International Journal of Strength and Conditioning

Effects of Co-Contraction Training on Neuromuscular Outcomes of Elbow Flexors and Extensors: A Systematic Review and Meta-Analysis

Marina M. Villalba[1], Rafael A. Fujita[1,2], Karine J. V. Stoelben[3,4], Nilson R. S. Silva[5] & Matheus M. Gomes[1,6]

[1]Ribeirão Preto College of Nursing, University of São Paulo, Brazil, [2]Faculty of Medicine, The University of British Columbia, Canada, [3]CHEO Research Institute, Children's Hospital of Eastern Ontario, Canada, [4]Clinical Biomechanics Research Unit, University of Ottawa, Canada, [5]College of Engineering, Boise State University, United States of America, [6]School of Physical Education and Sport of Ribeirão Preto, University of São Paulo, Brazil.

ABSTRACT

Co-contraction training has been proposed to improve muscle strength in the absence of external equipment, yet it is needed to elucidate the effects of co-contraction training and its applicability. Thus, we synthesized the effects of co-contraction training on elbow muscle strength, myoelectric activity, and muscle thickness. We searched papers from MEDLINE via PubMed, Web of Science, Scopus and Embase databases. The inclusion criteria were studies comprising adults between 18-64 years old; investigating chronic effects of co-contraction training on elbow muscles; comparing pre- and post-intervention or control values; presenting any of the outcomes; randomized, quasi-experimental, pre- and post-design; in English. Seven studies met the inclusion criteria. We performed a systematic review and meta-analysis following PRISMA recommendations. We used the revised RoB 2, ROBINS-I to verify the level of evidence. We also included a questionnaire for biomechanical studies and GRADE analysis. We extracted data independently by two investigators, considering the characteristics of study, participants and training, outcomes, and results. We calculated the effect sizes for each outcome. The analysis was carried out by combining and dividing flexors and extensors in a subgroup analysis. Comparing the experimental vs. control group, our results showed that co-contraction training increased isometric strength (SMD=0.51 [0.19, 0.83]) and agonist myoelectric activity (SMD=0.54 [0.25, 0.83]). Comparing pre- vs. post-training, co-contraction training also improved isometric strength (SMD=1.28 [0.75, 1.81]); concentric elbow extensor strength (SMD=0.64 [0.01, 1.26]); and myoelectric activity (SMD=0.46 [0.18, 0.73]). No effect was observed for muscle thickness. The co-contraction training improves muscle performance without morphological changes.

Keywords: co-activation; muscle strength; upper extremity.

- Co-contraction training increases muscle recruitment and promotes strength gains without modifying the involuntary antagonistic activity of elbow muscles in healthy adults with a very low level of evidence.
- Co-contraction training does not provide structural muscle change. However, there is a need for studies with longer training periods in this regard. Co-contraction training seems to be viable, effective, and easy to apply.
- The data synthesized in this meta-analysis suggest the need for more studies with greater methodological robustness involving co-contraction training. Following these suggestions, trainers and physical fitness trainers will have a

more reliable guide, providing subsidies on the effectiveness and applicability of this resistance training method.

INTRODUCTION

Resistance training (RT) is widely known to improve strength, muscle mass, and performance[1,2]. Furthermore, RT is significantly related to the maintenance and enhancement of functional capacity[3] and health[1]. The American College of Sports Medicine recommends the practice of moderate RT (approximately 60% of the individual's maximum load) for health promotion[4]. The practice of these recommendations only at gyms using external load/equipment might be a limiting factor in times of social isolation and other restrictions. However, a recent RT method called co-contraction training has been proposed to improve muscle strength in the absence of external load/equipment or gravity[5].

Co-contraction training is an alternative method of strength training, which can be performed outside gyms. This training is characterized by the simultaneous activation of agonist and antagonist muscles of a given joint (e.g., elbow flexors and extensors), generating direct mechanical resistance to the respective antagonist muscle group[5–7]. Co-contraction training has shown positive results in muscle recruitment level[7–9], as well as in incrementing strength and hypertrophy[5,6,10]. Counts et al.[11] observed an average increase of 0.2 cm in muscle thickness of the anterior portion of the upper arm, corresponding to approximately 33% change from baseline. This result is similar to those obtained with conventional resistance training with high and low intensity, which increased the biceps cross-sectional area by 20%[12]. It has been suggested that muscle growth occurs regardless of external load, since training recruits (35 to 50% of maximum activation) and places most of the musculature under tension[11].

Thus, co-contraction training could be a convenient method, considering its efficiency in improving and maintaining strength and muscle mass[2,5,6,9,13]. Furthermore, co-contraction seems to be a reliable, low-cost solution in situations such as social isolation (as in quarantine, during pandemic periods of COVID-19), hospitalization environments, while traveling, and in other detraining situations where there is no possibility of carrying out RT with external load. Co-contraction training versatility allows individuals to train in more comfortable and pleasant places, which could be helpful for people with social anxiety disorders.

However, there is no standardization among studies concerning training prescription and no evidence regarding which frequency and duration generate better results. Furthermore, studies show controversial results concerning co-contraction training outcomes. This divergence may be due to methodological differences in previous studies (e.g., duration of the training program, number of sets and repetitions, type of contraction, and populational characteristics). Even considering the benefits of co-contraction training pointed out by some studies, a synthesis of results is needed to elucidate the effects of co-contraction training in physical outcomes and its applicability. Thus, the present systematic review with meta-analysis aimed to integrate the effects of co-contraction training in elbow flexors and extensors on 1) strength, 2) myoelectric activity, and 3) muscle thickness in healthy adults. The findings presented in this study demonstrate the feasibility of utilizing a non-conventional approach, specifically co-contraction training, to improve physical outcomes. This meta-analysis contributes to a deeper understanding of co-contraction training and its potential application in daily life training protocols, benefiting professionals and practitioners seeking effective training methods.

METHODS

Eligibility criteria

This study was previously registered in the International Prospective Register of Systematic Reviews (PROSPERO ID #CRD42019141729). We used the PICOS strategy for guiding the eligibility of included studies. The 'Population' was considered as healthy adults including individuals between 18 and 64 years old, males and/or females, and non-athletes. The 'Intervention' comprised the co-contraction training for elbow flexors and extensors muscles, requiring at least four weeks of training, with a minimum of eight sessions in total (twice a week). A description of the training protocol was required. The 'Comparator' was considered as differences over time (pre vs. post intervention), and between groups (control vs. experimental). The 'Outcomes' included were elbow flexors and extensors muscle thickness, muscle torque, and EMG activity. Studies that investigated at least one of the outcomes were included. The 'Study Type' was considered as all randomized and non-randomized clinical trials, quasi-experimental with pre and post design. Theses, conference abstracts and proceedings were excluded. Only studies published in English were included. Studies were excluded when they failed to meet the eligibility criteria.

Information Sources

We searched four electronic databases (MEDLINE via PubMed, Web of Science, Scopus, and Embase - date of search: 10/21/2022), from the first records until October 2022. To find additional studies, we hand-searched bibliographies of potentially eligible studies. The gray literature search was conducted through The Open Access Repository for Sport, Exercise, and Health Research (SportRχiv), The Preprint Server for Biology (BioRχiv), and Clinical Trials Platform (date of search - 10/21/2022). This study followed PRISMA guidelines[14].

Search Strategy

Mesh terms, Emtree terms, and keywords combined with the Boolean operators "AND" and "OR" were used in the search (see Appendix, Supplemental Digital Content 1, which demonstrates the complete description of the search strategy).

Selection Process

We used Mendeley reference manager software (version 1.19.4, Mendeley Ltd.) for the study selection phase. After removing duplicate studies, two investigators (MMV and RAF) independently screened the records by title and abstract using predetermined eligibility criteria. Full texts were obtained when at least one investigator indicated that the study could be included. Studies were excluded when both reviewers agreed that the study failed to meet the eligibility criteria. Disagreements were resolved through discussion until a consensus was reached. A third reviewer (KJVS) helped with the final decision when necessary.

