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Review

Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: A systematic review and meta-analysis

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Abstract

Purpose: We aimed to perform a systematic review and meta-analysis of the effects of training to muscle failure or non-failure on muscular strength and hypertrophy.

Methods: Meta-analyses of effect sizes (ESs) explored the effects of training to failure *vs.* non-failure on strength and hypertrophy. Subgroup meta-analyses explored potential moderating effects of variables such as training status (trained *vs.* untrained), training volume (volume equated *vs.* volume non-equated), body region (upper *vs.* lower), exercise selection (multi- *vs*. single-joint exercises (only for strength)), and study design (independent *vs.* dependent groups).

Results: Fifteen studies were included in the review. All studies included young adults as participants. Meta-analysis indicated no significant difference between the training conditions for muscular strength (ES = −0.09, 95% confidence interval (95%CI): −0.22 to 0.05) and for hypertrophy (ES = 0.22, 95%CI: −0.11 to 0.55). Subgroup analyses that stratified the studies according to body region, exercise selection, or study design showed no significant differences between training conditions. In studies that did not equate training volume between the groups, the analysis showed significant favoring of non-failure training on strength gains (ES = −0.32, 95%CI: −0.57 to −0.07). In the subgroup analysis for resistance-trained individuals, the analysis showed a significant effect of training to failure for muscle hypertrophy (ES = 0.15, 95%CI: 0.03−0.26).

Conclusion: Training to muscle failure does not seem to be required for gains in strength and muscle size. However, training in this manner does not seem to have detrimental effects on these adaptations, either. More studies should be conducted among older adults and highly trained individuals to improve the generalizability of these findings.

Keywords: 1RM; Cross-sectional area; Data synthesis; Muscle size

1. Introduction

According to Henneman's size principle, motor units are recruited in an orderly fashion.[1] This principle dictates that as force production requirements increase, motor units are recruited according to the magnitude of their force output, with small motor units being recruited first.[2] Theoretically, in a resistance exercise set using moderate loads, lower threshold motor units associated with type I muscle fibers are initially recruited to lift the load.[2−4] As the lower threshold motor units become fatigued, increased recruitment occurs of the higher threshold motor units associated with type II muscle fibers in order to maintain force production.[2−4] Therefore, performing resistance exercise sets to momentary muscular failure (i.e., the maximum number of possible repetitions in a given set) is thought to be necessary to recruit all possible motor units.[3,4] Accordingly, some suggest this manner of training is optimal for achieving resistance training-induced increases in muscular strength and muscle size.[3,4]

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Given the hypothesis that training to muscle failure is important for catalyzing resistance training-induced adaptations, several studies examined the effects that this type of training has on muscular strength and hypertrophy, as compared to the effects of training that does not include reaching muscle failure.[5−21] However, detailed scrutiny of these studies highlights inconsistent findings. For example, some report that training to muscle failure results in greater increases in muscular strength and/or hypertrophy.[5,18] However, others suggest that both training options (i.e., training either to or not to muscle failure) can produce similar improvements with respect to these outcomes.[9,16] Some studies even indicate that training to failure has a detrimental effect.[5,6] The inconsistent evidence on this topic currently hinders the ability to draw practical recommendations for training program design.

In an attempt to provide greater clarity on the equivocal evidence on this topic, Davies and colleagues[22,23] performed a meta-analysis in which they pooled studies comparing the effects of training to muscle failure *vs.* non-failure on muscular strength gains. The analysis included 8 studies and indicated no significant difference between training to or not to muscle failure in terms of increases in muscular strength. Of the 8 studies included in this review, 4 equated training volume between the groups and 4 did not equate training volume. Since publication of the meta-analysis by Davies et al.,[22,23] 8 additional studies have been published that examine the topic.[8,11,13−17,21] Thus, an updated meta-analysis would theoretically have approximately a 2-fold increase in the number of included studies. Furthermore, while the effects of training to or not to muscle failure on muscular strength have been explored via meta-analysis, the same is not true for hypertrophy. Therefore, in this review, we performed an updated meta-analysis exploring the effects of training to failure on muscular strength as well as conducted the first meta-analysis exploring the effects of training to muscle failure on hypertrophy outcomes.

2. Methods

2.1. Search strategy

We performed the systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[24] Electronic searches of PubMed/MEDLINE, Scopus, and SPORTDiscus databases were conducted using the following search syntax: ("resistance training" OR "resistance exercise" OR "strength training" OR "strength exercise" OR "weight training" OR "weight exercise") AND ("repetition failure" OR "failure training" OR "non-failure training" OR "non failure training" OR "muscular failure" OR "muscle failure" OR "to failure" OR "not to failure" OR "without resting" OR "volitional interruption" OR "high fatigue" OR "low fatigue") AND ("1 repetition maximum" OR "1 RM" OR "1RM" OR "one repetition maximum" OR "MVC" OR "maximal voluntary contraction" OR "muscle strength" OR "muscular strength" OR "muscle hypertrophy" OR "muscular hypertrophy" OR "muscle fibre" OR "muscle fiber" OR "muscle thickness" OR "CSA" OR "cross-sectional area" OR "muscle size"). In addition to the primary search, we performed secondary searches by examining the reference lists of the included studies and by conducting forward citation tracking (i.e., examining studies that have cited the included studies) in the Scopus database. Two authors of the review (JG and BJS) conducted these searches independently. Following the initial searches, the lists of included and excluded studies were compared between the authors. Any discrepancies between them were resolved through discussion and agreement. The search was finalized on January 2, 2020.

