

EFFECTS OF VARIABLE RESISTANCE TRAINING ON MAXIMAL STRENGTH: A META-ANALYSIS

MIGUEL A. SORIA-GILA, IGNACIO J. CHIROSA, IKER J. BAUTISTA, SALVADOR BAENA, AND LUIS J. CHIROSA

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

ABSTRACT

Soria-Gila, MA, Chiroso, IJ, Bautista, IJ, Baena, S, and Chiroso, LJ. Effects of variable resistance training on maximal strength: A meta-analysis. *J Strength Cond Res* 29(11): 3260–3270, 2015—Variable resistance training (VRT) methods improve the rate of force development, coordination between antagonist and synergist muscles, the recruitment of motor units, and reduce the drop in force produced in the sticking region. However, the beneficial effects of long-term VRT on maximal strength both in athletes and untrained individuals have been much disputed. The purpose of this study was to compare in a meta-analysis the effects of a long-term (≥ 7 weeks) VRT program using chains or elastic bands and a similar constant resistance program in both trained adults practicing different sports and untrained individuals. Intervention effect sizes were compared among investigations meeting our selection and inclusion criteria using a random-effects model. The published studies considered were those addressing VRT effects on the 1 repetition maximum. Seven studies involving 235 subjects fulfilled the selection and inclusion criteria. Variable resistance training led to a significantly greater mean strength gain (weighted mean difference: 5.03 kg; 95% confidence interval: 2.26–7.80 kg; $Z = 3.55$; $p < 0.001$) than the gain recorded in response to conventional weight training. Long-term VRT training using chains or elastic bands attached to the barbell emerged as an effective evidence-based method of improving maximal strength both in athletes with different sports backgrounds and untrained subjects.

KEY WORDS one repetition maximum, elastic bands, chains, biomechanics

INTRODUCTION

Over the past few years, strength training protocols designed to optimize the efficiency and benefits of training have gained popularity (20,33). Strength training programs including variable resistance (VR) exercises are typically performed using

accessories, such as elastic bands or chains, and machines that allow for variation in the velocity of load displacement and its magnitude. One of the main objectives of the use of chains or elastic bands is to induce a high variation of stimuli and thus provoke neural adaptations improving the different expressions of strength, including maximal strength or the 1 repetition maximum (1RM) (3,28). These methods combine the resistance generated by fixed loads (e.g., barbell and disks) with the VR produced by elastic bands and chains attached to the barbell. The most characteristic feature of this training modality is that resistance directed against the target muscle or muscle group can be varied over the range of athletic movement (1,20). Many authors claim that this type of resistance training reduces the mechanical disadvantage of the sticking point encountered in free weight training (2–4,33,38). The sticking point or sticking region refers to the loss of velocity produced in external resistance exercise and was first described by the authors of classic studies such as Elliott et al. (18). More recently, van der Tillar and Ettema (44) discovered that the sticking region is dependent on loading and accounts for 35–45% of the range of movement. The sticking region is the most inefficient stage of a joint movement in that the muscle groups involved cannot meet the demands of exercise when working with loads as high as 90% of the 1RM (36) or even 80% (18). In this region, movement velocity decreases most likely because of compromised neural intermuscular and intramuscular coordination, resulting in a reduction in the force sustained (44). The rationale for variable resistance training (VRT) is that a greater absolute external load will be supported if this neuromechanical disadvantage is minimized by applying lower resistances (loads lower than 85% 1RM, Table 1 indicating the loads sustained at the end of the athletic movement) across less efficient movement ranges (2,18). According to van den Tillaar and Saterbakken (45), in practical terms, this means that these movement ranges could be avoided by controlling exercise velocity to increase the mechanical impulse of each exercise repetition for workloads greater than 80% 1RM at the start of the sticking region.

During a variable intrarepetition stimulus weight lifting protocol, a load increase takes place as the barbell is moved through the concentric phase of the range of motion, making it increasingly more difficult to maintain a high velocity and

Address correspondence to Miguel Á. Soria-Gila, ma88@correo.ugr.es.
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TABLE 1. Details of the studies included in the meta-analysis.*†

Subject characteristics							
Reference	n	Gender	Age ($\pm$ SD) (y)	Weight ($\pm$ SD) (kg)	Height ($\pm$ SD) (cm)	Training level	Sports activity
Anderson et al. (2)	44	Mixed	20 $\pm$ 1	66.2 $\pm$ 13.8	‡	Trained (4 $\pm$ 2 y)	Basketball, wrestling, and hockey
Bellar et al. (9)	11	Men	23.6 $\pm$ 3.2	84.4 $\pm$ 18.8	179 $\pm$ 8.5	Untrained	‡
Cronin et al. (15)	40	Mixed	23.1 $\pm$ 4.8	76.3 $\pm$ 11	175 $\pm$ 9	Trained (3 y)	‡
Ghigiarelli et al. (22)	36	Men	19.96 $\pm$ 1.03	96.3 $\pm$ 15	180.83 $\pm$ 6.24	Trained	American football (36 Division 1AA)
McCurdy et al. (31)	27	Men	20.63 $\pm$ 1.33	84.79 $\pm$ 5.84	178.89 $\pm$ 5.46	Trained (4.8 $\pm$ 2.7 y)	Baseball (Division II)
Rhea et al. (40)	48	Men	21.4 $\pm$ 2.1	‡	‡	Trained	Athletics (NCAA) Division I
Shoepe et al. (42)	29	Mixed	19.76 $\pm$ 1.33	66.8 $\pm$ 11.1	168.77 $\pm$ 10.3	Scarce training (12 mo)	Free weight lifting