Data Collection Process

Data regarding the study publication (author, year), characteristics of participants, characteristics of the training, measured outcomes, and training effects (statistical results) were extracted independently by two investigators (MMV and RAF) using a standardized spreadsheet. A third investigator (KJVS) solved discrepancies without a consensus. When these data were not described, we contacted the corresponding author by email.

In instances where the mean and standard deviation were not explicitly provided in the studies, and communication attempts with the authors proved unsuccessful, we employed ImageJ software[15] to extrapolate the averages and standard deviations from the graphical representations and figures within the articles to obtain this essential data.

For studies that presented more than one co-contraction training group, we considered the average of the groups. For studies that presented a co-contraction training group and another kind of training (e.g., conventional strength training), we considered the data of the co-contraction training only.

Data Analysis

Risk of Bias and Level of Evidence Assessment

Assessment of risk of bias in individual studies was performed according to the revised Cochrane risk of bias tool for randomized trials (RoB 2)[16] and the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) for non-randomized studies[17]. The tools considered the judgment of risk of bias arising from the randomization process according to the information provided in the article. We also evaluated the quality of each study using 15 questions described by Lopes et al.[18] designed specifically to assess biomechanical studies. The questions were answered using a score range from 0 to 2, based on the information described in each study, classified as: (0) clearly no, (1) maybe or inadequate information, and (2) clearly yes. As our meta-analysis included only seven studies, we did not perform the risk of publication bias across studies.

This study included the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) analysis. The GRADE system assigned evidence and recommendations of strength levels for each outcome included in the meta-analysis using the available handbook[19] and GRADEpro software. The quality of the evidence was classified into four levels: high, moderate, low, and very low. The factors considered to determine the level of evidence were study design, methodological limitations, inconsistency, indirect evidence, imprecision, and publication bias. All analyses of risk of bias and level of evidence were performed by two investigators (MMV and RAF) independently. Disagreements were resolved through discussion until consensus was reached and if necessary, a third reviewer (KJVS) helped with the final decision.

Statistical Analysis

We performed qualitative and quantitative analyses. In the qualitative analysis, the type of intervention, target population characteristics, type of outcome and intervention content, results, limitations, and methodological quality of the included studies were analyzed.

In the quantitative analysis, since the outcomes are continuous, we conducted the calculation of the effect sizes for each outcome through the software Review Manager (version 5.4.1). The standard mean difference through the Hedges' g value was determined by entering means, SD, and sample sizes before and after the resistance training programs (pre vs. post), and between groups (control vs. experimental) for any outcome variable reported by two or more studies. After testing for heterogeneity with the I-squared statistic method (a priori defined cut-offs at <75%), an inverse variance with random effects approach was performed. The analysis was carried out by combining flexors and extensors together and also dividing flexors and extensors in a subgroup analysis. Forest plots and 95% CIs were produced as per the Cochrane Handbook[20].

RESULTS

Study Selection

We performed the title and abstract screening of 30126 identified studies, in which twenty-two were selected for full-text review. After review, reviewers agreed to include seven articles for data extraction

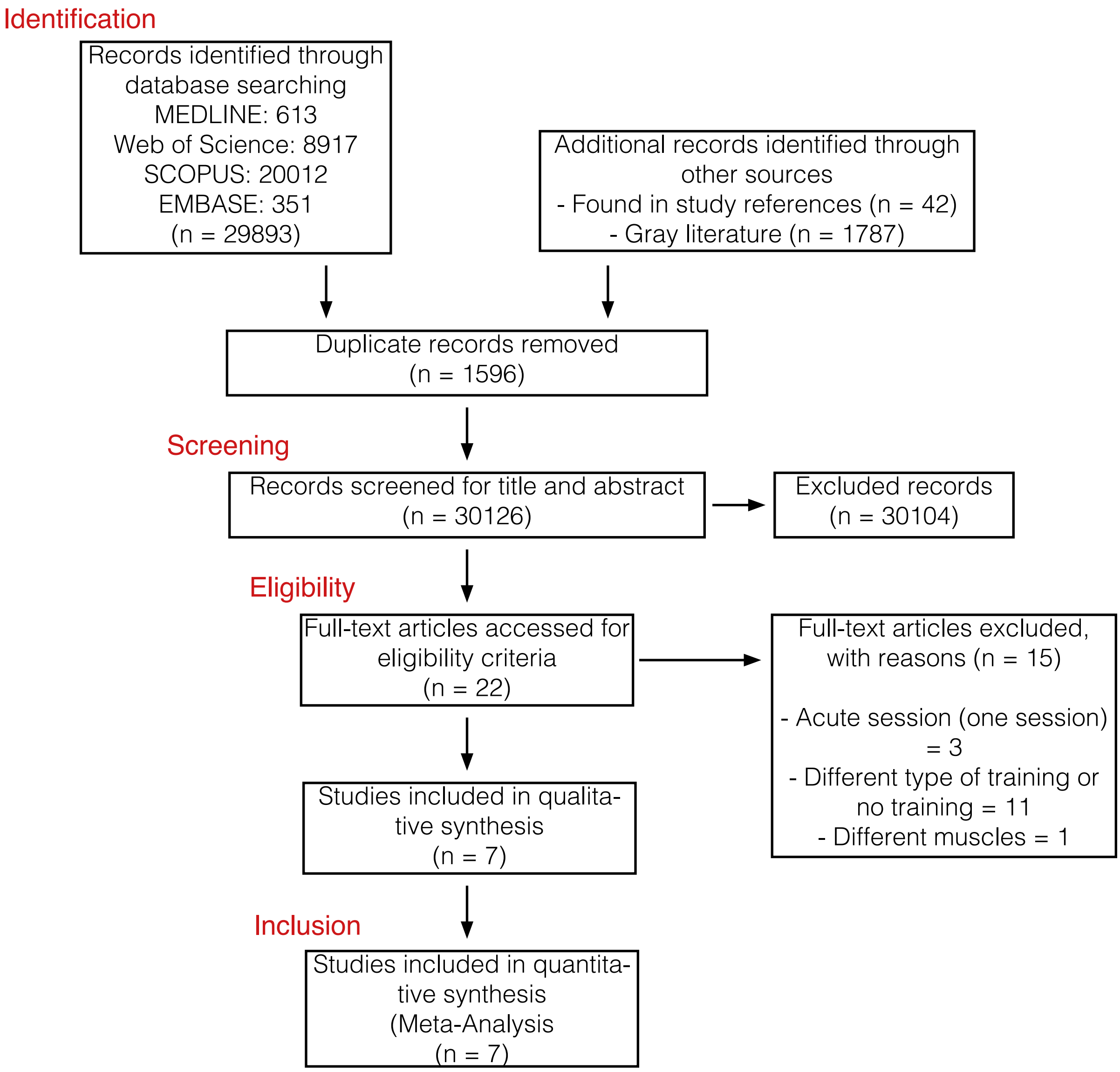

Figure 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA)[14] flow diagram of search results and study selection process.

Table 1. Participants and training characteristics.

