Journal of Science and Medicine in Sport 25 (2022) 1023–1032

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Review

Comparing the effects of variable and traditional resistance training on maximal strength and muscle power in healthy adults: A systematic review and meta-analysis

Vidar Andersen [a,*], Olaf Prieske [b], Nicolay Stien [a], Kristoffer Cumming [c], Tom Erik Jorung Solstad [a], Gøran Paulsen [d], Roland van den Tillaar [e], Helene Pedersen [a], Atle H. Saeterbakken [a]

[a] Department of Sport, Food and Natural Sciences, Western Norway University of Applied Sciences, Norway
[b] Division of Exercise and Movement, University of Applied Sciences for Sports and Management Potsdam, Germany
[c] Faculty of Health and Welfare, Østfold University College, Norway
[d] Department of Physical Performance, Norwegian School of Sport Sciences, Norway
[e] Department of Sports Sciences, Nord University, Norway

ARTICLE INFO

Article history:
Received 11 April 2022
Received in revised form 14 June 2022
Accepted 24 August 2022
Available online 28 August 2022

Keywords:
Strength training
Elastic bands
Chain resistance
Pneumatic resistance

ABSTRACT

Objectives: The aim of the study was to aggregate different effects between variable resistance training and traditional resistance training on maximal muscle strength and muscle power and identify potential sex- and training program-related moderator variables.
Design: Meta-analysis.
Methods: A systematic literature search was conducted in SPORTDiscus, PubMed, and Web of Science. Interventions were included if they compared variable resistance training and traditional resistance training in healthy adults and examined the effects on measures of maximal muscle strength and/or muscle power of the lower and/or upper body. A random-effects model was used to calculate weighted and averaged standardized mean differences. Additionally, univariate sub-group analyses were independently computed for sex and training-related moderator variables.
Results: Seventeen studies comprising a total of 491 participants (341 men and 150 women, age 18–37 years) were included in the analyses. In terms of maximal muscle strength, there were no statistically significant differences between variable resistance training and traditional resistance training for the lower ($p = 0.46$, standardized mean difference = −0.10) or the upper body ($p = 0.14$, standardized mean difference = −0.17). Additionally, there were no significant training-related differences in muscle power for the lower ($p = 0.16$, standardized mean difference = 0.21) or upper body ($p = 0.81$, standardized mean difference = 0.05). Sub-group analyses showed a significant moderator effect for training period and repetitions per set for maximal muscle strength in the lower body ($p = 0.03$–0.04) with larger strength gains following traditional resistance training when performing more repetitions per set ($p = 0.02$, standardized mean difference = 0.43). No other significant sub-group effects were found ($p = 0.18$–0.82).
Conclusions: Our results suggest that variable resistance training and traditional resistance training are equally effective in improving maximal muscle strength and muscle power in healthy adults.

1. Introduction

Traditionally, the external load in resistance training provided by the equipment (e.g., free weights) is constant throughout the whole range of motion. Noteworthy, when performing resistance training using free weights, the maximal load that can be lifted is often dependent on a small range of motion called the sticking region.[1] Beyond this region, there is a mismatch between the capacity of the muscle to develop force/torque and the force/torque created by the equipment/external load in favor of the muscle.[2,3] Variable resistance training (VRT) can be defined as resistance training where the resistance/load varies throughout the joint range of motion to match the external load and the changing muscle force potential.[2,4] VRT has become a popular training modality to ensure that the force capacity of the muscle is sufficiently stimulated throughout the whole joint range of motion.[5,6]

* Corresponding author.
E-mail address: vidar.andersen@hvl.no (V. Andersen).

https://doi.org/10.1016/j.jsams.2022.08.009
1440-2440/

Importantly, utilizing variable resistance to increase the resistance in one part of the movement, will decrease the load in the other parts of the movement. For example, by attaching elastic bands to the barbell in the squat exercise to increase the load in the upper parts of the movement when the bands get stretched, the load will eventually reduce in the lower parts of the movement when the bands are close to their original shape. Hence, an optimal stimulus throughout the whole joint range of motion can only be achieved in isokinetic devices performing repetitions with maximal effort.

VRT can be induced by different equipment which increases either the external load/force and/or its lever arm. The most popular equipment to gain a variable resistance throughout the range of motion is elastic bands/tubes, chains, and cam-based and pneumatic machines.[5] For example Melo et al.[7] reported that 12 weeks of VRT using elastic tubes induced significantly larger increases in maximal lower body muscle strength (i.e., isometric leg extensions) in physically active participants when compared with traditional resistance training (TRT). The training consisted of 2–4 sets at 6–12-RM performed three times per week. Further, Ataee et al.[8] used chains for the VRT program and found a significantly greater increase in maximal lower body muscle strength (i.e., squat 1-RM) following 4 weeks of VRT versus TRT in male power-trained athletes. The training protocol consisted of three sets of 5 repetitions at 85 % of 1-RM performed three times per week. Importantly, in the VRT-group, the load was set at 85 % of 1-RM in the bottom position of the movement and increased throughout the lift to 100 % of 1-RM in the top position. Therefore, larger training-induced gains in 1-RM in the VRT-group could be explained by using a higher training load. Finally, maximal upper body muscle strength and lower/upper body muscle power did not differ between groups following the intervention period.

Interestingly, four meta-analyses have been performed to compare the effects of VRT and TRT on measures of maximal muscle strength in different populations.[9–12] All the studies included original work that only used elastic bands/tubes to provide the variable resistance. Further, only de Oliveira et al.[10] conducted a meta-analysis on studies including healthy participants only. More precisely, they examined the effects of VRT using elastic bands compared with passive and active control conditions. The active control varied from training programs with bodyblade, aquatic resistance to weight machines. Based on their findings, the authors concluded that VRT programs with elastic bands were more effective than a passive control condition, but not superior to an active control. However, the study did not perform sub-group analyses for sex.

When attaching elastic bands or chains to free weights in order to generate variable resistance, the load increases throughout the range of motion. Therefore, differences in anthropometrics, such as stature, could influence the effectiveness of VRT. Further, VRT might not be optimal for strong individuals or in exercises with large force production and/or movement trajectory distances (e.g., the back squat).[13] Hence, effects of VRT compared with TRT could be affected by participants' strength level and/or stature. Given the sex-specific differences in strength levels and stature,[14] it could be of interest to examine the effects of VRT on muscle strength in men versus women. Notably, this has not previously been addressed in the literature.

Theoretically, VRT may lead to superior improvements in muscle power and force development compared with TRT. The suggested mechanism is a shorter deceleration phase and reciprocally higher mean power for each repetition with VRT than TRT.[15,16] For instance, Elliot et al.[16] showed that, ~52 % of the time in the ascending movement was used to decelerate the barbell when performing the bench press exercise with free weights at 80 % of 1-RM. Likewise, Newton et al.[17] observed that 40 % of the lift was used to decelerate the barbell when lifting bench press with maximal intended velocity (not throwing the barbell) using constant resistance at 45 % of 1-RM. Notably, it could be argued that using variable resistance would shorten the deceleration phase and hence increase the barbell velocity throughout the movement. In fact, this was examined by Frost et al.[15] who compared bench pressing with free weights versus pneumatic resistance in resistance-trained men. The results showed that pneumatic resistance led to higher velocity, acceleration, and power output over a spectrum of different loads. Importantly, the study of Frost et al.[15] was a cross-sectional study. Therefore, causality cannot be established and the results may not be extrapolated to long-term effects of VRT. Of note, no previous meta-analysis has compared the effects of VRT and TRT on muscle power.