Training characteristics								
Reference	VRT	Duration	Sets	Repetitions	Rest (s)	Intensity		
						PCR	PVR	PMR
Anderson et al. (2)	Elastic bands	3 d·wk ⁻¹ $\times$ 7 wk	3–6	2–10	120–180	85	15	85
Bellar et al. (9)	Elastic bands	2 d·wk ⁻¹ $\times$ 13 wk	5	5	90	85	15	85
Cronin et al. (15)	Elastic bands	2 d·wk ⁻¹ $\times$ 10 wk	3	8–15	‡	‡	‡	‡
Ghigiarelli et al. (22)	Elastic bands and chains	4–5 d·wk ⁻¹ $\times$ 7 wk	5–6	4–6	‡	‡	‡	85
McCurdy et al. (31)	Chains	2 d·wk ⁻¹ $\times$ 9 wk	5–7	5–10	‡	80–90	10–20	‡
Rhea et al. (40)	Elastic bands	2–3 d·wk ⁻¹ $\times$ 12 wk	4	10	‡	‡	‡	75–85
Shoepe et al. (42)	Elastic bands	3 d·wk ⁻¹ $\times$ 24 wk	3–6	6–10	60–120	80–65	20–35	65–95

*d·wk⁻¹ = days per week; VRT = variable resistance training; PCR = percentage constant resistance; PVR = percentage variable resistance; PMR = percentage maximum resistance; NCAA = National Collegiate Athletic Association.

†Individual details of each study in terms of sample size (n), subject characteristics, and resistance training characteristics.

‡Not defined.

acceleration (11,13,19,48). When using elastic bands, sufficient acceleration is needed in the early lifting stage to overcome elastic recoil and complete the movement (19). Contrarily to the use of bands, chains act by adding mass (19). The magnitude of this system of masses is proportional to the height reached by the barbell from the ground. The gradual increase produced in external resistance causes instability, which could induce an optimal stimulus for strength gains (32), and a high neuromuscular demand, increasing both motor unit recruitment and rate coding (25). Such neuromuscular adaptations could be the consequence of improved coordination between antagonist and synergist muscles controlling movement (2,8,9,16,31,38). Some authors have argued that greater muscle activation due to stored elastic energy translates to an improved rate of force development (RFD) (40). The resistance produced by elastic bands or chains generates the greatest workload at the end of the range of motion. In other words, a steady load increase is produced through the trajectory of movement, whereas in traditional training using free weights, this greatest load is sustained at the onset of the concentric phase (22,23). A further issue to consider is that elastic bands increase resistance in a curvilinear manner, whereas chains do so linearly because of their different physical and mechanical properties (15,19,33,34).

The results of recent studies (2,9) assessing the efficiency of combining elastic tension with the tension induced by free weights in traditional back squat exercise suggest that 80–85% of the load should be provided by free weights and 15–20% by VR. To improve peak power during explosive movements when elastic bands and free weights are used in the back squat, other authors (28,33,38,48) recommend figures of 20–35% and 65–80% for VR- and free-weight loaded resistance, respectively.

A further characteristic feature of varying resistance is that, besides increasing velocity, it increases the eccentric stimulus of training, and thus the strength needed to slow down or stop the load at the end of the eccentric phase, inducing greater myoelectric activity in the muscles (15). Researchers examining VRT using chains have also reported that this type of training induces stimulus variations, as a consequence of the oscillations that chains produce, which provoke better coordination between agonist, synergistic, and stabilizing muscles to control the load (11,31). Several studies (2,21,48) have detected improvements in muscular strength and power generated in bench press and squat exercises in response to elastic plus free weight loaded training, compared with similar training in the absence of elastic resistance. In addition, VRT improves resistance to fatigue through the physiologic response to an acute effect of fatigue during training (46). Individual differences in muscle contractile properties can also lead to different degrees of fatigue (47).

Based on the available literature, it is difficult to extract whether the different VRT programs show true benefits in improving muscular strength. The present meta-analysis was

designed to examine research-based information on the effects on maximal strength, or 1RM, of a long-term VRT program under different training conditions.

