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SYSTEMATIC REVIEW

Effect of Training Leading to Repetition Failure on Muscular Strength: A Systematic Review and Meta-Analysis

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Abstract

Background It remains unclear whether repetitions leading to failure (failure training) or not leading to failure (non-failure training) lead to superior muscular strength gains during resistance exercise. Failure training may provide the stimulus needed to enhance muscular strength development. However, it is argued that non-failure training leads to similar increases in muscular strength without the need for high levels of discomfort and physical effort, which are associated with failure training.

Objective We conducted a systematic review and meta-analysis to examine the effect of failure versus non-failure training on muscular strength.

Methods Five electronic databases were searched using terms related to failure and non-failure training. Studies were deemed eligible for inclusion if they met the following criteria: (1) randomised and non-randomised studies; (2) resistance training intervention where repetitions were performed to failure; (3) a non-failure comparison group; (4) resistance training interventions with a total of ≥3 exercise sessions; and (5) muscular strength assessment pre- and post-training. Random-effects meta-analyses were performed to pool the results of the included studies and generate a weighted mean effect size (ES).

Results Eight studies were included in the meta-analysis (combined studies). Training volume was controlled in four studies (volume controlled), while the remaining four studies did not control for training volume (volume uncontrolled). Non-failure training resulted in a 0.6–1.3 % greater strength increase than failure training. A small pooled effect favouring non-failure training was found (ES = 0.34; $p = 0.02$). Significant small pooled effects on muscular strength were also found for non-failure versus failure training with compound exercises (ES = 0.37–0.38; $p = 0.03$) and trained participants (ES = 0.37; $p = 0.049$). A slightly larger pooled effect favouring non-failure training was observed when volume-uncontrolled studies were included (ES = 0.41; $p = 0.047$). No significant effect was found for the volume-controlled studies, although there was a trend favouring non-failure training. The methodological quality of the included studies in the review was found to be moderate. Exercise compliance was high for the studies where this was reported ($n = 5$), although limited information on adverse events was provided.

Conclusion Overall, the results suggest that despite statistically significant effects on muscular strength being found for non-failure compared with failure training, the small percentage of improvement shown for non-failure training is unlikely to be meaningful. Therefore, it appears that similar increases in muscular strength can be achieved with failure and non-failure training. Furthermore, it seems unnecessary to perform failure training to maximise muscular strength; however, if incorporated into a programme, training to failure should be performed sparingly to limit the risks of injuries and overtraining.

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Key Points

This is the first systematic review and meta-analysis that has directly examined the effect of failure versus non-failure resistance training on muscular strength.

The review showed that similar gains in muscular strength can be achieved with non-failure compared with failure resistance training.

Numerous factors related to exercise prescription and training experience were shown to influence the effect of non-failure versus failure resistance training on muscular strength.

1 Introduction

American College of Sports Medicine (ACSM) position statements have provided recommendations for resistance training prescription targeting muscular strength [1, 2]. The most recent position statement recommends that individuals with no resistance training experience (i.e. novices) perform 1–3 sets of 8–12 repetitions at loads corresponding to 60–70 % of one repetition maximum (1RM) with 2–3 min recovery between sets/exercises, 2–3 times per week [1]. For individuals with 6–12 months' resistance training experience (intermediate and advanced, respectively), there is a greater emphasis on heavy loads (1–6 repetitions at 80–100 % of 1RM) and increased training frequency. However, it is expected that when the above recommendations are followed, performance during sets will differ between individuals relative to their 1RM, because of differences in previous training history and exercises performed [3, 4]. This may result in an individual being close to or reaching failure (i.e. inability to complete a repetition in a full range of motion, because of fatigue) at the completion of a set.

The theory that repetitions leading to failure (failure training) will elicit superior muscular strength gains, compared with repetitions that do not lead to failure (non-failure training) is commonly associated with Arthur Jones, the founder of Nautilus exercise machines [5]. In his writing of over 30 years, Arthur Jones has influenced a number of highly successful athletes (notably, bodybuilders) to use failure training in their programmes. While it is clear that moderate to heavy loads are required to achieve increased muscular strength, it is uncertain whether resistance training should be performed to failure for muscular strength to be enhanced [6, 7].

The rationale for performing resistance exercises to failure is to maximise motor unit recruitment [6]. While this has been postulated, it has not been demonstrated empirically. On the basis of the size principle, during a typical moderate to heavy set of resistance exercise, lower-threshold motor units composed of type I slow-twitch or type IIa fast-twitch muscle fibres are recruited first [8]. As consecutive repetitions are performed, the lower-threshold motor units are fatigued, which results in recruitment of higher-threshold motor units composed predominantly of type IIx fast-twitch muscle fibres. Once all of the available motor units have fatigued to a point where the load cannot be moved beyond a critical joint angle (also known as the 'sticking point'), failure has occurred [9]. Therefore, training to failure might enable a lifter to maximise motor unit recruitment, which may be an important stimulus for muscular strength development [10–12]. However, there is evidence that motor unit recruitment can be maximised without the need to perform resistance exercise to failure. Sundstrup et al. [13] found that full motor unit activation of muscles involved in the lateral raise was achieved 3–5 repetitions prior to failure in a group of untrained women. It has also been hypothesised that failure compared with non-failure training could lead to greater elevation of anabolic hormone levels [14], which may contribute to resistance training-induced changes in muscular strength [15, 16] although the most recent evidence shows that elevation of anabolic hormone levels is not required for significant increases in muscular strength [17].

Several issues have been raised concerning implementation of failure training in resistance training programmes. It has been suggested that the extra fatigue experienced from performing sets to failure may increase the risks of overtraining and overuse injuries [6, 7]. As a result, performing failure training is often advised for more experienced/advanced resistance trainers, because of the expectation that greater training stresses will be better tolerated by these individuals during and following a session (i.e. enhanced recovery) [6, 18]. Another potential concern about failure training is the negative effect it can have on the ability to stay within a selected repetition range while using a specific load (i.e. intensity). Performing consecutive sets to failure with a specific load has been shown to significantly reduce the number of repetitions that are possible [19–21]. Therefore, a reduction in load might be required to enable a lifter to stay within the selected repetition range, thus minimising large fluctuations in training volume (sets × repetitions), which can affect muscular strength gains [22–24]. However, increases in electromyographic (EMG) activity, presumably as a result of increased motor unit recruitment, have been shown during resistance exercise with relatively high versus lower loads performed to failure [25–27]. Furthermore, if the load is decreased substantially below 80 % of 1RM (e.g. as low as 50 % of 1RM), this also may result in a less effective stimulus for maximising muscular strength adaptations [22–24, 28, 29].

