Does Aerobic Training Promote the Same Skeletal Muscle Hypertrophy as Resistance Training? A Systematic Review and Meta-Analysis

Does aerobic training promote the same skeletal muscle hypertrophy as resistance training? A systematic review and meta-analysis

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Abstract

Background

Currently, there are inconsistencies in the body of evidence for the effects of resistance and aerobic training on skeletal muscle hypertrophy.

Objective

We aimed to systematically review and meta-analyze current evidence on the differences in hypertrophic adaptation to aerobic and resistance training, and to discuss potential reasons for the disparities noted in the literature.

Methods

The PRISMA guidelines were followed for this review. The Downs and Black checklist was used for the assessment of methodological quality of the included studies. A random-effects meta-analysis was employed. In total, three analyses were performed: (1) for whole-muscle knee extensor data; (2) for type I fiber cross-sectional area (CSA); and, (3) for type II fiber CSA.

Results

The final number of included studies in the present review is 21. All studies were of good or moderate methodological quality. The meta-analysis for whole-muscle hypertrophy resulted in a significant pooled difference ($p < 0.001$) in responses between the aerobic training and resistance training interventions. The pooled Hedge's g, favoring resistance over aerobic training, was 0.66 (95% confidence interval (CI) = 0.41, 90; $I^2 = 0\%$). The meta-analysis for type I fiber CSA data resulted in a significant pooled difference ($p < 0.001$) between the aerobic training and resistance training groups. The pooled Hedge's g, favoring resistance training over aerobic training, was 0.99 (95% CI = 0.44, 1.54; $I^2 = 24\%$). The meta-analysis of

type II fiber CSA data resulted in a significant pooled difference ($p < 0.001$) between the aerobic training and resistance training groups. The pooled Hedge's g, favoring resistance training over aerobic training, was 1.41 (95% CI = 0.83, 1.98 I^2 = 8%).

Conclusions

The results of this systematic review and meta-analysis suggest that single mode aerobic training does not promote the same skeletal muscle hypertrophy as resistance training. This finding was consistent with measurements of muscle hypertrophy both at the whole-muscle and myofiber levels. While these results are specific to the knee extensor musculature, it can be hypothesized that similar results would be seen for other muscle groups as well.

Key points

- The results of this systematic review and meta-analysis suggest that single mode aerobic training does not promote the same skeletal muscle hypertrophy as resistance training.
- The greater effectiveness of resistance over aerobic training was consistent when analyzing hypertrophic responses both at the whole-muscle and myofiber level.
- Given the superiority of resistance training for stimulating knee extensor hypertrophy, it can be hypothesized that similar results would be observed for other muscle groups as well.

1 Introduction

Adaptations to exercise training are primarily thought to occur in a mode-specific manner [1]. In this regard, aerobic training is considered to be the primary mode of exercise for improving markers of cardiorespiratory fitness, such as maximal oxygen consumption (VO_{2max}) [2]. Resistance training, on the other hand, is seen as the principal mode of exercise that elicits adaptations such as muscular hypertrophy [3]. However, it is evident from the literature that there is a certain degree of crossover in both the early post-exercise responses and longer-term adaptations induced by these two modes of exercise [1, 4].

Although resistance training can increase VO_{2max} (predominately shown in previously untrained individuals) [5], aerobic training is more effective for enhancing cardiorespiratory fitness [6-9]. Since the seminal work by DeLorme in the 1940s [10] and as acknowledged in a recent historical review [11], it has been well accepted that resistance training provides a superior stimulus for skeletal muscle hypertrophy compared with aerobic training. However, some authors have challenged this convention [12]. A recent narrative review by Konopka and Harber [12] suggested both modes of training might be equally effective for stimulating knee extensor muscular hypertrophy. Following the publication of the review by Konopka and Harber [12], these conclusions have been reiterated elsewhere [13, 14]. For instance, Ceccarelli et al. [13] wrote "Notably, also aerobic exercise has revealed an anabolic potential comparable to resistance exercise by altering protein metabolism and inducing skeletal muscle hypertrophy" and cited Konopka and Harber [12] to support these claims. Other authors have made similar claims regarding the hypertrophic potential of aerobic exercise [14].

