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Applied Sciences

DOI:
[10.3390/app12031593](https://doi.org/10.3390/app12031593)

Published: 02/02/2022

Publisher's PDF, also known as Version of record

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):
Yagiz, G., Akaras, E., Kubis, H.-P., & Owen, J. A. (2022). The Effects of Resistance Training on Architecture and Volume of the Upper Extremity Muscles: A Systematic Review of Randomised Controlled Trials and Meta-Analyses. *Applied Sciences*, 12(3), Article 1593.
<https://doi.org/10.3390/app12031593>

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Review

The Effects of Resistance Training on Architecture and Volume of the Upper Extremity Muscles: A Systematic Review of Randomised Controlled Trials and Meta-Analyses

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Abstract: To systematically review the effects of exercise on fascicle geometry and muscle size parameters of the upper extremity muscles, the CENTRAL, CINAHL, PubMed and OpenGrey databases were searched on 31 July 2021. Finally, 17 randomised controlled trials (RCTs) were included in this systematic review. High-intensity bench press training ($g = 1.03$) and 12 RM bench press exercises ($g = 1.21$) showed a large effect size on increasing pectoralis major muscle size. In the elbow extensors, large effects were reported for an increase in muscle size with isometric maximal voluntary co-contraction training ($g = 1.97$), lying triceps extension exercise ($g = 1.25$), and nonlinear periodised resistance training ($g = 2.07$). In addition, further large effects were achieved in the elbow flexors via traditional elbow flexion exercises ($g = 0.93$), concentric low-load forearm flexion-extension training ($g = 0.94$, $g = 1$), isometric maximal voluntary co-contraction training ($g = 1.01$), concentric low-load forearm flexion-extension training with blood flow restriction ($g = 1.02$, $g = 1.07$), and nonlinear periodised resistance training ($g = 1.13$, $g = 1.34$). Regarding the forearm muscles, isometric ulnar deviation training showed a large effect ($g = 2.22$) on increasing the flexor carpi ulnaris and radialis muscle size. Results show that these training modalities are suitable for gaining hypertrophy in the relevant muscles with at least four weeks of training duration. Future RCTs should investigate the effects of exercise modalities on the triceps brachii fascicle geometry, the infraspinatus muscle thickness (MT) and the subscapular MT due to their associations with sports performance.

Keywords: biceps brachii; cross-sectional area; fascicle length; flexor carpi ulnaris; flexor carpi radialis; muscle architecture; muscle thickness; pectoralis major; pennation angle; triceps brachii



Citation: Yagiz, G.; Akaras, E.; Kubis, H.-P.; Owen, J.A. The Effects of Resistance Training on Architecture and Volume of the Upper Extremity Muscles: A Systematic Review of Randomised Controlled Trials and Meta-Analyses. *Appl. Sci.* **2022**, *12*, 1593. <https://doi.org/10.3390/app12031593>

Academic Editor: Nikolaos Zaras

Received: 12 January 2022

Accepted: 30 January 2022

Published: 2 February 2022

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1. Introduction

Training-induced muscle adaptations are one of the core elements in training strategies for players, coaches, sports teams, sports federations or non-athletes. The number of studies focusing on muscle architecture has increased due to increasing access to technology for non-invasive muscle visualisation methods, e.g., magnetic resonance imaging (MRI) and ultrasound measurements. For example, investigating relationships between muscle architectural parameters and sports performance, muscle strength or sports injuries, and adaptations resulting from training, detraining, bed rest, or micro-gravity has received attention from researchers. Approximately 65% of PubMed database records containing the term “muscle architecture” have been published in the last decade (Supplementary Table S1).

The term muscle architecture has a broad definition in the literature and includes the anatomical cross-sectional area (ACSA) and physiological cross-sectional areas (PCSA) of muscles, fascicle length (FL), muscle thickness (MT), muscle length and pennation angle (PA) [1]. These skeletal muscle architectural parameters identify the functional traits

of a muscle [2]. Studies revealed that muscle architectural parameters are predictors of strength [3–14], athletic performance [15–26] and athletic injuries [27–34].

The upper extremity muscles include muscles involving shoulder joint movements, e.g., rotator cuff muscles, the pectoralis major muscle, and the deltoid muscle; arm muscles, e.g., biceps brachii and triceps brachii; forearm muscles, e.g., flexor and extensor carpi ulnaris, flexor and extensor carpi radialis; and hand and wrist muscles, such as palmaris brevis, lumbrical muscles, hypothenar and thenar muscles [35]. Muscle size parameters of the upper extremity muscles are strongly correlated with better lifting ($r = 0.77$ – 0.91) [17], swimming ($r = -0.56$) [36], rowing ($r^2 = 0.195$) [37], and shot put performances ($r = 0.68$) [38]. Additionally, the upper extremity muscle sizes are significantly correlated with the upper extremity strength parameters such as elbow joint torque ($r = 0.705$ – 0.945) [39], elbow flexion maximal power ($r = 0.81$) [40], elbow extensor strength ($r = 0.7$ – 0.78) [41], finger extension force ($r_s = 0.85$) [42], bench press strength ($r = 0.866$) and bench throw peak power ($r = 0.821$) [43], and shoulder external rotation strength ($r = 0.287$) [44]. Regarding the upper extremity muscles' fascicle geometry, the triceps brachii FL is one of the best predictors of better 200 -m front crawl swimming time ($r^2 = 0.392$) [36] and significantly correlated with better swimming ($r = -0.64$) [36] and lifting performances ($r = 0.45$ – 0.52) [17]. The triceps brachii PA was significantly correlating with elbow extension strength parameters ($r = 0.471$ – 0.563) [45].

Training-induced muscle architectural changes may depend on the exercise's contraction type. Eccentric (lengthening) and concentric (shortening), and isometric training can lead to comparable hypertrophic responses in skeletal muscles [46,47]. Kawakami et al. [48] noted muscle size increments are accompanied by pennation angle increases in hypertrophied muscles. By comparison, Franchi, Reeves, and Narici [46] highlighted that the underlying myogenic and molecular responses may be different in eccentric and concentric muscle actions because the eccentric training is considered to favour increases in fascicle length, and concentric training to favour higher increments of pennation angle [46]. A recent study by Pincheira et al. [49] showed that eccentric training can increase fascicle length by increasing sarcomere lengths. Another study stated that concentric, eccentric and isometric exercises can lead to similar increases in total DNA and RNA quantities, which are representative of muscle hypertrophy; however, concentric and isometric training increases muscle insulin-like growth factor 1 mRNA levels, whereas eccentric training does not increase these levels [46]. In short, there may be different underlying myogenic and molecular mechanisms of different training-induced muscle adaptations depending on the contraction type.

In consideration of the importance of the architectural parameters of upper extremity muscles for strength, power, rate of force development and sports performance, screening training-induced adaptations in the architecture of the upper extremity muscles may be a reference point for future training and conditioning directions for both athletes and non-athletes who target the upper extremities. Therefore, this systematic review with meta-analyses aimed to screen and reveal the effects of exercise on all available upper extremity muscles' volumes and architectural parameters that include fascicle geometry and muscle size variables.

2. Materials and Methods

This review followed the guidance of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [50]. The PRISMA 2020 checklist includes a 27 -item checklist for all sections of a systematic review. The PRISMA 2020 checklist is shown in Supplementary File S1. Before this systematic review, a review protocol was registered on INSPLASY (INPLASY202050074) [51].

2.1. Information Sources and Database Search Strategy

On 31 July 2021, Cochrane Central Register of Controlled Trials (CENTRAL), CINAHL, PubMed, and OpenGrey database searches were completed by using a combination of the

key terms of 'Exercis*', 'Training*', 'Architectur*', 'Fascic*', 'Fiber Length', 'Fibre Length', 'Pennat*', 'Pinnat*', 'Morphology', 'Muscle Thickness', 'Cross Sectional Area', 'Cross-sectional Area', 'Muscle Volume', 'Muscle Structure', and 'Muscle Length' without any time, language, study type etc. restrictions. Detailed search strategies for each database are presented in Supplementary File S2.

2.2. Eligibility Criteria and Study Selection Process

Firstly, the duplicate records were automatically removed via the EndNote X⁹ computer [52] program by the first author. Then, the remaining citations were imported to the Rayyan web application [53], which was designed for screening eligible studies for systematic reviews. The first and second authors independently screened the citations for eligibility, and they were blinded to decisions until the end of the screening process. Any conflicts that arose about the inclusion of the studies was firstly solved by discussion between the first and second authors. The third and fourth authors were considered referees if there were unresolved discussions. This conflict -solving mechanism was also applied during the risk of bias assessment and data extraction processes. Bangor University libraries retrieved non-available full-texts.