Study	Design	Participant Characteristics					Training Characteristics								
		Groups	**Age (years)**	**Number/ Gender**	**Body Mass (kg)**	**Stature (cm)**	**Weekly Fre-quency**	**Program Duration (weeks)**	**Type of Contrac-tion**	**Duration of Contrac-tion**	**Range of Motion**	**Repe-titions/ Sets**	**Rest Intervals**	**Upper Limb**	**Intensity**
Macken-zie et al., 2010	Quasi-Ex-perimental	Trained Limb	18-21	20F	NI	NI	3	6	Dynamic	4s Con-centric/4s Eccentric	~180°	6-12/2-5	2 min between Sets	Left	Maximal Self Re-sistance
		Control Limb					-	-	-	-	-	-	-	Right	-
Maeo et al., 2013	Rand-omized	Trained	21.8 (1.6)	13M	61.7 (7.2)	1.69 (0.07)	3	4	Isometric at 90° of Flexion	4s	~0°	10/5	4s between each Con-traction, 2 min between Sets	Right	Maximal Self Re-sistance
		Control	21.9 (1.6)	10M	64.7 (5.8)	1.71 (0.06)	-	-	-	-	-	-	-	-	-
Driss et all., 2013	Quasi-Ex-perimental	Trained	28.1 (6.7)	10NI	78.1 (13)	1.78 (0.06)	3	4	Isometric at 90° of Flexion	4s	~0°	6/4	30s between reps, 90s be-tween Sets	Right	Maximal Self Re-sistance
		Control	26.3 (6.2)	10NI	75.6 (7.6)	176 (0.04)	-	-	-	-	-	-	-	-	-
Maeo et al., 2014	Rand-omized	Trained	21.4 (1.4)	9M	61.7 (9.1)	1.67 (0.08)	3	12	Isometric at 90° of Flexion	4s	~0°	10/5	4s between each Con-traction, 2 min between Sets	Right	Maximal Self Re-sistance
		Control	22.0 (1.8)	7M	66.4 (6.2)	1.73 (0.05)	-	-	-	-	-	-	-	-	-
Counts et al., 2016	Pre and Post	No Load	22.0 (2.0)	15 (6M/9F)	72.0 (14)	1.70 (0.07)	3	6	Dynamic	1.5s Con-centric/1.5s Eccentric	~180°	20/4	30s between Sets	Counter-balanced	Maximal Self Re-sistance
Zbidi et al., 2016	Rand-omized	Trained (morning)	23.6 (2.6)	10M	72.3 (8.7)	1.75 (0.09)	3	6	Isometric at 90° of Flexion	5s	~0°	8/6	30s between each Con-traction, 2 min between Sets	Right	Maximal Self Re-sistance
		Trained (evening)	23.7 (4.8)	10M	68.3 (8.2)	1.79 (0.08)	3	6	Isometric at 90° of Flexion	5s	~0°	8/6	4s between 30ach Con-traction, 2 min between Sets	Right	Maximal Self Re-sistance
Zbidi et al., 2017	Pre and Post	Trained	26.0 (3.9)	16M	78.9 (8.5)	1.80 (0.08)	3	6	Isometric at 90° of Flexion	5s	~0°	8/6	30s between each Con-traction, 2 min between Sets	Right	Maximal Self Re-sistance

Data presented as mean (SD) or absolute value. F: Female; M: Male; NI; Not Informed.

(Figure 1). Data from five studies[9–11,13,21] were estimated from the figures using ImageJ software[15] when possible and inserted in the quantitative analysis.

Study Characteristics

The seven studies included a total of 130 participants (Table 1). One study included only females, three only males, one both sexes, and one did not report this information. All studies included at least one intervention group performing co-contraction training in the elbow extensor and flexor muscles. Training duration varied between 4 and 12 weeks with three sessions per week.

Strength was analyzed by all studies either during co-contraction, or submaximal and maximal isometric and isokinetic effort. Data on eight outcomes were unable to be obtained or estimated from three studies[10,11,13]. Fourteen outcomes related to myoelectric activity were analyzed in five studies[5,6,9,10,13]. Muscle thickness was assessed in three studies[9–11] (see Appendix, Supplemental Digital Content 2, which demonstrates all outcomes of each study with pre- and post-values).

Risk of Bias and Level of Evidence in studies

Three studies included in our systematic review were randomized trials and were classified by the RoB 2 (Figure 2A). The studies were classified as some concerns in the risk of bias arising from the randomization process. In the risk of bias due to deviations from intended intervention, one study was classified as some concerns and two studies as high risk of bias. In the risk of bias of missing outcome data, one study was classified as low risk and two studies were classified as high risk of bias. In the fourth item, risk of bias in measurement of the outcome, all studies were categorized as some concerns. Finally, on the last item, risk of bias in selection of the reported result, one study was categorized as low risk and two studies were categorized as some concerns.

The other four studies included were classified by the ROBINS-I (Figure 2B). In the risk of bias due to confounding, all studies were classified as low risk of bias. All studies were classified with no information

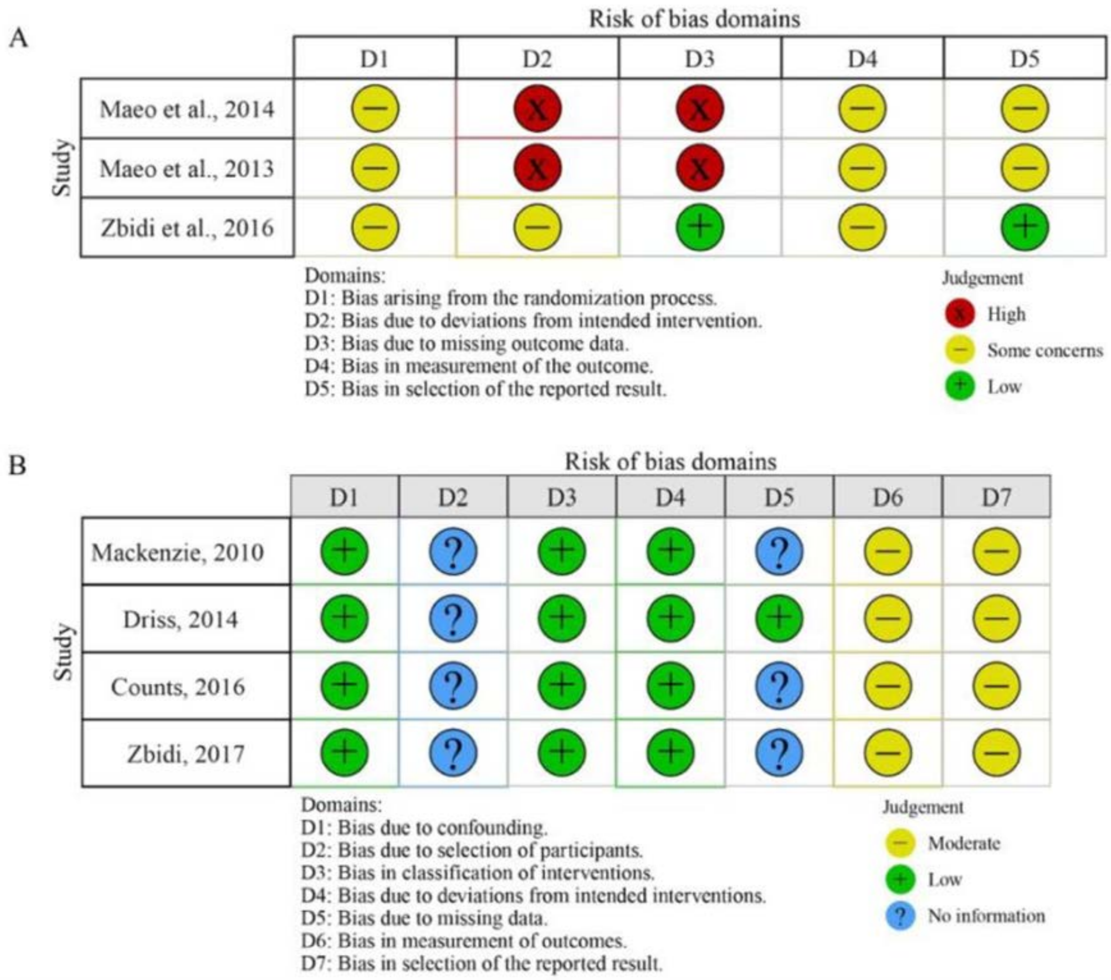

Figure 2. Risk of bias classification of randomized trials (A) and non-randomized studies (B).

on the risk of bias due to selection of participants. All studies were classified as low risk of bias in the third and fourth items (classification of intervention and deviations from intended interventions). In the risk of bias due to missing data, only one study was classified as low risk of bias and three were classified as no information. Finally, all studies were classified as moderate risk of bias in the last two items (risk of bias in measurement of outcomes and selection of the reported result).