Given the increases in protein synthesis with aerobic exercise [15], it is not surprising that several studies have reported considerable muscle hypertrophy following long-term aerobic training [16, 17]. Furthermore, some studies comparing resistance and aerobic training have observed that these training modes may produce comparable hypertrophy of the knee extensor musculature [18, 19]. However, this effect has not been corroborated by all studies that compared these two modes of exercise. For example, superior muscle hypertrophy has been reported with resistance training compared to aerobic training [20, 21]. Furthermore, in some cases, muscle growth has been observed with resistance training, but not aerobic training [6].

In addition to assessing hypertrophic adaptations at the whole-muscle level, muscular hypertrophy can also be assessed at the myofiber level. Some studies have reported increases in type I, but not type II, muscle fiber cross-sectional area (CSA) with aerobic cycling training [16, 17]. By contrast, resistance training is primarily considered to induce hypertrophy of type II muscle fibers [22]. However, Kraemer et al. [23] demonstrated that resistance training increased both type I and type II fiber CSA, while aerobic running training decreased the CSA of both fiber types. Contradictory findings have also been noted in the literature, with one study showing increased type I fiber CSA with aerobic training, but not resistance training (although both modes were equally effective for increasing type IIx muscle fiber CSA) [24].

If we only observe the results from individual studies, the conclusions regarding the effects of aerobic and resistance exercise on skeletal muscle hypertrophy might be that: (a) both modes of exercise are equally effective [18, 19]; (b) resistance exercise is superior to aerobic exercise [23]; or (c) aerobic exercise is superior to resistance exercise [24]. This clearly demonstrates the inconsistencies in the current body of evidence for the effects of resistance and aerobic training on skeletal muscle hypertrophy. Such evidence is important to inform exercise prescription strategies for maximizing skeletal muscle hypertrophy. Given the lack of clarity on the effects of single-mode resistance training and aerobic training on skeletal muscle hypertrophy at both the whole-muscle and myofiber levels, we aimed to systematically review and meta-analyze current evidence on the differences in hypertrophic adaptation to aerobic and resistance training, and to discuss potential reasons for the disparities noted in the literature.

2 Methods

2.1 Literature search

This review was performed following the PRISMA guidelines [25] with literature searches conducted through Scopus, PubMed/MEDLINE, and SPORTDiscus. The following syntax was used for the search: ("resistance training" OR "resistance exercise" OR "strength training" OR "strength exercise" OR "weight training" OR "weight exercise" OR "resistive exercise" OR "resistive training") AND ("aerobic training" OR "aerobic exercise" OR "endurance training" OR "endurance exercise" OR running OR cycling) AND (hypertrophy OR "cross-sectional area" OR "muscle size" OR growth OR "lean body mass" OR "muscle fiber" OR biopsy OR "skeletal muscle" OR "muscle thickness"). The search was carried out on March 28th, 2018. For the purpose of study selection, the search results were downloaded to the EndNote software (X8; Clarivate Analytics, New York, USA). The study selection was independently performed by two authors (JG and LM) to prevent selection bias. In the secondary search, the reference lists of all included publications were screened and the studies that cited the included studies were examined through the Scopus database. Furthermore, relevant review papers [12, 26] and books [27] were searched for additional relevant studies.

2.2 Inclusion criteria

Studies meeting the following criteria were included: (1) published in English and in a peer-reviewed journal; (2) compared single-mode resistance training (an exercise type that requires exertion of force against a resistance performed in a dynamic fashion [11]) and single-mode aerobic training (any form of continuous or interval aerobic training was considered) as long as both types of exercise were performed by similar muscle groups; (3) muscular hypertrophy was measured directly at the whole-muscle level (using ultrasound, magnetic resonance imaging [MRI], and/or computed tomography [CT]) or at the myofiber level using histological assessments of muscle biopsies; (4) the training program lasted a minimum of four weeks; (5) the participants were apparently healthy adults without any chronic disease or musculoskeletal injury. The studies that employed dietary interventions in which the participants were in a diet-prescribed caloric deficit during the training program were not considered for this review. By contrast, the studies with dietary interventions such as protein supplementation for both groups were considered eligible and were included in the review.