On the basis of a subset of studies from a meta-analysis by Peterson et al. [18], non-failure compared with failure training was found to be more efficacious for increasing muscular strength. However, a major limitation of the meta-analysis by Peterson et al. [18] was that studies using failure training were compared with different studies that used a non-failure intervention. Therefore, none of the included studies directly compared failure and non-failure training. Recent reviews [6, 7] that included literature directly comparing failure and non-failure training reported that relatively few studies have examined failure versus non-failure resistance training while equating for all variables. In particular, it was emphasised that training studies examining this practice should equalise training volume to minimise the effect of this potential confounder on results. While these reviews are very informative and insightful, they were not led via an explicit and reproducible protocol [30]. As a result, it is often not possible to replicate the findings, and attempts at synthesis may not always be as rigorous as intended (i.e. there is a potential for bias).

Studies that have examined the effects of failure compared with non-failure resistance training on muscular strength have used sample sizes ranging from 11 to 15 participants per group [14, 31, 32]. Such sample sizes may be too small to provide sufficient statistical power for studies where non-significant differences between the two training methods are found. Therefore, use of a meta-analytical approach would be useful to overcome the issue of low statistical power leading to non-significant differences.

The purpose of this review was to use the systematic review and meta-analytical approach to examine the effect of failure compared with non-failure resistance training on muscular strength. Where possible, subgroup analyses were conducted to determine whether interventions that controlled for volume, training status and exercise type influenced these effects. Information gathered from this meta-analysis will be useful to strength and conditioning coaches (and athletes) for devising resistance training programmes to maximise muscular strength development.

2 Methods

2.1 Search Strategy and Study Selection

A search from the earliest record up to and including July 2015 was carried out using the following electronic databases: Scopus, Medline, PubMed, SportDiscus and Web of Science. The search strategy combined the terms 'weight-lifting', 'weight lifting', 'weight-training', 'weight training', 'resistance-training', 'resistance training', 'resistance exercise', 'strength-training' and 'strength training' with 'muscular failure', 'muscular exhaustion', 'muscular fatigue', 'repetition failure', 'failure', 'repetition exhaustion', 'muscular fatigue', 'repetition maximum' and 'RM' with 'nonfailure', 'non-failure', 'cluster', 'cluster-set', 'intra-set rest', 'intraset rest', 'intra-set rest interval', 'intraset rest interval', 'interrepetition rest' and 'inter-repetition rest'. The titles and abstracts of the retrieved articles were individually evaluated by two reviewers (TD and DH) to assess their eligibility for the review and meta-analysis. Disagreements were solved by consensus or, if necessary, by a third reviewer (RO). The reviewers were not blinded to the studies' authors, institutions or journals of publication. Abstracts that did not provide sufficient information regarding the inclusion criteria were retrieved for full-text evaluation. The corresponding authors of potentially eligible articles were contacted if there were missing data. This systematic review and meta-analysis is reported in accordance with the recommendations and criteria outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [33].

2.2 Eligibility Criteria

Articles were eligible for inclusion if they met the following criteria: (1) randomised and non-randomised studies; (2) resistance training intervention where repetitions were performed to failure (inability to complete the concentric phase of a repetition); (3) a comparison group that did not perform repetitions to failure; (4) resistance training interventions that included a total of three or more exercise sessions; and (5) assessment of muscular strength pre- and post-training.

2.3 Data Extraction

Two reviewers (TD and DH) separately and independently evaluated full-text articles and conducted data extraction, using a standardised, predefined form. Relevant data regarding participant characteristics (age, training experience and body weight), study characteristics (training frequency, exercises prescribed, sets, repetitions, rest between sets or repetitions, intensity, intervention length and compliance) and muscular strength testing were collected. Shortly after these extractions, the reviewers crosschecked the data to confirm their accuracy. Any discrepancies were discussed in order to find a consensus decision, with disagreements resolved by consultation with a third reviewer (MH). All studies, except for one, assessed muscular strength via RM testing [34], while three studies used both maximal voluntary contraction and RM testing [32, 35, 36].

It was decided that only RM testing data would be extracted, to allow for more accurate representation of the effect of failure versus non-failure training, hence the study that did not include RM testing was excluded [34]. Additionally, three studies compared a group that performed failure training with groups performing various types of non-failure training [36–38]. In this situation, the non-failure group with a more similar exercise prescription (i.e. number of repetitions/sets, repetition speed, etc.) to that of the failure group was included to reduce the risk of confounding the results (e.g. repetition speeds).

2.4 Quality Analysis

The methodological quality of studies meeting the inclusion criteria was assessed using the Downs and Black checklist [39]. The tool consists of 27 items rated as 'no = 0, unable to determine = 0, and yes = 1', and includes criteria such as a clear description of the aims, interventions, outcome measurements and participants; representativeness of participant groups; appropriateness of statistical analyses; and correct reporting. The checklist was slightly modified so that the final item (number 27) relating to statistical power was consistent with the scoring used for the other items (i.e. from the original score of '0–5' to 'no = 0, unable to determine = 0, and yes = 1'). Additionally, an extra item was added to the checklist, which was 'exercise supervision'; therefore, the modified tool consisted of 28 items (see Electronic Supplementary Material Table S1). The summed scores ranged from 0 to 28 points, with higher scores reflecting higher-quality research. Scores above 20 were considered good; scores of 11–20 were considered moderate and scores below 11 were considered poor methodological quality [40]. Studies were independently rated by two reviewers (TD and DH) and checked for internal (intra-rater) consistency across items before the scores were amalgamated into a spreadsheet for discussion. Disagreements between ratings were resolved by discussion, or advice was sought from a third reviewer (MH) if no consensus was reached by discussion.

2.5 Statistical Analysis

All analyses were conducted using Comprehensive Meta-analysis version 2 software (Biostat Inc., Englewood, NJ, USA), with the level of significance set at $p < 0.05$. Effect size (ES) values were calculated as standardised differences in the means (δ). According to Cohen [41], an ES of 0.2 is considered a small effect, 0.5 is a moderate effect and 0.8 is a large effect. Within-group change in strength (%) was determined by calculation of the difference between pre- and post-intervention. The mean relative percentage change (post- minus pre-training muscular strength, divided by pre-training muscular strength, multiplied by 100) was calculated for the failure and non-failure groups. Between-study variability was examined for heterogeneity, using the I^2 statistic for quantifying inconsistency [42]. The heterogeneity thresholds were set as $I^2 = 25\ \%$ (low), $I^2 = 50\ \%$ (moderate) and $I^2 = 75\ \%$ (high) [42]. To be conservative, a random-effects model of meta-analysis was applied to the pooled data. A funnel plot and rank correlations between effect estimates and their standard errors (SEs), using Kendall's τ statistic [43], were used to examine publication bias. For rank correlations, publication bias was suggested when a significant result ($p < 0.05$) was found.

The primary analysis compared the effect of failure versus non-failure resistance training programmes on outcomes of muscular strength. Subgroup analyses were performed on muscular strength outcomes when training volume was controlled (volume controlled) and not controlled (volume uncontrolled) in failure and non-failure groups. Additionally, subgroup analyses were also performed on muscular strength in relation to training status and exercise type (compound versus isolated exercises; upper versus lower body exercises). There was one study that assessed muscular strength with both the bench press and squat [31] and, in this instance, an analysis was run with each of these exercises separately. The results of these two separate analyses were presented as values for when this bench press (analysis A) and squat data (analysis B) were included, respectively. For the volume-controlled and volume-uncontrolled subgroup analyses, the effect of training status (trained versus untrained) could not be analysed, because of the small number of studies ($n < 3$). Additionally, the small number of studies meant that the effect of the exercise type could be analysed only in the volume-uncontrolled group ($n = 3$).