METHODS

A meta-analysis was designed following the recommendations and criteria proposed by the Cochrane Review Group (26). Each step (article identification, filtering, eligibility assessment, and inclusion/exclusion of a study) was performed by the present authors.

Selection and Inclusion/Exclusion Criteria

All randomized controlled studies assessing the effects of a 7-week or longer VRT intervention providing maximal strength as the main outcome variable were identified. There were no restrictions made on the search regarding gender, training status, sport specialty, or body mass index.

A study was included if VRT intervention duration was ≥ 7 weeks and involved ≥ 2 sessions per week. The former cutoff was based on the finding that 6 weeks of resistance training is sufficient to improve the maximal strength of the knee extensors by 35%, as a consequence of an increase in the motor unit firing rate (29). The number of sessions per week was based on the findings of Rhea et al. (39). The use of elastic bands or chains was also an inclusion criterion although the training method (e.g., bench press or back squat) used to improve strength was not a limitation. Only articles providing preintervention and postintervention 1RM data were included. Studies were excluded if designed to treat a disorder or disease.

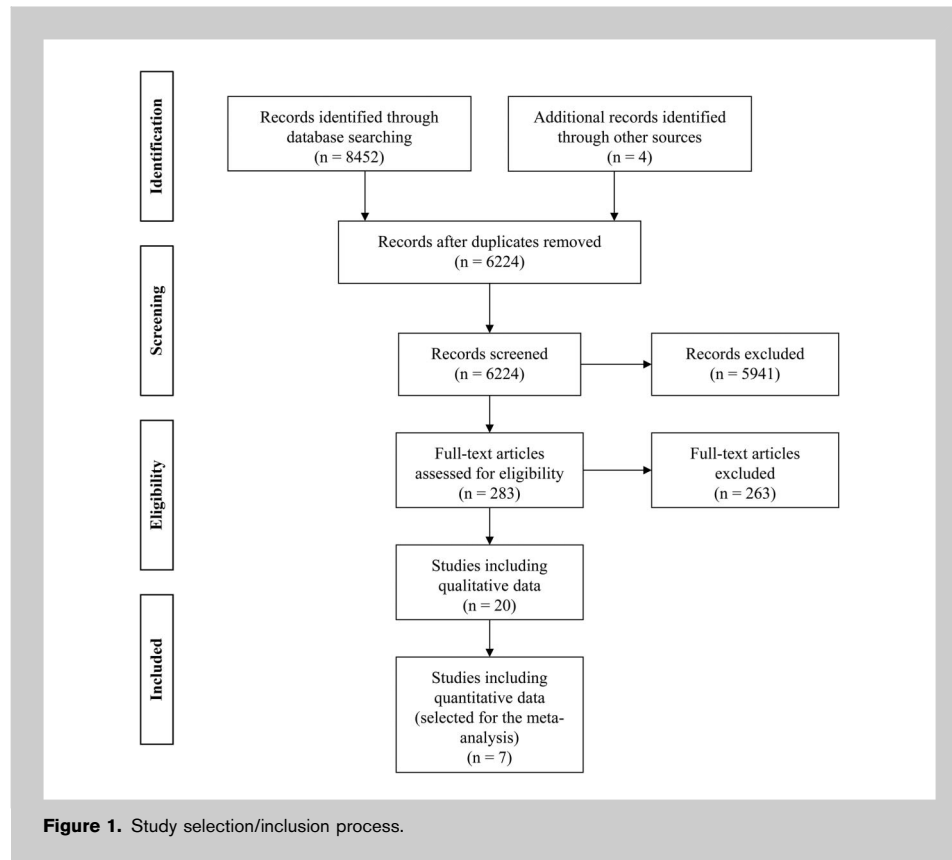
Articles were required to report on at least 1 subject group undergoing VRT and to include a control group of individuals training using the more traditional method (i.e., using free weights). Also as an inclusion criterion, we considered all valid and reliable methods commonly used to measure maximum strength in the different studies (14,32,34).

Search Methods

The following databases were searched for articles published before January 2014: MEDLINE, PubMed; Scopus, SPORT-Discus, and Web of Science using the keywords bench press, bungee weight, chain, concentric, eccentric, elastic bands, exercise, force, free weight, load, lower limb, maximal, muscle, neuromuscular, output, performance, power, resistance program, rubber bands, squat, strength, traditional, training, upper limb, variable, and velocity. Annual scientific conference abstracts, comments, or duplicated publications of the same study were not included. We also examined references listed and cited in the articles identified, including review articles, to identify additional studies. The full texts of the all the articles selected were examined by 3 of the present authors (M.A.S.-G., I.J.C., and S.B.).