2.3 Study coding and data extraction

The following data were extracted onto an Excel spreadsheet from the studies that met the inclusion criteria: (1) participants' characteristics, including age, height, sex, and training status (e.g., trained/untrained); (2) exercise prescription details for the resistance training and aerobic training groups; (3) participants' compliance with the training programs; (4) means and standard deviations for pre- and post-training muscle hypertrophy measurements. When required, the Web Plot Digitizer software (V.3.11. Texas, USA: Ankit Rohatgi, 2017) was used for the extraction of data from figures. The coding was performed independently by two authors (JG and LM). Coding files were crosschecked between the authors, and any observed differences were resolved via discussion and agreement.

2.4 Methodological quality

The Downs and Black checklist [28] was used for the assessment of the methodological quality of the included studies. The standard checklist has 27 items, which refer to: reporting (items 1-10); external validity (items 11-13); internal validity (items 14-26); and statistical power (item 27). However, given the specificity of included studies (i.e., exercise interventions), we added two items that refer to reporting of compliance (item 28) and supervision of the exercise programs (item 29), as done by others [29-31]. With the adjusted checklist, the maximum score was 29 points. The following classification was used for scoring the studies: (1) good methodological quality (>20 points); (2) moderate methodological quality (11-20 points); and (3) poor methodological quality (<11 points) [29-31]. Two authors (JG and FS), independently performed the quality assessment, and any observed differences were resolved via discussion and agreement.

2.5 Statistical analysis

Standardized mean differences (Hedge's g) and 95% confidence intervals (CIs) were calculated based on the following data: (1) pre- and post-intervention mean muscular hypertrophy values; (2) pre- and post-intervention standard deviations; (3) correlations between pre- and post-intervention measurements; and (4) the number of participants in each group. If the studies presented standard errors (SEs), they were converted to standard deviations using the formula ($SE \cdot \sqrt{n}$). None of the included studies presented pre-to-post correlation values. Therefore, correlations were estimated with the following formula: $r' =$

$\frac{s_{pre}^2+s_{post}^2-s_D^2}{2 \cdot s_{pre} \cdot s_{post}}$, where s_{pre} is the standard deviation of the pre-intervention score, s_{post} is the standard deviation of the post-intervention score, and s_D is the standard deviation of the change score (pre- to post-intervention) calculated as: $s_D = \left(\frac{Ss_{pre}^2}{n} + \frac{s_{post}^2}{n}\right)^{1/2}$. This procedure for estimating correlation is explained in detail in the Cochrane Handbook [32]. In total, three analyses were performed: (1) for whole-muscle knee extensor data; (2) for type I fiber CSA; and, (3) for type II fiber CSA. A meta-analysis for upper-body musculature and other lower-body muscle groups, such as posterior thigh muscles, could not be performed due to the small number of studies assessing these muscle groups. If the studies presented multiple data points, such as the assessment of hypertrophy on both legs, or CSA values for different subtypes of type II fibers (i.e., type IIa, type IIx, etc.), the standardized mean differences and variances were calculated separately and the average values were used for the analysis. While we did not include studies in which the participants were in a diet-prescribed caloric deficit, two studies [7, 33] have reported significant weight loss in the group doing aerobic exercise, and one study reported significant weight loss in the group performing resistance training [20]. To explore the extent to which these studies impacted the pooled findings we conducted two sensitivity analyses. One sensitivity analysis was performed by excluding the studies that reported significant weight loss in the group doing aerobic exercise, and the second sensitivity analysis excluded the study in which a significant weight loss was observed in the resistance training group. These analyses were carried out only for whole-muscle knee extensor data given that the studies reporting significant weight loss did not measure fiber CSA.

The following effect size scale was used for the classification of magnitudes: small (≤0.2); medium (0.2-0.5); large (0.5-0.8); and very large effects (>0.8) [34]. The I^2 statistic was used to assess heterogeneity. We considered I^2 values of ≤50% to indicate low levels of heterogeneity; 50-75% moderate levels of heterogeneity; and >75% high levels of heterogeneity. SEs were plotted against Hedge's g to detect funnel plot asymmetry. The asymmetry was tested using the trim and fill method [35]. The random-effects model was used for all analyses. The statistical significance threshold was set at $p < 0.05$. All analyses were performed using the Comprehensive Meta-analysis software, version 2 (Biostat Inc., Englewood, NJ, USA).