Despite a growing interest in elastic bands, machines, and chains as tools to provide variable resistance during resistance training, the effect on maximal muscle strength and power, particularly when directly compared with TRT, is not conclusive. To date, there is no systematic review of the literature regarding the effects of VRT versus TRT on maximal muscle strength and muscle power in healthy adults. This knowledge would be valuable for e.g., athletes and coaches, as well as for physically active individuals. Thus, the aim of the present systematic review and meta-analysis was to compare the effects of VRT versus TRT on maximal muscle strength and muscle power of both the lower body and upper body in healthy adults. Further, sub-group analyses were performed to examine whether factors such as sex, training volume, and training intensity were significantly modulating the training-induced effects.

2. Methods

This study was not registered with PROSPERO because systematic reviews in the field of sport science are not accepted with this platform. However, the present systematic review and meta-analysis adhered to the recommended PRISMA guidelines.[18]

2.1. Search strategy

A systematic search was conducted (February 2022) in three separate databases (SportsDiscus, PubMed, and Web of Science). An independent researcher (VA) conducted the search using keywords related to variable resistance, resistance training, and muscle strength (maximal and explosive). With respect to previous meta-analyses,[9–12] Boolean operators "AND" and "OR" were used to combine different keywords (("variable resistance" OR "elastic band" OR "elastic tube" OR "rubber band" OR "Thera-band" OR "rubber tube" OR "elastic resistance" OR "CAM-based machine" OR "pneumatic machine" OR "pneumatic resistance" OR "chain resistance" OR "chains free weight") AND ("resistance training" OR "strength training" OR "explosive training" OR "power training" OR "plyometric training" OR "ballistic training") AND ("maximal strength" OR "repetition maximum" OR "RM" OR "MVC" OR "height" OR "speed" OR "velocity" OR "distance" OR "acceleration" OR "power" OR "power output" OR "force" OR "RFD" OR "rate of force development" OR "horizontal jump" OR "vertical jump" OR "SJ" OR "CMJ" OR "CMJas" OR "squat jump" OR "counter movement jump" OR "maximal strength" OR "explosive strength" OR "repetition maximum" OR "RM" OR "MVC" OR "maximal voluntary contraction")). Review articles published before February 2022 [4,5,9–12] were analyzed (by VA) to identify potential studies eligible to be included in the present analysis. Additionally, the reference lists of all articles fulfilling the inclusion criteria were screened (by TES) for publications not identified by the original search. Only full-text articles written in English or in one of the Scandinavian languages were included. Hence, conference abstracts, unpublished data, or studies not published in peer reviewed journals were excluded.

2.2. Selection criteria

The studies had to meet the following criteria to be included in the analysis: participants: 1) healthy and free from injury; 2) aged ≥18 and ˂60 years of age; 3) intervention: exercise movement resisted by variable resistance (minimum: 3 weeks of training); 4) reported indicator of maximal muscle strength and/or muscle power; 5) included comparator (similar program using traditional resistance, e.g., free weights, body weight, and traditional machines). Studies comparing only different VRT programs were excluded as none of the groups could serve as a comparator (i.e., conducting TRT).

Several articles were discovered in the initial search (Fig. 1). Many of these were excluded due to the following reasons: 1) did not compare the VRT with a TRT; 2) differences in training related variables (e.g., load and volume) between the interventions; 3) participants were children or adolescents, patients, injured, had diseases, or were elderly (i.e., >60 years of age); 4) did not measure maximal muscle strength or muscle power; 5) the intervention was shorter than three weeks; 6) used machines which controlled the velocity (i.e., isokinetic machines); 7) means and standard deviations were not reported in the articles, and 8) the authors did not respond to our inquires. An overview of the exclusion process is shown in Supplementary material 1.

2.3. Study quality and assessment of risk of bias

The methodological quality of the studies was assessed using the Physical Therapy Evidence Database (PEDro) scale.[19] The scale consists of eleven items of which ten items give a point if they are fulfilled. In training interventions, it is problematic to blind the participants, and assessors and therapists/instructors are rarely blinded. Therefore, items 5, 6, and 7 were excluded from the assessment. Hence, the maximal score was seven. The included articles were assessed against the remaining criteria of the scale. Points were only scored if the criteria were clearly met. Based on previous reviews of exercise interventions,[20,21] a score of 6–7 was defined as "excellent quality", 5 as "good quality", 4 as "moderate quality", and 0–3 as "poor quality". Further, a score of ≥6 was defined as having a low risk of bias.[19] The articles were divided between two pairs of researchers (pair 1; VA and KTC and pair 2; AHS and NS). If there was a disagreement between the researchers within the pair, a third researcher (VA or AHS, respectively) was included to achieve consensus through discussion.

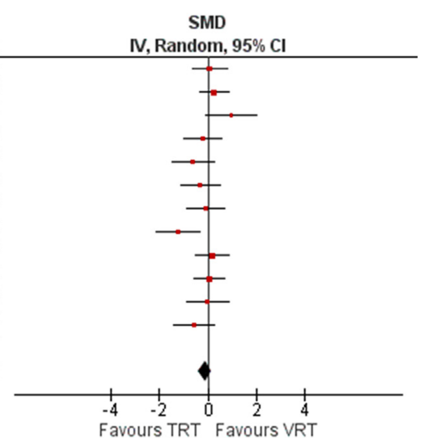
2.4. Data extraction

A template from a previous systematic review and meta-analysis from our research group was used in the data extraction.[22] The data were extracted by one author (VA) while a second author (AHS) double-checked the data. Disagreements were solved through personal communication between the two authors. Each study was coded for the following variables: sex, number of participants, training volume (training period, total number of sessions, number of sets per session, and number of repetitions per set), training intensity, intended training velocity and outcomes (i.e., measures of maximal muscle strength and/or muscle power). Strength/power measures were further divided into maximal muscle strength of the lower body, maximal muscle strength

A) Effects of VRT vs. TRT on lower body maximal strength

Study or Subgroup	SMD	SE	VRT Total	TRT Total	Weight	SMD IV, Random, 95% CI
Andersen 2015	0.08	0.37	15	15	9.2%	0.08 [-0.65, 0.81]
Anderson 2008	0.26	0.3	23	21	12.0%	0.26 [-0.33, 0.85]
Ataee 2014	0.98	0.54	8	8	5.2%	0.98 [-0.08, 2.04]
Boyer 1990 (INT1)	-0.21	0.41	20	10	8.0%	-0.21 [-1.01, 0.59]
Boyer 1990 (INT2)	-0.61	0.44	20	10	7.2%	-0.61 [-1.47, 0.25]
Colado 2010	-0.31	0.42	12	11	7.7%	-0.31 [-1.13, 0.51]
Loturco 2020	-0.08	0.4	12	13	8.3%	-0.08 [-0.86, 0.70]
Pipes 1978	-1.24	0.46	12	12	6.7%	-1.24 [-2.14, -0.34]
Rhea 2009	0.19	0.35	16	16	10.0%	0.19 [-0.50, 0.88]
Sawyer 2021	0.06	0.32	20	20	11.2%	0.06 [-0.57, 0.69]
Shoepe 2011	0	0.45	10	10	7.0%	0.00 [-0.88, 0.88]
Walker 2013	-0.55	0.43	11	12	7.5%	-0.55 [-1.39, 0.29]
Total (95% CI)			**179**	**158**	**100.0%**	**-0.10 [-0.37, 0.17]**