Statistical Analyses

Study Inclusion. To select the studies for final inclusion in the meta-analysis, the 3 reviewers independently screened the



references identified for eligibility. Abstracts were assessed for the studies' fulfillment of inclusion/exclusion criteria. Study quality criteria were also considered (experimental design, subject withdrawal, and possible conflicts of interest). The recently developed QAREL checklist (30) was used to evaluate the methodological quality of included interrater reliability and agreement studies. This checklist was chosen

Effect Size. The effects of the intervention were calculated for each study using the pretraining and posttraining mean and *SDs* recorded for the main outcome measure (1RM) in the VRT and control (conventional training) groups. The pooled ES was estimated in terms of the change in *SD* produced. When a study lacked the necessary data to estimate the *SD* change, the following equation was used:

$$SD \text{ change} = \sqrt{([SD \text{ pre}]^2 + [SD \text{ post}]^2 - 2 \times \text{corr} - [\text{pre, post}] \times SD \text{ pre} \times SD \text{ post})}, \quad (1)$$

because it seems to be the only available quality appraisal tool for reliability studies at the moment. Any disagreement between reviewers was resolved by consensus.

Interstudy Heterogeneity. Variation between studies was assessed in terms of the effect under investigation (i.e., maximal strength). Effect sizes (ES) are provided as differences in weighted means, along with the corresponding 95% confidence interval (CI). To estimate interstudy heterogeneity, the χ^2 method was used with significance set at $p \leq 0.05$. The

where, corr is a correlation factor that relates pretraining and posttraining results based on the data provided by Rhea et al. (40) (0.96 for the VRT groups and 0.97 for the control groups).

A random-effects model was used to examine the grouped data extracted from the different studies. The relative strength of the intervention effect and 95% CIs for each study were illustrated in a forest plot. The ES of the intervention was calculated as the difference between pretraining and posttraining 1RM mean.

index I^2 was also determined, where 0% indicates homogeneity and 100% heterogeneity (27).

Coding of Studies. Each study was read and coded by the main investigator according to the following variables: descriptive information including sample size, gender, age, weight, height, training level, sports activity, type of VRT, extremities trained, training duration, sets, repetitions, rest, percentage constant resistance, percentage VR, and percentage maximum resistance (PMR).

Coder drift was assessed (37) by randomly selecting 4 studies for recoding. Per case agreement was determined by dividing the variables coded the same by the total number of variables. A greater mean agreement level was observed (93%) than the minimum accepted level of 90%.

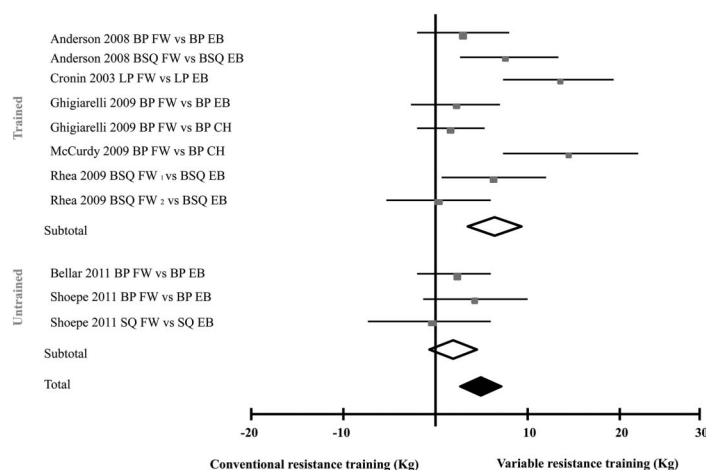


Figure 2. Forest plot of the results of the meta-analysis of random effects showing the difference in mean weighted 1RM and 95% CI detected for the bench press, leg press, back squat, and squat (5.03 kg; 95% CI: 2.26–7.80 kg; $Z = 3.55$; $p < 0.001$) in trained and untrained subjects. Gray squares indicate the intervention effect. Square sizes are proportional to the weights assigned to each study in the meta-analysis. The horizontal line joins the lower and the upper limits of the effect at a 95% CI. The diamonds represent the subgroup mean difference ($\diamond$) and pooled mean difference ($\blacklozenge$). BP = bench press; LP = leg press; SQ = squat; BSQ = back squat; EB = elastic band; CH = chain; FW = free weight; CI = confidence interval; 1 = fast-velocity group; 2 = slow-velocity group.

In a separate sensitivity analysis, we determined the contribution of each study to the overall improvement in maximal strength detected in this meta-analysis by successively

omitting the results of each study from the comparisons made using the data from the remaining studies. All calculations were performed using the RevMan software package (Review Manager-Version 5.2; The Cochrane Collaboration, 2012).

omitting the results of each study from the comparisons made using the data from the remaining studies. All calculations were performed using the RevMan software package (Review Manager-Version 5.2; The Cochrane Collaboration, 2012).

ing using free weights with chains (22,31), whereas others compared several experimental groups subjected to different VRT interventions (elastic bands or chains) with a control group (traditional free weight training) (15,22). In the study by Rhea et al. (40), several experimental groups undertaking different training protocols with chains were compared. Another study compared the effects of training with elastic bands attached to free weights in bench presses and squats (42).