3. Results

3.1 Search results

The flow diagram of the literature search is presented in Fig. 1. The initial search from the three databases resulted in a total of 2,809 search results. After the removal of duplicates, the number of search results was reduced to 1,953. Out of the remaining search results, 1896 studies were excluded based on title or abstract. Fifty-seven full-text papers were read, and 19 studies were found that met the inclusion criteria [7-9, 18-21, 23, 33, 36-45]. Forward citation tracking and reference list screening included another 2,859 publications, of which, two were included [6, 24]. Therefore, the final number of included studies in this review is 21.

*****Insert Fig. 1 about here*****

3.2 Study characteristics

The pooled number of participants across studies was 509 (median n = 22). The participants' characteristics from the included studies can be found in Table 1. The average duration of the training interventions amounted to 18 weeks (range: 8-36 weeks). The most common training frequency was three times per week (range: 2-4). A summary of the training programs and study details from individual studies can be found in Table 2. In two instances, the whole-muscle and fiber CSA values were reported in separate papers, even though they were collected in the same sample of participants [37, 38, 44, 45]. Fourteen studies used whole-muscle measures of hypertrophy [6-9, 18-21, 33, 37, 39, 41, 43, 44], while ten studies [6, 23, 24, 36, 38, 39, 40, 42, 43, 45] used histological assessments (five studies [6, 37-39, 43-45] used both). Five studies used CT [7, 9, 33, 43, 44], five studies used MRI [18, 21, 37, 39, 41], and four studies used ultrasound [6, 8, 19, 20]. All studies that measured muscle fiber CSA used samples from the vastus lateralis muscle and ATPase histochemistry for the identification of muscle fiber types.

*****Insert Table 1 about here*****

*****Insert Table 2 about here*****

3.3 Methodological quality

Based on the assessment of methodological quality, the included studies were classified as being of either good or moderate quality (Electronic Supplementary Material Table S1). Specifically, five studies [6, 23, 44, 45, 33] were classified as being of good quality, while the remaining studies were classified as being of moderate quality [7-9, 18-21, 24, 36-43]. The median methodological quality score was 19 (range = 15 to 24). Eight studies [6, 18, 21, 24, 36-39] did not report participants' compliance with the training programs and, thus, did not receive a point on the item 28. It was unclear in six studies [7, 36-38, 40, 41] whether the training programs were supervised; therefore, these studies did not receive a point on the item

29 of the checklist. The methodological quality ratings for all studies can be found in Electronic Supplementary Material Table S1.

3.4 Meta-analysis results

The meta-analyses were conducted only for the differences between the effects of resistance training and aerobic training on hypertrophy of knee extensors, because no or limited data were available for other muscles groups.

3.4.1 Whole-muscle area

Of the 14 studies that assessed whole-muscle hypertrophy, ten studies [6, 7, 9, 19, 33, 37, 39, 41, 43, 44] were included in the final analysis. Four studies were not included due to the lack of necessary data (i.e., mean ± standard deviation values) presented in the manuscript, and the authors did not present the data upon a written request [8, 18, 20, 21]. The meta-analysis resulted in a significant pooled difference ($p < 0.001$) in whole-muscle hypertrophy responses between the aerobic training and resistance training interventions (Fig. 2). The pooled Hedge's g, favoring resistance over aerobic training, was 0.66 (95% CI = 0.41, 90; $I^2 = 0\%$), which corresponds to a large effect size. The funnel plot and trim and fill method did not suggest any funnel plot asymmetry. The sensitivity analysis, in which the two studies [7, 33] that reported significant weight loss in the group doing aerobic exercise were excluded, resulted with a pooled Hedge's g, favoring resistance over aerobic training, of 0.49 (95% CI = 0.19, 0.78; $I^2 = 0\%$). The second sensitivity analysis, in which the study by Izquierdo et al. [20] that reported significant weight loss in the group doing resistance exercise was excluded, resulted with a pooled Hedge's g, favoring resistance over aerobic training, of 0.66 (95% CI = 0.39, 0.93; $I^2 = 0\%$).