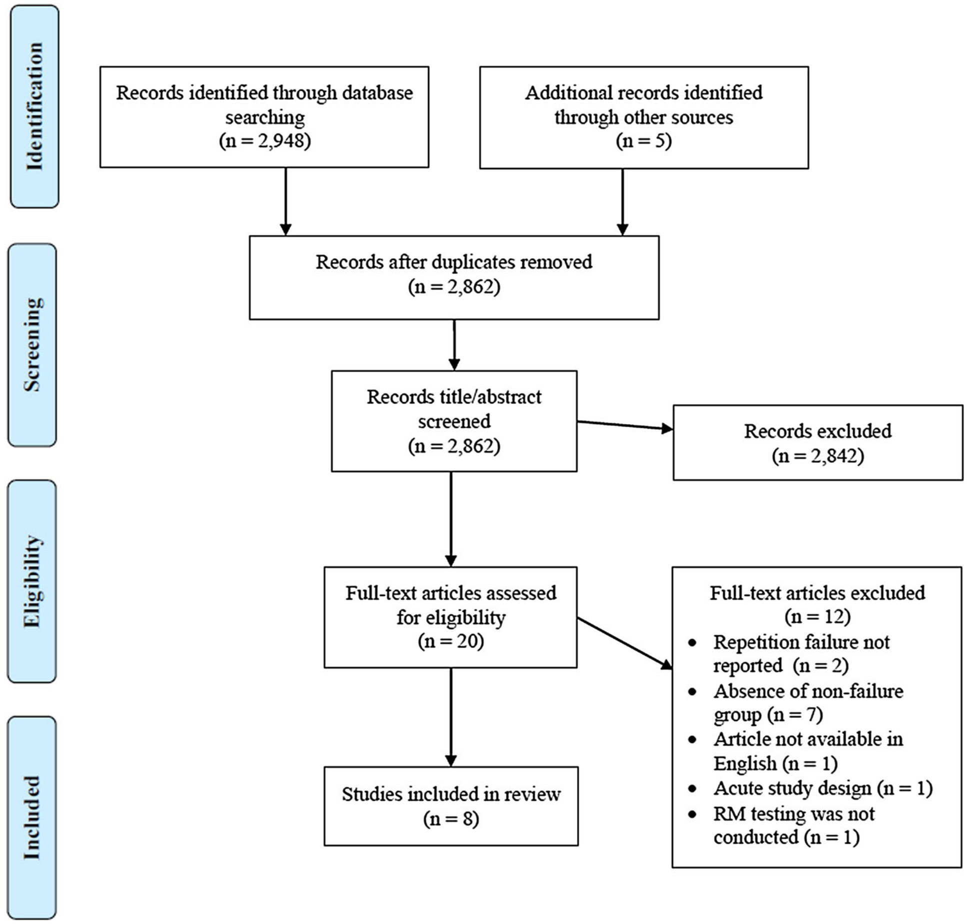
3 Results

3.1 Description of Studies

The database searches yielded 2948 potential articles, and five additional articles were identified from reference lists (Fig. 1). On the basis of the eligibility criteria, eight articles were included in the systematic review and meta-analysis. There was a total of 199 participants (159 males and 40 females) aged 18–35 years. Participants had previous resistance training experience (trained, $n = 112$) or no prior resistance training experience (untrained, $n = 87$) (Table 1).

Of the eight studies that were included, one exercise was used for the resistance training intervention in four studies [14, 32, 35, 36], and two or more exercises were used in the

Fig. 1 Flow diagram. *RM* repetition maximum



other four studies [31, 37, 38, 44] (Table 2). Exercise specifics for the failure group included 1–4 sets of 4–12 repetitions at loads of either 75–92 % of 1RM or 6–10RM. The non-failure group performed 3–40 sets of 1–10 repetitions at loads of either 75–92 % of 1RM or 6–10RM. Training volume was controlled in only four of the eight studies [14, 31, 32, 35]. For the studies with uncontrolled training volumes, a greater training volume was found in the failure group in two studies [36, 37] and in the non-failure group in the other two studies [38, 44]. Sets were performed with explosive concentric and controlled eccentric phases in both the failure and non-failure groups in two studies [31, 37], and in the non-failure group only in two studies [36, 44], while repetition speed was controlled (∼2 s per contraction phase) in two studies [35, 36] (only in the failure group in one of these studies [36]). Furthermore, one study had participants perform repetitions at a preferred cadence [32], while no information about repetition speed was reported for either group in two studies [14, 38], or for the failure group in one study [44]. Rest periods between sets ranged from 30 s to ∼4 min for both the failure and non-failure groups. Training was performed 2–3 times per week, with interventions lasting for a period of 6–14 weeks.

Muscular strength was assessed in terms of 1RM in seven studies [31, 32, 35–38, 44] and 6RM in one study [14]. A combination of compound exercises (involving more than one major muscle group) and isolated exercises (involving only one major muscle group) were used to assess muscular strength. The bench press was used for muscular strength testing in three studies [14, 31, 37], squat in three studies [31, 38, 44], bicep curl in two studies [32, 36] and leg extension in one study [35]. All studies familiarised participants with the muscular strength test/s. Additionally, five studies assessed the reliability of the muscular strength test with $r \geq 0.86$ [14, 31, 37, 38, 44].

3.2 Methodological Quality

The mean quality rating score was 19.5 ± 1.7 out of a possible score of 28 (see Electronic Supplementary Material Table S2). All studies scored 0 (not reported or unable to be determined) for having a representative sample, blinding of participants/investigators, recruiting