2.2. Inclusion criteria

Based on the following criteria, we included studies that: (a) randomized participants (of any age) to the experimental groups; (b) compared the effects of resistance training to *vs.* not to muscle failure; (c) assessed changes in muscular strength and/or hypertrophy; (d) had a training protocol lasting for a minimum of 6 weeks; and (e) involved apparently healthy participants. For muscular strength outcomes, we considered studies that used either isometric or dynamic tests, or both. For muscular hypertrophy, we considered studies that assessed changes at the muscle fiber and/or whole muscle level. We considered studies with independent sample groups as well as those with dependent sample groups. We did not include studies that used blood flow restriction resistance training or concurrent training interventions (e.g., combined resistance and aerobic training).

2.3. Data extraction

From each included study, we extracted the following data: (a) lead author and year of publication; (b) sample size and participant characteristics, including age and resistance training experience; (c) details of the resistance training programs; (d) muscular strength test(s) used and/or the site and tool used for the muscular hypertrophy assessment; and (e) pre- and post-intervention mean ± SD of the strength and/or hypertrophy outcomes. Data extraction was performed independently by 2 authors (JG and BJS). Any discrepancies in the extracted data were resolved through discussion and consensus.

2.4. Methodological quality

We assessed the methodological quality of the included studies using the 27-item Downs and Black checklist.[25] This checklist addresses different aspects of the study design, including: reporting (Items 1−10), external validity (Items 11−13), internal validity (Items 14−26), and statistical power (Item 27). Given the specificity of the included studies (i.e., exercise intervention), we modified the checklist by adding 2 items, 1 pertaining to the training programs (Item 28) and 1 to training supervision (Item 29).[22,26−28] On this checklist, each item is scored with 1 if the criterion is satisfied and with 0 if the criterion is not satisfied. Based on the summary score, studies were classified as being of: good quality (21−29 points), moderate quality (11−20 points), or poor quality (less than 11 points).[22,26,27] Studies were independently rated by 2

reviewers (JG and FS) who settled any observed differences with discussion and agreement.

2.5. Statistical analyses

For each hypertrophy or strength outcome, the contrast between the training to failure *vs.* non-failure groups was calculated as the difference in effect sizes (ESs), where the ES was determined as the posttest−pretest mean change in each group, divided by the pooled pretest standard deviation, and multiplied by an adjustment for small sample bias.[29] ESs were interpreted as: small (≤0.20), moderate (0.21−0.50), large (0.51−0.80), and very large (>0.80).[30] ESs are presented with their respective 95% confidence interval (95%CI). The variance of the difference in ESs depends on the within-subject posttest−pretest correlation, which was not available from the published data for many of the studies. Among studies for which this correlation could be estimated (back-solving from paired *t* test *p* values or SD of posttest−pretest change scores, when presented), the median value was 0.86; the moderately conservative value of 0.75 was used to calculate the variance for all studies. Sensitivity analyses (not presented) were performed using correlations ranging from 0.25 to 0.85; results were consistent with those using 0.75. Typically, when studies report multiple ESs, 1 approach is to use study average ES, but this may result in a loss of information.[31] Therefore, we used a robust variance meta-analysis model, with adjustments for small samples, to account for correlated ESs within studies.[32] This meta-analysis model is specifically designed to be used when dealing with dependent ESs (e.g., multiple strength tests in a single study).[31] Meta-analysis was conducted separately for the hypertrophy outcomes and strength outcomes. In addition, subgroup analyses were performed to explore the effects of training status (trained *vs.* untrained), training volume (volume equated *vs.* volume not equated), body region (upper *vs.* lower), exercise selection (multi- *vs.* single-joint exercises (only for strength)), and study design (independent *vs*. dependent groups). For hypertrophy outcomes, a sensitivity analysis was performed in which the muscle fibre data was excluded from the analysis. Publication bias was checked by examining funnel plot asymmetry and calculating trim-and-fill estimates. The trim-and-fill estimates (not presented) were similar to the main results. Calculations were performed using the robumeta package within R (Version 3.6.1; the R Foundation for Statistical Computing, Vienna, Austria).[33] All meta-analyses were performed using the robust variance random effects model. Effects were considered statistically significant at a *p* value of <0.05.

3. Results

3.1. Search results

The primary search resulted in 1972 potentially relevant references. Of these results, 15 studies[7−21] were identified that satisfied the inclusion criteria. A screening of the reference lists of the included studies and an examination of newer studies that cite them resulted in an additional 591 and 744 results, respectively. However, we did not find any additional relevant studies in the secondary searches. Therefore, the final number of included studies was 15, as presented in Fig. 1.[7−21]

3.2. Study characteristics

Fifteen studies explored muscular strength outcomes (Table 1). The pooled number of participants in the studies was 394 (265 males and 129 females). All participants in the studies were young adults. The sample sizes in the individual studies ranged from 9 to 89 participants, with a median of 25. Six studies[7,10−12,17,21] included resistance-trained participants, while the others were conducted on untrained individuals (Table 1). The duration of the training programs ranged from 6 to 14 weeks, with a median of 8 weeks. Training frequency ranged from 2 to 3 days per week. Muscular strength was most commonly assessed using the 1-repetition maximum (1RM) test. Other strength tests included the 6RM and 10RM, as well as different isometric or isokinetic strength (e.g., knee extension, elbow flexion).