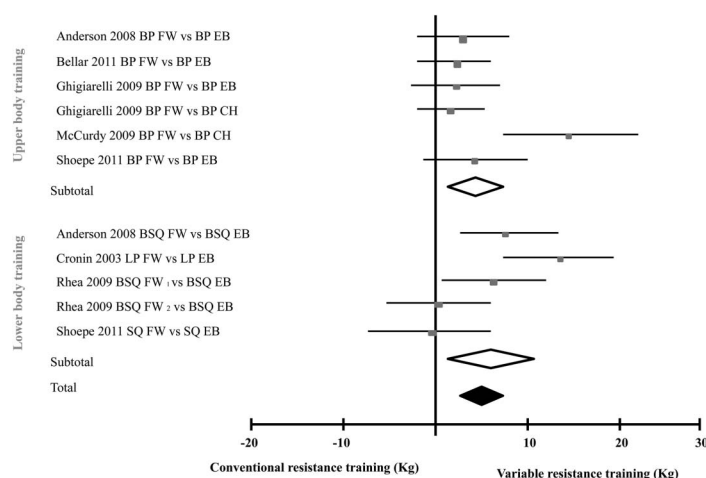


Figure 3. Forest plot of the results of the meta-analysis of random effects showing the difference in mean weighted 1RM and 95% CI detected for the bench press, leg press, back squat, and squat (5.03 kg; 95% CI: 2.26–7.80 kg; $Z = 3.55$; $p < 0.001$) in upper-body training and lower-body training subjects. Gray squares indicate the intervention effect. Square sizes are proportional to the weights assigned to each study in the meta-analysis. The horizontal line joins the lower and the upper limits of the effect at a 95% CI. The diamonds represent the subgroup mean difference ($\diamond$) and pooled mean difference ($\blacklozenge$). BP = bench press; LP = leg press; SQ = squat; BSQ = back squat; EB = elastic band; CH = chain; FW = free weight; CI = confidence interval; 1 = fast-velocity group; 2 = slow-velocity group.

RESULTS

Study Characteristics

Seven studies providing results for 16 subject groups met the criteria for inclusion in our meta-analysis (2,9,15,22,31,40,42), (Figure 1). Publication dates were 2003–2011. An overview of the characteristics of the 7 studies included in this meta-analysis is provided in Table 1. All studies selected were designed to address the same issue although working hypotheses differed slightly. Some studies compared the effects on the 1RM of training

Subject Characteristics

The data examined were obtained from 235 subjects aged 18.3–27.9 years (mean $\pm$ SD: 21.21 $\pm$ 2.11 years) (Table 1). Four of the 7 studies were conducted only in men (10 groups) and 3 in both men and women (6 groups). The participants of 2 studies were untrained subjects or had less than 12 months of experience (4 groups). In 5 studies, subjects had experience of 2 years or longer or were trained (12 groups). Trained subjects

TABLE 2. Results of the 7 studies included in the meta-analysis.*

1RM													
		Control groups						Experimental groups					
Reference	Exercise	n	Pretreatment (kg)	SD (kg)	Posttreatment (kg)	SD (kg)	ES	n	Pretreatment (kg)	SD (kg)	Posttreatment (kg)	SD (kg)	ES
Anderson et al. (2)	BP	21	81.07	32.82	84.41	33.37	0.43	23	80.69	35.34	87.37	35.52	0.66
	BSQ	21	108.19	35.61	115.28	33.70	0.86	23	105.80	33.70	121.75	35.70	1.58
Bellar et al. (9)	BP	11	101.50	19.60	109.00	20.30	1.60	11	100.00	18.90	109.90	19.40	1.80
Cronin et al. (15)	LP	12	122.00	34.10	118.95	33.25	0.39	14	128.00	27.50	139.14	29.90	1.30
Ghigiarelli et al. (22)	BP	12	141.80	23.00	149.50	23.00	1.44	12	127.70	25.00	137.70	25.00	1.40
	BP							12	129.50	15.00	138.60	14.00	2.13
McCurdy et al. (31)	BP	27/2†	102.65	14.42	109.09	12.98	1.85	27/2†	151.85	27.12	174.26	13.47	1.52
Rhea et al. (40)	BSQ	16	115.94	36.07	119.18	35.56	0.38	16	116.00	31.43	125.81	30.69	1.10
	BSQ	16	122.31	39.04	131.94	36.43	1.08						
Shoepe et al. (42)	BP	12	56.30	30.30	66.70	27.00	1.40	12	53.60	21.00	59.30	24.50	0.77
	SQ	12	66.90	16.50	88.90	23.20	2.72	12	69.30	27.00	91.40	31.90	2.27

*n = number of subjects in each group; ES = effect size; BP = bench press; BSQ = back squat; SQ = squat; LP = leg press.

†Not defined.

were Division I athletes (National Collegiate Athletic Association [NCAA]), baseball players (Division II) and American football players (36 Division 1AA players).