*****Insert Fig. 2 about here*****

3.4.2 Myofiber area

Ten studies [6, 23, 24, 36, 38-40, 42, 43, 45] were included in the final analysis of type I CSA. The meta-analysis for type I fiber CSA data resulted in a significant pooled difference ($p < 0.001$) between the aerobic training and resistance training groups (Fig. 3). The pooled Hedge's g, favoring resistance training over aerobic training, was 0.99 (95% CI = 0.44, 1.54; $I^2 = 24\%$), which corresponds to a very large effect size.

*****Insert Fig. 3 about here*****

One of the ten studies was [40] excluded from the analysis for type II fiber CSA, as it only reported results for type I fiber CSA. Therefore, the analysis of type II CSA included nine studies [6, 23, 24, 36, 38, 39, 42, 43, 45]. The meta-analysis of type II fiber CSA data resulted in a significant pooled difference ($p < 0.001$) between the aerobic training and resistance training groups (Fig. 4). The pooled Hedge's g, favoring resistance training over aerobic training, was 1.41 (95% CI = 0.83, 1.98 $I^2 = 8\%$), which corresponds to large effect size. The funnel plots and trim and fill method did not suggest any funnel plot asymmetry in either of the analyses for fiber CSA.

*****Insert Fig. 4 about here*****

4 Discussion

The majority of included studies comparing hypertrophic responses to aerobic and resistance training examined hypertrophy of the knee extensor musculature. Therefore, the results of this systematic review and meta-analysis suggest that single-mode resistance training is more effective for inducing knee extensor skeletal muscle hypertrophy compared with single-mode aerobic exercise. This finding was consistent when analyzing hypertrophic responses both at the whole-muscle and myofiber level. Therefore, the results of this meta-analysis do not support the assertions by Konopka and Harber [12] that resistance training and aerobic training undertaken in isolation are equally effective at stimulating knee extensor muscle hypertrophy. While some of the studies included in this meta-analysis show that aerobic training may indeed stimulate lower-body muscle hypertrophy [17-21, 43], our results indicate a favoring of resistance over aerobic training. Given the results for knee extensor hypertrophy, it seems likely that similar results would be observed for other muscle groups as well. Furthermore, these results are based on analyses with low heterogeneity and on studies that were classified as having moderate or good methodological quality.

Due to the lack of available data for other muscle groups, the meta-analyses were conducted only for the knee extensor muscles. Nevertheless, two out of three studies that assessed other lower-body muscle groups, such as posterior thigh musculature (e.g., knee flexors) also reported that resistance training resulted in greater hypertrophy of this muscle group as compared to aerobic training [18, 43]. Resistance training allows for the incorporation of multiple exercises involving distinct movement patterns that enable activation of different muscle groups (and regions within the active musculature), which is rarely the case with the common types of aerobic exercise (e.g., running or cycling). It is, therefore, likely that the effects of resistance training for inducing muscle hypertrophy as compared to aerobic exercise extends to muscle groups other than the knee extensors.

With aerobic cycling training, a large number of muscular contractions (from 118,000 to 145,000 contractions per leg) has been suggested as a requirement to impart a sufficient stimulus for muscle hypertrophy [12]. Such training sessions usually last from 30 to 45 min. In comparison, with resistance training, protocols involving three sets performed at 80% of one repetition maximum (1RM) and lasting approximately 5 to 10 min per session have been shown to result in a robust growth of the knee extensor musculature [46]. Therefore, regardless of the potential for aerobic training to induce some degree of muscle hypertrophy, resistance training is likely a more time-efficient mode of exercise for achieving this outcome. This may be important given that the lack of time for exercise is commonly proposed as an important perceived barrier to exercise participation [47, 48].