Seven studies[11,13−17,19] explored hypertrophy outcomes (Table 1). The pooled number of participants across studies was 219 (130 males and 89 females). All participants in the studies were young adults. In the individual studies, sample sizes ranged from 10 to 89 participants, with a median of 25. Two studies[11,17] involved resistance-trained participants, while the others employed untrained individuals as study participants (Table 1). Resistance training programs

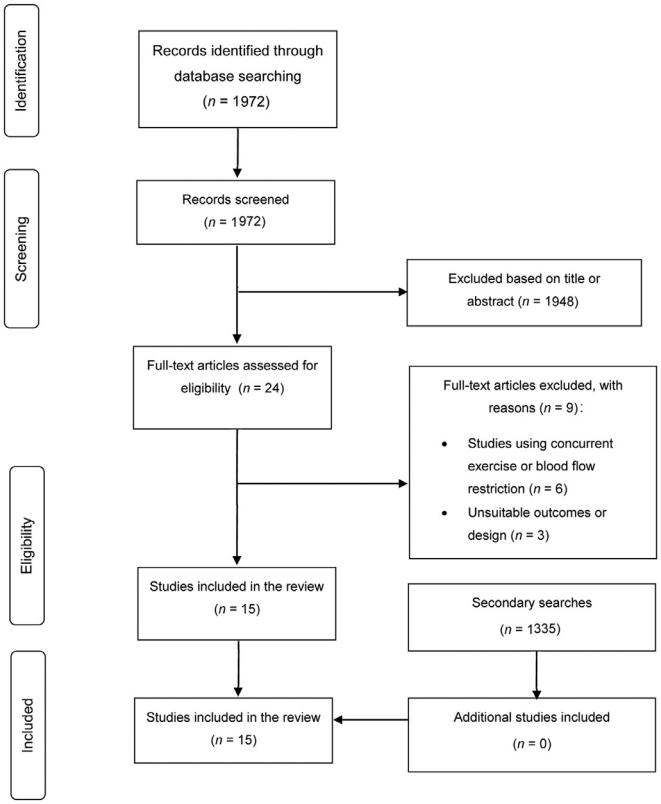

Fig. 1. Flow diagram of the search process.

Table 1
Summary of studies included in the review.

Study	Participant	Training load	Set and repetition scheme	Volume equated	Training duration and weekly frequency	Assessed outcomes
Drinkwater et al. (2005)[7]	26 elite junior male team game players with previous experience in resistance training	Failure: 80%−105% 6RM Non-failure: 80%−105% 6RM	Failure: 4 sets × 6 repetitions Non-failure: 8 sets × 3 repetitions	Yes	6 weeks, 3 days per week	6RM bench press
Fisher et al. (2016)[8]	9 young untrained men	Failure: 80% of maximal torque Non-failure: 80% of maximal torque	Failure: 25 repetitions in as few sets as possible Non-failure: 5 sets × 5 repetitions	Yes	6 weeks, 2 days per week	Isometric knee extension and flexion
Folland et al. (2002)[9]	23 young untrained men and women	Failure: 75% 1RM Non-failure: 75% 1RM	Failure: 4 sets × 10 repetitions Non-failure: 40 repetitions with 30 of rest between each repetition	Yes	9 weeks, 3 days per week	1RM and isometric knee extension
Izquierdo et al. (2006)[10]	29 young male Basque ball players with previous experience in resistance training	Failure: 6−10RM, or 80% 6−10RM Non-failure: 6−10RM, or 80% 6−10RM	Failure: 3 sets × (6−10 repetitions) Non-failure: 6 sets × (3−5 repetitions)	Yes	11 weeks, 2 days per week	1RM bench press and squat
Karsten et al. (2021)[11]	18 young resistance-trained men	Failure: 75% 1RM Non-failure: 75% 1RM	Failure: 4 sets × 10 repetitions) Non-failure: 8 sets × 5 repetitions	Yes	6 weeks, 2 days per week	1RM bench press and squat, vastus medialis, elbow flexor, anterior deltoid muscle thickness
Kramer et al. (1997)[12]	30 young resistance-trained men	Failure: 8−12RM Non-failure: 90%−100% 10RM	Failure: 1 set × (8−12 repetitions) Non-failure: 3 sets × 10 repetitions	No	14 weeks, 3 days per week	1RM squat
Lacerda et al. (2020)[13]	10 young untrained men	Failure: 50%−60% 1RM Non-failure: 50%−60% 1RM	Failure: 3−4 sets performed to failure Non-failure: total number of repetitions in the group training to failure was divided into multiple sets	Yes	14 weeks, 2−3 days per week	1RM and isometric knee extension, rectus femoris and vastus lateralis CSA
Lasevicius et al. (2019)[14]	25 young untrained men	Failure (high load): 80% 1RM Non-failure (high load): 80% 1RM Failure (low load): 30% 1RM Non-failure (high load): 30% 1RM	Failure (high load): 3 sets to muscle failure Non-failure (high load): 60% of the total repetitions in the group training to failure was used per set; additional sets were added to match the total number of repetitions between the groups Failure (low load): 3 sets to muscle failure Non-failure (high load): 60% of the total repetitions in the group training to failure was used per set; additional sets were added to match the total number of repetitions between the groups	Yes	8 weeks, 2 days per week	1RM knee extension, quadriceps CSA
Martorelli et al. (2017)[15]	89 young untrained women	Failure: 70% 1RM Non-failure (volume equated): 70% 1RM Non-failure (volume non-equated): 70% 1RM	Failure: 3 sets to muscle failure Non-failure (volume equated): 4 sets × 7 repetitions Non-failure (volume non-equated): 3 sets × 7 repetitions	Yes/No	10 weeks, 2 days per week	1RM and isokinetic elbow flexion, elbow flexor muscle thickness
Nóbrega et al. (2018)[16]	27 young untrained men	Failure (high load): 80% 1RM Non-failure (high load): 80% 1RM Failure (low load): 30% 1RM Non-failure (low load): 30% 1RM	Failure (high load): 3 sets to muscle failure Non-failure (high load): 3 sets not to muscle failure (1−3 repetitions in "reserve") Failure (low load): 3 sets to muscle failure Non-failure (low load): 3 sets not to muscle failure (1−3 repetitions in "reserve")	Yes	12 weeks, 3 days per week	1RM knee extension, vastus lateralis CSA
Pareja-Blanco et al. (2017)[17]	22 resistance-trained men	Failure: 70%−85% 1RM Non-failure: 70%−85% 1RM	Failure: velocity loss of 40% Non-failure: velocity loss of 20%	No	8 weeks, 2 days per week	1RM squat, quadriceps CSA, muscle fiber CSA
Rooney et al. (1994)[18]	27 young untrained men and women	Failure: 6RM Non-failure: 6RM	Failure: 1 set × (6−10 repetitions) Non-failure: 6−10 sets × 1 repetition	Yes	6 week, 3 days per week	1RM and isometric elbow flexion
Sampson et al. (2016)[19]	28 young untrained men	Failure: 85% 1RM Non-failure (rapid shortening): 85% 1RM Non-failure (stretch-shortening): 85% 1RM	Failure: 4 sets × 6 repetitions Non-failure (rapid shortening): 4 sets × 4 repetitions Non-failure (stretch-shortening): 4 sets × 4 repetitions	No	12 weeks, 3 days per week	1RM and isometric elbow flexion, elbow flexor CSA
Sanborn et al. (2000)[20]	17 young untrained women	Failure: 8−12RM Non-failure: 80%−100% of 2−10RM	Failure: 1 set × (8−12 repetitions) Non-failure: (3−5 sets) × (2−10 repetitions)	No	8 weeks, 3 days per week	1RM squat
Vieira et al. (2019)[21]	14 young resistance-trained men	Failure: 10RM Non-failure: 90% of the load used in the group training to failure	Failure: 3 sets × 10 repetitions Non-failure: 3 sets × 10 repetitions	Yes	8 weeks, 3 days per week	1RM bench and leg press, 10RM bench press, leg press, seated row, and squat machine