Variable Resistance Training

Mean training program duration was 12 ± 5 weeks (range, 7–24 weeks). From 2 to 5 training sessions were conducted per week, with a mean of 3 ± 1 per week. Training took the form of upper limb exercise (bench press) in 4 studies (10 groups), lower limb exercise (back squat) in 1 study (2 groups), and both upper and lower limb training (bench press and back squat) in 2 studies (4 groups). Chains attached to the barbell in the bench press were used in 2 studies (2 groups), and elastic bands attached to the barbell in bench press or back squat exercise were used in 5 studies (6 groups each).

Publication Bias and Interstudy Heterogeneity

A scatter plot of intervention effect (1RM) against the study size showed a funnel-shaped symmetric distribution indicating no publication bias. The treatment effect, or 1RM, yielded the values $\chi^2 (10) = 27.21$; $p = 0.002$; $I^2 = 63\%$ indicating moderate interstudy heterogeneity.

Maximal Strength (One Repetition Maximum)

The mean strength gain produced was greater in the subjects undertaking long-term VRT, the ES being 1.42 ± 0.51 expressed as the mean $\pm$ SD (difference in the weighted mean 1RM was 5.03 kg; 95% CI: 2.26–7.80 kg; $Z = 3.55$; $p < 0.001$; Figure 2) than in those subjected to a conventional resistance training program, with an ES of 1.24 ± 0.71 . Furthermore, a subgroup analysis by training status indicated a significantly better 1RM gain in response to VRT, $ES = 1.35 \pm 0.43$, vs. traditional training, $ES = 0.98 \pm 0.56$, for trained subjects (pooled estimate = 6.12 kg; 95% CI: 2.43, 9.80 kg; $Z = 3.25$; $p = 0.001$; Figure 2). However, in untrained subjects, the greater improvement produced in the 1RM with VRT, $ES = 1.62 \pm 0.77$, compared with conventional training, $ES = 1.91 \pm 0.71$ was nonsignificant (pooled estimate = 2.56 kg; 95% CI: -0.55, 5.68 kg; $Z = 1.61$; $p = 0.11$; Figure 2). Another subgroup analysis revealed that for upper extremity training, significant differences in 1RM gains existed between the VRT program, $ES = 1.38 \pm 0.57$, and traditional training program, $ES = 1.36 \pm 0.48$ (pooled estimate = 3.99 kg; 95% CI: 0.92, 7.06 kg; $Z = 2.54$; $p = 0.01$; Figure 3). Similarly, for lower limb training, VRT also led to a significantly better improvement in the 1RM, $ES = 1.47 \pm 0.49$, than conventional training, $ES = 1.09 \pm 0.96$ (pooled estimate = 6.07 kg; 95% CI: 0.95, 11.20 kg; $Z = 2.32$; $p = 0.02$; Figure 3). In Table 2, we provide details of the effects of the VRT program detected in each study.

Sensitivity

In each comparison (preintervention vs. postintervention) in which the results of 1 study were omitted, no significant differences were detected ($p < 0.001$) in each case indicating the significant contribution of all the studies to the overall strength gains observed.

DISCUSSION

In this meta-analysis, we compared the effects of traditional vs. VRT on the adaptive response produced in terms of maximal strength. The studies meeting the selection and inclusion criteria for the meta-analysis were those by Cronin et al. (15), Anderson et al. (2), Ghigiarelli et al. (22), McCurdy et al. (31), Rhea et al. (40), Bellar et al. (9), and Shoepe et al. (42). Participants were either untrained (with under 12 months' experience in strength training) or trained (longer than 2 years' experience). Our results indicate that VRT over at least 7 weeks (≥ 2 sessions per week) leads to a significantly greater strength gain ($p < 0.001$) than that produced in response to a traditional strength training program. When subjects were stratified according to training status, trained individuals achieved a significantly greater strength gain with the VRT than the traditional training program ($p = 0.001$). However, the strength gains observed for the nontrained subjects undertaking a VRT program vs. a traditional program did not vary significantly ($p = 0.11$). When stratified according to the extremities trained, for both the lower and upper limbs, VRT gave rise to significantly better gains in 1RM than conventional training ($p \leq 0.02$).

According to the Rhea scale (38) used to determine the magnitude of the ES in a study comparing the effects of resistance training as a function of training status, in trained subjects who undertook a VRT ($ES = 1.35 \pm 0.43$) vs. conventional training program ($ES = 0.98 \pm 0.56$), the ES was moderate, although sufficient for a significant difference to exist between the 2 groups. This indicates that in individuals with more experience in resistance exercises such as the bench press and back squat, ≥ 7 weeks of VRT is an effective stimulus for them to show a performance peak during training.

However, in our study, a moderate ES was also observed in untrained subjects undertaking both a VRT program ($ES = 1.62 \pm 0.77$) or conventional training program ($ES = 1.91 \pm 0.71$). It should be noted that subjects labeled in our study as "trained subjects," would according to Rhea classification (38), be considered "recreationally trained" given they had more than 1 year of experience but a training duration of less than 5 years.