Table 1 Characteristics of participants

Study	Subjects	Sex: M/F [%]	Age [years][a]	Height [cm][a]	Weight [kg][a]	Training status
Drinkwater et al. [14]	Failure: $n = 15$	100/0	17–18	NR	NR	T
	Non-failure: $n = 11$	100/0	17–18	NR	NR	T
Folland et al. [35]	Failure: $n = 12$	66.7/33.3	22.0 ± 2.0	181.0 ± 9.0	70.0 ± 3.0	UT
	Non-failure: $n = 11$	63.6/36.4	20.0 ± 1.0	176.0 ± 10.0	68.0 ± 7.0	UT
Izquierdo et al. [31]	Failure: $n = 14$	100/0	24.8 ± 2.9	180.0 ± 1.0	81.1 ± 4.2	T
	Non-failure: $n = 13$	100/0	23.9 ± 1.9	181.0 ± 1.0	80.5 ± 7.4	T
Izquierdo-Gabbaren et al. [37]	Failure: $n = 14$	100/0	25.4 ± 4.2	181.0 ± 3.7	79.8 ± 5.3	T
	Non-failure: $n = 15$	100/0	26.7 ± 5.7	182.0 ± 4.9	83.2 ± 6.3	T
Kramer et al. [38]	Failure: $n = 16$	100/0	20.3 ± 1.9	181.5 ± 6.1	78.4 ± 8.4	T
	Non-failure: $n = 14$	100/0	20.3 ± 1.9	181.5 ± 6.1	76.8 ± 10.1	T
Rooney et al. [32]	Failure: $n = 13$	42.9/57.1	18–35	NR	NR	UT
	Non-failure: $n = 14$	42.9/57.1	18–35	NR	NR	UT
Sampson and Groeller [36]	Failure: $n = 10$	100/0	23.4 ± 6.6	180.3 ± 5.6	76.9 ± 0.2	UT
	Non-failure: $n = 10$	100/0	23.7 ± 6.2	179.1 ± 7.5	85.0 ± 13.7	UT
Sanborn et al. [44]	Failure: $n = 9$	0/100	18–20	NR	62.8 ± 9.2	UT
	Non-failure: $n = 8$	0/100	18–20	NR	70.9 ± 12.1	UT

F females, *M* males, *NR* not reported, *T* trained, *UT* untrained

[a] The data are reported as mean ± standard deviation or as a range

participants over the same period of time and randomised intervention assignment concealment. One out of eight studies reported on adverse events [35], and actual probability values were reported by only three studies [32, 36, 44]. All studies reported study aims, outcomes, participant characteristics and confounders. Additionally, in all studies, the treatment was representative of the majority of participants, there was no data dredging, outcome measures were accurate and recruitment of participants was from the same population. The compliance rate was reported in five studies and was ≥89 % [31, 35–38]. Only one study [35] did not randomise participants into intervention groups. Exercise sessions were supervised in six studies [31, 32, 35, 37, 38, 44], while it is unknown whether sessions were supervised in one study [36], and no exercise supervision was provided in another study [14].

3.3 Muscular Strength

3.3.1 Combined Studies (Volume Controlled and Uncontrolled)

Non-failure training was found to increase muscular strength by 23.4 and 24.2 % in analyses A and B, respectively, while failure training increased muscular strength by 22.8 and 22.9 %, respectively (Table 3). The differences in the change in muscular strength between non-failure and failure had small pooled ES values of 0.34 (95 % confidence interval [CI] 0.06–0.62) and 0.33 (95 % CI 0.06–0.61) for analyses A and B, respectively. A statistically significant effect was found ($p = 0.02$) and favoured the non-failure group (Fig. 2). The subgroup analysis found that the effect was similar when the analysis was restricted to studies that used compound exercises ($n = 5$) [ES = 0.38, 95 % CI 0.03–0.73, $p = 0.03$ for analysis A; ES = 0.37, 95 % CI 0.03–0.72, $p = 0.03$ for analysis B]. Analysis of the types of compound exercises used (squat versus bench press) led to a non-significant effect (squat: ES = 0.34, 95 % CI −0.11 to 0.80, $p = 0.14$; bench press: ES = 0.36, 95 % CI −0.07 to 0.80, $p = 0.10$). When only studies that used isolated exercises were included (i.e. bicep curl and leg extension), a non-significant effect was also found (ES = 0.23, 95 % CI −0.24 to 0.70, $p = 0.34$). No significant effect was found between failure and non-failure training (23.2 % versus 18.3 % increases in muscular strength, respectively) when only upper body exercises were analysed (ES = 0.28, 95 % CI −0.07 to 0.62, $p = 0.12$). Additionally, no significant effect was found for failure versus non-failure training when only lower body exercises were included; however, there was a trend towards greater increases in muscular strength following non-failure training (ES = 0.37, 95 % CI 0.03–0.76, $p = 0.07$).

Training status was found to produce a significant effect, with greater muscular strength gains in trained participants following non-failure training in analysis A (trained:

Table 2 Training characteristics of studies

Study	Group	Exercise prescription	Volume controlled between groups	Frequency [days/week]	Duration [weeks]	Strength test
Drinkwater et al. [14]	Failure	BP: 4 × 6 reps @ 80–105 % of 6RM (rep speed NR), 3 min 50 s rest between sets	Yes	3/7	6	6RM BP
	Non-failure	BP: 8 × 3 reps @ 80–105 % of 6RM (rep speed NR), 1 min 40 s rest between sets				
Folland et al. [35]	Failure	LE: 4 × 10 reps @ 75 % of 1RM (controlled concentric and eccentric phases), 30 s rest between sets	Yes	3/7	9	1RM LE
	Non-failure	LE: 40 × 1 rep @ 75 % of 1RM (controlled concentric and eccentric phases), 30 s rest between sets				
Izquierdo et al. [31]	Failure	BP: 3 × 6–10RM (explosive concentric/controlled eccentric phases), 2 min rest between sets	Yes	2/7	11	1RM BP and SQ
		SQ: 3 × 6–10 reps @ 80 % of 6–10RM (explosive concentric/controlled eccentric phases), 2 min rest between sets				
	Non-failure	BP: 6 × 3–5 reps @ 6–10RM (explosive concentric/controlled eccentric phases), 2 min rest between sets				
		SQ: 6 × 3–5 reps @ 80 % of 6–10RM (explosive concentric/controlled eccentric phases), 2 min rest between sets				
Izquierdo-Gabbaren et al. [37]	Failure	BP, SCR, LPD, PC: 3–4 × 4–10 reps @ 75–92 % of 1RM (explosive concentric/controlled eccentric phases), 2 min rest between sets	No (F)	2/7	8	1RM BP
	Non-failure	BP, SCR, LPD, PC: 3–4 × 2–5 reps @ 75–92 % of 1RM (explosive concentric/controlled eccentric phases), 2 min rest between sets				
Kramer et al. [38]	Failure	SQ, PP, BP, MTP, LC, BR: 1 × 8–12RM	No (NF)	3/7	14	1RM SQ
	Non-failure	SQ, PP, BP, MTP, LC, BR: 3 × 10 reps @ 90–100 % of 10RM (rep speed NR), ~2–3 min rest between sets				
Rooney et al. [32]	Failure	BC: 1 × 6–10 reps @ 6RM (preferred cadence)	Yes	3/7	6	1RM BC
	Non-failure	BC: 6–10 × 1 rep @ 6RM (preferred cadence), 30 s rest between sets				
Sampson and Groeller [36]	Failure	BC: 4 × 6 reps @ 85 % of 1RM (2 s elbow flexion/2 s elbow extension), 3 min rest between sets	No (F)	3/7	12	1RM BC
	Non-failure	BC: 4 × 4 reps @ 85 % of 1RM (maximal acceleration elbow flexion/2 s elbow extension), 3 min rest between sets				
Sanborn et al. [44]	Failure	SQ, ¼ SQ, BP, SP, MTP, SS, SLDL, UR: 1 × 8–12RM (rep speed NR)	No (NF)	3/7	8	1RM SQ
	Non-failure	SQ, ¼ SQ, BP, SP, MTP, SS, SLDL, UR: 3–5 × 2–10 reps @ 80–100 % of 2–10RM (explosive concentric phase for leg exercises), rest between sets NR				