The following inclusion criteria were considered (1) being a randomised controlled trial, (2) being a full-text journal article in the English language, (3) exercise interventions lasting at least four weeks in healthy adults between 18 and 50 years old, (4) solely investigating exercise interventions, (5) using a non-invasive imaging technique (i.e., magnetic resonance imaging (MRI), ultrasonography) to assess muscle architectural parameters of a defined muscle or muscle groups of the upper extremities; and (6) presenting outcomes related to at least one muscle architectural parameter.

2.3. Outcome Measures

Changes in architectural parameters involving cross-sectional areas, fascicle length, muscle thickness, muscle volume and pennation angle of upper extremity muscles due to an exercise intervention were the outcome measures of this systematic review and meta-analysis.

2.4. Risk of Bias Assessments of Eligible Studies

For assessing the risk of bias of the included studies, the Cochrane Collaboration's tool for assessing the risk of bias in randomised trials [54] was employed. The first and second authors independently assessed the risk of bias for each eligible study regarding random sequence generation (selection bias), allocation concealment (selection bias), blinding participants and personnel (performance bias), blinding outcome assessment (detection bias), incomplete outcome data (attrition bias), selective reporting (reporting bias) and other biases. Risk of bias categories were marked as "high risk of bias", "unclear risk of bias", and "low risk of bias".

2.5. Data Extraction

Information for groups, age, gender, number and physical activity levels of participants, type of exercises allocated for groups, the materials used during the exercise, exercising procedure, duration, number of sessions, sets and repetitions, targeted muscle or muscle groups, measurement device and region, type of muscle architectural parameters, pre-test and post-test values, statistical analyses and results were independently extracted from eligible studies by the first and second authors.

2.6. Meta-Analyses

Meta-analyses of this review were conducted via the Review Manager computer program (RevMan 5.4.1) [55]. A non-training control of the placebo group was considered the comparator for this systematic review. RevMan automatically calculates Hedges' (adjusted) *g* effects size (standardised mean difference (SMD)) using the mean difference

(MD) from baseline and the standard deviation (*SD*) of these mean differences for exercise and control groups [56]. The difference between the Hedges' *g* and Cohen's *d* is the adjustments of Hedges' *g* effect size calculations for a small sample having fewer than 20 participants [57]. Effect size interpretation was considered the commonly used interpretation for both Hedge's *g* [58] and Cohen's *d* [59] that small (0.2), medium (0.5) or large (0.8) [60].

The standard deviations of the mean changes from baseline is defined as a common missing outcome data [61] and difficulties for running a meta-analysis without missing *SDs* explained by previous systematic reviews [62,63]. For calculating missing *SDs*, a formula was defined as [64,65]:

$$SD_{change} = \sqrt{SD_{baseline}^2 + SD_{final}^2 - (2 \times r \times SD_{baseline} \times SD_{final})}$$

SDchange means the *SD* of the mean changes from baseline, *SDbaseline* represents the *SD* of the pre-test, *SDfinal* corresponds to the *SD* of the post-test, and the *r* symbolise the correlations between the baseline and final measurements; this correlation value is not generally presented in the studies. For instance, among the studies eligible for this systematic review, none demonstrate this *r*-value. Based on this, this systematic review employed the following process for obtaining the missing outcome data: Firstly, given additional data, e.g., confidence intervals, *p*-values, *t*-values, *F*-values, and standard errors were controlled and missing *SDchanges* from baseline were estimated using RevMan [55]. However, the first step could not be applied due to the lack of information in the included studies. As a second step, corresponding authors of the included studies were contacted to request their data -sets or the mean and *SDchanges* from baseline values, as previously recommended [61–63]. Thirdly, if the corresponding authors did not share their data with this systematic review, and the *SDbaseline* and *SDfinal* values were known, the *SDchange* value was calculated by assigning a value of 0.7 to the *r* in the formula [64,65], to provide a conservative estimate [66] as undertaken by previous systematic reviews [67–70]. Finally, if there were still missing outcome data, the study was not included in the meta-analysis and is mentioned separately in the -text.

The heterogeneity of a meta-analysis was measured by the chi-squared (χ^2 or Chi²) statistic and the level of heterogeneity was estimated by the *I*² statistic, which indicates the percentage ratio of the variability in effect estimates caused by heterogeneity rather than chance [71]. *I*² results were interpreted as low (25%), moderate (50%) and high (75%) [72]. When statistical heterogeneity was absent (*p* > 0.05 in the Chi² statistics), a meta-analysis was performed for a continuous data, inverse variance, fixed-effect model [73] and a 95% confidence interval (95% CI). However, when statistical heterogeneity was observed, a meta-analysis was performed using a more conservative random effect model for continuous data, inverse variance and a 95% CI [73].

2.7. Level of Evidence of the Meta-Analyses

Each meta-analysis result in RevMan was exported to GRADEpro GDT software [74], and the level of evidence (LoE) of meta-analyses was graded by applying the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) method as described in the GRADE handbook [75], and recommended by the Cochrane Collaboration's tool for assessing the risk of bias in randomised trials [54], and the Cochrane Handbook for Systematic Reviews of Interventions [61]. The GRADE approach categorises the LoE of each meta-analysis as high, moderate, low and very low [75]. The GRADEpro GDT software measures LoE of meta-analyses based on the study design, risk of bias, inconsistency, indirectness, imprecision and publication bias features.

3. Results

3.1. Study Screening and Selection

Initially, 8388 records were identified from database searches. After removing duplicates, 6524 records were screened based on titles and abstracts, and 6460 of these records were excluded according to pre-determined exclusion criteria. Finally, 64 records were examined based on the full -texts, and 17 randomised controlled trials (RCTs) [76–92] were included in this systematic review. The study screening and selection process is illustrated in a PRISMA 2020 flow diagram (Figure 1).

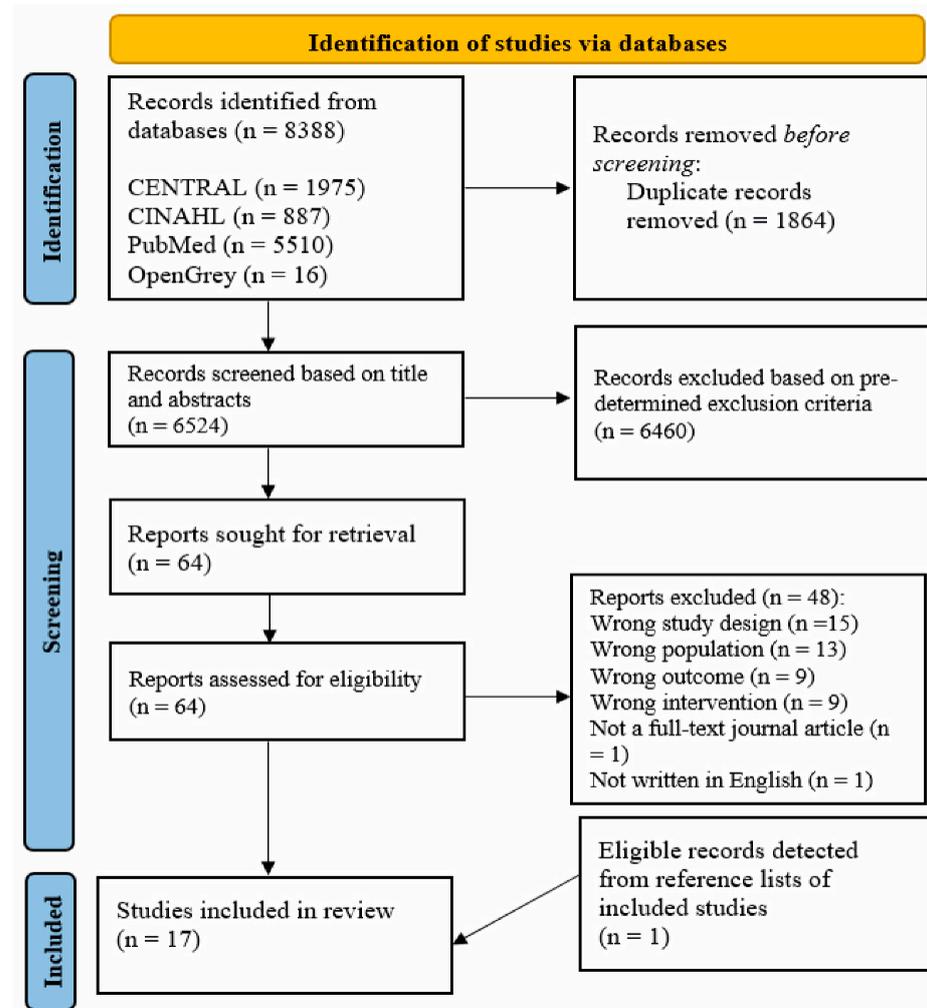


Figure 1. PRISMA 2020 flow diagram.