It also remains unclear whether a VRT program of duration under 7 weeks or longer than 12 weeks would be adequate for athletes to develop sufficient neural and muscular adaptations in a short time span to improve their 1RM while also continuing to improve their 1RM over the ensuing weeks. Only one of the studies reviewed here (42) examined a VRT program lasting longer than 12 weeks. This 24-week intervention in untrained subjects produced no significant impact on 1RM.

Evidence has only recently started to mount indicating that VRT leads to a greater RFD and muscular power than the more conventional form of resistance training (42). The findings of the latter study suggest that during VRT, the training impulse and muscle activation achieved on completion of

each repetition are enhanced. According to Shoepe et al. (42), this means that the lifter develops greater force in the final portion of the concentric phase. Despite this, no significant strength differences were detected in response to a 24-week program of traditional training and VRT training combining elastic and free weight loading in subjects with limited RT experience. McCurdy et al. (31) also noted improved strength gains in individuals undertaking the VRT program but again differences with respect to controls were not significant. These authors attributed the strength gains observed to the different stability involved in the variable and conventional training protocols, such that the neuromuscular activity required for a strength improvement depends on the stabilization needed to control resistance (5). Accordingly, for a more unstable load, greater neuromuscular activation is necessary and force production is significantly reduced (6). Our findings confirm those of the study by Shoepe et al. (42) in that subjects unaccustomed to free weight training showed no significant differences when comparing the effects of conventional and VRT. Thus, an optimal level of stability could be a prerequisite for an improvement in maximal strength. Chain-loaded VRT is slightly more unstable than free weight resistance training (31). Consequently, once an individual becomes accustomed to VRT and acquires more neuromuscular control, VRT can be an optimal stimulus to develop the different expressions of strength.

The general trend detected in this meta-analysis is in line with the findings of the study by Anderson et al. (2), in which significant 1RM improvements were obtained both in the bench press and squat. Participants of this study were trained athletes who showed no muscle cross-section increase at the end of the training period, suggesting improvements at the neural level. Variable resistance training emerged as a beneficial strategy for trained athletes, offering new stimuli inducing fitness adaptations. The strength gains produced in these athletes could also be attributed to increased muscle tension in the more mechanically productive regions of the range of movement, accompanied by reduced loading in the less efficient sticking region. According to Anderson et al. (2), during traditional free weight training, the barbell gains velocity during muscle shortening until the sticking region. In the latter study, subjects executing VRT achieved approximately 10% less resistance in the lower region of the range of movement and 10% more resistance toward the top, or end, of the athletic movement. Acceleration remained constant over a long period within each repetition, determining that deceleration is reduced in VRT. Bellar et al. (9) argue that another method of modifying resistance during a traditional resistance exercise is to add elastic resistance. Thus, variable-resistance loading during the bench press makes the lifting movement no longer isoinertial. The percentage-load variation produced by elastic bands here was 15%, and this modified the strength production pattern during lifting. This type of variable stimulation could be responsible for beneficial neural adaptations. In the subject populations entered in our meta-analysis, resistance

exercise led to improved performance in terms of maximal strength gains (2,9,15,22,31,40,42).

Elastic recoil during eccentric contraction in VRT training may differently challenge the neuromuscular system during each repetition (2). Häkkinen et al. (24) reported increased electromyographic activity and a controlled increase in velocity during eccentric actions. In another study, Cronin et al. (15) concluded that VRT using elastic bands attached to a jump squat machine induced greater electromyographic activity in eccentric contractions compared with traditional training methods. Anderson et al. (2) proposed that greater muscle fiber recruitment and stimulation during the eccentric portion of each repetition may bring about greater neuromuscular adaptations and/or type IIx fiber recruitment with VRT than with free weights alone. This explanation offered by Anderson et al. (2) is consistent with the preferential recruitment of high-threshold motor units during high-force eccentric contractions reported by Nardone et al. (35).

In the study by Ghigiarelli et al. (22), significant maximal strength increases were observed in VR compared with traditional resistance-trained individuals, regardless of the use of chains or elastic bands. Wallace et al. (48) observed that adding elastic-loaded resistance to free weight training in the back squat led to maximal strength and power improvements when working with loads approaching 85% of the 1RM.

According to Cronin et al. (15), the ability to quickly complete a stride and return to the starting position or move in another direction is a determining factor for success in sports, such as squash, badminton, tennis, and fencing, among others. In their study, subjects undertaking VRT using elastic bands on the leg press machine showed improvement in the move toward the stride, especially in the last part of the eccentric phase. These subjects were able to complete a stride faster than their peers who trained on the same machine in the traditional way. Thus, it seems that VRT serves to improve the transition from eccentric to concentric phase exercise, and thus, shortens the stretch-shortening cycle, which would potentiate the concentric phase (12) and expedite the stride. Despite an increased prevalence of VRT programs using heavy chains and elastic bands, some studies have generated contradictory results (4,10,48), whereas others have found that VRT programs offer promising results in the long term (15,22).