¼ *SQ* quarter squat, *BC* bicep curl, *BP* bench press, *BR* bent-over row, *(F)* higher volume completed by the failure group, *LC* leg curl, *LE* leg extension, *LPD* lateral pull-down, *MTP* mid-thigh pull, *(NF)* higher volume completed by the non-failure group, *NR* not reported, *PC* power clean, *PP* push press, *rep(s)* repetition(s), *RM* repetition maximum, *SCR* seated cable row, *SLDL* straight-legged deadlift, *SP* shoulder press, *SQ* squat, *SS* shoulder shrug, *UR* upright row

ES = 0.37, 95 % CI 0.001–0.75, $p = 0.049$; untrained: ES = 0.30, 95 % CI −0.12 to 0.73, $p = 0.16$). Statistical significance was just missed in analysis B (ES = 0.36, 95 % CI −0.01 to 0.73, $p = 0.06$). The heterogeneity of the effect of failure versus non-failure training on muscular strength was zero ($I^2 = 0$ %). Both the funnel plot and Kendall's τ statistic ($\tau = 0.18$, $p = 0.54$ for analysis A; $\tau = 0.32$, $p = 0.27$ for analysis B) did not reveal publication bias in any study.

Table 3 Summary of the effects of failure versus non-failure training on muscular strength

	Failure				Non-failure				Std diff in mean: effect size (SE)	95 % CI	*p* value[c]
	n	Pre-training [kg][a]	Post-training [kg][a]	Change [%][b]	*n*	Pre-training [kg][a]	Post-training [kg][a]	Change [%][b]			
15Volume controlled											
Drinkwater et al. [14][d]	15	69.3 ± 8.7	76.64 ± 9.9	10.6	11	67.5 ± 7.24	71.0 ± 8.7	5.2	0.41 (0.40)	−0.38 to 1.19	0.31
Folland et al. [35][e]	12	85.0 ± 5.8	114.0 ± 6.8	34.1	11	80.0 ± 8.7	112.0 ± 6.8	40.0	0.44 (0.42)	−0.39 to 1.23	0.30
Izquierdo et al. [31][d,f]	14	79.0 ± 19.1	93.4 ± 21.9	18.2	15	79.4 ± 8.8	90.6 ± 10.6	14.2	0.19 (0.37)	−0.54 to 0.92	0.61
Izquierdo et al. [31][d,g]	14	167.0 ± 20.5	198.86 ± 21.0	19.0	15	168.8 ± 11.9	202.8 ± 10.8	20.2	0.13 (0.37)	−0.6 to 0.86	0.73
Rooney et al. [32]	13	12.5 ± 8.4	19.5 ± 10.2	56.0	14	13.9 ± 8.6	19.4 ± 12.2	39.6	0.13 (0.39)	−0.62 to 0.89	0.73
Mean effect[f]	–	–	–	29.7		–	–	24.8	0.28 (0.20)	−0.10 to 0.67	0.15
Mean effect[g]	–	–	–	29.9		–	–	26.3	0.27 (0.20)	−0.12 to 0.65	0.18
Volume uncontrolled											
Izquierdo-Gabarren et al. [37][d]	14	96.9 ± 7.6	98.4 ± 4.9	1.8	15	95.8 ± 9.1	100.4 ± 7.1	4.7	0.51 (0.38)	−0.24 to 1.25	0.18
Kramer et al. [38]	16	101.9 ± 20.6	114.1 ± 18.7	12.0	14	98.5 ± 27.7	123.7 ± 43.2	25.6	0.40 (0.37)	−0.32 to 1.13	0.28
Sampson and Groeller [36]	10	19.9 ± 3.7	25.7 ± 3.8	29.3	10	22.3 ± 3.6	28.6 ± 4.31	28.0	0.12 (0.45)	−0.75 to 1.0	0.78
Sanborn et al. [44]	9	48.1 ± 10.5	57.9 ± 8.1	20.4	8	53.3 ± 15.5	69.2 ± 11.5	29.8	0.62 (0.50)	−0.36 to 1.60	0.21
Mean effect	–	–	–	15.9	–	–	–	22.0	0.41 (0.21)	0.01 to 0.82	0.047
Mean effect, total[f]	–	–	–	22.8	–	–	–	23.4	0.34 (0.14)	0.06 to 0.62	0.02
Mean effect, total[g]	–	–	–	22.9	–	–	–	24.2	0.33 (0.14)	0.06 to 0.61	0.02

CI confidence interval, *SE* standard error, *Std diff* standardised difference

[a] The data are reported as mean ± standard deviation

[b] Post-training value minus pre-training value, divided by pre-training value, multiplied by 100

[c] Statistical significance accepted as $p \leq 0.05$

[d] Data extrapolated from graphs

[e] Standard deviation extrapolated from a graph

[f] Includes the bench press data from Izquierdo et al. [31]

[g] Includes the squat data from Izquierdo et al. [31]