While resistance training likely provides a greater (and more time-efficient) stimulus for inducing muscle hypertrophy compared with aerobic training modalities, it is possible the time courses of muscular growth induced by these two exercise modes are different. As little as two weeks of resistance training has been shown to result in significant hypertrophy of the knee extensor muscle group [49]. However, it is possible that the hypertrophy rate is slower in response to aerobic training [26]. Therefore, Konopka and Harber suggested that to achieve similar muscular growth, aerobic training frequency should be higher than the resistance training frequency [12]. These authors suggested that four to five sessions of aerobic training per week might be needed to achieve comparable muscle growth to ‘traditional’ resistance exercise programs [12]. Nineteen out of the 21 studies included in the present meta-analysis employed aerobic training frequencies of two and three times per week. Therefore, it is possible that greater increases in muscle size with aerobic training would be observed if the included studies had employed higher training frequencies.

The differential effects of aerobic and resistance exercise stimuli for inducing muscle hypertrophy might be explained by differences in their capacity to activate post-exercise anabolic signaling responses in skeletal muscle. For example, the degree of post-exercise p70S6K (p70 kDa ribosomal protein subunit kinase 1) phosphorylation in skeletal muscle is in some studies highly correlated (r = 0.82-0.99) with muscular hypertrophy consequent to long-term resistance training [50-52]. It has been reported that the phosphorylation of p70S6K is increased immediately following both aerobic and resistance exercise [53]. However, when assessed four hours after training, the phosphorylation of p70S6K remained increased only with resistance exercise, and similar results were seen for muscle protein synthesis [53]. These acute differences in signaling responses between aerobic and resistance exercise might also reflect potential differences in the time course of muscular growth induced by both exercise modes. Future chronic studies might consider exploring this topic further by incorporating measurements of muscle hypertrophy at multiple time points during aerobic and resistance training interventions.

One additional matter worthy of discussion when comparing these two modes of exercise is motor unit recruitment. Henneman's size principle suggests that motor units are recruited in an orderly fashion [54]. During exercise, smaller motor units are recruited first and, as force production requirements increase, larger units are sequentially recruited as well [55].

Therefore, resistance exercise performed to momentary muscular failure ultimately elicits activation of the entire motor unit pool, which, in turn, should stimulate increases in muscle size. However, during long-lasting submaximal exercise, such as continuous cycling (the most common form of aerobic exercise across the included studies) the highest threshold motor units are not necessarily activated [55]. Therefore, it is possible that the greater muscular hypertrophy observed with resistance training is, at least partially, explained by these differences in recruitment.

The meta-analysis results for type I and type II fiber CSA support those seen for whole-muscle measures of hypertrophy. Given that the present meta-analysis favored resistance training for increasing both type I and type II fiber CSA, there appears to be no fiber-type specific hypertrophy response to aerobic versus resistance training. Some of the differences in results between the studies for muscle fiber CSA could be due to the modality of aerobic training. For instance, Kraemer et al. [23] reported that aerobic training, in the form of running, induced a decrease in type I and type II fiber CSA. The majority of remaining studies included in this meta-analysis employed cycling as opposed to running. Cycling may have a more localized stress on the knee extensor musculature than running, and, thus, might have a more pronounced effect on the hypertrophic response of this muscle group. That said, Coggan and colleagues measured fiber CSA of the gastrocnemius muscle and reported that walking/running was sufficient for increasing muscle fiber CSA [56], albeit in untrained older adults. Running involves concentric actions coupled with eccentric actions and, thus, it may result in higher levels of muscle damage than cycling (likely due to the shock waves associated with the loading pattern of running), which is a concentric-only mode of exercise [57]. In that regard, some studies show that, during the initial phases of training, in the presence of damage, muscle protein synthesis may be directed more towards restoring this damage than to building the contractile protein pool [58].

The study by Nelson et al. [24] is the only one that showed an advantage for aerobic training over resistance training for type I fiber CSA hypertrophy. However, it needs to be acknowledged that in this study there were considerable differences between the groups at baseline. For instance, the group doing resistance training had on average 8% of body fat, while the aerobic training group had on average 20% of body fat. Furthermore, the group doing resistance training had a relative VO_{2max} of on average 55 $mL \cdot kg^{-1} \cdot min^{-1}$ while the aerobic training group had an average value of 44 $mL \cdot kg^{-1} \cdot min^{-1}$. It might be that these differences between the groups at baseline influenced the results of the study.