3.2. Risk of Bias Assessments

The low risk of bias scores range from two [92] to five [77] of seven sections of the Cochrane Collaboration’s tool for assessing the risk of bias in randomised trials [54] among the included RCTs [76–92]. A risk of bias summary figure, which shows review authors’ judgements about each risk of bias item for each included study (Figure 2), and a risk of bias graph, which shows the review authors’ conclusions about each risk of bias item presented as percentages across all included studies (Figure 3) were created via RevMan for further use in determining the level of evidence of meta-analyses using GRADEpro GDT software [74].

	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Akagi et al. (2016)	+	?	-	?	+	+	+
Dankel et al. (2020)	+	+	-	+	+	+	?
Farthing et al. (2005)	+	?	-	?	?	+	?
Hill et al. (2018)	+	?	-	?	+	+	+
Hill et al. (2020)	+	?	-	?	+	+	+
Krentz et al. (2017)	+	?	-	?	?	+	?
Kubo et al. (2021)	+	?	-	?	?	+	+
Maeo et al. (2014)	+	?	-	?	+	+	+
Maeo et al. (2014a)	+	?	-	?	+	+	+
Matta et al. (2011)	+	?	+	?	?	+	+
Pinto et al. (2012)	+	?	-	?	?	+	?
Radaelli et al. (2015)	+	?	-	?	?	+	+
Simao et al. (2012)	+	?	-	?	?	+	+
Spineti et al. (2010)	+	?	-	?	+	+	?
Spineti et al. (2014)	+	?	-	?	+	+	?
Yasuda et al. (2011)	+	?	-	?	?	+	+
Yasuda et al. (2011a)	+	?	-	?	?	?	+

Figure 2. Risk of bias summary: review authors’ judgements about each risk of bias item for each included study. References for the studies in the table with the same publication year are Maeo et al. (2014) [83], Maeo et al. (2014a) [84], Yasuda et al. (2011) [91] and Yasuda et al. (2011a) [92].

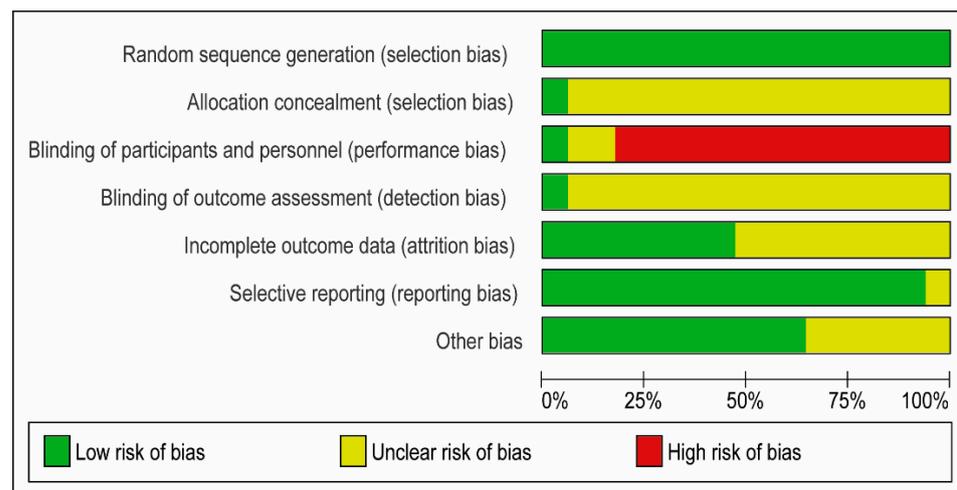


Figure 3. Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.

3.3. Participants' and Intervention Characteristics of the Included Studies

Participants' characteristics in the eligible studies, including age, gender, sample size and physical activity level of participants, are presented in Supplementary Table S1. Additionally, intervention characteristics of the included studies that involve the type of exercises allocated for groups, exercise material, exercising procedure, total weeks, sessions, sets and repetitions, targeted muscle or muscle groups, measurement device and region, type of muscle architectural parameters, pre-test and post-test values, statistical analyses and results are shown in Supplementary Table S2.

3.4. Meta-Analyses

Initially, none of the included 17 RCTs [76–92] showed the required SD changes from baseline to allow a meta-analysis to be performed. Additionally, in-text information provided by the included studies was not enough to calculate these missing SDs from baseline using the RevMan calculator [55]. Therefore, corresponding authors of the eligible studies were contacted to obtain the required data. Missing outcome data of seven RCTs [76,77,79,83,84,89,90] were collected in this way. As a second step, if the corresponding authors did not share their data with this systematic review, and the SD_{baseline} and SD_{final} values were known, the SD_{change} value was calculated by assigning a value of 0.7 to the r in the formula [64,65], to provide a conservative estimate [66] as used by previous systematic reviews [67–70]. Using this method, four additional RCTs [78,82,88,91] were included in quantitative analyses. In total, eleven RCTs [76–79,82–84,88–91] were included in the meta-analyses of this systematic review. Due to the insufficient outcome data, six RCTs [80,81,85–87,92] were not included in a meta-analysis. However, participants and intervention characteristics and the results of these studies are presented in Supplementary Tables S1 and S2.

3.4.1. The Chest

Ten weeks of 12RM resistance bench press training [82] showed a large effect on increasing the pectoralis major MV ($g = 1.21$ [0.21, 2.21]), whereas 10-weeks of 4RM and 8RM resistance bench press training [82] showed a medium effect on increasing the same parameter ($g = 0.61$ [−0.29, 1.51], $g = 0.64$ [−0.23, 1.5], respectively) (Figure 4). Overall, the bench press training showed a large effect ($g = 0.79$ [0.26, 1.32], LeO = low) on increasing the pectoralis major muscle volume. Six weeks of high-intensity bench press training [91] led to large increments in the pectoralis major muscle CSA ($g = 1.03$ [0.09, 1.98], LeO = very low) (Figure 5). Additionally, 6-weeks of low-intensity bench press training with BFR [91]

led to medium increments in the pectoralis major muscle CSA ($g = 0.63 [-0.27, 1.54]$, LeO = very low) (Figure 6).

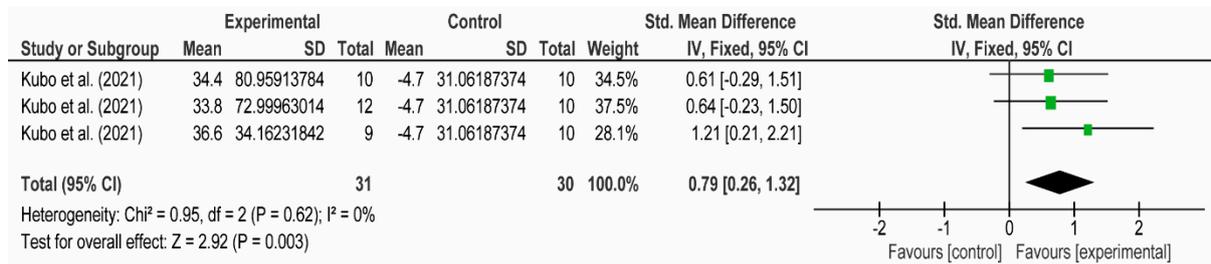


Figure 4. The effect size of 10-weeks of resistance training on increasing the pectoralis major MV. The lines respectively correspond to 4RM, 8RM and 12RM training groups.

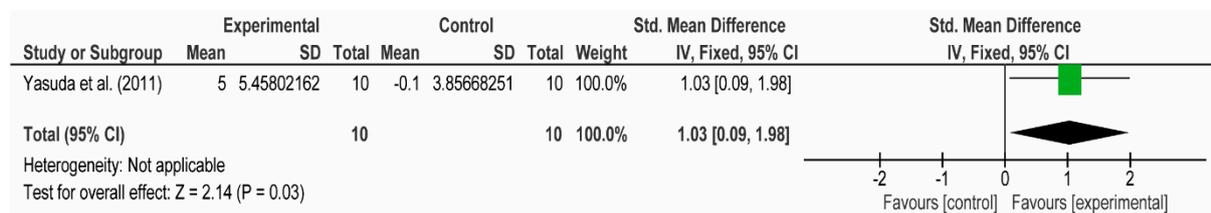


Figure 5. The effect size of 6-weeks of high-intensity resistance training on the pectoralis major muscle CSA.