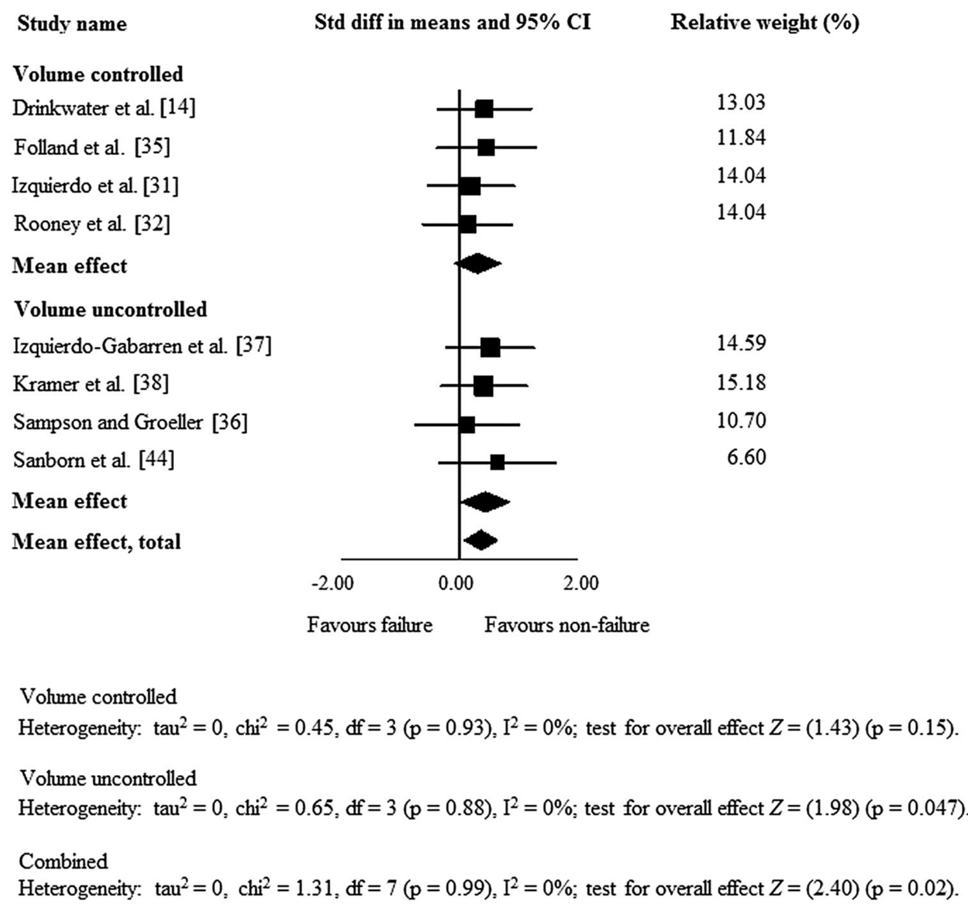


Fig. 2 Forest plot of the results of the meta-analysis. The *black squares* and *error bars* signify the standardised difference (*Std diff*) values in the means (effect size) and 95 % confidence interval (*CI*) values, respectively. The *black diamonds* represent the pooled effect sizes. *df* degrees of freedom

3.3.2 *Studies with Volume Controlled*

Failure training increased muscular strength by 29.7 and 29.9 % in analyses A and B, respectively, while non-failure training increased muscular strength by 24.8 and 26.3 % in analyses A and B, respectively (Table 3). The differences in the change in muscular strength between non-failure and failure had small pooled ES values of 0.27 (95 % CI −0.11 to 0.65) and 0.26 (95 % CI −0.12 to 0.64) in analyses A and B, respectively. No statistically significant effect was found in analyses A and B ($p = 0.15$ and $p = 0.18$, respectively), although there was a trend favouring non-failure training (Fig. 2). The heterogeneity of the effect of failure versus non-failure training on muscular strength was zero ($I^2 = 0$ %). Both the funnel plot and Kendall's τ statistic ($\tau = 0.50$, $p = 0.31$ for analysis A; $\tau = 0.83$, $p = 0.09$ for analysis B) did not reveal publication bias in any study.

3.3.3 *Studies with Volume Uncontrolled*

Non-failure training increased muscular strength by 22.0 %, while failure training increased muscular strength by 15.9 % (Table 3). The differences in the change in muscular strength between non-failure and failure had a small ES of 0.41 (95 % CI 0.01–0.82). A statistically significant effect was found ($p = 0.047$) and favoured the non-failure group (Fig. 2). When studies that used only compound exercises were analysed ($n = 3$), a slightly greater significant effect was found, favouring the non-failure group (ES = 0.49, 95 % CI 0.03–0.95, $p = 0.04$). The heterogeneity of the effect of failure versus non-failure training on muscular strength was zero ($I^2 = 0$ %). Both the funnel plot and Kendall's τ statistic ($\tau = 0.17$, $p = 0.73$) did not reveal publication bias in any study.

4 Discussion

To our knowledge, this is the first systematic review with a meta-analysis to directly investigate the effect of failure versus non-failure resistance training on muscular strength. The data show that despite both practices increasing muscular strength, non-failure training was found to be slightly more effective (i.e. there was a small effect). However, the effectiveness of non-failure training was influenced by training volume, training status and exercise type. A significant small effect of non-failure training on muscular strength remained only when studies that did not control for training volume were analysed. For studies that controlled for training volume, there was no significant effect on muscular strength between failure and non-failure training. Significant increases in muscular strength were found following non-failure training in individuals with previous training experience compared with novices, and for interventions that used compound exercises compared with isolated exercises. Additionally, there was a slightly stronger effect favouring non-failure training compared with failure training on muscular strength in volume-uncontrolled studies that used only compound exercises. The heterogeneity of the effects for all meta-analyses was equal to zero, suggesting that all of the studies examined the same effect. Despite no publication bias being found, the methodological quality of the included studies was only moderate, with little information provided on adverse events to allow a comment on the safety of these resistance training practices.

4.1 Combined Studies

A wide range of morphological [45] and neurological [46] factors contribute to increases in muscular strength following resistance training. An increase in the cross-sectional area of skeletal muscle fibres, which is regarded as the primary adaptation to long-term resistance training, can lead to greater force production via promotion of an increase in the number of cross-bridges arranged in parallel (preferential type II fibres) [47, 48]. Some other morphological adaptations that may contribute to increases in muscular strength include hyperplasia, changes in fibre type, muscle architecture, myofilament density and the structures of connective tissue and tendons [49]. While training-induced muscle hypertrophy is considered a slow process, significant changes have been found over relatively short training periods of 8–12 weeks [50–53], similar to the length of the interventions included in this review (6–14 weeks). Unfortunately, only one of the included studies assessed the cross-sectional area of the trained muscle, with an increase of ~11.3 % being found following failure and non-failure training, with no significant difference between groups [36]. Three other studies assessed changes in lean body mass (determined via skinfold measures) and showed either a decrease or a small increase (~2 %) following training [31, 37, 38]. However, estimation of lean body mass, especially via skinfold measures, is not valid for assessing changes in muscle mass [54].

Muscular hypertrophy appears to proceed in a linear manner during the first 6 months of training [55], while substantial neurological adaptations are thought to be responsible for the rapid increase in strength in the first weeks of training (~4 weeks) [56]. This is supported by the disproportionately larger increase in muscular strength than in cross-sectional area during the early stages of resistance training [50, 57]. It is likely that muscular strength gains following the resistance training interventions in the studies included in this review were mostly attributable to neurological adaptations. These adaptations are related to coordination and learning of an exercise, which lead to improved activation of the muscles involved [58, 59]. The force that a muscle exerts ultimately depends on the number of motor units that are active (motor unit recruitment) and the rates at which motor units are recruited (rate coding) [60]. It has been postulated, although not empirically demonstrated, that motor unit recruitment can be maximised with failure training, which may provide a stimulus for greater muscular strength gains [6]. However, the findings from this review showed that non-failure training resulted in a 0.6–1.3 % greater muscular strength increase than failure training. Such a small increase in strength is unlikely to be considered meaningful. For example, it would represent only a 0.6–1.3 kg increase for a 100 kg bench press. These findings should be interpreted as meaning that similar muscular strength gains can be achieved without resistance training that involves high levels of discomfort and physical effort, as are experienced with failure training.