Heterogeneity: Tau² = 0.06; Chi² = 15.55, df = 11 (P = 0.16); I² = 29%
Test for overall effect: Z = 0.74 (P = 0.46)



B) Effects of VRT vs. TRT on upper body maximal strength

Study or Subgroup	SMD	SE	VRT Total	TRT Total	Weight	SMD IV, Random, 95% CI
Anderson 2008	0.09	0.3	23	21	15.3%	0.09 [-0.50, 0.68]
Ataee 2014	0.09	0.5	8	8	5.5%	0.09 [-0.89, 1.07]
Boyer 1990 (INT1)	-0.6	0.43	20	10	7.5%	-0.60 [-1.44, 0.24]
Boyer 1990 (INT2)	-0.43	0.45	20	10	6.8%	-0.43 [-1.31, 0.45]
Calatayud 2015	-0.23	0.45	10	10	6.8%	-0.23 [-1.11, 0.65]
Colado 2010	0	0.42	12	11	7.8%	0.00 [-0.82, 0.82]
Duric 2021 (INT1)	-0.34	0.5	12	6	5.5%	-0.34 [-1.32, 0.64]
Duric 2021 (INT2)	-0.22	0.51	12	6	5.3%	-0.22 [-1.22, 0.78]
Frost 2016	-0.08	0.55	8	6	4.6%	-0.08 [-1.16, 1.00]
Ghigiarelli 2009 (INT1)	-0.02	0.51	12	6	5.3%	-0.02 [-1.02, 0.98]
Ghigiarelli 2009 (INT2)	-0.07	0.51	12	6	5.3%	-0.07 [-1.07, 0.93]
McCurdy 2009	-0.05	0.38	14	14	9.6%	-0.05 [-0.79, 0.69]
Pipes 1978	-0.6	0.42	12	12	7.8%	-0.60 [-1.42, 0.22]
Shoepe 2011	-0.19	0.45	10	10	6.8%	-0.19 [-1.07, 0.69]
Total (95% CI)			**185**	**136**	**100.0%**	**-0.17 [-0.40, 0.06]**

Heterogeneity: Tau² = 0.00; Chi² = 3.96, df = 13 (P = 0.99); I² = 0%
Test for overall effect: Z = 1.49 (P = 0.14)

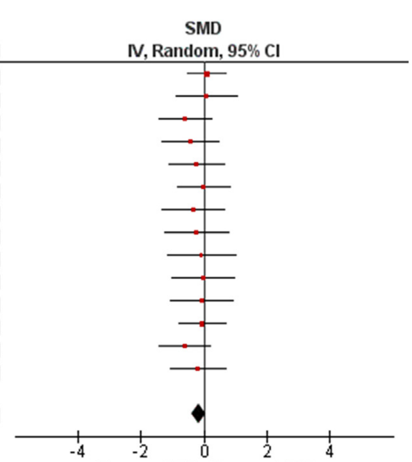


Fig. 1. The effects of variable resistance training (VRT) on maximal muscle strength in the lower body (A) and upper body (B) compared to traditional resistance training (TRT). CI = confidence interval, df = degrees of freedom, IV = inverse variance. Random = random effects model, SE = standard error, SMD = standardized mean difference.

of the upper body, lower body muscle power and upper body muscle power.

According to previous recommendations,[23,24] if multiple outcomes were reported in the same study, the outcomes were ranked based on their significance for the fitness component tested (i.e., maximal muscle strength and muscle power) and their resemblance to regular training. The variable with the highest ranking was included in the analysis (Supplementary material 2).

2.5. Statistical analyses

The effects of VRT versus TRT on maximal muscle strength and muscle power were determined by the following equations: pre/post-test between-subject standardized mean differences (SMDs) = (mean1 − mean2) / S_{pooled}[25] with mean1 being defined as the mean pre/post-test value of the VRT group and mean2 as the mean pre/post-test value of the TRT group, and S_{pooled} as the pooled standard deviation. The SMD was adjusted for sample size using the factor (1 − (3 / 4N − 9)), with N representing the total sample size.[26] Additionally, adjusted SMD values were calculated as the difference between pre-test SMDs to post-test SMDs.[27] Finally, to weight each included study according to the magnitude of the respective standard error, and to aggregate weighted mean adjusted SMDs, a random effects model was applied. At least two intervention groups had to be included in order to aggregate SMD values for each outcome.[28] The meta-analysis was conducted by OP using Review Manager 5.4.1 (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen, Denmark).

Sub-group analyses were performed (by OP and VA) for sex and training-related programming parameters (training period, total number of sessions, number of sets per session, and number of repetitions per set), training intensity and intended training velocity. More specifically, participants aged 18–60 years were defined as adults. Participants were categorized according to sex (men, women, mixed) based on potential differences in training-related adaptations to resistance training.[29] To analyze the potential contributions from training programming moderator variables, parameters were categorized as follows: training period (˂8 vs. ≥8 weeks), number of training sessions (˂16 vs. 16–23 vs. >23 sessions), number of sets per session (≤4 vs. >4–8 vs. >8 sets per session), number of repetitions per set (˂8 vs. 8–12 vs. >12 repetitions per set), training intensity (low intensity (˂60 % of 1-RM) vs. high intensity (≥60 % of 1-RM) vs. mixed intensity (low and high intensity)) and intended training velocity (maximal intended velocity vs. controlled velocity). These analyses were only performed if two or more studies were included in the different sub-groups. Studies which did not report a specific variable were deleted from those sub-group analyses.

A p value of <0.05 indicated a statistically significant effect. SMD values were classified as trivial (SMD < 0.2), small (0.2 ≤ SMD < 0.5), medium (0.5 ≤ SMD < 0.8), and large (SMD ≥ 0.8).[30]

The level of between-study heterogeneity was assessed using the I^2 statistics.[31] I^2 outcomes of 25, 50, and 75 % correspond to low, moderate, and high heterogeneity.[32] Values above 75 % were rated as heterogeneous. In addition, chi-square statistic (X^2) was included to determine whether the results of the analysis were due to chance. In such cases, low p values, or high X^2 statistics, relative to degrees of freedom (df), would be observed.

3. Results

3.1. Study characteristics

The systematic search process is presented in Supplementary material 1. A total number of 718 potential articles were identified in the original search, of which 18 studies met the inclusion criteria. One of these[7] was excluded due to being an outlier and the remaining 17 studies were included in the analyses. The included studies comprised of 491 participants (n = 256 in VRT group and n = 235 in TRT group, Table 1). For sub-group analyses according to sex, three studies included only females (n = 113), eleven studies included only males (n = 294) and three studies included both sexes (n = 84).

Regarding the training program variables, three studies did not report the number of sets per session[33–35] and two studies did not report the number of repetitions per set.[33,35] The mean duration of the training period was 9 weeks (range 3–24) and the mean number of training sessions was 23 (range 7–72) sessions. The mean number of sets per session was 5 (range 3–11) with a mean of 7 repetitions per set (range 3–20). Nine studies used training intensities of ≥60 % of 1-RM,[8,34–41] two studies used training intensities <60 % of 1-RM[42,43] while six studies varied the training using intensities both higher and lower than 60 % of 1-RM.[33,44–48] Furthermore, in six of the studies the participants were instructed to lift with maximal intended velocity,[42–46,48] while in four of the studies the participants were instructed to use a controlled tempo.[8,35,36,40] Seven studies did not report any instructions regarding the lifting velocity.[33,34,37–39,41,47]

Regarding the quality of the studies, the median quality score was 7 points (95 % confidence interval 6.5–7.5) on the PEDro scale. Thirteen studies were of excellent quality (score 6 or higher), three of good quality (score 5), while one study was defined as a poor-quality study (score 3) (see Table 1). Accordingly, thirteen studies were defined as studies with low risk of bias (score 6 or above), while four were defined as studies with high risk of bias (score below 6).