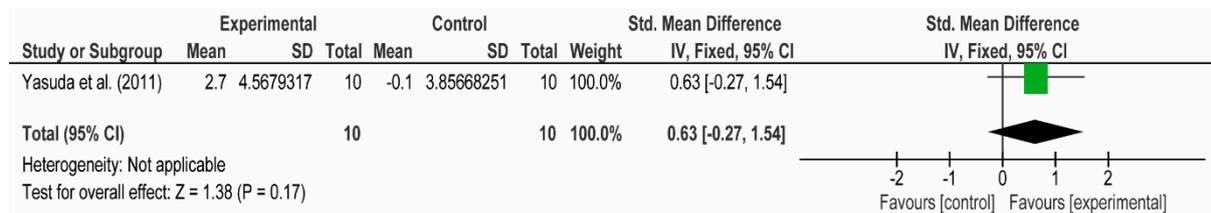


Figure 6. The effect size of low-intensity bench press training with blood-flow restriction on the pectoralis major CSA.

3.4.2. The Posterior Arm

Six weeks of lying triceps extension exercise [76], which was performed via a dumbbell adjusted at 80% of 1 repetition maximum (RM), showed a large effect size ($g = 1.25 [0.33, 2.16]$, LeO = moderate) to increase the triceps brachii long head MT (Figure 7). Six weeks of high-intensity bench press training [91] showed a medium effects size on increasing the triceps brachii muscle CSA ($g = 0.72 [-0.19, 1.63]$, LeO = very low) (Figure 8). Six weeks of low-intensity bench press training with BFR [91] showed a small effect on increasing the triceps brachii muscle CSA ($g = 0.41 [-0.48, 1.3]$, LeO = very low) (Figure 9). Twelve weeks of linear periodised resistance training [88,90] showed a trivial effect on increasing the triceps brachii MT ($g = 0.15 [-0.40, 0.7]$, LeO = very low) (Figure 10). Twelve weeks of nonlinear periodised resistance training [88,90] showed a small effect on increasing the triceps brachii MT ($g = 0.33 [0.56, 1.7]$, LeO = very low) (Figure 11). On the contrary, 12-weeks of nonlinear periodised resistance training [89] illustrated a large effect size on increasing the triceps brachii MV ($g = 2.07 [1.26, 2.89]$, LeO = high) (Figure 12). The isometric maximal voluntary co-contraction training [83,84] (4 and 12 weeks of study duration combinations) showed a large effect on increasing the MT of the elbow extensors ($g = 1.97 [-0.63, 4.56]$, LeO = moderate) (Figure 13).

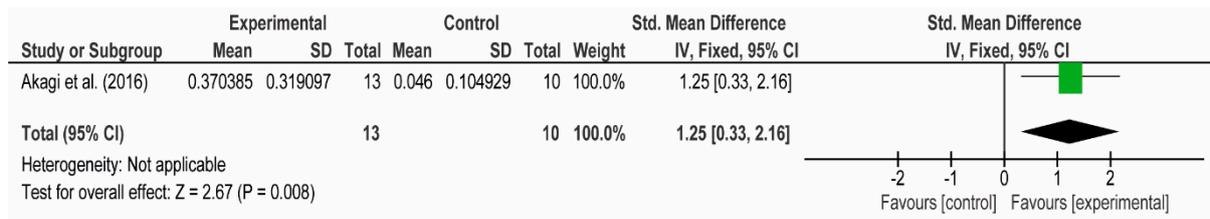


Figure 7. The effect size of 6-weeks of lying triceps extension exercise (sequential concentric and eccentric elbow extensions) on the triceps brachii long head MT.

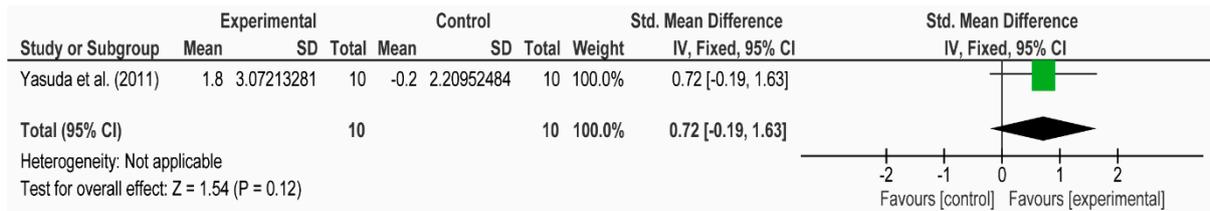


Figure 8. The effect size of 6-weeks of high-intensity training on the triceps brachii muscle CSA.

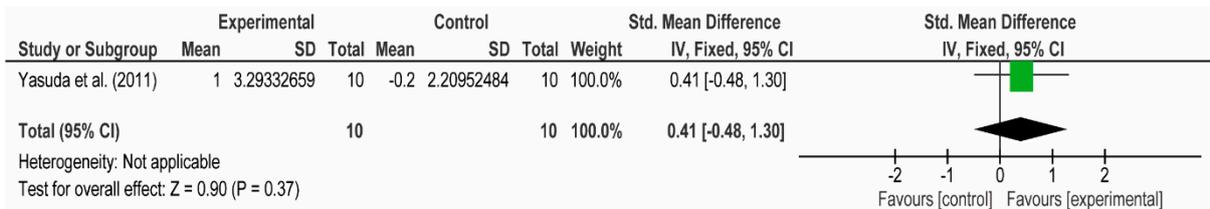


Figure 9. The effect size of low-intensity bench press training with blood-flow restriction on the triceps brachii CSA.

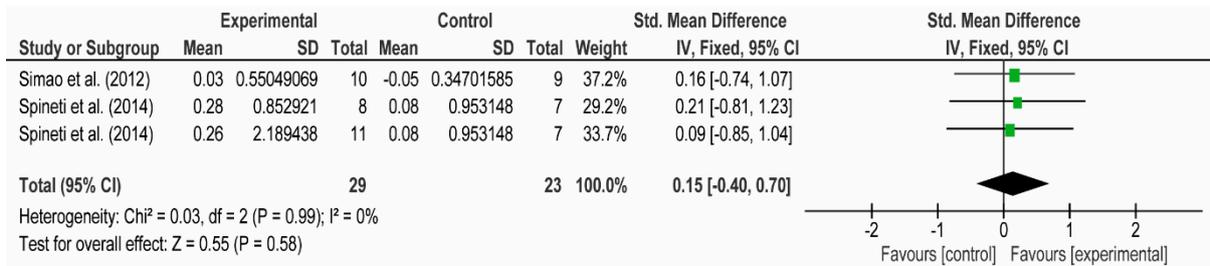


Figure 10. The effect size of 12-weeks of linear periodised resistance training on increasing the triceps brachii MT. The lines for Spineti et al. [90] respectively represent linear periodised large to small muscle training and small to large muscle training groups.

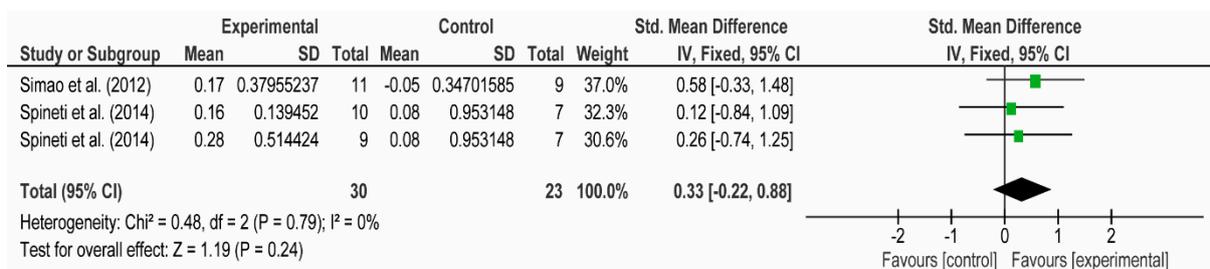


Figure 11. The effect size of 12-weeks of nonlinear periodised resistance training on increasing the triceps brachii MT. The lines for Spineti et al. [90] respectively represent nonlinear periodised large to small muscle training and small to large muscle training groups.

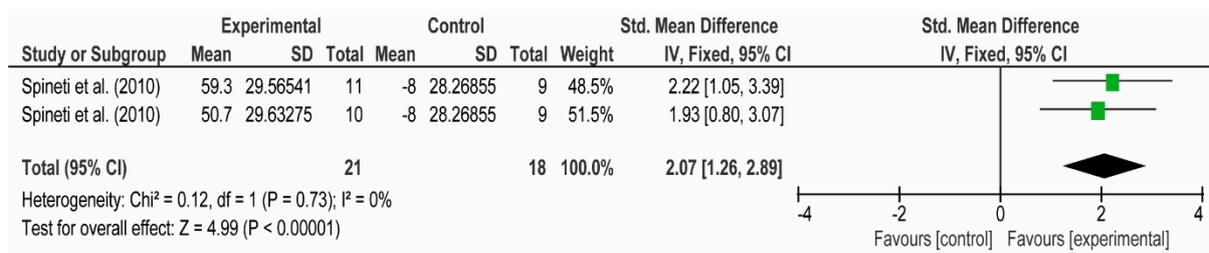


Figure 12. The effect size of 12-weeks of nonlinear periodised resistance training on increasing the triceps brachii MV. The lines for Spineti et al. [89] respectively represent nonlinear periodised large to small muscle training and small to large muscle training groups.