Previous studies have shown that as muscle becomes progressively more fatigued during an exercise, the ability to maintain a constant force is only partly achieved by recruitment of additional motor units [61–63]. Additionally, several studies have reported a decline in motor unit firing rates (rating coding) as a muscle fatigues [64–67]. Therefore, on the basis of the assumption that maximising motor unit recruitment is of major importance in muscular strength adaptations, it is possible that failure training might not be necessary for this to be achieved. This is supported by findings from a study by Sundstrup et al. [13], where full motor unit activation of muscle was found to be achieved 3–5 repetitions prior to failure during a resistance exercise. For the exercise interventions included in this review, the non-failure group was no more than five repetitions from repetition failure during sets in six of the eight studies [14, 31, 36–38, 44]. Consequently, performing repetitions to the point where the participant was approximately five repetitions away from failure may have resulted in a level of motor unit recruitment similar to that achieved by failure training. So it would appear that failure training compared with non-failure training, when using a particular load setting, does not lead to further gains in muscular strength.

Besides the need to attain a certain level of muscular fatigue to maximise motor unit recruitment, it has been suggested that relative intensities (i.e. loads) need to be

≥70 % of 1RM [28, 29]. Both Mitchell et al. [68] and Schoenfeld et al. [69] found there was no difference in the muscular hypertrophy response following low versus high training loads performed to failure. However, these equal hypertrophic effects did not translate into similar strength gains, with higher compared with lower training loads (70–80 % versus 30–50 % of 1RM) proving to be more efficacious. The lack of a relationship between muscular hypertrophy and strength gains following low- and high-load training to failure may be due to muscle fibre-specific hypertrophy. For example, low-load training to failure may result in greater increases in type I muscle fibre size, while greater increases in type II fibre size may occur from high-load training to failure.

The hypothesis for muscle fibre-specific hypertrophy following training with different loads was formulated by Schoenfeld et al. [27] on the basis of findings from muscle activation during low-resistance exercise (30 % of 1RM) versus high-resistance exercise (75 % of 1RM) to failure. The results showed that exercising with a low load (30 % of 1RM) did not maximally activate the full motor unit pool of the targeted muscle group (i.e. reduced activation of higher-threshold motor units), compared with a higher load (75 % of 1RM). Other studies have also found that greater motor unit activation occurs during failure training with a higher load (~70 % of 1RM) than with lower loads (20–50 % of 1RM) [25, 26]. Most of the studies included in this review used a minimum of 75 % of 1RM (or equivalent), with little difference between the intensities used for the failure and non-failure groups. Therefore, it seems that the intensities that were used were sufficient to maximise motor unit recruitment and would not have confounded the effects of failure versus non-failure training on muscular strength.

The speed at which resistance exercise repetitions are performed has been shown to influence strength adaptations. Munn et al. [70] found that 11 % greater strength gains occurred when resistance exercises were performed at fast compared with slow speeds. Both fast and slow contractions exhibit a similar order of motor unit recruitment (the size principle) [71]. However, the absolute force level at which a motor unit is recruited has been shown to vary with the speed of muscle contraction [72]. As the rate of force development increases, the motor unit recruitment threshold is shown to decrease, so motor units are activated earlier. This can result in three times as many motor units being recruited with faster compared with slower contractions to produce a given amount of peak force [72]. Rate coding has also been shown to vary with the speed of contraction, with high instantaneous discharge rates that decrease thereafter for fast contractions [72, 73], whereas for slower contractions, discharge rates increase progressively [74]. Furthermore, training studies that have used faster contractions have shown large improvements in the rate of force development [73, 75, 76]. Only three of the studies included in this review controlled for repetition speed [31, 35, 37], which may have affected the results. However, Sampson and Groeller [36] found similar gains in muscular strength with failure training at a controlled speed, compared with non-failure training where maximal acceleration during the concentric phase was performed. The non-failure group in that study did have a 30 % lower training volume, and this may have confounded the results.

4.2 Training Volume

While significant increases in muscular strength can be achieved with relatively low training volumes, performing high training volumes has been shown to result in larger strength gains [22–24]. A criticism of some studies that have examined failure versus non-failure training is that training volume was not equalised to minimise the effect of this potential confounder on the results [6, 7]. However, for this review, it was decided to not exclude studies on the basis of whether an attempt was made to control training volume, provided that the loadings used between intervention groups were similar. For half of the studies that did not control for training volume (i.e. two out of four studies), there were apparent differences in the numbers of sets performed between groups [38, 44]. The non-failure groups performed approximately four sets, whereas the failure groups performed one set. This was expected to be a concern on the basis of findings from a meta-analysis conducted by Krieger [22], where training involving 2–3 sets of resistance exercise was associated with a 46 % increase in muscular strength, compared with one set. For the other studies that did not control for training volume, there were noted differences in the numbers of repetitions performed during sets (i.e. 2–5 more repetitions were performed by the failure groups) [36, 37]. Therefore, it could be assumed that any confounding bias due to training volume may have been negated by higher training volumes being distributed equally between the volume-uncontrolled studies (i.e. higher volume in two failure and two non-failure studies, respectively).

The findings from our review suggest that differences in training volume had a confounding effect on muscular strength. For the volume-uncontrolled studies, there was an ~11.5 % increase in strength in the non-failure groups that performed more sets (greater training volume), compared with a ~0.8 % increase in strength in the non-failure groups that performed fewer repetitions (lower training volume) [36–38, 44]. However, it is difficult to ascertain whether other factors (e.g. type of exercise, speed of contraction, etc.) contributed to the larger strength gains in the non-failure groups with the higher training volume from a greater number of sets. Taking a conservative approach, it seems that failure training does not offer any advantage in terms of maximising muscular strength, compared with non-failure training.

4.3 Exercise Type

The findings from this review suggest that the effectiveness of failure versus non-failure training for increasing muscular strength may depend on which exercise is performed. Compound resistance exercises, which are considered to be superior to isolated exercises for increasing muscular strength [77], showed greater strength gains following non-failure compared with failure training. An explanation for this result may relate to the increased demands of performing compound exercises compared with isolated exercises. Compound exercises place greater stress on the neuromuscular system because of the greater muscle groups that are stimulated and thus greater loads that are lifted [1]. As a result of these more demanding exercises, there is the potential for increased muscle damage and metabolic stress, and thus greater fatigue, following failure training.

There is evidence that increases in dynamic 1RM are disproportionately greater than increases in isometric strength [59, 78]. This suggests that factors such as learning of a movement/exercise and coordination of the muscle groups involved play a role in early increases in muscular strength. It is well known that compound exercises are more complex than isolated exercises because of the greater muscle groups and joints involved in the movements. As such, performing compound exercises to failure may result in development of less efficient movement patterns and suboptimal postures to generate forces (i.e. development of poor exercise technique). The results from the subgroup analysis also showed a trend towards greater gains in muscular strength with lower body exercise than with upper body exercise following non-failure training ($p = 0.07$). Like the results of compound exercises, this may have resulted from the increased demands/skill requirements of lower compared with upper body exercises and led to lesser muscular strength gains in the failure group, because of fatigue-related factors.