Abbreviations: CSA = cross-sectional area; RM = repetition maximum.

in the studies lasted 6−14 weeks (10 weeks on average) with a training frequency of 2−3 days per week. Hypertrophy was most commonly assessed by the changes in muscle cross-sectional area or thickness of the quadriceps muscle. Some studies assessed alternative sites for muscle thickness, such as the elbow flexor and anterior deltoid. One study also assessed cross-sectional area changes in types I and II muscle fibers.[19]

3.3. Methodological quality

The median score on the modified Downs and Black checklist was 21 points (range: 19−24 points). Five studies[7,14,18−20] were classified as being of moderate methodological quality, whereas all other studies were considered to be of good methodological quality (Table 2). None of the studies were classified as being of low quality.

3.4. Meta-analysis results

When considering all available studies, the meta-analysis for muscular strength gains indicated no significant difference between the training conditions ($p = 0.198$; ES = −0.09, 95%CI: −0.22 to 0.05; Fig. 2). Subgroup analysis for studies that did not equate training volume showed a moderate significant effect favoring non-failure training on strength gains ($p = 0.025$; ES = −0.32,y 95%CI: −0.57 to −0.07). In the subgroup analyses for studies that did equate training volume, however, there was no significant difference between training conditions with respect to strength gains ($p = 0.860$; ES = 0.01, 95%CI: −0.12 to 0.15). Subgroup analyses that stratified the studies according to training status, body region, exercise selection, or study design showed no significant differences between training conditions (Table 3).

When considering all available studies, the meta-analysis for hypertrophy indicated no significant difference between the training conditions ($p = 0.152$; ES = 0.22, 95%CI: −0.11 to 0.55; Fig. 3). The sensitivity analysis did not have a meaningful impact on the results. Notably, in the subgroup analysis for resistance-trained individuals, the analysis showed that training to failure had a significant effect on muscle hypertrophy ($p = 0.039$; ES = 0.15, 95%CI: 0.03−0.26). Subgroup analyses that stratified the studies according to training volume, body region, or study design, however, did not demonstrate significant differences between training conditions (Table 3).

4. Discussion

The results of this systematic review and meta-analysis suggest that training to muscle failure may produce similar increases in muscular strength and muscle size as non-failure training. This finding remained consistent among subgroup analyses, which suggests that the impact of training to failure is not likely to be moderated by variables such as body region, exercise selection, or study design. The subgroup analyses of studies that did not equate training volume between the groups stood out because it found that muscular strength gains favored training that did not include muscle failure. On the other hand, another subgroup analysis found that training to failure might be a benefit in terms of muscle hypertrophy for resistance-trained individuals.