The methodological quality scores ranged from 17 to 21 of a possible 30 points (see Table, Supplemental Digital Content 3, which demonstrates all quality scores for each study). All the studies reached the maximum/best score in four questions: 6 - clearly describe interventions, 8 - describe methods in detail, 13 - clearly define outcome variables, and 14 - conduct appropriate statistical analysis. On the other hand, all studies had a zero/worse score in questions: 9 - attempt to blind the assessors, 10 - report the measurement's test-retest reliability, and 11 - describe characteristics of patients lost to follow-up. In the questions not previously mentioned, the studies received scores varying between zero and two: 1 - clearly define the aim/hypothesis, 2 - perform sample size power analysis, 3 - clearly define participants' demographics, 4 - clearly define participants' characteristics, 5 - clearly state inclusion and exclusion criteria, 7 - allow participants proper training practice before the test, 12 - monitor participants' compliance with the intervention, and 15 - provide estimates of random variability.

The GRADE analysis showed a very low level of evidence for all outcomes when comparing groups (see Table, Supplemental Digital Content 4, which demonstrates summary of evidence level for comparisons between groups (experimental vs. control)), and comparing pre- and post-training (see Table, Supplemental Digital Content 5, which demonstrates summary of evidence level for comparisons between times (pre vs. post)).

Strength results

Isometric strength presented a combined and subgrouping (independent muscle group) effect in favor of co-contraction training compared to controls (Figure 3A). Also, there was a combined and subgrouping effect in favor of post training compared to pre training (Figure 3B). For Zbidi et al.[21] we calculated the mean and standard deviation of the two intervention groups (morning training group and evening training group) before (pre) and after (post) performing the training. A pre vs. post comparison was performed for concentric isokinetic strength at 60º/s, presenting a combined effect of training and subgrouping effect for elbow extensors (Figure 4). However, the heterogeneity was moderate in both analyses. For Counts et al.[11] we considered only the values of the no load group, as this was the group corresponding to the co-contraction training. Antagonist strength during agonist contraction presented no effect of training (pre vs. post comparison) in combined (moderate heterogeneity) or subgrouping (substantial heterogeneity for elbow flexors) analysis (Figure 5).

Myoelectric activity results

We performed a meta-analysis of two myoelectric activity outcomes: the values of agonist activity and the co-contraction (presented by the root mean square (RMS)). The elbow flexors and extensors agonist myoelectric activity during MVIC presented an effect favoring co-contraction training in both combined and subgrouping analysis when comparing experimental vs. control groups (Figure 6A). We found a combined effect favoring training comparing pre- and post-training for elbow flexors and extensors agonist activity (Figure 6B). However, elbow extensors were responsive to training in the subgrouping analysis, while elbow flexors were not (Figure 6B). The meta-analysis for the co-contraction myoelectric activity of elbow flexors and extensors during MVIC presented a combined effect favoring co-contraction training compared to controls. However, in the subgrouping analysis, no effect was observed between groups (Figure 7A) or between moments (pre- vs. post-training) (Figure 7B).

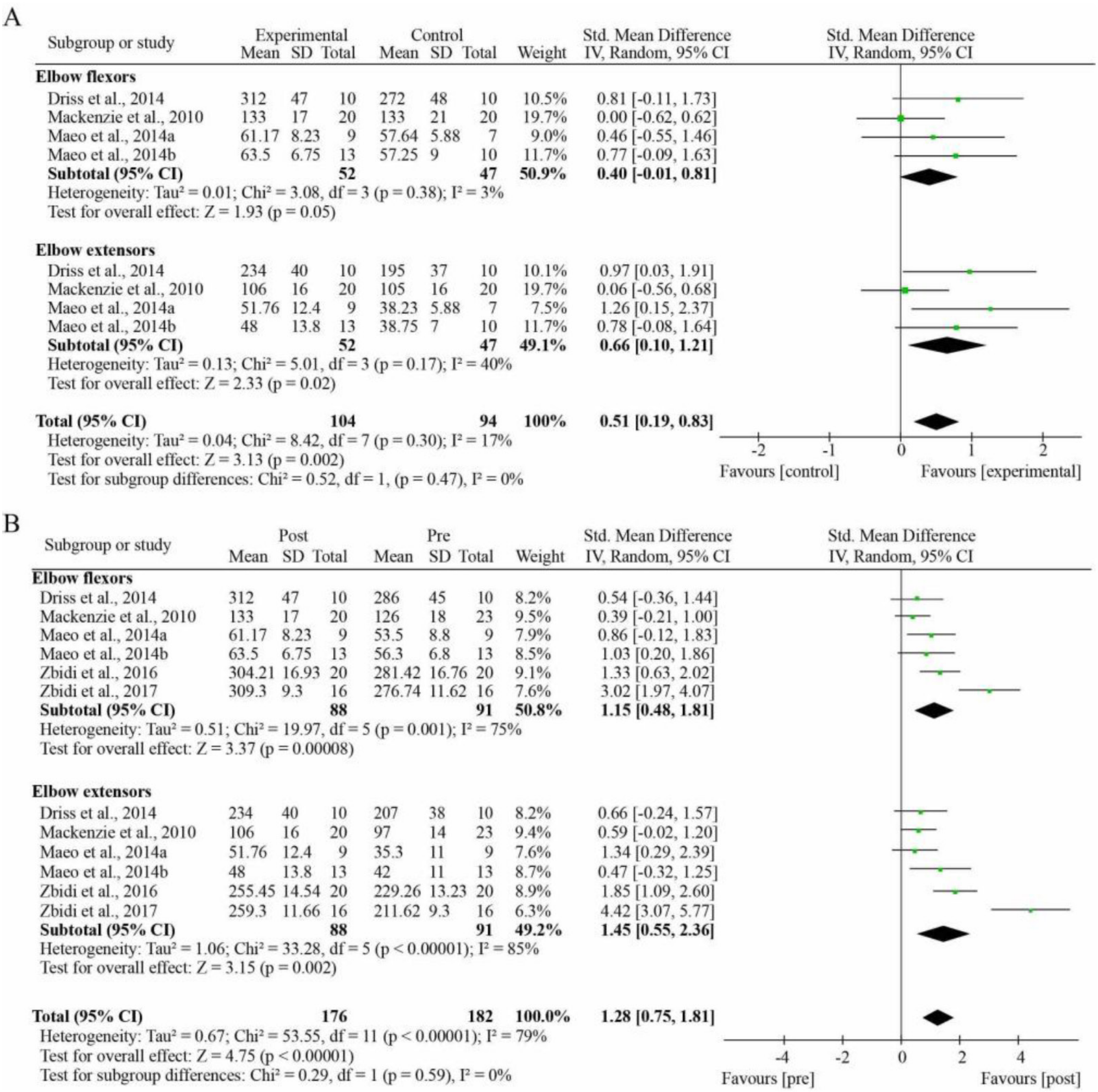

Figure 3. Forest plot (random effects) describing the distribution of studies favoring Control group (left) or Experimental group (right) calculated from the between-groups comparison (A) or favoring pre-training (left) or post-training (right) calculated from the between-moments comparison (B) on maximal isometric muscle strength.