3.2. Main analyses

3.2.1. Maximal muscle strength

Eleven of the included studies examined the effects of VRT versus TRT on maximal muscle strength in the lower body. The analysis showed no significant differences between the two training modalities ($p = 0.46$; $I^2 = 29$ %, $Chi^2 = 15.55$, $df = 11$, Fig. 1A). For the upper body, eleven studies were included, and this analysis also showed no significant difference between VRT and TRT effects on muscle strength ($p = 0.14$; $I^2 = 0$ %, $Chi^2 = 3.96$, $df = 13$, Fig. 1B).

3.2.2. Muscle power

Seven studies were included in the analysis for comparing the effects of VRT versus TRT on lower body muscle power. The results showed no significant differences between the two training modalities ($p = 0.16$; $I^2 = 10$ %, $Chi^2 = 6.66$, $df = 6$, Fig. 2A). Regarding upper body muscle power, four studies were included (six interventions) and the analysis revealed no significant differences between VRT and TRT effects on muscle power ($p = 0.81$; $I^2 = 0$ %, $Chi^2 = 2.48$, $df = 5$, Fig. 2B).

3.3. Sub-group analyses

3.3.1. Subject-related moderating variables

The influence of sex on VRT/TRT effects on maximal muscle strength and muscle power is displayed in Table 2. Univariate sub-group analyses revealed that sex did not significantly moderate the effects of VRT versus TRT on maximal muscle strength (p > 0.05). Subgroup analyses were not applicable for muscle power.

3.3.2. Training-related programming parameters

Effects of training-related programming parameters for VRT/TRT effects on maximal muscle strength and muscle power are displayed in Table 3. Univariate sub-group analyses revealed that training period (number of weeks) and number of repetitions per set significantly moderated the effects of VRT versus TRT on maximal lower body strength (p = 0.03–0.04). Significant and small-sized effects on maximal lower body strength were observed in favor of TRT for 8–12 repetitions per set (SMD = −0.33, p = 0.03), but not for <8 repetitions per set (p = 0.20). For training period, no significant effects were found for the comparison of VRT versus TRT (p = 0.08–0.25). Further, total number of sessions,

Table 1
Characteristics of the included studies.

Study	Equipment compared	Subjects	Age (years)	Intervention	Outcomes	PEDro score
Andersen, 2015	Free weight vs. free weight + EB	30♀ VRT = 15 TRT = 15	VRT = 24 ± 6 TRT = 24 ± 6	2 sessions/week for 10 weeks 4 sets @ 6–10-RM Tempo; controlled	Maximal muscle strength and muscle power lower body	6
Anderson, 2008	Free weight vs. free weight + EB	22♀, 22♂ VRT = 22 TRT = 22	20 ± 1	3 sessions/week for 7 weeks 3–6 sets @ 72–98 % of 1-RM Tempo; N/A	Maximal muscle strength lower and upper body Muscle power lower body	6
Apanukul, 2015	Free weight vs. free weight + pneumatic	30♂ VRT = 10 TRT = 10	20.1 ± 0.1	2 sessions/week for 8 weeks 3 sets @ 30 % of 1-RM Tempo; maximal	Muscle power lower body	7
Ataee 2014	Free weight vs. free weight + chains	16♂ VRT = 8 TRT = 8	20.5 ± 2.0	3 sessions/week for 4 weeks 3 sets @ 85 % of 1-RM Tempo; controlled	Maximal muscle strength and muscle power lower and upper body	7
Boyer, 1990	Free weights vs. Pneumatic machine vs. EB	60♀ VRT_{PR} = 20 VRT_{EB} = 20 TRT = 20	19–37	3 sessions/week for 12 weeks 3 sets @ 6–10-RM Tempo; N/A	Maximal muscle strength lower and upper body	5
Calatayud, 2015	Free weights vs. BW + EB	15♂ 5♀ VRT = 10 TRT = 10	VRT = 20.6 ± 1.7 TRT = 22.7 ± 3.3	2 sessions/week for 5 weeks 5 sets @ 6-RM	Maximal muscle strength upper body	7
Colado, 2010	Free weights + machines vs. EB	23♀ VRT = 12 TRT = 11	VRT = 21.4 ± 0.4 TRT = 21.7 ± 0.8	2–4 sessions/week for 8 weeks 3–4 sets @ 7–9 OMNI-RES AM scale Tempo; N/A	Maximal muscle strength lower and upper body	6
Duric, 2021	Free weights vs. free weights + EB vs. EB	36♂ VRT_{FW+EB} = 12 VRT_{EB} = 12 TRT = 12	20.5 ± 2.0	3 sessions/week for 8 weeks 6–9 sets @ 50 % of 1-RM	Maximal muscle strength and muscle power upper body	7
Frost, 2016	Free weight vs. pneumatic machine	14♂ VRT = 8 TRT = 6	23.9 ± 4.1	3 sessions/week for 8 weeks 2–6 sets @ 75–92.5 % of 1-RM Tempo; maximal	Maximal muscle strength and muscle power upper body	3
Ghigiarelli, 2009	Free weight vs. free weight + chains vs. free weight + EB	36♂ VRT_{EB} = 12 VRT_{Chain} = 12 TRT = 12	VRT_{EB} = 20.3 ± 1.1 VRT_{Chain} = 19.6 ± 0.9 TRT = 20.0 ± 1.1	4 sessions/week for 7 weeks 5–6 sets @ light to heavy loading Tempo; maximal	Maximal muscle strength and muscle power upper body	7
Loturco, 2020	Free weight vs. free weight + EB	25♂ VRT = 12 TRT = 13	18.5 ± 0.6	3 sessions/week for 4 weeks 4–6 sets @ bar velocity 0.4–1.2 m/s Tempo; maximal	Maximal muscle strength and muscle power lower body	7
McCurdy, 2009	Free weight vs. free weight + chains	28♂ VRT = 14 TRT = 14	20.6 ± 1.3	2 sessions/week for 9 weeks 1–6 sets @ 60–90 % of 1-RM Tempo; N/A	Maximal muscle strength upper body	5
Pipes, 1978	Machine vs. pneumatic machine	24♂ VRT = 12 TRT = 12	18–26	3 sessions/week for 10 weeks 3 sets @ 75 % of 1-RM Tempo; N/A	Maximal muscle strength lower and upper body	7
Rhea, 2009	Free weight vs. free weight + EB	32♂ VRT = 16 TRT = 16	21.4 ± 2.1	2–3 sessions/week for 12 weeks 4 sets @ 75–85 % of 1-RM Tempo; maximal	Maximal muscle strength and muscle power lower body	7
Sawyer 2021	Free weight vs. free weight + EB	40♂ VRT = 20 TRT = 20	18–25	3 sessions/week for 3 weeks 5 sets @ 50–93 % of 1-RM Tempo; N/A	Maximal muscle strength and muscle power lower body	6
Shoepe, 2011	Free weight vs. free weight + EB	10♀, 10♂ VRT = 10 TRT = 10	VRT = 20.0 ± 1.4 TRT = 19.9 ± 1.2	3 sessions/week for 24 weeks 3–5 sets @ 67–95 % of 1-RM Tempo; controlled	Maximal muscle strength lower and upper body	5
Walker, 2013	Machine vs. CAM-based machine	23♂ VRT = 11 TRT = 12	VRT = 27 ± 5 TRT = 29 ± 5	2 sessions/week for 20 weeks 2–4 sets @ 60–85 % of 1-RM Tempo; N/A	Maximal muscle strength lower body	7

EB = elastic bands, N/A = not available, VRT = variable resistance training, TRT = traditional resistance training, RM = repetition maximum, m/s = meters per second.

number of sets per session, training intensity, and intended training velocity did not significantly moderate the effects of VRT versus TRT on maximal muscle strength and muscle power ($p > 0.05$).

