Cross-education of unilateral resistance training as a strategy to mitigate immobilisation-induced neuromuscular decline: A systematic review and meta-analysis

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Abstract

Limb immobilisation leads to a rapid and pronounced loss of muscle strength and size. Cross-education – contralateral resistance training of the non-immobilised limb - has emerged as a resistance training strategy to mitigate deficit in the immobilisation limb. A systematic review and three-level hierarchical meta-analysis were conducted (Eight studies were included; n = 189) to quantify the effects of cross-education on strength and muscle mass during unilateral upper limb immobilisation in healthy participants, examining the influence on training modality, muscle specificity and immobilisation model. Standardised mean change effect sizes (SMCR, Hedges' g) were calculated for strength and muscle size. Cross-education attenuated strength loss compared with immobilisation alone (g = 0.53, p < 0.001), with effect magnitude moderated by immobilisation location and training modality. Proximal immobilisation yielded greater attenuation (overall: g = 0.62; eccentric: g = 0.82; concentric-eccentric: g = 0.68) than distal immobilisation (overall: g = 0.42; eccentric: g = 0.34; isometric: g = 0.63). Regarding muscle size, cross education produced a small preservation effect in the immobilised limb (g = 0.19, p = 0.01). This effect was only evident in proximal immobilisation (g = 0.40) compared to distal (g = 0.06). Strong positive associations were observed between adaptations in the trained and immobilised limbs for strength (r = 0.79) and muscle size (r = 0.81). These findings indicate that cross-education attenuates losses in muscle strength and size during immobilisation. However, these results should be interpreted with caution due to the varying risk of bias among the included studies.

New and Noteworthy

- Training the non-immobilised limb during unilateral immobilisation reduces strength loss in the immobilised limb.
- These attenuations were most pronounced in proximal upper limb muscles (i.e., elbow, shoulder) compared to distal immobilisation models (i.e., wrist).
- Cross-education offers a practical, low-cost rehabilitation strategy that clinicians can easily implement when patients have one limb immobilised, with eccentric resistance exercise of the non-immobilised limb appearing particularly effective for attenuating losses in an immobilised limb.

Introduction

The use of immobilisation in the treatment of upper and lower extremity injuries dates back to ancient times (1), serving to reduce pain, promote rest, and minimise the risk of exacerbating the injury. Modern limb immobilisation, through casting, bracing or surgical fixation, is characterised by a reduction in external mechanical loading that leads to rapid and pronounced losses in muscle strength and size (2, 3). The rate of these declines is at their highest within the first few days of a limb immobilisation period, before beginning to plateau after approximately two weeks (3, 4), with median daily rates of strength decline 2.0% and 1.2% in the knee extensors and elbow flexors, respectively (5). These rapid early strength losses are largely attributed to neural changes such as reductions in neural drive, motor unit excitability and firing rates rather than a reduction in muscle size (6-8). Following immobilisation, restoration of limb strength is critical for safe return to work or sport, as residual strength deficits and asymmetries are established predictors of reinjury (9, 10). Given the rate and magnitude of these losses, cross-education of the contralateral non-immobilised limb has emerged as a targeted strategy to attenuate neuromuscular decline during the immobilisation period itself.

During limb immobilisation, active movement and weight-bearing activities are avoided to maintain the integrity of the injured structure. Interventions that can blunt this muscle loss and preserve strength during the immobilisation phase are therefore appealing as a means of accelerating the overall rehabilitation process (11, 12). First documented in the late 1800s by Scripture et al. (13), cross-education refers to the increase in motor output (i.e., force generation, skill) of the untrained limb following unilateral motor training of the opposite limb (14, 15). In healthy participants not undergoing immobilisation, a meta-analysis demonstrated that unilateral strength training produced average strength gains of 9.6% in the upper limb and 16.4% in the lower limb contralateral to the trained limb following interventions lasting from 3 to 12 weeks (16). Carroll et al. (17) showed that these contralateral strength gains reach approximately 52% of those observed in the trained limb, highlighting the importance of maximising trained limb strength to optimise the cross-education effect in the untrained contralateral limb.

Effective cross-education interventions require near-maximal training intensities to maximise strength gains in the untrained limb (16, 18, 19). The magnitude of strength transfer is greatest when training emphasises eccentric muscle actions, which induce greater reductions in intracortical inhibition and greater increases in corticospinal excitability

compared to other contraction types (20, 21). Additionally, cross-education exhibits training specificity across multiple dimensions, including muscle action type (22, 23), contraction velocity (24, 25), and muscle group (26, 27), with the greatest strength transfer occurring in contralateral homologous muscles when assessed using the same training modality (14, 16).

The utility of cross-education has naturally led to investigations into its effectiveness for preserving neuromuscular function during unilateral limb immobilisation, with several studies documenting attenuation of both strength loss and muscle atrophy in the immobilised limb (28-34). However, there has not yet been a synthesis of how the anatomical location of immobilisation moderates these effects, despite evidence of marked regional variability in upper-limb responses to immobilisation. A recent meta-analysis quantifying regional effects of disuse (35) reported heterogeneous strength and mass losses across the upper arm (strength: -16.67%; mass: -5.03%), forearm (strength: -21.42%; mass: -1.56%), and hand (strength: -10.46%; mass: -4.57%). This regional variability suggests that the efficacy of cross-education may differ substantially depending on the immobilisation model and muscle group targeted, underscoring the need for a synthesis that accounts for these factors.