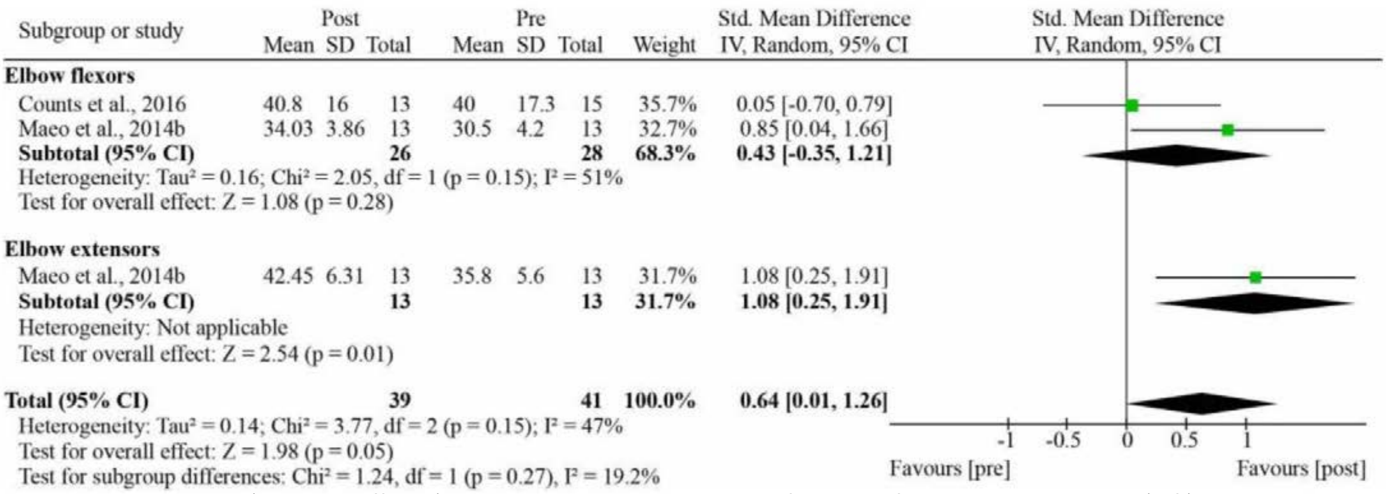

Figure 4. Forest plot (random effects) describing the distribution of studies favoring pre-training (left) or post-training (right) calculated from the between-moments comparison on concentric strength at 60º/s.

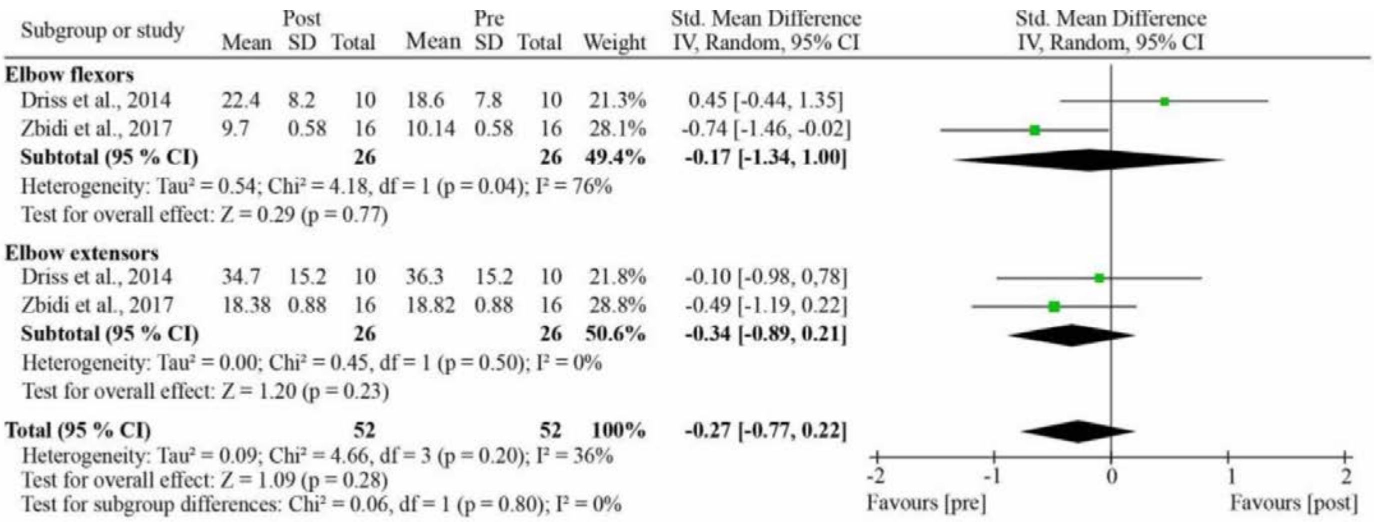

Figure 5. Forest plot (random effects) describing the distribution of studies favoring pre-training (left) or post-training (right) calculated from the between-moments comparison on antagonist strength during agonist contraction.

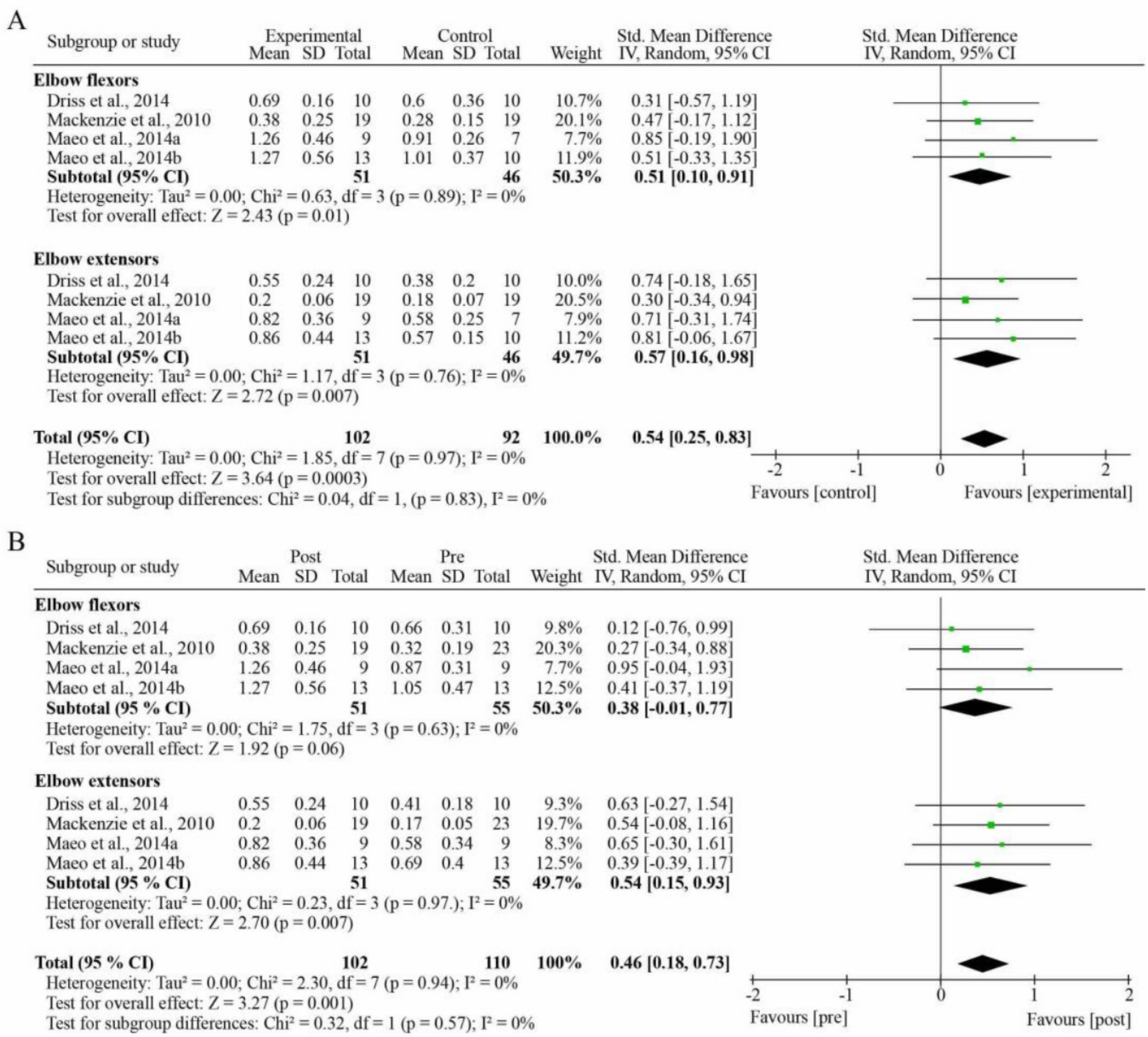

Figure 6. Forest plot (random effects) describing the distribution of studies favoring Control group (left) or Experimental group (right) calculated from the between-groups comparison (A) or favoring pre-training (left) or post-training (right) calculated from the between-moments comparison (B) on agonist activity.