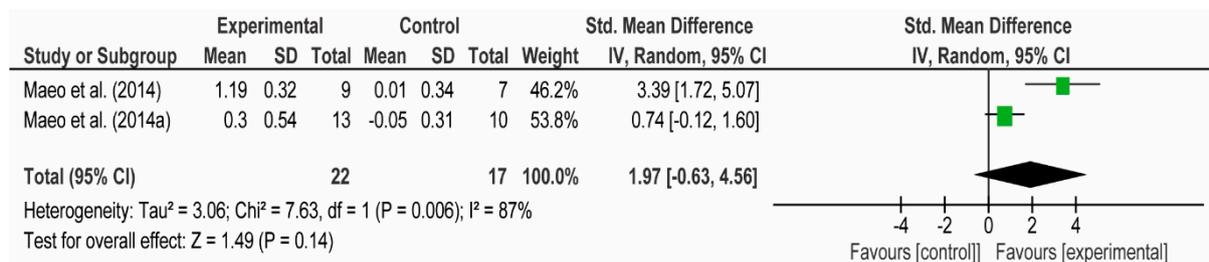


Figure 13. The effect size of isometric maximal voluntary co-contraction training on the elbow extensors MT. References for the studies in the table with the same publication year are Maeo et al. (2014) [83], Maeo et al. (2014a) [84].

3.4.3. The Anterior Arm

Four weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training with vBFR (40% of lowest pressure needed to restrict brachial artery) [79] showed a large effect size on increasing the biceps brachii MT ($g = 1.07$ [0.12, 2.02], LeO = low) (Figure 14), and on increasing the biceps brachii CSA ($g = 1.02$ [0.07, 1.96], LeO = low) (Figure 15). Additionally, 4-weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training [79] showed a large effect size on increasing the biceps brachii MT ($g = 0.94$ [0.01, 1.87], LeO = low) (Figure 16), and on increasing the biceps brachii CSA ($g = 1$ [0.06, 1.94], LeO = low) (Figure 17). Twelve weeks of linear periodised resistance training [88,90] showed a medium effect on increasing the biceps brachii MT ($g = 0.73$ [0.18, 1.28], LoE = very low) (Figure 18). In contrast, 12-weeks of nonlinear periodised resistance training [88,90] showed a large effect on increasing the biceps brachii MT ($g = 1.13$ [0.56, 1.7], LeO = low) (Figure 19). Similarly, 12-weeks of nonlinear periodised resistance training [89] illustrated a large effect size on increasing the biceps brachii MV ($g = 1.34$ [0.63, 2.06], LeO = moderate) (Figure 20). Six weeks of traditional elbow flexion exercises [77] using a dumbbell showed a large effect size on increasing the elbow flexors MT ($g = 0.93$ [0.69, 1.17], LeO = high) (Figure 21), whereas heavy training [77] showed a small effect on the same parameter ($g = 0.38$ [0.15, 0.6], LeO = high) (Figure 22). Finally, the isometric maximal voluntary co-contraction training [83,84] (4 and 12 weeks of study duration combinations) showed a large effect on increasing the MT of the elbow flexors ($g = 1.01$ [0.33, 1.69], LeO = moderate) (Figure 23).

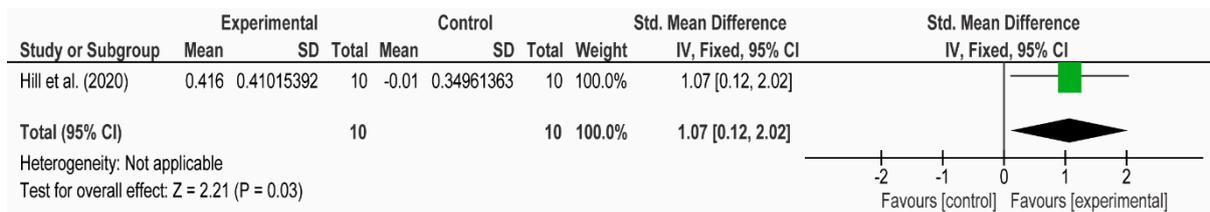


Figure 14. The effect size of 4-weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training with vBFR (40% of lowest pressure needed to restrict brachial artery) on increasing the biceps brachii MT.

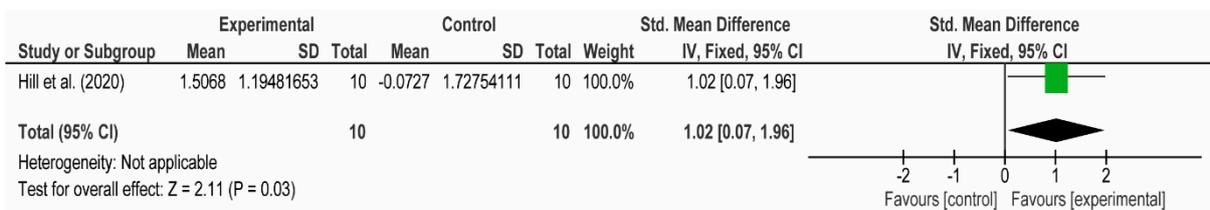


Figure 15. The effect size of 4-weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training with vBFR (40% of lowest pressure needed to restrict brachial artery) on increasing the biceps brachii CSA.

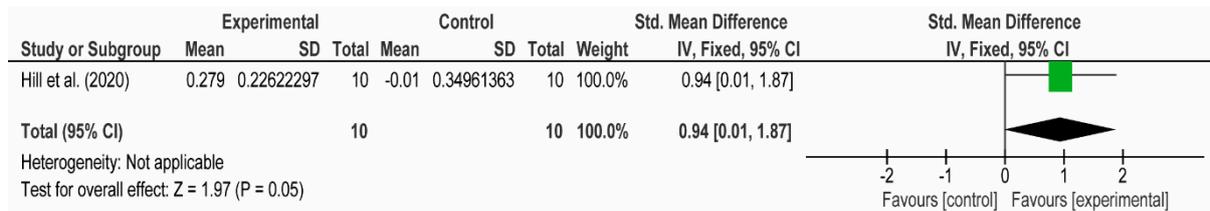


Figure 16. The effect size of 4-weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training on increasing the biceps brachii MT.

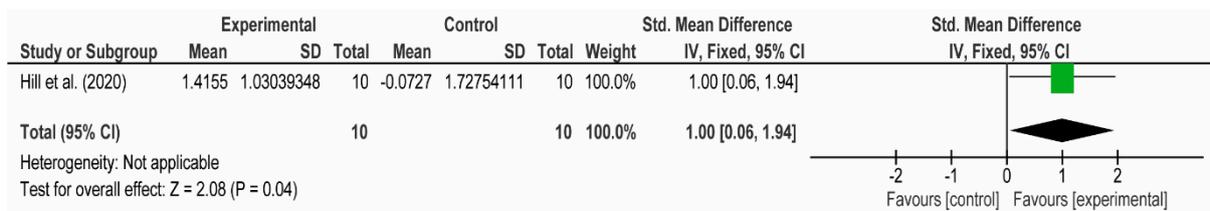


Figure 17. The effect size of 4-weeks of concentric low-load (at 30% of concentric elbow flexion peak torque) forearm flexion-extension training on increasing the biceps brachii CSA.

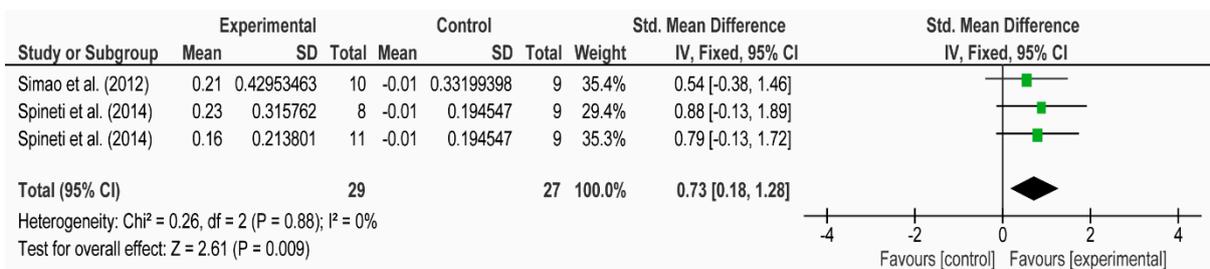


Figure 18. The effect size of 12-weeks of linear periodised resistance training on increasing the biceps brachii MT. The lines for Spinetti et al. [90] respectively represent linear periodised large to small muscle training and small to large muscle training groups.