4. Discussion

The aim of the present study was to compare the effects of VRT versus TRT on maximal muscle strength and muscle power in the lower and upper body in healthy adults. The main analyses revealed no significant differences between the two training modalities for all outcome variables. Independent sub-group analyses showed that TRT was superior to VRT for increasing maximal strength in the lower body when a greater number of repetitions per set were performed.

Overall, the quality of the included studies was acceptable, with 94 % of the studies rated as good quality or above (PEDro score of ≥5 points) and 76 % of the studies defined as having low risks of bias. Still, differences between the studies regarding programming parameters (training duration, frequency, volume, intensity and intended training velocity) should be kept in mind when interpreting the findings.

4.1. Main analyses

The lack of differences between VRT and TRT effects on maximal muscle strength and muscle power is in accordance with previous meta-analyses.[9–11] Importantly, these meta-analyses have focused on comparing TRT with elastic bands-VRT only, omitting other forms of variable resistance. Furthermore, only one of the previous meta-analyses focused on healthy adults,[10] excluding elderly and/or different groups of patients. De Oliveira et al.[10] included seven interventions measuring muscle strength (MVC) in the upper and lower body in

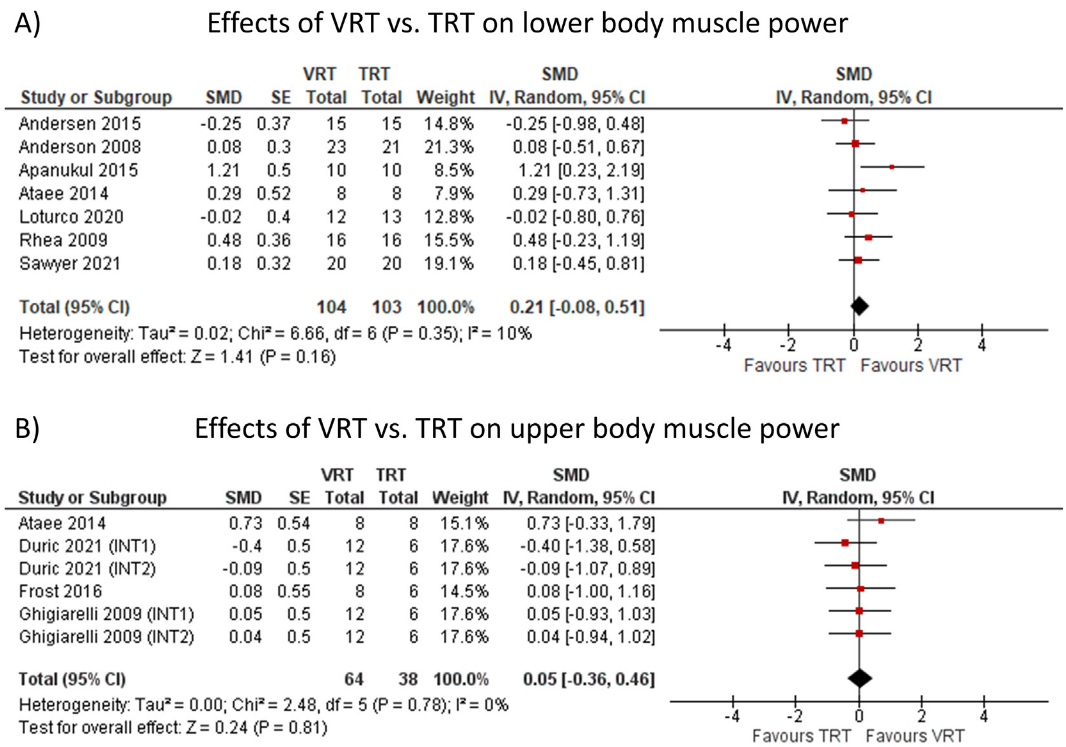


Fig. 2. The effects of variable resistance training (VRT) on muscle power in the lower body (A) and upper body (B) compared to traditional resistance training (TRT). CI = confidence interval, df = degrees of freedom, IV = inverse variance. Random = random effects model, SE = standard error, SMD = standardized mean difference.

addition to the trunk. The authors reported no differences between elastic- and other forms of training (p = 0.59, mean difference 0.11) and, thereby, support our findings. Importantly, no previous review or meta-analysis has examined the effects of VRT on muscle power. In general, when comparing VRT and TRT, muscle power seems less emphasized compared to maximal muscle strength. As a result, the number of interventions examining muscle power is smaller than for maximal muscle strength. Therefore, we were not able to perform all sub-group analyses using muscle power as the outcome.

The rationale for using variable resistance has been maximizing the force output throughout the whole joint range of motion and thereby increasing the training stimuli for the muscles.[5,6] However, since the load varies throughout the movement, increasing the load in one part of the motion (e.g., by adding elastic bands to a barbell) will reduce the load in the other. For example, when attaching elastic bands to the barbell and floor in the squat exercise, the load will be higher in the upper parts of the movement when the bands are stretched. However, in the lower parts of the movement when the elastic bands are close to their resting length, the total load will be close to equal to the constant load. Therefore, it can be speculated that the two modalities provide relatively equal stimuli, especially if the loads are matched in the middle of the trajectory. Consequently, when summarizing the stimuli over the complete range of motion similar strength gains can be expected.[41] Especially when measuring maximal dynamic strength, as most of the studies included in the present meta-analysis, it is likely that the average stimuli throughout the movement are most important and not the stimuli in the different parts of the range of motion.

An increase in maximal muscle strength can increase muscle power.[49] Hence, the lack of difference in maximal muscle strength gains between the modalities could also explain the lack of differences in the effects on muscle power between VRT and TRT. Measuring power output during dynamic movements is important.[50] However, to optimally obtain these adaptions, the intended velocity during training should be maximal. For example, Behm and Sale[51] compared ballistic isometric and dynamic contractions and demonstrated that the intention to perform ballistic contractions in general was more important

Table 2
Subgroup analyses for sex.

Sub-group	Studies (N)	Participants (N)	Estimated effect size mean (95 % CI)	Within group p	Between group p	Witching group I^2 (%)	Effect descriptor
Maximal muscle strength							
Lower body							
Sex					0.44		
Male	6	160	−0.12 (−0.62–0.39)	0.65		59	Trivial
Female	4	113	−0.23 (−0.63–0.17)	0.26		0	Small
Mixed	2	64	0.18 (−0.31–0.67)	0.47		0	Trivial
Upper body							
Sex					0.64		
Male	8	154	−0.18 (−0.50–0.15)	0.30		0	Trivial
Female	4	103	−0.31 (−0.74–0.12)	0.16		0	Small
Mixed	3	64	0.00 (−0.49–0.49)	0.99		0	Trivial
Muscle power							
Lower and upper body							
Sex	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CI = confidence interval, N = number, RM = repetition maximum, N/A = not applicable.