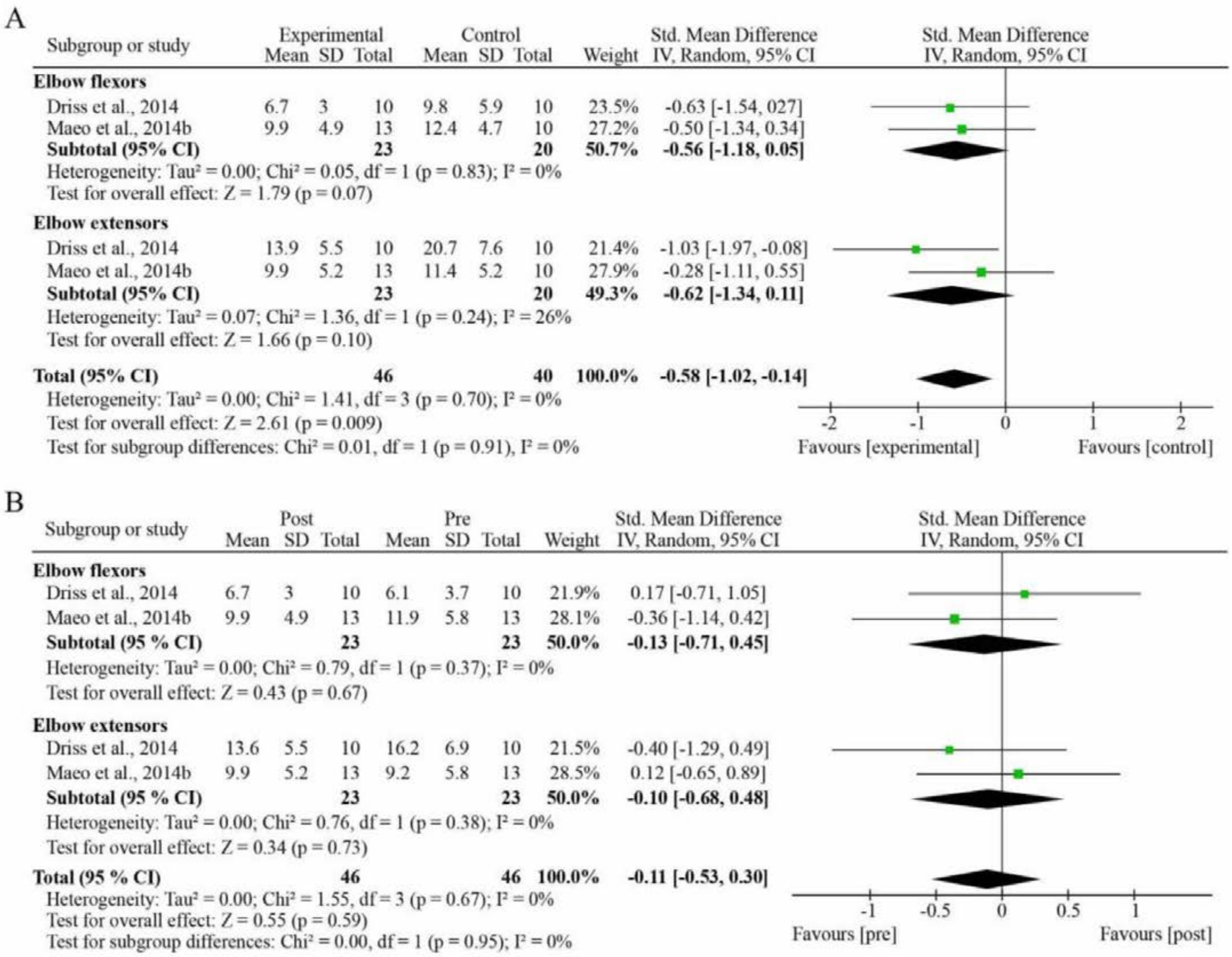

Figure 7. Forest plot (random effects) describing the distribution of studies favoring Control group (right) or Experimental group (left) calculated from the between-groups comparison (A) or favoring pre-training (left) or post-training (right) calculated from the between-moments comparison (B) on antagonist co-contraction during MVIC.

Muscle thickness results

No training effect was observed when comparing groups (Figure 8A) or moments (pre- vs. post-training, Figure 8B) for muscle thickness of elbow flexors and extensors. For Counts et al.[11] we considered only muscle thickness measurements at 60% of the upper arm, since the other two articles[9,10] that presented this variable also used this measurement.

DISCUSSION

The present meta-analysis synthesizes the effects of co-contraction training on muscle strength, myoelectric activity, and muscle thickness of the elbow flexors and extensors in healthy adults. We compared pre- and post-training and control and co-contraction training groups. Our main findings showed that co-contraction training increased isometric and concentric strength and improved elbow muscles myoelectric activity. On the other hand, no differences in muscle thickness, co-contraction myoelectric activity, and antagonist strength were observed. Altogether, our results suggest that co-contraction training is an interesting approach to increase muscle performance and be beneficial in circumstances where conventional RT is not available, such as in the COVID pandemic lockdowns. However, high-quality studies are needed concerning this kind of training since most of the included studies had low quality and the level of evidence was very low.

The compilation of results indicates that co-contraction training is an alternative method of RT capable of increasing muscle strength and recruitment with no external loads. Co-contraction training with maximum voluntary effort effectively improves muscle strength similarly to conventional RT, even with a large range of program durations between studies. The studies included in the present meta-analysis[5,6,9–11,13] showed similar average strength gains for elbow flexors and extensors muscles to those found in studies carrying out conventional RT[22–24]. Therefore, we suggest that increased agonist activity with co-contraction training supported increased muscle strength. It can be inferred that in co-contraction training, the opposing muscles' resistance appears to elicit a training response in the agonistic muscles.

Strength gains can be attributed to neural adaptations considering the short-term training period of the included studies (from 4 to 12 weeks)[13,25]. Among these adaptations are improvements in muscle fiber recruitment, muscle fiber conduction velocity, and muscle synchronization[25,26], resulting in an increased muscle recruitment magnitude and justifying higher strength. Furthermore, since the included studies showed an increase in myoelectric activity values (between 20% and 44%), co-contraction training might be a sufficient training stimulus to induce strength gains[7,10,27].

In the current results, involuntary co-contraction and antagonist strength during isometric MVIC did not change in the elbow flexor or extensor muscles after the intervention. If the results had shown the opposite, the co-contraction could be considered as a negative RT alternative by increasing the energy expenditure during torque production[28–32]. This unchanged antagonist strength and co-contractions, associated with increases in myoelectric activity of agonist muscles during MVIC, may occur due to the different neural processes underlying the voluntary and involuntary recruitment of motor units during a maximum force task[6,13,33]. Humprey[34] demonstrated that some cortical cells are active during co-contraction tasks but not during flexion-extension movements. Some experiments using motor cortex magnetic stimulation also provided evidence