4.1. Muscular strength

In 2009, the American College of Sports Medicine published a position stand on resistance training prescription for healthy adults.[34] Even though training to muscle failure is briefly mentioned, the position stand stops short of making any recommendations in regard to this training variable for the development of strength. Critics of this position stand[3,4] suggested that individuals seeking to improve strength should perform repetitions to muscle failure based on the premise that this method of training is optimal for maximizing strength gains. As such, there is an apparent disagreement in the literature relative to recommendations for this training variable. Based on the current evidence and our pooled analysis comprising approximately 400 participants, it seems that training to muscle failure is not necessary for increases in muscular strength. Nonetheless, training in this manner does not appear to have detrimental effects on these adaptations, suggesting that the choice of training to failure *vs.* non-failure can be based more or less on personal preference alone. Finally, the upper and lower limits of the 95%CIs were within the zones of small to moderate ES suggesting that even if there were a benefit to either of these methods of training, the benefit is likely to be negligible for most individuals.

As previously noted, the subgroup analysis for training volume showed significant favoring for the effects of non-failure training on muscular strength gains. However, in the majority of studies that did not equate training volume between the groups, participants that did not train to muscle failure performed more sets (i.e., more volume) than did the individuals training to muscle failure.[12,17,19,20] For example, in a study done by Kramer et al.,[12] the group that trained to muscle failure performed a single set per exercise for 8−12 repetitions, whereas the group that did not train to muscle failure performed 3 sets of 10 repetitions (while not reaching muscle failure). This is relevant to emphasize because it has been previously shown that training volume increases strength in a linear dose−response manner.[35] Therefore, the significant effect of training that does not include muscle failure seems to be primarily related to the differences in training volume between the groups. Indeed, when considering only studies that equated for training volume between the groups, the pooled ES amounted to 0.01 nested within a 95%CI of −0.12 to 0.15, suggesting highly similar increases in strength regardless of whether an individual does or does not reach failure during training.

4.2. Muscle hypertrophy

The meta-analysis for hypertrophy outcomes suggests that similar increases in muscle size can be attained regardless of whether or not training is carried out to muscle failure. This

Table 2
Results of the methodological quality assessment using the modified Downs and Black checklist.

Study	Reporting (Items 1–10)										External validity (Items 11–13)			Internal validity (Items 14–26)											Power, compliance, supervision (Items 27–29)			Total score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
Drinkwater et al. (2005)[7]	1	1	1	1	1	1	1	0	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	1	20
Fisher et al. (2016)[8]	1	1	1	1	1	1	1	0	1	1	1	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	1	21
Folland et al. (2002)[9]	1	1	1	1	1	1	1	0	0	0	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	21
Izquierdo et al. (2006)[10]	1	1	1	1	1	1	1	0	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	23
Karsten et al. (2021)[11]	1	1	1	1	1	1	1	0	1	1	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	23
Kramer et al. (1997)[12]	1	1	1	1	0	1	1	1	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	0	1	1	1	1	21
Lacerda et al. (2020)[13]	1	1	1	1	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	24
Lasevicius et al. (2019)[14]	1	1	1	1	1	1	1	0	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	0	1	1	0	1	19
Martorelli et al. (2017)[15]	1	1	1	1	1	1	1	0	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	22
Nóbrega et al. (2018)[16]	1	1	1	1	1	1	1	1	1	1	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	24
Pareja-Blanco et al. (2017)[17]	1	1	1	1	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	1	1	0[a]	1	0[a]	0	1	1	1	1	23
Rooney et al. (1994)[18]	1	1	1	1	1	1	1	0	0	1	1	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	1	20
Sampson et al. (2016)[19]	1	1	1	1	0	1	1	0	1	1	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	0	1	1	1	0[a]	20
Sanborn et al. (2000)[20]	1	1	1	1	0	1	1	1	1	1	1	0[a]	1	0[a]	0[a]	1	1	1	0[a]	1	1	0[a]	1	0[a]	0	1	1	0	1	20
Vieira et al. (2019)[21]	1	1	1	1	1	1	1	1	1	0	1	0[a]	1	0[a]	0[a]	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	23

Note: 1 = criteria met; 0 = criteria not met.
[a] Item was unable to be determined, scored 0.

means that, based on the current body of literature, training to momentary muscle failure does not seem to be required for increases in muscle size. However, we should again highlight that training to muscle failure does not appear to produce any detrimental effects on muscle hypertrophy. Still, it should be considered that the upper limit of the 95%CI in this analysis was 0.55, which is in the range of a large effect. Therefore, while we did not show significant differences between training to failure *vs.* non-failure, the wide 95%CI also underlines the need for future research on the topic.

The subgroup analysis performed for resistance-trained participants indicated that, for them, training to failure had a significant effect on muscle hypertrophy. Indeed, it is conceivable that, as an individual approaches his or her genetic ceiling for muscular adaptations, a greater intensity of effort may be required to elicit further gains. However, this analysis was limited by the small number of included studies. Specifically, only 2 studies[11,17] were included: one that equated training volume between the groups, and one that did not. While the results presented in our review offer preliminary support for training to failure in resistance-trained participants, future studies are needed to provide greater clarity on the influence of training status when exercise variables are strictly controlled, particularly in highly trained individuals.

