods, such as using a %1RM, have consistently been shown to be effective for improving muscle function [1, 10–14]. Indeed, the CLES indicated that the probability of a randomly selected individual increasing their muscle strength following a non-VBT resistance training intervention is 90%. Thus, more trials and larger samples are clearly needed to increase the precision of the effects and to detect a small difference between conditions, if a difference exists.

Future studies should follow best practise guidelines for trial randomisation procedures [69]. No study included in this review provided information on the allocation concealment mechanism. Moreover, although it is extremely difficult to blind participants and intervention facilitators in sport and exercise science research [70], future studies should endeavour to blind outcome assessors and data analysts. Furthermore, prospective trial registration in future VBT research is warranted to align with the Declaration of Helsinki [71] and International Committee of Medical Journal Editors (ICMJE) recommendations [72]. These practises will reduce the risk of bias in future studies and thus contribute to a higher overall quality of evidence.

This review has several strengths. In line with Cochrane guidelines [73], we searched preprint servers and trial registries, in addition to general and specific bibliographic databases, in order to reduce the risk of publication bias and identify as much evidence as possible. We performed

various sensitivity analyses on the main meta-analysis models to examine whether decisions made in the review process influenced the overall findings. We also prospectively registered the protocol and analysis plan [32], and made the search results, data, statistical code and risk of bias judgements publicly available on OSF [54]. However, the review does have some limitations. We restricted the literature search to full-text manuscripts available in English, and may therefore have missed some relevant studies written in other languages, although this is unlikely. In addition, there were some minor deviations from the pre-registered protocol, although these are fully documented and justified in Online Resource 1. Moreover, the meta-analyses on pre-post changes do not provide true estimations of treatment effects due to the absence of a non-exercise control condition.

PRACTICAL IMPLICATIONS

The VBT paradigm has a sound theoretical basis. That is, there are plausible physiological mechanisms as to how velocity feedback may enhance resistance training adaptations, which have been communicated previously [25]. However, our review shows that this is not reflected in the current empirical evidence. Further, it should be considered that VBT requires the use of relatively expensive devices, additional time to set up the equipment, and may be challenging to implement in large group settings, requiring additional staff members to competently monitor the velocity data. In contrast, alternative methods of regulating resistance training load, such as using a %1RM, RPE or RIR, are relatively simple to implement in large group settings and do not require the use of technology. Thus, VBT incurs a greater time and financial burden compared with alternative training methods, and the evidence is currently uncertain as to whether this translates into greater training adaptations.

CONCLUSIONS

In conclusion, our systematic review and meta-analysis showed no evidence of a difference between VBT and alternative resistance training methods for changes in muscle strength, power, or sprint speed. Moreover, the overall body of evidence is of very low quality, mostly due to risk of bias within individual studies and the imprecision of pooled effect estimates. Therefore, the current evidence does not support the use of objective velocity feedback over alternative methods of regulating resistance training load for improvements in strength, power or speed.

Further well-designed trials with larger samples are required to increase the precision of the effect estimates and overall quality of evidence.

Author contributions

STO conceived the study, designed the methods, performed the GRADE quality assessment and statistical analyses, and wrote the initial draft. AH and LP performed the systematic searches, removed duplicates, screened the abstracts, assessed full-texts for eligibility and extracted outcome data. OJ and TWJ conducted the risk of bias assessment. JS assisted in the methods design, quality assessment and statistical analyses. All authors reviewed the methods, confirmed eligibility for included studies, and were involved in interpreting the data, critically revising the manuscript for intellectually important content, and approved the submitted version for publication.

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Data and supplementary material accessibility

All supplementary material as well as the pre-registered protocol, search results, data, code, and justifications for risk of bias judgements are available on the Open Science Framework (https://osf.io/86njf/; doi: 10.17605/OSF.IO/86NJF).

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