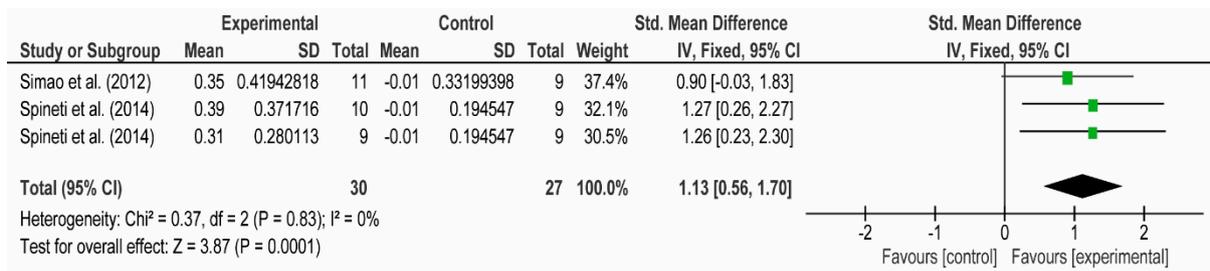


Figure 19. The effect size of 12-weeks of nonlinear periodised resistance training on increasing the biceps brachii MT. The lines for Spinetti et al. [90] respectively represent nonlinear periodised large to small muscle training and small to large muscle training groups.

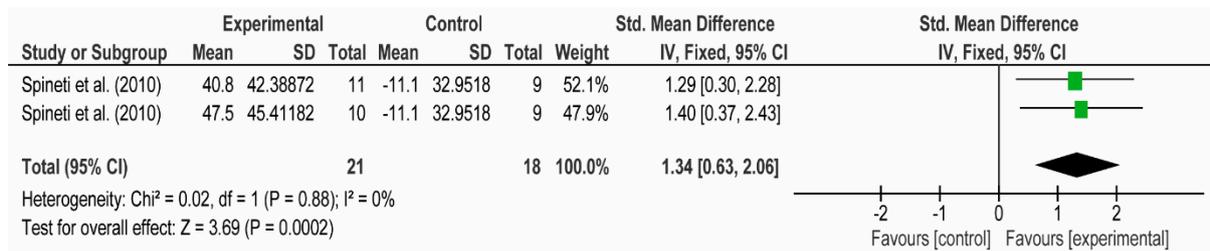


Figure 20. The effect size of 12-weeks of nonlinear periodised resistance training on increasing the biceps brachii MV. The lines for Spinetti et al. [89] respectively represent nonlinear periodised large to small muscle training and small to large muscle training groups.

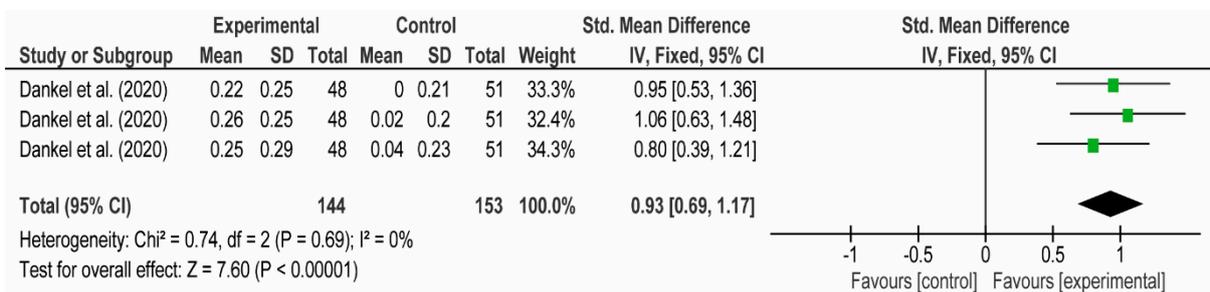


Figure 21. The effect size of 6-weeks of traditional elbow flexion exercise on the elbow flexors' MT. The lines respectively represent 50%, 60% and 70% measurement levels of elbow flexors' MT.

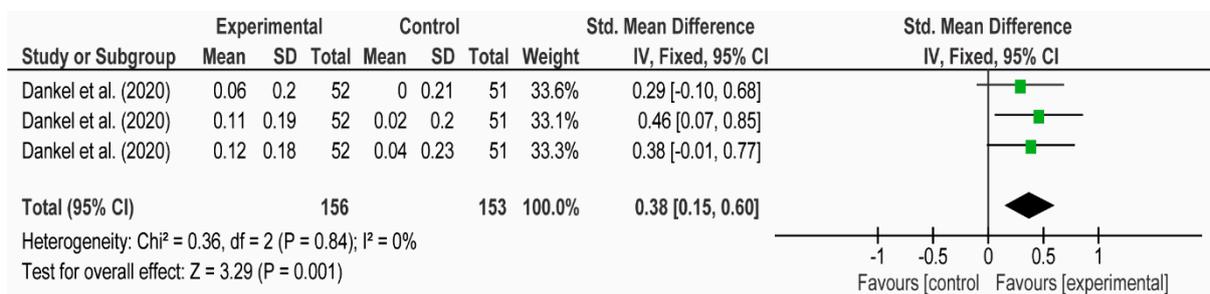


Figure 22. The effect size of 6-weeks of heavy elbow flexion exercise on the elbow flexors' MT. The lines respectively represent 50%, 60% and 70% measurement levels of elbow flexors' MT.

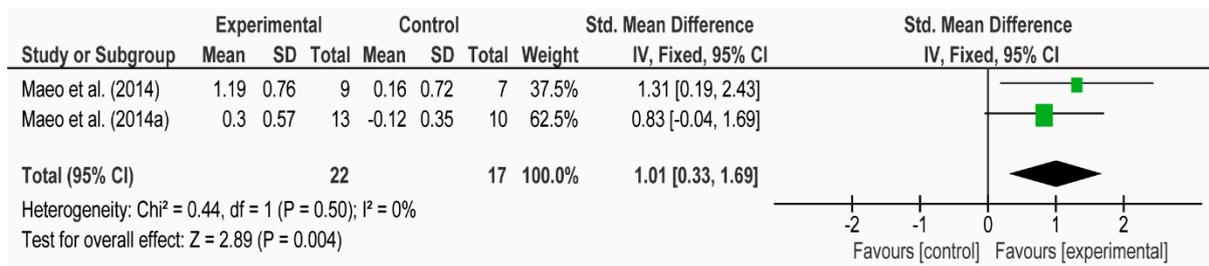


Figure 23. The effect size of isometric maximal voluntary co-contraction training on the elbow flexors MT. References for the studies in the table with the same publication year are Maeo et al. (2014) [83], Maeo et al. (2014a) [84].

3.4.4. Forearm

Six weeks of isometric ulnar deviation training [78] showed a large effect ($g = 2.22$ [−0.9, 5.33], LeO = very low) on increasing the flexor carpi ulnaris and radialis MT of the trained right and left hands (Figure 24).

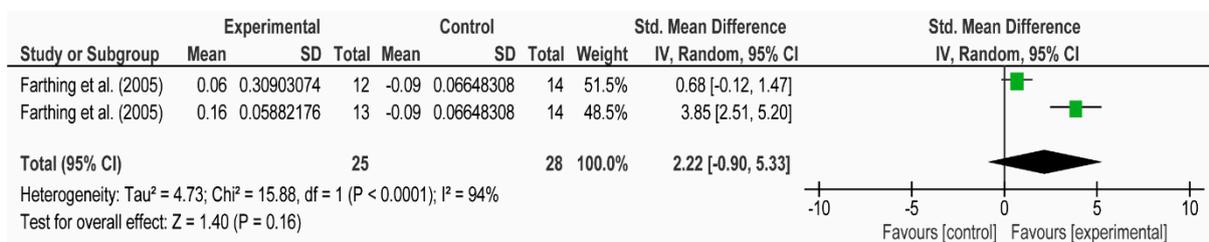


Figure 24. The effect size of 6-weeks of isometric ulnar deviation training [78] on flexor carpi ulnaris and radialis MT of the trained right and left hands. The first line represents the right hand (dominant) trained group, and the second line represents the left hand (non-dominant) trained group.

3.5. Level of Evidence of the Meta-Analyses

The LoE of each meta-analysis was determined using the GRADEpro GDT software [74] according to the GRADE handbook [75] as described in the methodology section of this systematic review. The LoE values of meta-analyses ranged from very low to high. The LoE of each meta-analysis is presented in Supplementary File S3.