The finding observed in the main meta-analysis for hypertrophy could be explained by the loads used in the majority of included studies. In general, studies used moderate to high loads (e.g., 60%–90% 1RM) in their resistance training programs (Table 1). This aspect is relevant because the upper limit of motor unit recruitment is thought to be around 60%–85% of maximum force (depending on the muscle group).[36–38] In other words, when exercising with such training loads, high-threshold motor units tend to be recruited from the onset of the exercise, and the additional increase in force beyond the upper limit of motor unit recruitment is accomplished by rate coding.[36–38] Therefore, training to muscle failure may not be needed for motor unit recruitment when using moderate or high loads. However, it should be noted that simply because a fiber has been recruited does not mean that it has been sufficiently stimulated to hypertrophy. Thus, while the level of recruitment may provide a partial mechanistic explanation of these findings, it would appear that other factors are involved as well.[39]

Recently, it has been hypothesized that training to muscle failure becomes increasingly more important when exercising with lower loads (e.g., 30% of maximum force), due to the delayed recruitment of larger motor units.[40] In support of this idea, Lasevicius et al.[14] compared training to muscle failure *vs*. non-failure with loads of 30% and 80% 1RM. The study used a within-subject unilateral design whereby 1 limb trained to failure at the given load and the other did not. Results indicated that training to failure promoted greater increases in muscle size in groups training with low loads. Alternatively, in the groups performing high-load training, similar increases in muscle size were noted with and without training to muscle failure. Nóbrega et al.[16] performed a similar experiment and

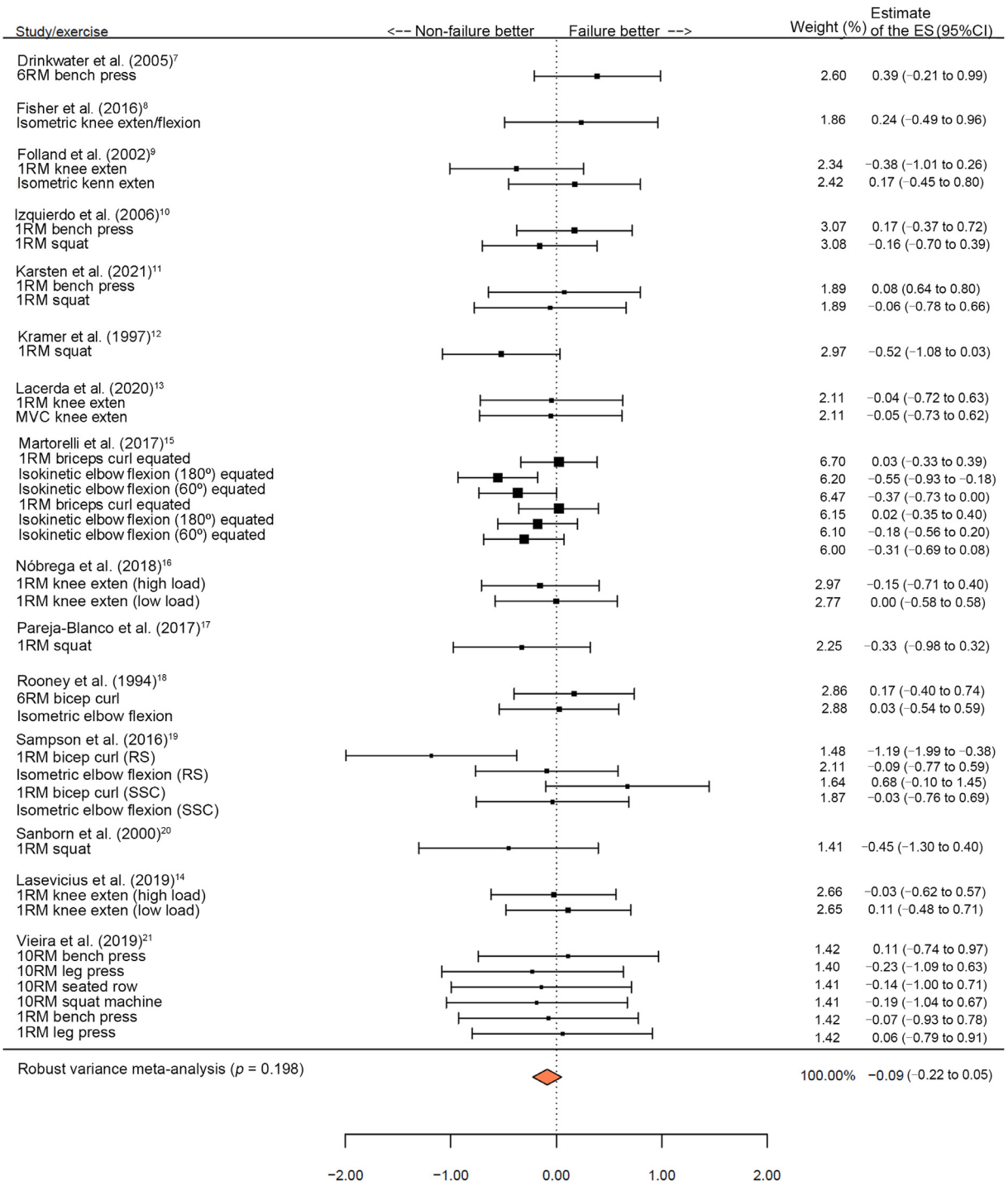

Fig. 2. The forest plot from the meta-analysis of the effects of training to failure *vs.* non-failure on muscular strength. The X axis denotes Cohen's *d* (ES) while the whiskers denote the 95%CI. [a] The sum of the percentages is not 100% due to the rounding. 95%CI = 95% confidence interval; ES = effect size; MVC = maximal voluntary contraction; RM = repetition maximum; RS = rapid speed; SSC = stretch-shortening cycle.