Table 3
Subgroup analyses, training-related moderating variables.

Sub-group	Studies (N)	Participants (N)	Estimated effect size mean (95 % CI)	Within group p	Between group p	Witching group I^2 (%)	Effect descriptor
Maximal muscle strength							
Lower body							
Training period					0.04		
˂8 weeks	4	125	0.21 (−0.15–0.56)	0.25		0	Small
≥8 weeks	8	212	−0.28 (−0.60–0.03)	0.08		17	Small
Total number of sessions					0.18		
˂16 sessions	3	81	0.21 (−0.33–0.74)	0.45		27	Small
16–23 sessions	3	97	0.07 (−0.33–0.47)	0.73		0	Trivial
>23 sessions	6	159	−0.36 (−0.77–0.05)	0.08		33	Small
Number of sets per session					0.61		
≤4 sets	5	117	−0.05 (−0.67–0.58)	0.88		63	Trivial
5–8 sets	4	137	0.03 (−0.31–0.37)	0.85		0	Trivial
>8 sets	1	N/A	N/A	N/A		N/A	N/A
Number of repetitions per set					0.03		
˂8 repetitions	5	157	0.20 (−0.11–0.52)	0.20		0	Small
8–12 repetitions	6	160	−0.43 (−0.78–0.07)	0.02		11	Small
>12 repetitions	0	N/A	N/A	N/A		N/A	N/A
Training intensity					0.38		
˂60 % of 1-RM	0	N/A	N/A	N/A		N/A	N/A
≥60 % of 1-RM	9	240	−0.18 (−0.54–0.19)	0.35		45	Trivial
Mixed	3	97	0.07 (−0.33–0.47)	0.74		0	Trivial
Intended training velocity					0.78		
Maximal	2	57	0.07 (−0.44–0.59)	0.78		0	Trivial
Controlled	4	90	−0.07 (−0.89–0.76)	0.87		71	Trivial
Upper body							
Training period					0.25		
˂8 weeks	5	116	0.00 (−0.38–0.37)	0.98		0	Trivial
≥8 weeks	9	205	−0.28 (−0.57 - -0.01)	0.06		0	Small
Total number of sessions					0.25		
˂16 sessions	4	72	−0.07 (−0.55–0.41)	0.78		0	Trivial
16–23 sessions	4	109	0.01 (−0.36–0.39)	0.94		0	Trivial
>23 sessions	6	140	−0.41 (−0.78 - -0.05)	0.03		0	Small
Number of sets per session					0.71		
≤4 sets	2	44	0.00 (−0.59–0.59)	1.00		0	Trivial
5–8 sets	8	174	−0.16 (−0.46–0.15)	0.32		0	Trivial
>8 sets	1	N/A	N/A	N/A		N/A	N/A
Number of repetitions per set					0.44		
˂8 repetitions	8	166	−0.07 (−0.38–0.25)	0.68		0	Trivial
8–12 repetitions	4	107	−0.40 (−0.83–0.02)	0.06		0	Small
>12 repetitions	0	N/A	N/A	N/A		N/A	N/A
Training intensity					0.82		
˂60 % of 1-RM	2	36	−0.28 (−0.98–0.42)	0.43		0	Small
≥60 % of 1-RM	8	207	−0.20 (−0.49–0.08)	0.17		0	Small
Mixed	4	78	−0.05 (−0.52–0.41)	0.82		0	Trivial
Intended training velocity					0.94		
Maximal	5	86	−0.15 (−0.60–0.30)	0.53		0	Trivial
Controlled	3	60	−0.27 (−0.79–0.24)	0.30		0	Small
Muscle power							
Lower body							
Training period					0.48		
˂8 weeks	4	125	0.12 (−0.24–0.47)	0.52		0	Trivial
≥8 weeks	3	82	0.43 (−0.35–1.20)	0.28		65	Small
Total number of sessions					0.76		
˂16 sessions	3	81	0.14 (−0.3–0.58)	0.54		0	Trivial
16–23 sessions	3	94	0.27 (−0.46–1.00)	0.47		65	Small
>23 sessions	1	N/A	N/A	N/A		N/A	N/A
Number of sets per session					0.17		
≤4 sets	4	93	0.45 (−0.03–0.93)	0.07		21	Small
5–8 sets	3	114	0.03 (−0.34–0.40)	0.88		0	Trivial
>8 sets	0	N/A	N/A	N/A		N/A	N/A
Number of repetitions per set	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Training intensity					0.46		
˂60 % of 1-RM	1	N/A	N/A	N/A		N/A	N/A
≥60 % of 1-RM	3	90	0.01 (−0.41–0.42)	0.98		0	Trivial
Mixed	3	97	0.22 (−0.18–0.63)	0.27		0	Small
Intended training velocity					0.20		
Maximal	3	77	0.50 (−0.14–1.14)	0.12		46	Medium
Controlled	2	46	−0.07 (−0.66–0.52)	0.82		0	Trivial
Upper body							
Training period					0.34		
˂8 weeks	3	52	0.25 (−0.33–0.83)	0.40		0	Small
≥8 weeks	3	50	−0.15 (−0.73–0.43)	0.61		0	Trivial

(continued on next page)

Table 3 (*continued*)

Sub-group	Studies (N)	Participants (N)	Estimated effect size mean (95 % CI)	Within group p	Between group p	Witching group I^2 (%)	Effect descriptor
Total number of sessions					0.56		
<16 sessions	3	52	0.25 (−0.33–0.83)	0.40		0	Small
16–23 sessions	1	N/A	N/A	N/A		N/A	N/A
>23 sessions	2	36	−0.24 (−0.94–0.45)	0.49		0	Small
Number of sets per session	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Number of repetitions per set	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Training intensity					0.32		
<60 % of 1-RM	2	36	−0.24 (−0.94–0.45)	0.49		0	Small
≥60 % of 1-RM	1	N/A	N/A	N/A		N/A	N/A
Mixed	3	50	0.06 (−0.53–0.64)	0.85		0	Trivial
Intended training velocity	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CI = confidence interval, N = number, RM = repetition maximum, N/A = not applicable.

than the specificity of the movement (isometric vs. dynamic contractions). This fact may be even more important when comparing VRT and TRT since it has been shown that VRT has a shorter deceleration time compared with TRT[15] and therefore has a potential for increased training stimuli. Four out of the eleven studies examining muscle power used either a controlled velocity (i.e., the participants were not allowed to lift as fast as they could) or not reported the velocity at all. This may have affected the results. For example, in the study of Andersen et al.,[36] the participants were instructed to perform each repetition in a controlled and self-selected tempo. Of note, this was also the only study examining muscle power in the lower body which, to some extent, favored TRT over VRT (SMD = 0.25).

4.2. Sub-group analyse

The sub-group analyses partially support our speculation for recommending maximal intended velocity to obtain effects on muscle power when using VRT. Although not reaching statistical significance between the groups (p = 0.20), the magnitude of the effect size was substantially larger in the maximal intended velocity group (SMD = 0.50 favoring VRT) compared to controlled velocity (SMD = −0.07 favoring TRT) when measuring lower body muscle power. Unfortunately, due to few included studies, it was not possible to conduct the same analyses for the upper body.