4. Discussion

To the authors’ knowledge, this systematic review with meta-analyses is the first screening of RCTs for the effects of all types of exercises on the architecture of upper extremity muscles. This systematic review with meta-analyses aimed to overview the effects of exercise interventions on improving the architecture of upper extremity muscles. The meta-analyses of this systematic review revealed that most exercise interventions with at least 4-weeks of exercise duration showed large effect sizes for increasing the size of individual upper extremity muscle or muscle groups (Figures 25–28). In summary, the following exercises showed large effects on increasing the size of the targeted muscles: high-intensity concentrically-biased bench press training for the pectoralis major; lying concentrically-biased triceps extension, isometric maximal voluntary co-contraction training, and nonlinear periodised resistance training for the triceps brachii; traditional concentric elbow flexion exercise, low-load concentric forearm flexion-extension training without and with blood-flow restriction, isometric maximal voluntary co-contraction training, and nonlinear periodised resistance training for the biceps brachii; and isometric ulnar deviation training for the flexor carpi ulnaris and radialis.

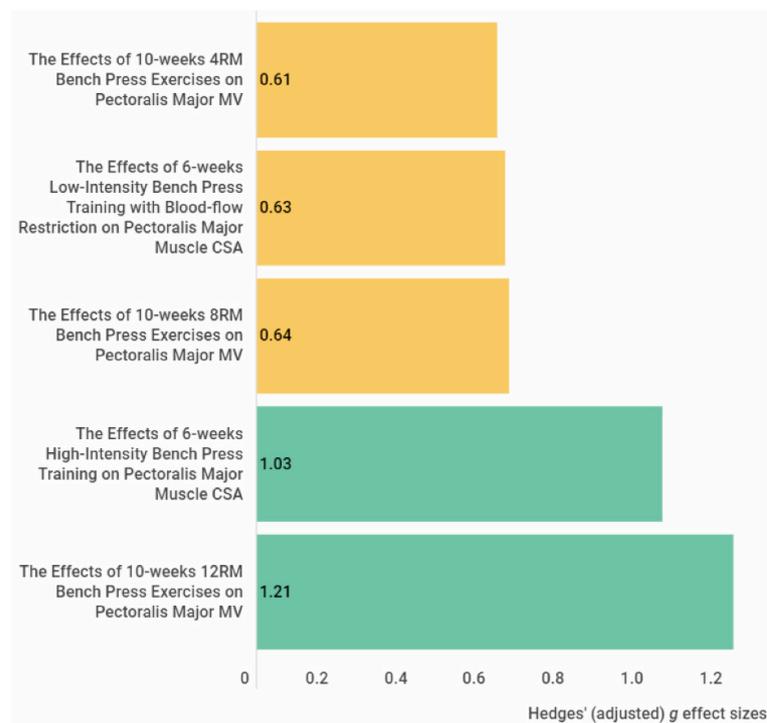


Figure 25. The effect size of the exercise interventions on the pectoralis major muscle cross-sectional area and volume. The yellow colour indicates a medium effect size, and the green colour indicates a large effect size. Abbreviations: CSA, cross-sectional area, MV, muscle volume.

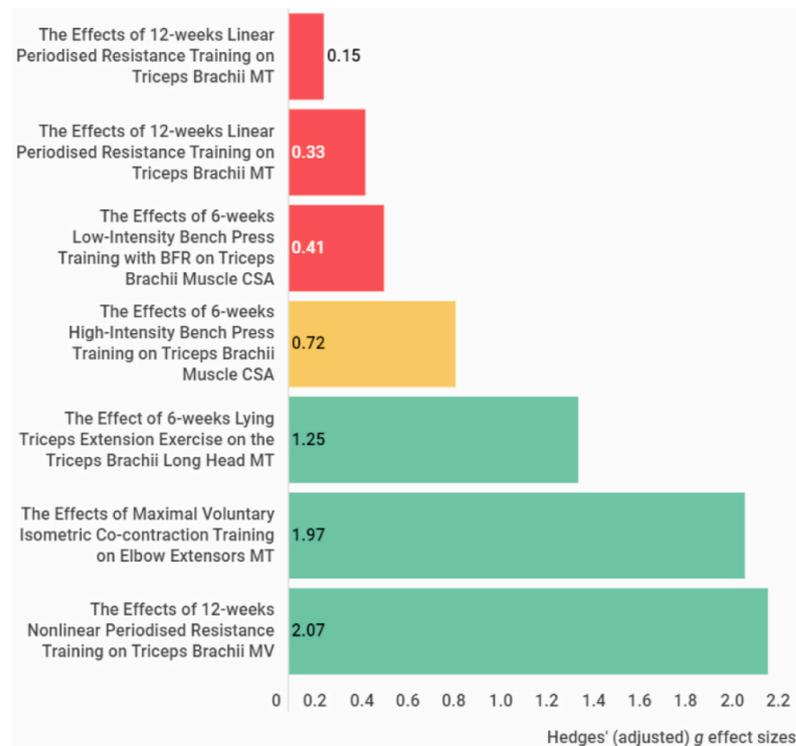


Figure 26. The effect size of the exercise interventions on the elbow extensor muscle thickness, cross-sectional muscle area and muscle volume. The red colour indicates a small or trivial effect size, the yellow colour indicates a medium effect size, and the green colour indicates a large effect size. Abbreviations: CSA, cross-sectional area; MT, muscle thickness; MV, muscle volume.

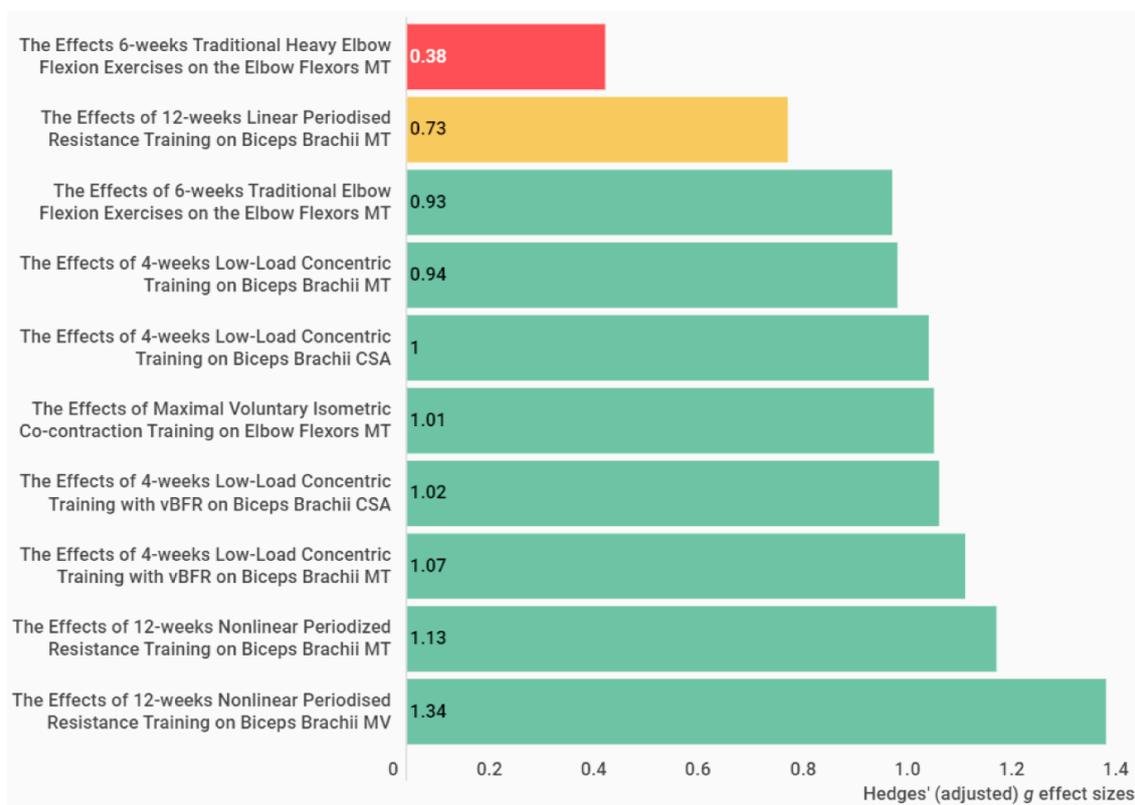


Figure 27. The effect size of the exercise interventions on the elbow flexors muscle thickness, muscle cross-sectional area and muscle volume. The red colour indicates a small or trivial effect size, the yellow colour indicates a medium effect size, and the green colour indicates a large effect size. Abbreviations: CSA, cross-sectional area; MT, muscle thickness; MV, muscle volume.