Variable resistance training using heavy chains modifies the kinetics of the barbell for all movement ranges, increasing the mechanical advantage of the athlete's movement (4,10,38). However, because of the gradual resistance reduction at the end of the eccentric phase, the time taken to reach maximum acceleration (at the start of the concentric phase) decreases in that range of movement zone causing neural adaptation (22,31). McCurdy et al. (31) identified the individual range of movement as an important factor to consider when quantifying the workload. Behm and Sale (7) described the user's intention to displace the barbell as rapidly as possible as the main force driving neural adaptations

of muscular power and strength. Neuromuscular adaptations are specific to the nature of the training load (43). Thus, it has been proposed that the different characteristics of load distribution during VRT affect muscle recruitment patterns (2). In the study by Anderson et al. (2), subjects in the VRT group were able to complete the prescribed exercise sets, whereas some of the control group subjects had to pause for 5–10 seconds between some repetitions to complete a set.

In their study, Rhea et al. (40) noted maximal strength gains when they compared subjects in whom VRT involved high-velocity movements ($0.6\text{--}0.8\text{ m}\cdot\text{s}^{-1}$) with subjects in the traditional training group working at slower velocities ($0.2\text{--}0.4\text{ m}\cdot\text{s}^{-1}$). These results support the idea that the RFD can be improved through VRT training using elastic bands (2,15,16,22). Wallace et al. (48) suggested that the RFD increase could correspond to an earlier phase in which the peak velocity is reached in VRT. This is because as resistance progressively increases with the mechanical advantage, higher levels of force are generated during the concentric phase just at the moment when muscles approach their optimal length-tension relationship (17). A further factor inducing an increase in RFD is a shorter muscle tissue stretch-shortening cycle (40). The muscle is able to store elastic energy during the eccentric phase of movement and then releases this energy as kinetic energy during the concentric phase of the lift (15). According to Rhea et al. (40), when the time taken needed to reach maximal force is not limited, strength relates more to activation of muscle mass with some relationship to synchronization. Athletes using elastic bands as the VRT stimulus showed both improved muscular strength and power, most likely because of simultaneously improved motor unit synchronization and coding velocity, although this needs to be confirmed in further work (40).

The finding of this meta-analysis that VRT training using chains or elastic bands leads to strength gains has obvious implications to be considered by coaches and specialists in sport sciences. This new training modality enables both elite athletes and untrained individuals to more rapidly and efficiently achieve adaptations in their functional capacity than the more traditional resistance training methods.

As a limitation to this meta-analysis, we should mention that many studies were excluded because of the strict inclusion criteria established. Similarly, because of missing data in some of the selected studies, a correlation factor (Equation 1) had to be calculated from the data provided by Rhea et al. (40). A further limitation was the possible effects of publication bias (41). Despite these limitations, this meta-analysis provides an overview of the research in this field and offers an explanation based on the scientific literature of the benefits of the use of VRT to increase maximal strength.

PRACTICAL APPLICATIONS

This meta-analysis provides research-based data supporting the benefits of VRT using chains or elastic bands as an

effective strategy to increase maximal strength (1RM) in athletes of different sports disciplines. Thus, VRT could be used as a complement to traditional training to vary the athletic stimulus once the user has adapted to the previous stimulus, leading to faster training-induced adaptations.

This training modality could help avoid overload during the range of athletic movement and may therefore be used throughout a sport's season to gradually improve a competition skill. It is also a useful tool to strengthen certain muscle groups while subjecting injured muscles to lower resistances during a rehabilitation process.

Variable resistance training is an economic simple strategy for use with barbells in exercises such as the bench press or back squat. The chains or elastic bands are quick to attach and unattach meaning that strength conditioning coaches can readily prescribe a different exercise after a variable-resistance exercise without wasting valuable training time. Our results indicate that training status affects the impacts of conventional and VRT. For untrained subjects, we would not recommend VRT, because similar strength gains are produced with traditional free weight training. In contrast, in trained individuals, VRT will lead to improved strength gains over traditional training. This type of protocol would be ideal in adults with training experience to achieve stimulus variations and thus avoid plateaus in their physical fitness. This issue should be borne in mind by strength conditioning experts and coaches to better design training regimens.

Based on our findings, it would also seem that both upper and lower limb VRT produces greater adaptations than conventional free weight training, indicating similar effects of this training form on both halves of the body.

Our findings provide direction for future studies designed to determine whether other percentages of VR work and/or PMR will produce the same 1RM adaptations or whether single-joint exercises will give rise to similar results as multijoint actions. Future research efforts should also explore whether the impacts of VRT are reduced with training duration and establish the minimum period for VRT to produce the strength gains detected here.

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