Greater levels of fatigue, which may result from failure training, can negatively affect the training volume attained during an exercise session because of reductions in repetitions or loads during performance of consecutive sets [19–21]. However, exercise compliance in the studies included in this review was considered high for the five studies where this was reported. Therefore, a more probable explanation for the superior strength gains following non-failure compared with failure training with compound exercises (and the trend for lower body exercises) may be related to post-session recovery. Participants performing non-failure training could have recovered faster than participants performing failure training. This may have led towards a greater rate of progress (i.e. loading and training stimulus) and adaptation in the non-failure group, and thus greater strength gains. Furthermore, because of the average exercise intervention lasting approximately 9 weeks, the ability to recover and progressively overload following subsequent training sessions over this relatively short duration would likely have a positive influence on strength gains.

4.4 Training Status

It is commonly thought that any benefit derived from performing failure compared with non-failure resistance training for developing muscular strength would be observed in strength-trained athletes [6, 18]. Trained athletes are able to tolerate high training stresses, and it has been suggested that failure training might provide an extra stimulus to increase muscular strength [28, 29], since strength gains tend to slow down or even plateau following long-term training [77]. However, the findings from this review showed that trained participants responded more favourably to non-failure compared with failure training (~14 and ~12 %, respectively), suggesting that regular failure training may be too demanding for strength athletes. Ahtiainen and Häkkinen [79] found that strength athletes compared with non-athletes experienced greater muscle activation and neural fatigue during high-intensity resistance exercise. In this review, even though failure training did increase the muscular strength of the trained participants, it appears that too great a training demand may not optimise muscular strength development. For untrained participants, the similar increases in muscular strength with failure versus non-failure training (a ~34 % increase in both groups) suggests that subtle differences in resistance training prescription may not have a large impact on muscular strength. This is probably due to the large strength gains that novices typically experience following a resistance training programme [18]. However, as a lifter becomes more experienced and the strength gains are lesser, slight manipulation of training variables, such as failure versus non-failure training, may have a significant effect.

4.5 Methodological Quality

The quality of the studies included in this review was rated as moderate on the basis of the Downs and Black checklist scores [39]. Across the eight studies that were included in this review, the criteria were fully met for only 12 of the 28 items. The criteria for nine items were met by the majority of the studies (≥5); however, for the rest of the items, these were either minimally met or not met by any studies. In particular, the reporting of adverse events as a consequence of the intervention was not reported by any studies. This information is of major importance for assessment of whether failure training predisposes lifters to injuries. Additionally, it would help to inform the scientific community on whether other factors, such as training status and type of exercises performed, increase the risks of injury or overtraining during failure training. The criteria for two internal validity (bias) items were not met by any study: (1) attempting to blind the study participants; and (2) attempting to blind the assessors of the main outcomes. While the methodological quality of the studies included in this review could have been improved through blinding of the assessors, blinding of participants in exercise interventions is not possible. Also, there was one internal validity item where the criterion was not met by any study. This item asked whether the randomised intervention assignment was concealed from both participants and investigators. Failure to meet the criterion for this item increases the risk that participants may have been allocated to a more or less appropriate group.

It could not be determined whether the majority of studies met the criteria for two validity items. If the criteria for these items were not met, this may have biased the results of this review. One of these items was whether the participants were representative of the entire population from which they were recruited. Thus, there is a possibility that participants with preconceived thoughts about failure and non-failure training may have been recruited. The other item for which the criterion was not met was whether participants were recruited over the same time period. Not meeting the criterion for this item increases the risk that a study was run until a desired conclusion was achieved. However, despite the concerns over the items for which the criteria were not met or were unable to be determined, there is a good possibility that the methodological quality of the included studies was underestimated. This suggests that there would be lower risks that reporting, external validity and internal validity (bias and confounding) influenced the overall results.

4.6 Strengths, Limitations and Future Directions

The strengths of our review include the systematic nature of the search, the rigorous nature of the data extraction and the quality assessment of the studies. Studies that found non-significant differences between the two training methods may have had small sample sizes that provided insufficient statistical power to detect significant differences; therefore, a meta-analysis approach was used to overcome this issue. Furthermore, the numerous subgroup analyses allowed the effects of many potential confounders, such as training volume, training status and exercise type, to be examined.

While this review offers quantitative evidence to support the efficacy of non-failure compared with failure training for muscular strength development, there are certain limitations that should be discussed. First, the exercise prescription used in the interventions differed slightly between studies in terms of the number of exercises, repetition speed, intensity (loads) and rest between sets. Even though an attempt to address the effects of some confounders was conducted (through subgroup analyses), there is the potential that some of the other training variables may have confounded the results. Also, the level of resistance training experience of the participants varied between studies, with some participants being experienced at a recreational level, while others regularly used resistance exercise as part of their overall training for a team sport. This may have reduced the ability to generalise findings to athletes where resistance exercise contributes to a larger portion of overall training. Finally, half of the studies included in the review had durations of only 6–8 weeks. Because of the short duration of these studies, which is considered the minimum for significant increases in muscular strength [56], the statistical effect of the interventions may have been reduced. However, there was no publication bias, which provides confidence that the interventions were similar. Therefore, the only difference between the studies was their power to detect changes in muscular strength following failure versus non-failure training.

The small number of studies that were included in this review shows that there is a need for further research to examine the effect of failure versus non-failure training on muscular strength. It is likely that the small number of ES values available for some of the analyses had an impact upon whether a significant statistical effect was reached. Therefore, this may reduce the ability to generalise the precise effects of failure versus non-failure training on muscular strength. For novice and intermediate resistance trainers (with <12 months' experience), the findings of this review suggest that performing sets of an exercise to failure does not lead to greater muscular strength gains than non-failure sets. Provided that a load ≥70 % of 1RM is used, sets of repetitions can be performed to a point that is close to failure. The extra physical effort required to perform sets to failure, as well as the high levels of discomfort, might be perceived as a stimulus to enhance adaptations associated with muscular strength. However, when the risk/benefit of failure training is weighed up in conjunction with the findings from this review, it seems that non-failure training would be the preferable training method, at least when targeting muscular strength.

Advanced resistance trainers and athletes who use resistance training as part of their overall training programme should limit the use of failure training on the basis of the results of this review. Failure training could lead to greater joint compression, which may increase the risks of joint damage or injuries. Additionally, if failure training is performed regularly, this may result in overtraining. Nevertheless, if failure training is to be implemented in a resistance training programme, restricting its use to selected sets (i.e. the final set) and types of exercises (i.e. upper rather than lower body) may be important in producing the desired training effects.

5 Conclusion

This systematic review with meta-analysis demonstrates that similar increases in muscular strength can be achieved with failure compared with non-failure resistance training. Training volume, resistance training experience and type of exercise were shown to have an impact on muscular strength following failure and non-failure training. However, the overall results tend to suggest that despite high levels of discomfort and physical effort following failure training, non-failure training leads to similar gains in muscular strength. This information is important to athletes who regularly use resistance training as part of their overall training programme, so that the risks of injuries and overtraining can be reduced. However, caution is warranted over the precise effects of non-failure compared with failure training on muscular strength, because of training variables (number of exercises, repetition speed, etc.) that may have confounded the results.

Compliance with Ethical Standards

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