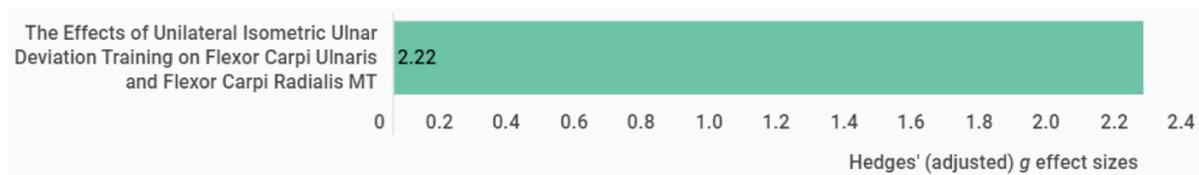


Figure 28. The effect size of the exercise interventions on the forearm flexors muscle thickness. The green colour indicates a large effect size. Abbreviations: MT, muscle thickness.

In addition to the training modalities included in the meta-analyses, six RCTs [75,76,80–82,87] were not included in the meta-analyses due to missing outcome data. The findings and intervention characteristics of the RCTs are presented in Supplementary Table S3. Among these RCTs, Matta et al. [85] investigated the effects of a nonlinear periodised strength training program on biceps brachii and triceps brachii MT and the triceps brachii long head PA and reported significant alterations in the outcome measures depending on the arm sites. The study of Matta et al. [85] was the only RCT that measured the PA of a muscle, which is a fascicle geometry component, among the eligible RCTs. The triceps brachii long head PA was significantly correlated with the strength parameters of the elbow extensors [45]. By comparison, the triceps brachii long head FL was one of the best predictors of a better swimming performance [36] and significantly correlated with lifting performance parameters [17]. However, there was no RCT that investigated the effects of an exercise intervention on the FL of triceps brachii long head. Although it did not meet the inclusion criteria of this systematic review, a recent uncontrolled trial [93] compared the effects of concentrically-biased cable push-down and cable overhead extension exercises, and Stasinaki and colleagues [93] did not report significant alterations in the FL of the triceps brachii long head even when the concentric

elbow extension starts from a fascicle lengthened position. This may be due to the effects of concentric training. A future RCT should examine the impacts of eccentric training on the FL of triceps brachii long head.

In terms of the muscle size parameters, the triceps brachii MT has been found to be strongly correlated with elbow extension strength [41]. Additionally, the triceps brachii MT was stated as being significantly correlated with better swimming performance ($r = -0.56$) [36]. Moreover, elbow extensors' and flexors' muscle size parameters (ACSA, PCSA and MV) showed significant strong correlations with elbow joint torque ($r = 0.705-0.945$) [39]. Furthermore, the elbow extensors' cross-sectional muscle area (CSA) was correlated with rowing performance, and was the significant best predictor of arm pull during the rowing activity in rowers ($r^2 = 0.195$) [37]. Elbow flexors CSA showed a strong correlation with elbow flexion maximal power ($r = 0.81$) [40]. Arm muscles CSA was significantly correlated with shot put performance ($r = 0.68$) [38]. The pectoralis major muscle CSA was strongly correlated with bench press strength ($r = 0.866$), and muscle volume was strongly correlated with bench throw peak power ($r = 0.821$) [43]. Either concentric, isometric, eccentric or blood-flow restricted resistance training modalities led to significant muscle hypertrophies. Based on these findings, athletes, healthy individuals aiming to increase their related performance or muscle strength parameters, astronauts after a space mission [94] and patients experiencing muscle atrophies after bedrest [95,96], which were mentioned above, may refer to the training regimens that showed large effects sizes on increasing the pectoralis major, arm and forearm muscles' size parameters. However, exercise selection should cautiously be made due to the small numbers of studies included in each meta-analysis.

Additionally, the infraspinatus MT was significantly correlated with shoulder external rotation strength in professional baseball pitchers ($r = 0.287$) [44]. The subscapular MT was the best single predictor for powerlifting performance in professional powerlifters [17]. However, this systematic review did not detect any RCTs focusing on exercise-induced alterations in these muscle architectural parameters. Future RCTs may be conducted to investigate exercise-induced alteration in these muscle architectural parameters in the relevant samples, such as exercise-induced alterations in the infraspinatus MT in baseball pitchers, in the subscapular MT in powerlifters, and in the fascicle geometry of the triceps brachii in swimmers.

Regarding the effect size calculations of the RCTs, initially, none of the RCTs reported the required SDs of the mean changes from baseline for exercise and control groups. The difficulties associated with conducting a meta-analysis without this variable are well described in the literature [61–63]. Therefore, this systematic review strongly suggests that future RCTs should share their raw data, or mean changes from baseline and SDs of the mean changes from baseline, with their publications for more comparable future studies and meta-analyses. Additionally, for the effect sizes reported in individual RCTs, the calculations were generally in respect of the baseline and post-test scores of the intervention groups of post-test scores of the intervention and control groups. Both approaches may lead to wrong interpretations and fewer comparisons between the RCTs. Therefore, this systematic review strongly suggests that future RCTs should calculate the effect sizes based on the mean changes from baseline and their SD in an intervention group comparing the same parameters with a control group, as calculated in this systematic review. Finally, random allocation, and blinding of participants and assessors, were the most common risks of bias among the RCTs. Thus, following the CONSORT statement [97] for parallel-group randomised trials may reduce the risk of biases caused by the methodology, and this can be recommended for future RCTs.

A limitation of this study may be the small numbers of the RCTs included in each meta-analysis. A further limitation of our review is the inclusion of only English language articles, which may have led to the omittance of some data in the analysis. Similar to previous relevant meta-analytic studies that included both genders in the meta-analyses [62,63,98], this systematic review did not address the question of the influence of sex for a differential

response to training in the meta-analyses, which adds a limitation to the outcomes provided. More RCTs may have led to stronger conclusions in this systematic review. Another limitation is not being able to perform assessments of meta-regression or publication bias, which are not suitable for performing each meta-analysis due to the few RCTs [61] included in the meta-analyses of this systematic review. An additional confounding factor is the difference between training interventions, which can lead to uncountable variability in the results of the meta-analyses.

5. Conclusions

Regarding the pectoralis major muscle size, 6-weeks of high-intensity bench press training [91] and 10 weeks of 12 RM bench press exercises [82] can be applied for hypertrophy in this muscle. To achieve hypertrophy in elbow extensors, 6-weeks of lying triceps extension exercise [76], isometric maximal voluntary co-contraction training [83,84], and 12-weeks of nonlinear periodised resistance training [89] may be a suitable intervention. From the perspectives of elbow flexors, 6-weeks of traditional elbow flexion exercises [77], 4-weeks of concentric low-load forearm flexion-extension training [79], isometric maximal voluntary co-contraction training [83,84], 4-weeks of concentric low-load forearm flexion-extension training with vBFR [79], or 12-weeks of nonlinear periodised resistance training [88,90] can be applied to gain hypertrophies in the elbow extensors. Finally, 6-weeks of isometric ulnar deviation training can be used to increase the flexor carpi ulnaris and radialis muscle size [78].

However, these results should be cautiously interpreted due to the small numbers of the RCTs included in each meta-analysis. More RCTs are needed to provide more precise and more robust conclusions about the effects of exercise on the architecture of the upper extremity muscles. Additionally, all the eligible studies of this systematic review were restricted to muscle size measurements, and not did not expand towards the fascicle geometry such as the FL of the triceps brachii long head. Future RCTs can examine the effects of exercise on the triceps brachii FL and PA, the infraspinatus MT and the subscapular MT, due to their associations with sports performance.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app12031593/s1>, File S1: The PRISMA 2020 Checklist, File S2: Database search histories, File S3: Level of evidence of the meta-analyses, Table S1: A PubMed database search, Table S2: Participants' characteristics, Table S3: Intervention characteristics.

Author Contributions: Conceptualisation, G.Y., H.-P.K. and J.A.O.; methodology, G.Y. and E.A.; software, G.Y.; validation, G.Y. and E.A.; formal analysis, G.Y.; investigation, G.Y. and E.A.; resources, G.Y.; data curation, G.Y. and E.A.; writing—original draft preparation, G.Y.; writing—review and editing, H.-P.K. and J.A.O.; visualisation, G.Y.; supervision, H.-P.K. and J.A.O.; project administration, G.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This systematic review received no external funding. The first author, Gokhan Yagiz, is sponsored for his postgraduate studies by the Republic of Turkey, Ministry of National Education: YLSY-40409183010. However, this sponsor did not involve any process of this manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data employed in this systematic review was presented in tables, figures and Supplementary Files.

Acknowledgments: This systematic review will also be published as a chapter of Gokhan Yagiz's Ph.D. Thesis. The authors wish to thank those authors who shared the requested missing outcome data with this systematic review.

Conflicts of Interest: Gokhan Yagiz, Esedullah Akaras, Hans-Peter Kubis and Julian Andrew Owen declare that they do not have any conflicting interests in this systematic review's content.

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