The only statistical difference between different sub-groups was observed for number of repetitions per set for maximal lower body muscle strength. The analyses showed that performing more repetitions in a set (8–12 repetitions) favored TRT. This finding supports a general observation of the data, indicating a trend that higher training volume (training weeks, number of sessions, or number of repetitions) favors TRT when measuring maximal muscle strength. Importantly, the observed effects were trivial to small, and no other statistical differences were reached. The finding might be a result of training specificity since maximal muscle strength was examined using similar approaches as during TRT (e.g., constant resistance with free weights) in all of the included interventions.[52] A higher training volume gives more time to practice, which may favor the training modality most similar to the testing condition. Consequently, it would be interesting to examine if the results will favor VRT if the testing condition of maximal muscle strength complied more closely with VRT exercises, e.g., 1-RM using variable resistance.

Of note, there were no sex-specific differences for the effects of VRT and TRT on maximal muscle strength or muscle power. Previous research indicated that VRT may not be optimal when a great amount of force is required to optimally stimulate the muscles.[13] In general, men appear to be stronger for most of the muscle groups by 1.5 to 2 times when compared with women.[53] Therefore, it could be speculated that VRT effects may be lower in men compared with women. However and importantly, in the study of Iversen et al.,[13] VRT consisted of variable resistance only (i.e., only elastic bands) without combined constant resistance, whereas most of the included studies in this meta-analysis used combined constant and variable resistance. Consequently, in the studies combining variable and constant resistance, it can be argued that the proportion of the variable resistance is rather low (i.e., the amount of constant resistance is significant in both VRT and TRT). This would produce less difference between VRT and TRT stimuli which could explain the similar training effects in the included studies.

For the remaining sub-group analyses, there were also no significant differences between the groups. This supports the main findings that the effects of VRT and TRT on maximal muscle strength and muscle power appear to be very similar and that these effects are irrespective of individual- or training related moderator variables. Of importance, the lack of using maximal intended velocity in several of the studies may have affected the muscle power-findings also in the sub-group analyses.

4.3. Limitations

There are some limitations that must be acknowledged. TRT was included as a comparator to VRT, while no passive control group was included. Importantly, the effectiveness of VRT has already been demonstrated.[10] Therefore, the aim of this study was to compare the efficacy of VRT versus TRT. Furthermore, variable resistance is a general term which encompasses a large heterogeneity of approaches. For example, the total resistance may consist of variable resistance only (e.g., using only elastic bands)[54] or of a combination of constant and variable resistance (e.g., combining free weights and elastic bands).[36] In most of the studies combining variable and constant resistance, the amount of the load coming from variable resistance was not controlled or reported. Accordingly, differences in the methodology between the included studies may undermine the accuracy of the inter-study comparison and contributed to some of the heterogeneity in the present analysis (I^2 = 0–79 %). Importantly, I^2 exceeded 75 % in only one of the analyses, which is rated as considerable.[32] Finally, dividing the continuous data into dichotomous variables for the subgroup analyses may lead to residual confounding and reduce statistical power.[55] For example, treating volume and load as independent factors may be problematic when comparing VRT and TRT. More precisely, the resistance in VRT varies throughout the movement. If the resistances during VRT and TRT are matched for one specific position of the movement, the total load will be higher (if matched in the bottom position) or lower (if matched in the top potion) compared with TRT. This would also affect the total volume lifted. To account for this, it seems reasonable to combine the two factors in one measure, e.g., volume load (load × repetitions).

5. Conclusion

This is the first meta-analysis to compare the effects of VRT versus TRT on maximal muscle strength and muscle power in healthy adult individuals. Our results suggest that similar strength and power gains can be expected from the two training modalities.Practical implications. Our findings suggesting similar effects of VRT and TRT allows coaches, recreational trained individuals, and others engaged in resistance training to consider VRT as an alternative to TRT which can be included into long-term periodized resistance training. Further, selection of one modality should rather be based on preference than effects. VRT may have some practical advantages, for example is elastic bands being more portable than TRT. Consequently, VRT (elastic bands) may be a good alternative when travelling.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2022.08.009.

CRediT authorship contribution statement

VA conceived the original idea and wrote the first draft of the manuscript, conducted the search strategy, scored the included papers, and extracted the data from the included studies. OP analyzed the data, made the figures, and provided critical feedback, comments and input. NS scored the included papers and provided critical feedback and input. KTC scored included papers and provided critical feedback, comments, and input. TES screened for potential papers, provided critical feedback, and commented on the manuscript. GP, RT and HP provided critical feedback and commented on the manuscript. AHS supervised the project, helped extracting the data, scored the included papers, and provided critical feedback and input. All authors read and approved the final manuscript.

Funding information

This study was conducted without any funding from companies, manufacturers or outside organizations.

Declaration of interest statement

The authors declare no conflict of interest.

Confirmation of ethical compliance

The study was conducted in accordance with the established ethical standards and the national legislation.

Acknowledgement

There are no acknowledgements related to this study.