reported comparable hypertrophy effects in both high- and low-load training groups, regardless of whether or not they trained to failure. However, in this study, the groups not training to failure performed only 1−2 repetitions less per set than the group training to failure. In the Lasevicius et al.[14] study, the limb that did not exercise to failure, trained with 60% of the total repetitions (per set) performed by the limb that trained to failure; additional sets were added to match the total number of repetitions between the conditions. These methodological differences are likely to account for the conflicting evidence. As such, this is an area requiring further scientific attention.

Table 3
Results of the subgroup meta-analyses.

Subgroup analysis	Classification	ES (95%CI)	*p*
Outcome: muscular strength			
Training status	Trained	−0.09 (−0.48 to 0.29)	0.554
	Untrained	−0.08 (−0.22 to 0.06)	0.224
Training volume	Volume equated	0.01 (−0.12 to 0.15)	0.860
	Non-volume equated	−0.32 (−0.57 to −0.07)	0.025
Body region	Lower body	−0.15 (−0.33 to 0.02)	0.079
	Upper body	0.00 (−0.35 to 0.35)	0.985
Strength test exercise	Multi-joint	−0.13 (−0.47 to 0.21)	0.386
	Single-joint	−0.05 (−0.20 to 0.09)	0.405
Study design	Independent groups	−0.12 (−0.31 to 0.06)	0.157
	Dependent groups	0.03 (−0.18 to 0.23)	0.709
Outcome: muscle hypertrophy			
Training status	Trained	0.15 (0.03 to 0.26)	0.039
	Untrained	0.23 (−0.25 to 0.71)	0.244
Training volume	Volume equated	0.15 (−0.15 to 0.45)	0.237
	Non-volume equated	0.36 (−0.52 to 1.23)	0.218
Body region	Lower body	0.07 (−0.11 to 0.26)	0.323
	Upper body	0.41 (−0.83 to 1.65)	0.220
Study design	Independent groups	0.36 (−0.27 to 0.99)	0.147
	Dependent groups	0.03 (−0.33 to 0.38)	0.773

Note: Negative values denote favoring of non-failure training and positive values indicate favoring of training to muscle failure.
Abbreviations: 95%CI = 95% confidence interval; ES = effect size.

4.3. Generalizability of the results

While this meta-analysis showed no significant differences between the effects of training to muscle failure or non-failure on muscle strength and hypertrophy, these results are specific to the population analyzed in all included studies—young adults. Therefore, future work is needed to explore the effects of training to failure *vs*. non-failure among middle-aged and older adults. Additionally, our results are specific to studies that used isolated traditional resistance training programs. There is evidence that avoiding muscle failure may be important when using blood flow restriction training and in concurrent exercise programs.[5,6,41] For example, in a study by Carroll et al.,[5] the participants coupled resistance training with a low-volume sprint interval training. While this study did not satisfy our inclusion criteria due to its utilization of concurrent exercise programs, its results did indicate that failure training had a detrimental effect on muscle hypertrophy in resistance-trained men. Therefore, the findings presented herein cannot necessarily be generalized to adaptations that occur with concurrent training.

4.4. Areas for future research

Although our findings provide evidence that consistently training to failure is not obligatory for enhancing muscular strength and hypertrophy, the current literature is not sufficient to determine the level of effort necessary to maximize these adaptations. It is currently unclear whether the same effects would be achieved if an individual stops the set, for example, 5 repetitions before failure *vs.* 2 repetitions before failure. Future research should seek to quantify the lower threshold as to how many repetitions short of failure would be sufficient to elicit an optimal adaptive response. This should be quantified across various repetition ranges, as the relative magnitude of load will necessarily influence results.

4.5. Methodological quality and limitations

All included studies were classified as being of moderate or good methodological quality. Therefore, the results presented in this review are not confounded by the inclusion of studies that were of low methodological quality. However, there is 1 significant limitation noted in some of the included studies. Specifically, 5 studies[4,7,8,18,20] did not report participants' adherence to the training programs (Table 2). In the studies that did report adherence to the training interventions, it was very similar between the groups (Table 1). Thus, while there is no reason to believe that adherence was not similar between the groups in papers that did not report these data, future studies should ensure that this information is clearly presented.