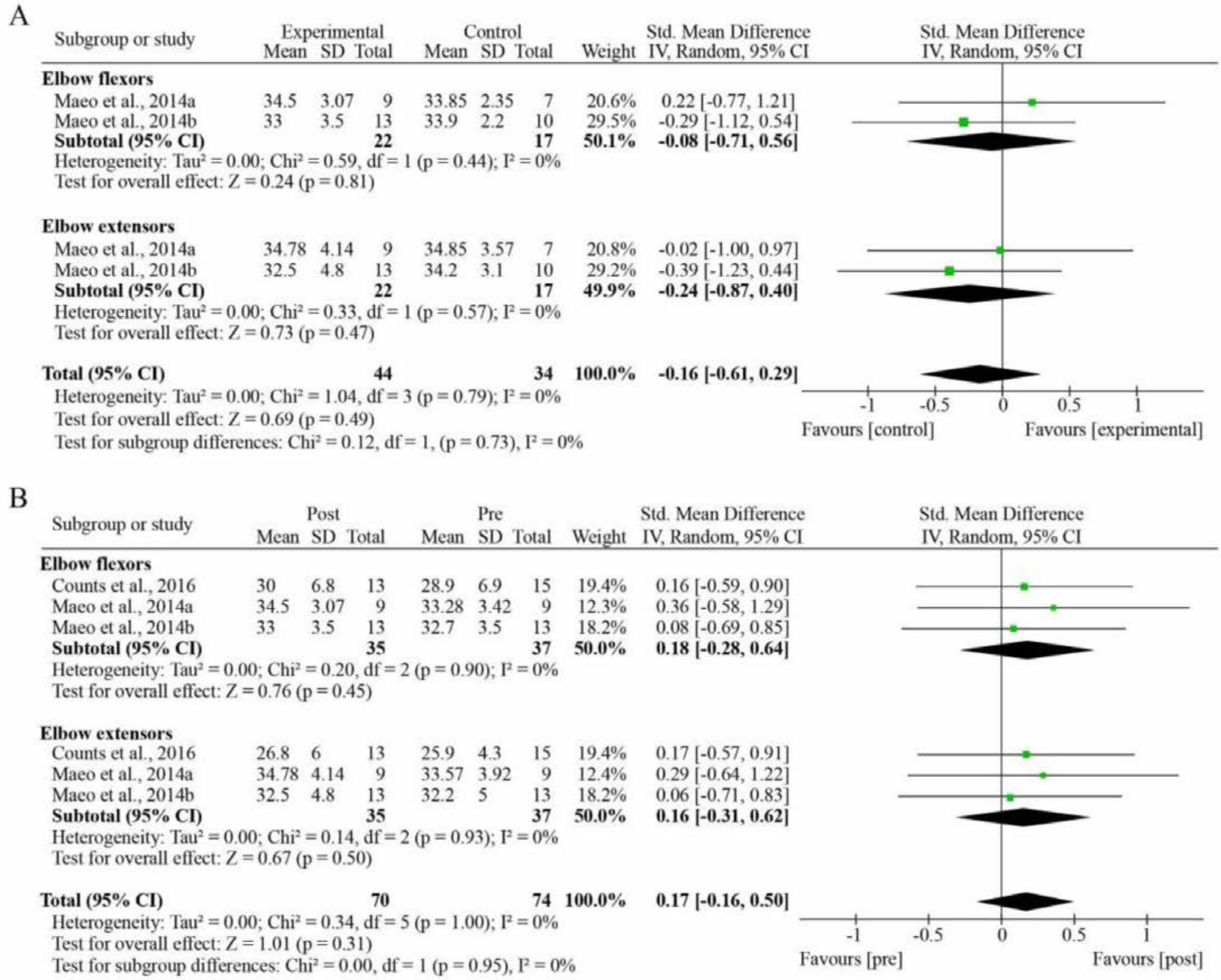

Figure 8. Forest plot (random effects) describing the distribution of studies favoring Control group (left) or Experimental group (right) calculated from the between-groups comparison (A) or favoring pre-training (left) or post-training (right) calculated from the between-moments comparison (B) on muscle thickness.

for differential cortical control during flexion-extension movements and co-contractions[35,36]. Therefore, co-contraction training does not induce unfavorable antagonist adaptation that impairs agonist strength during MVIC.

Regarding muscle thickness, the meta-analysis did not show significant changes after co-contraction training. One possible explanation for this result is that the training period may have been too short to promote hypertrophy. Previous studies have shown hypertrophic gains after 9-14 weeks of resistance training[37,38] with no changes in muscle hypertrophy until the eighth week of training[39,40]. Maeo et al.[10] showed a significant increase in muscle thickness after 12 weeks of co-contraction training but not after four weeks. It is possible that for co-contraction training, there is a need to expand the training period to identify hypertrophic effects. These data provide further support for the notion that co-contraction training can lead to an improvement in muscle strength, even in the absence of significant muscle growth. This can be attributed to neural adaptations resulting from the training. Together, the results suggest that co-contraction training is a practical and effective option that can be applied in a variety of settings, including hospitals, during pandemics or lockdowns, while on vacation, at home, and even in environments with reduced gravity.

Most of the studies included in the present meta-analysis were considered to present a possible risk of bias. The risk of bias due to deviations from the intended interventions was the criterion with the highest risk, followed by missing outcome data. In addition, when analyzing the methodological quality of the studies, many had low scores for aspects considered essential to increase the reliability and validity, especially for biomechanical studies (see Table, Supplemental Digital Content 3, which demonstrates all quality scores for each study). The lack of information reported in the methods section may have led to increased bias. Recently, report checklists were developed to strengthen reporting in studies. We recommend that new studies consider using these checklists and registering the studies before starting. This aspect prevents a lack of transparency and selection of reports, increasing credibility. The increased risk of bias influenced the level of evidence, leading to the very low level of evidence found in GRADE.

We endeavored, through the PRISMA checklist, to present the processes carried out in this review as clearly as possible. However, some observations should be emphasized: (a) a) the limited number of included studies in some analyses may restrict inference drawing and pose a potential bias risk; (b) protocols for risk of bias, methodological quality, and scientific evidence revealed low evidence scores. The methodological restrictions mentioned could potentially impact the results obtained in this study. Additionally, these results are valid for elbow muscles. It is uncertain whether they can be generalized to larger muscle groups (e.g., knee joint muscles).
In this sense, we suggest that further studies are needed on the subject, with higher methodological rigor (which present mainly sample randomization, blinding of the study, follow-up, intention-to-treat analysis, power analysis, and justification of sample size) to provide a better conclusion on the co-contraction training of elbow extensor and flexor muscles.

In conclusion, the results of this systematic review with meta-analysis provide evidence supporting the viability, effectiveness, and ease of application of co-contraction training. This training method enhances muscle recruitment and facilitates strength gains in healthy adults, without altering the involuntary antagonistic activity of elbow muscles. However, it does not lead to structural muscle changes. Co-contraction training can serve as an alternative to conventional training for promoting strength improvements, offering valuable insights for trainers and physical fitness professionals. Nevertheless, the current meta-analysis emphasizes the need for future studies with stronger methodological rigor in investigating co-contraction training. By addressing this recommendation, trainers and physical fitness professionals will have a more reliable reference, offering substantial evidence on the effectiveness and practicality of this resistance training approach.

ACKNOWLEDGMENTS

Brazilian National Council for Scientific and Technological Development (CNPq – Brazil) supports MMV (Finance code 140098/2020-8), RAF (Finance code 140064/2021-4), and KJVS (Finance code 168725/2018-5). This study was supported in part by grant#2020/03282-0, São Paulo Research Foundation (FAPESP) (MMG) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 (NRSS).