References

1. van den Tillaar R, Andersen V, Saeterbakken AH. The existence of a sticking region in free weight squats. *J Hum Kinet* 2014;42:63-71.
2. Frost DM, Cronin J, Newton RU. A biomechanical evaluation of resistance: fundamental concepts for training and sports performance. *Sports Med* 2010;40(4):303-326.
3. Kulig K, Andrews JG, Hay JG. Human strength curves. *Exerc Sport Sci Rev* 1984;12:417-466.
4. McMaster DT, Cronin J, McGuigan M. Forms of variable resistance training. *Strength Cond J* 2009;31(1):50-64.
5. Wallace BJ, Bergstrom HC, Butterfield TA. Muscular bases and mechanisms of variable resistance training efficacy. *Int J Sports Sci Coach* 2018;13(6):1177-1188.
6. Suchomel TJ, Nimphius S, Bellon CR et al. The importance of muscular strength: training considerations. *Sports Med* 2018;48(4):765-785.
7. Melo Mde O, Brodt GA, Gomes LE et al. Effects of added elastic tubes on open-chain knee extensor strength training. *Sports Biomech* 2013;12(2):195-203.
8. Ataee J, Koozehchian MS, Kreider RB et al. Effectiveness of accommodation and constant resistance training on maximal strength and power in trained athletes. *PeerJ* 2014;2:e441.
9. de Lima FF, Cavalheri V, Silva BSA et al. Elastic resistance training produces benefits similar to conventional resistance training in people with chronic obstructive pulmonary disease: systematic review and meta-analysis. *Phys Ther* 2020;100(11):1891-1905.
10. de Oliveira PA, Blasczyk JC, Souza Junior G et al. Effects of elastic resistance exercise on muscle strength and functional performance in healthy adults: a systematic review and meta-analysis. *J Phys Act Health* 2017;14(4):317-327.
11. Lopes JSS, Machado AF, Micheletti JK et al. Effects of training with elastic resistance versus conventional resistance on muscular strength: a systematic review and meta-analysis. *SAGE Open Med* 2019;7:2050312119831116.
12. Martins WR, de Oliveira RJ, Carvalho RS et al. Elastic resistance training to increase muscle strength in elderly: a systematic review with meta-analysis. *Arch Gerontol Geriatr* 2013;57(1):8-15.
13. Iversen VM, Mork PJ, Vasseljen O et al. Multiple-joint exercises using elastic resistance bands vs. conventional resistance-training equipment: a cross-over study. *Eur J Sport Sci* 2017;17(8):973-982.
14. Nimphius S, McBride JM, Rice PE et al. Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *J Sports Sci Med* 2019;18(1):101-108.
15. Frost DM, Cronin JB, Newton RU. A comparison of the kinematics, kinetics and muscle activity between pneumatic and free weight resistance. *Eur J Appl Physiol* 2008;104(6):937-956.
16. Elliott BC, Wilson GJ, Kerr GK. A biomechanical analysis of the sticking region in the bench press. *Med Sci Sports Exerc* 1989;21(4):450-462.
17. Newton RU, Kraemer WJ, Häkkinen K et al. Kinematics, kinetics, and muscle activation during explosive upper body movements. *J Appl Biomech* 1996;12(1):31-43.
18. Page MJ, McKenzie JE, Bossuyt PM et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Syst Rev* 2021;10(1):89.
19. Maher CG, Sherrington C, Herbert RD et al. Reliability of the PEDro scale for rating quality of randomized controlled trials. *Phys Ther* 2003;83(8):713-721.
20. Kummel J, Kramer A, Giboin LS et al. Specificity of balance training in healthy individuals: a systematic review and meta-analysis. *Sports Med* 2016;46(9):1261-1271.
21. Grgic J, Lazinica B, Mikulic P et al. The effects of short versus long inter-set rest intervals in resistance training on measures of muscle hypertrophy: a systematic review. *Eur J Sport Sci* 2017;17(8):983-993.
22. Prieske O, Muehlbauer T, Granacher U. The role of trunk muscle strength for physical fitness and athletic performance in trained individuals: a systematic review and meta-analysis. *Sports Med* 2016;46(3):401-419.
23. Thiele D, Prieske O, Chaabene H et al. Effects of strength training on physical fitness and sport-specific performance in recreational, sub-elite, and elite rowers: a systematic review with meta-analysis. *J Sports Sci* 2020;38(10):1186-1195.
24. Cumpston M, Li T, Page MJ et al. Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. *Cochrane Database Syst Rev* 2019;10:ED000142.
25. Kelley GA, Kelley KS. Statistical models for meta-analysis: a brief tutorial. *World J Methodol* 2012;2(4):27-32.
26. Hedges LV, Olkin I. *Statistical Methods for Meta-analysis,* Academic Press, 2014.
27. Durlak JA. How to select, calculate, and interpret effect sizes. *J Pediatr Psychol* 2009;34(9):917-928.
28. Higgins JP, Thomas J, Chandler J et al. *Cochrane Handbook for Systematic Reviews of Interventions,* John Wiley & Sons, 2019.
29. Moran J, Sandercock G, Ramirez-Campillo R et al. A meta-analysis of resistance training in female youth: its effect on muscular strength, and shortcomings in the literature. *Sports Med* 2018;48(7):1661-1671.
30. Cohen J. In: Hillsdale NJ, ed. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed., L. Erlbaum Associates, 1988.
31. Liberati A, Altman DG, Tetzlaff J et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *J Clin Epidemiol* 2009;62(10):e1-e34.
32. Higgins JP, Thompson SG, Deeks JJ et al. Measuring inconsistency in meta-analyses. *BMJ* 2003;327(7414):557-560.
33. McCurdy K, Langford G, Ernest J et al. Comparison of chain- and plate-loaded bench press training on strength, joint pain, and muscle soreness in Division II baseball players. *J Strength Cond Res* 2009;23(1):187-195.
34. Boyer BT. A comparison of the effects of three strength training programs on women. *J Appl Sport Sci Res* 1990;4(3):88-94.
35. Shoepe TC, Ramirez DA, Rovetti RJ et al. The effects of 24 weeks of resistance training with simultaneous elastic and free weight loading on muscular performance of novice lifters. *J Hum Kinet* 2011;29:93-106.
36. Andersen V, Fimland MS, Kolnes MK et al. Elastic bands in combination with free weights in strength training: neuromuscular effects. *J Strength Cond Res* 2015;29(10):2932-2940.
37. Anderson CE, Sforzo GA, Sigg JA. The effects of combining elastic and free weight resistance on strength and power in athletes. *J Strength Cond Res* 2008;22(2):567-574.
38. Calatayud J, Borreani S, Colado JC et al. Bench press and push-up at comparable levels of muscle activity results in similar strength gains. *J Strength Cond Res* 2015;29(1):246-253.
39. Colado JC, Garcia-Masso X, Pellicer M et al. A comparison of elastic tubing and isotonic resistance exercises. *Int J Sports Med* 2010;31(11):810-817.
40. Pipes TV. Variable resistance versus constant resistance strength training in adult males. *Eur J Appl Physiol Occup Physiol* 1978;39(1):27-35.
41. Walker S, Hulmi JJ, Wernbom M et al. Variable resistance training promotes greater fatigue resistance but not hypertrophy versus constant resistance training. *Eur J Appl Physiol* 2013;113(9):2233-2244.
42. Apanukul S, Suwannathada S, Intiraporn C. The effects of combined weight and pneumatic training to enhance power endurance in tennis players. *J Exerc Physiol Online* 2015;18(2):8-16.
43. Duric S, Knezevic OM, Sember V et al. Effects of resistance training with constant, inertial, and combined loads on muscle power and strength output. *Front Physiol* 2021;12:709263.
44. Ghigiarelli JJ, Nagle EF, Gross FL et al. The effects of a 7-week heavy elastic band and weight chain program on upper-body strength and upper-body power in a sample of division 1-AA football players. *J Strength Cond Res* 2009;23(3):756-764.
45. Loturco I, Pereira LA, Reis VP et al. Traditional free-weight vs. variable resistance training applied to elite young soccer players during a short preseason: effects on

strength, speed, and power performance. *J Strength Cond Res* 2020. doi:10.1519/JSC.0000000000003899.
46. Rhea MR, Kenn JG, Dermody BM. Alterations in speed of squat movement and the use of accommodated resistance among college athletes training for power. *J Strength Cond Res* 2009;23(9):2645-2650.
47. Sawyer J, Higgins P, Cacolice PA et al. Bilateral back squat strength is increased during a 3-week undulating resistance training program with and without variable resistance in DIII collegiate football players. *PeerJ* 2021;9:e12189.
48. Frost DM, Bronson S, Cronin JB et al. Changes in maximal strength, velocity, and power after 8 weeks of training with pneumatic or free weight resistance. *J Strength Cond Res (Lippincott Williams & Wilkins)* 2016;30(4):934-944.
49. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med* 2016;46(10):1419-1449.
50. Cormie P, McGuigan M, Newton R. Developing maximal neuromuscular 463 power. Part 1-biological basis of maximal power production. *Sports Med* 2011;464(41).
51. Behm DG, Sale DG. Intended rather than actual movement velocity determines velocity-specific training response. *J Appl Physiol (1985)* 1993;74(1):359-368.
52. Behm DG. Neuromuscular implications and applications of resistance training. *J Strength Cond Res* 1995;9(4):264-274.
53. Danneskiold-Samsøe B, Bartels EM, Bülow PM et al. Isokinetic and isometric muscle strength in a healthy population with special reference to age and gender. *Acta Physiol (Oxf)* 2009;197(Suppl 673):1-68.
54. Lubans DR, Aguiar EJ, Callister R. The effects of free weights and elastic tubing resistance training on physical self-perception in adolescents. *Psychol Sport Exerc* 2010;11(6):497-504.
55. Altman DG, Royston P. The cost of dichotomising continuous variables. *Bmj* 2006;332(7549):1080.