While it seems that resistance training is more efficient for inducing hypertrophy of both type I and type II muscle fibers compared with aerobic training, given the relatively small number of studies undertaken thus far, further work is warranted on this topic. An aspect that makes it difficult to compare aerobic exercise training to resistance training on a single outcome (in this case muscle hypertrophy) is the various characteristics of the training programs (intensity, duration, etc.) across the included studies. Many resistance training programs in the included studies were designed to induce hypertrophy. On the contrary, most aerobic training programs were mainly focused on examining VO_{2max} or metabolic changes within the muscle, with muscle growth being a secondary or tertiary measure. Therefore, future studies should consider matching different exercise modalities based on effort and duration as the acute physiological responses (i.e., VO_2, blood lactate, energy expenditure, muscle swelling, and electromyography outcomes) may be quite similar between these two modes of exercise [59].

It is currently unclear whether matching resistance and aerobic training on the basis of effort and duration results in similar long-term adaptations.

4.1 Limitations

Most of the studies done thus far employed untrained individuals (Table 1) and these individuals are much more likely to positively respond to both aerobic and resistance exercise. The specificity of adaptive responses to aerobic and resistance training becomes more clear over time. This has also been shown in terms of protein synthetic responses to exercise, which become more more-specific (i.e., mitochondrial vs. myofibrillar) after a training period [53]. The study by Kraemer et al. [23] is the only one that included resistance-trained individuals. Therefore, while it may be expected that even a greater effect of resistance training (as compared to aerobic) would be seen in trained individuals. However, future studies among resistance-trained population are needed. In the present analysis, we pooled different forms of aerobic exercise such as cycling and walking/running, which may not have the same hypertrophic potential, as previously discussed. Additionally, the participants across the included studies ranged from young to older adults, and the responses to these modes of exercise might not be uniform across populations of different ages. Although we did used the random-effects model to address heterogeneity between the study designs, it remains unclear to what extent these factors influenced the pooled findings.

4.2 Methodological quality

Based on the methodological quality assessment, we can conclude that the results of the present meta-analysis were likely not confounded by poor study designs, as all included studies were deemed to be of moderate or good quality. The study by Nelson and colleagues

[24] had the lowest score on the Downs and Black checklist. However, this study is the earliest of all included studies in the present meta-analysis, and older studies often lack detail in their methodology sections. The two items added to the checklist (i.e., items 28 and 29) captured some important limitations in several of the included studies that are specific to exercise interventions. Studies that reported training adherence showed similar compliance between both types of training interventions. That said, it is important to highlight that several studies did not report participant adherence to the training intervention. This is a point of concern, given that any between-group differences in training adherence may have a pronounced effect on the muscular adaptations associated with each training intervention. Future studies should, therefore, ensure that training adherence is clearly reported for each training intervention, so that the comparison between training modes remains valid. Furthermore, in several of the included studies, it was not clear if the training programs had been supervised or not. This is an important consideration, as compared to unsupervised training, supervision has been shown to improve training outcomes such as gains in strength and lean body mass [60]. Studies should, therefore, explicitly state whether training programs were performed under supervision, to allow better interpretation of study methods and ultimately greater practical applicability.

5 Conclusions

The results of this systematic review and meta-analysis confirms the common belief that resistance training is more effective than aerobic training for promoting skeletal muscle hypertrophy and challenge recent suggestions that both forms of exercise are equally effective. This finding was consistent with measurements of muscle hypertrophy both at the whole-muscle and myofiber levels. While these results are specific to the knee extensor musculature, it could be hypothesized that similar results would likely be seen for other muscle groups as well. Although the identified studies were of moderate-to-good quality, future research comparing hypertrophic responses to resistance and aerobic training should include assessments of not only the knee extensors but also other muscle groups. Future studies should also consider incorporating different modalities of aerobic exercise (e.g., cycling vs. running) and including trained individuals, which likely show divergent adaptive responses to exercise compared with untrained individuals.

Compliance with Ethical Standards

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Conflict of interest

Jozo Grgic, Luke C. Mcllvenna, Jackson J. Fyfe, Filip Sabol, David J. Bishop, Brad J. Schoenfeld and Zeljko Pedisic declare that they have no conflicts of interest relevant to the content of this review.

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