REFERENCES

1. Drenowatz C, Greier K. Resistance Training in Youth - Benefits and Characteristics. J Biomed. 2018;3:32-39. doi:10.7150/jbm.25035
2. Gentil P, Bottaro M, Noll M, et al. Muscle activation during resistance training with no external load - effects of training status, movement velocity, dominance, and visual feedback. Physiology & behavior. 2017;179:148-152. doi:10.1016/j.physbeh.2017.06.004
3. Peterson MD, Rhea MR, Sen A, Gordon PM. Resistance exercise for muscular strength in older adults: A meta-analysis. Ageing Research Reviews. 2010;9(3):226-237. doi:10.1016/j.arr.2010.03.004
4. Progression Models in Resistance Training for Healthy Adults. Medicine & Science in Sports & Exercise. 2009;41(3):687-708. doi:10.1249/MSS.0b013e3181915670
5. MacKenzie SJ, Rannelli LA, Yurchevich JJ. Neuromuscular Adaptations Following Antagonist Resisted Training. Journal of Strength and Conditioning Research. 2010;24(1):156-164. doi:10.1519/JSC.0b013e3181bd4317
6. Driss T, Serrau V, Behm DG, Lesne-Chabran E, Le Pellec-Muller A, Vandewalle H. Isometric training with maximal co-contraction instruction does not increase co-activation during exercises against external resistances. Journal of sports sciences. 2014;32(1):60-69.
7. Serrau V, Driss T, Vandewalle H, Behm DG, Lesne-Chabran E, Le Pellec-Muller A. Muscle activation of the elbow flexor and extensor muscles during self-resistance exercises: comparison of unilateral maximal cocontraction and bilateral self-resistance. Journal of Strength and Conditioning Research. 2012;26(9):2468-2477. doi:10.1519/JSC.0b013e31823bc0a2
8. Fujita RA, Villalba MM, Silva NRS, Pacheco MM, Gomes MM. Mind-Muscle Connection: Verbal Instructions Alter Electromyographic Activity for Elbow Flexors and Extensors During Co-Contraction Training. Perceptual and Motor Skills. 2021;128(1):375-389. doi:10.1177/0031512520949089
9. Maeo S, Yoshitake Y, Takai Y, Fukunaga T, Kanehisa H. Neuromuscular adaptations following 12-week maximal voluntary co-contraction training. European journal of applied physiology. 2014;114(4):663-673. doi:10.1007/s00421-013-2801-x
10. Maeo S, Yoshitake Y, Takai Y, Fukunaga T, Kanehisa H. Effect of Short-term Maximal Voluntary Co-contraction Training on Neuromuscular Function. International Journal of Sports Medicine. 2013;35(02):125-134. doi:10.1055/s-0033-1349137
11. Counts BR, Buckner SL, Dankel SJ, et al. The acute and chronic effects of "NO LOAD" resistance training. Physiology & behavior. 2016;164:345-352.
12. Bemben DA, Fetters NL, Bemben MG, Nabavi N, Koh ET. Musculoskeletal responses to high- and low-intensity resistance training in early postmenopausal women: Medicine & Science in Sports & Exercise. 2000;32(11):1949-1957. doi:10.1097/00005768-200011000-00020
13. Zbidi S, Zinoubi B, Hammouda O, Vandewalle H, Serrau V, Driss T. Co-contraction training, muscle explosive force and associated electromyography activity. The Journal of sports medicine and physical fitness. 2017;57(6):725-733. doi:10.23736/S0022-4707.16.06363-5
14. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. International Journal of Surgery. 2021;88:105906. doi:10.1016/j.ijsu.2021.105906
15. Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. Nature Methods. 2012;9(7):671-675. doi:10.1038/nmeth.2089
16. Higgins JPT, Altman DG, Gotzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. BMJ. 2011;343(oct18 2):d5928-d5928. doi:10.1136/bmj.d5928
17. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. Published online October 12, 2016:i4919. doi:10.1136/bmj.i4919
18. Lopes TJA, Simic M, Myer GD, Ford KR, Hewett TE, Pappas E. The Effects of Injury Prevention Programs on the Biomechanics of Landing Tasks: A Systematic Review With Meta-analysis. Am J Sports Med. 2018;46(6):1492-1499. doi:10.1177/0363546517716930
19. Holger Schünemann, Jan Brożek, Gordon Guyatt, Andrew Oxman. Handbook for Grading the Quality of Evidence and the Strength of Recommendations Using the GRADE Approach. Updated October 2013.
20. Julian PT Higgins, Sally Green. Cochrane Handbook for Systematic Reviews of Interventions, Version 5.1.0 [Updated March 2011].
21. Zbidi S, Zinoubi B, Vandewalle H, Driss T. Diurnal Rhythm of Muscular Strength Depends on Temporal Specificity of Self-Resistance Training. Journal of strength and conditioning research. 2016;30(3):717-724. doi:10.1519/JSC.0000000000001144
22. McBride JM, Blaak JB, Triplett-McBride T. Effect of resistance exercise volume and complexity on EMG, strength, and regional body composition. European Journal of Applied Physiology. 2003;90(5-6):626-632. doi:10.1007/s00421-003-0930-3
23. Moore DR, Young M, Phillips SM. Similar increases in muscle size and strength in young men after training with maximal shortening or lengthening contractions when matched for total work. Eur J Appl Physiol. 2012;112(4):1587-1592. doi:10.1007/s00421-011-2078-x
24. Shepstone TN, Tang JE, Dallaire S, Schuenke MD, Staron RS, Phillips SM. Short-term high- vs. low-velocity isokinetic lengthening training results in greater hypertrophy of the elbow flexors in young men. Journal of Applied Physiology. 2005;98(5):1768-1776. doi:10.1152/japplphysiol.01027.2004
25. Sale DG. Neural adaptation to resistance training. Medicine and science in sports and exercise.

1988;20(5 Suppl):S135-45.
26. Behm DG. Neuromuscular Implications and Applications of Resistance Training. The Journal of Strength & Conditioning Research. 1995;9(4). https://journals.lww.com/nsca-jscr/Fulltext/1995/11000/Neuromuscular_Implications_and_Applications_of.14.aspx
27. Tyler AE, Hutton RS. Was Sherrington right about co-contractions? Brain research. 1986;370(1):171-175.
28. Macaluso A, Nimmo MA, Foster JE, Cockburn M, McMillan NC, De Vito G. Contractile muscle volume and agonist-antagonist coactivation account for differences in torque between young and older women. Muscle Nerve. 2002;25(6):858-863. doi:10.1002/mus.10113
29. Mian OS, Thom JM, Ardigo LP, Narici MV, Minetti AE. Metabolic cost, mechanical work, and efficiency during walking in young and older men. Acta Physiol. 2006;186(2):127-139. doi:10.1111/j.1748-1716.2006.01522.x
30. Pereira MP, Gonçalves M. Muscular coactivation (CA) around the knee reduces power production in elderly women. Archives of Gerontology and Geriatrics. 2011;52(3):317-321. doi:10.1016/j.archger.2010.04.024
31. Reeves ND, Maganaris CN, Narici MV. Plasticity of dynamic muscle performance with strength training in elderly humans. Muscle Nerve. 2005;31(3):355-364. doi:10.1002/mus.20275
32. Lee LW, Kerrigan DC. Identification of kinetic differences between fallers and nonfallers in the elderly. Am J Phys Med Rehabil. 1999;78(3):242-246. doi:10.1097/00002060-199905000-00011
33. Pierrot-Deseilligny E, Burke D. The Circuitry of the Human Spinal Cord: Its Role in Motor Control and Movement Disorders. 1st ed. Cambridge University Press; 2005. doi:10.1017/CBO9780511545047
34. Humphrey DR, Reed DJ. Separate cortical systems for control of joint movement and joint stiffness: reciprocal activation and coactivation of antagonist muscles. Adv Neurol. 1983;39:347-372.
35. Nielsen J, Petersen N, Deuschl G, Ballegaard M. Task-related changes in the effect of magnetic brain stimulation on spinal neurones in man. The Journal of Physiology. 1993;471(1):223-243. doi:10.1113/jphysiol.1993.sp019899
36. Pierrot-Deseilligny E, Burke D. The Circuitry of the Human Spinal Cord: Spinal and Corticospinal Mechanisms of Movement. Cambridge University Press; 2012.
37. Folland JP, Williams AG. The Adaptations to Strength Training: Morphological and Neurological Contributions to Increased Strength. Sports Medicine. 2007;37(2):145-168. doi:10.2165/00007256-200737020-00004
38. Roth SM, Martel GF, Ivey FM, et al. Skeletal Muscle Satellite Cell Characteristics in Young and Older Men and Women After Heavy Resistance Strength Training. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2001;56(6):B240-B247. doi:10.1093/gerona/56.6.B240
39. Gabriel DA, Kamen G, Frost G. Neural Adaptations to Resistive Exercise: Mechanisms and Recommendations for Training Practices. Sports Medicine. 2006;36(2):133-149. doi:10.2165/00007256-200636020-00004
40. Staron RS, Karapondo DL, Kraemer WJ, et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. Journal of Applied Physiology. 1994;76(3):1247-1255. doi:10.1152/jappl.1994.76.3.1247