An important methodological consideration of this review is that we included studies with independent groups as well as those with dependent groups. In a design with dependent groups, limbs are assigned to perform 1 of 2 training routines (e.g., either training to or not to failure). This design has certain advantages, such as minimizing the variability in responses between individuals. Still, this model's limitation is the possible cross-education effect, which dictates that training 1 limb increases strength in both limbs.[42] However, we also conducted subgroup analyses where the studies were stratified according to their study design. There was no significant difference between training to failure *vs.* non-failure in subgroup analyses for studies with independent *vs.* dependent groups, therefore reinforcing the primary analysis results. As mentioned previously, training to muscle failure may be more important with lower as opposed to higher loads. In the present review, we included studies that utilized both high and low loads in their respective training routines, which might be a limitation of the review, even though it should be considered that only 2 studies used very low loads (i.e., 30% 1RM).[14,16]

5. Conclusion

The findings of this review suggest that training to or not to muscle failure may produce similar increases in muscular strength and muscle size. This finding generally remained consistent in subgroup analyses that stratified the studies according to body region, exercise selection, or study design. Still, when volume was not controlled for, there was favoring of non-failure training on strength gains, as well as favoring of training to failure for hypertrophy in resistance-trained individuals. More studies should be conducted among older adults and highly trained individuals in order to improve the generalizability of these findings.

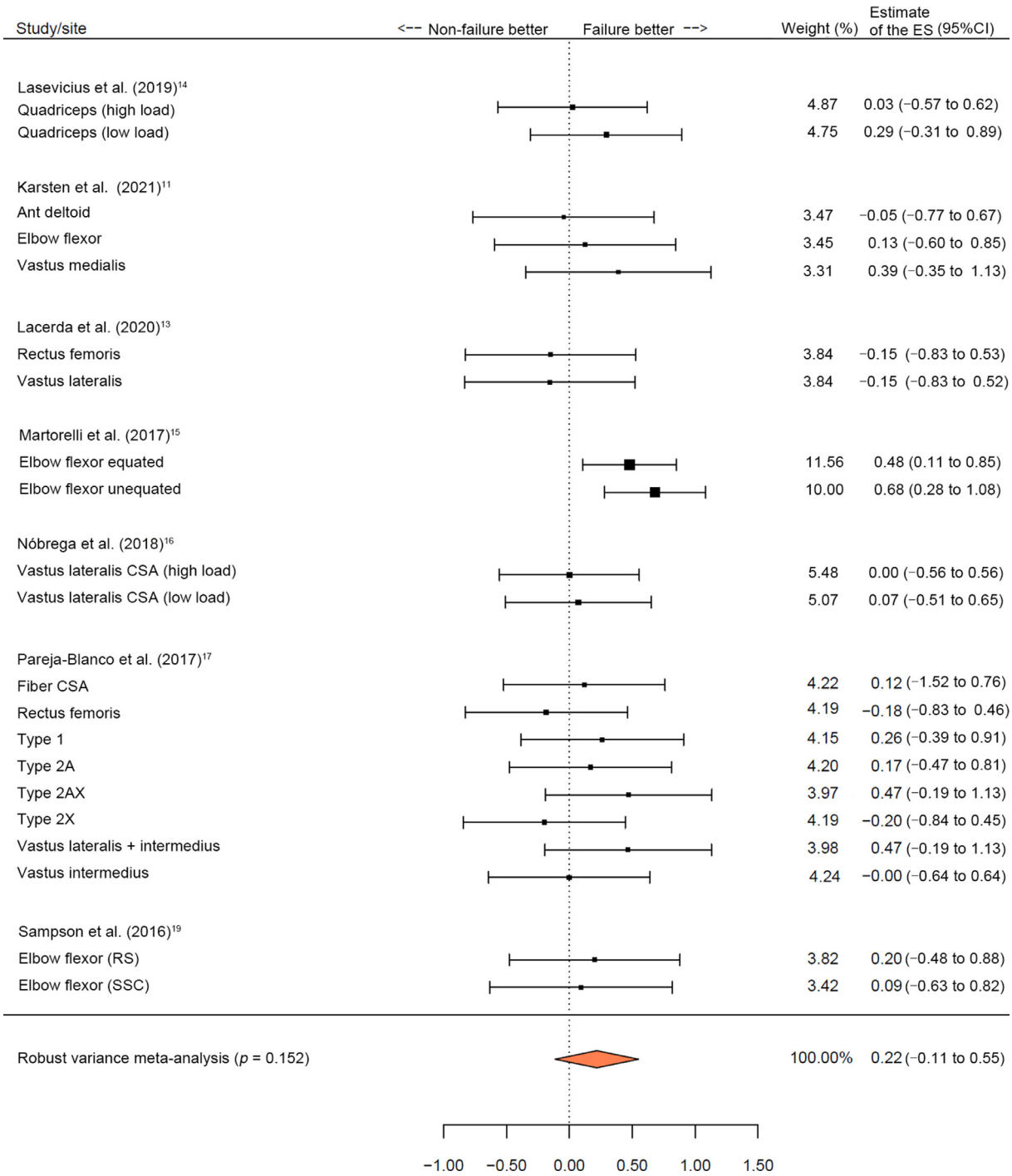

Fig. 3. The Forest plot from the meta-analysis on the effects of training to failure *vs.* non-failure on muscle hypertrophy. The X axis denotes Cohen's *d* (ES) while the whiskers denote the 95%CI. [a] The sum of the percentages is not 100% due to the rounding. 95%CI = 95% confidence interval; CSA = cross-sectional area; ES = effect size; RS = rapid speed; SSC = stretch-shortening cycle.

Authors' contributions

JG conceived the idea for the review, performed the searches, data extraction, and methodological quality assessment, and drafted the manuscript; BJS conceived the idea for the review, performed the searches and data extraction, and critically revised the manuscript content; JO analyzed the data and critically revised the manuscript content; FS performed the methodological quality assessment and critically revised the manuscript content. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interest.

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