Therefore, the objective of this systematic review and meta-analysis was to quantify the effects of cross-education on muscle strength and size during unilateral limb immobilisation in healthy individuals. Subgroup analyses examined the moderating influence of training modality (i.e., eccentric, concentric, isometric, or combined), immobilisation model (i.e., proximal vs distal limb musculature), and muscle group specificity on these outcomes.

Methods

Overview

This systematic review and meta-analysis were conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (36).

Search strategy

A literature search employing terms related to cross-education during immobilisation was developed and executed across multiple databases: PubMed, Web of Science, Latin America and the Caribbean Literature on Health Sciences (LILACS), Epistemonikos, Embase (Elsevier), and the Cumulative Index to Nursing and Allied Health Literature (CINAHL). Searches were conducted from August 2024 through March 2026, with no restrictions on initial publication date. A complete list of search terms and strings is provided in Table 1.

Backward citation analysis was performed through systematic screening of reference lists from included studies and relevant reviews. Studies were imported into Rayyan (37), a web-based systematic review platform, where duplicates were removed. Following the initial search period, additional literature known to the authors through direct collaboration was incorporated. Further backward citation analysis was conducted using Research Rabbit citation mapping software (38), supplemented by forward citation analysis via Google Scholar and use of large language models (GPT 4.1, Open AI) in July 2024.

Eligibility criteria

Studies were evaluated for inclusion using Population/Intervention/Comparison/Outcomes (PICO) criteria.

Population

The target population comprised healthy young adults aged 18–40 years, of any sex, free from confounding musculoskeletal injury at the time of intervention. Only uninjured participants were included, rather than those undergoing immobilisation as treatment for injury, due to the confounding effects of injury-induced muscle atrophy and the heterogeneity in injury severity that would preclude accurate quantification of cross-education effects.

Intervention

The intervention protocol required unilateral immobilisation of at least 14 days affecting a portion of the upper or lower extremities, during which participants performed resistance training of at least one muscle group with the non-immobilised limb (e.g., dumbbell bicep curls using the right arm during shoulder sling immobilisation of the left arm).

Comparators

A comparator group undergoing identical immobilisation procedures without resistance training or other interventions in the non-immobilised limb was required. Where multiple cross-education training protocols were employed within a single study (e.g., eccentric-only versus concentric-only training), comparisons between different training methodologies were also eligible for inclusion. When present, data from true control groups (neither immobilisation nor cross-education) were also extracted and included in the data table, but not included in the meta-analyses.

Outcomes

Studies were required to report at least one quantitative measure of muscle strength or size in both limbs, with measurements taken both before and after the immobilisation period to enable calculation of within-group changes. Outcomes were measures of strength and size of the trained homologous muscle group in the immobilised limb (e.g., wrist flexors in the immobilised limb if the wrist flexors of the opposite limb were trained). Secondary outcomes were measures of strength and size of untrained muscles in the immobilised limb (e.g., wrist extensors in the immobilised limb if the wrist flexors of the opposite limb were trained).

Exclusion criteria

Studies were excluded if: (1) participants underwent immobilisation as treatment for musculoskeletal injury; (2) resistance training was performed in whole-body interventions or on a non-homologous limb to the injured limb (e.g., whole-body interventions, training of muscles not affected by immobilisation) (3) training was applied directly to the immobilised limb during the immobilisation period; (4) no training occurred during the immobilisation period (i.e., training occurred only before or after immobilisation); (5) the disuse model was not unilateral limb immobilisation (e.g., bed rest); or (6) insufficient data were available following contact with authors to assess intervention effects for at least one measure of muscle strength or size.

Study selection

Two reviewers (M.R. and L.C.) independently screened titles and abstracts, with studies imported into Rayyan for management. Full texts were retrieved for studies meeting or potentially meeting inclusion criteria. Disagreements were resolved through consensus discussion.

Data extraction and coding

Data extraction was performed by three authors (L.S., J.A., and M.C.), with coding conducted by two authors (L.S. and J.A.) in Microsoft Excel. Extracted data included: (1) study characteristics (DOI, author, year, location); (2) participant demographics (age, sex, height, weight, training experience, handedness); (3) immobilisation parameters (type, daily duration, total duration); (4) training protocols (contraction type, target muscles, intensity, repetitions, sets, frequency); (5) outcome measures (type and methodology); and (6) pre- and post-immobilisation means and standard deviations for all groups and measures of muscle strength and size. When numerical data were unavailable in published articles, corresponding authors were contacted to obtain the missing information. All contacted

authors provided the requested data, removing the need for data estimation. The complete coded dataset is available as supplementary material at https://doi.org/10.5281/zenodo.19383506.

Assessment of methodological quality

Methodological quality and risk of bias were independently assessed by L.S., M.R., and J.A. using the Cochrane Risk of Bias 2 (RoB 2) tool for randomised controlled trials, with disagreements resolved through discussion. Assessment domains (D#) included: D1: bias arising from the randomisation process; D2: Bias due to deviations from intended intervention; D3: Bias due to missing outcome data; D4: Bias in measurement of the outcome; and D5: Bias in selection of the reported result. If details were not reported in the publication, the corresponding author was contacted to seek clarity in the method being assessed. Each criterion was rated as "high", "some concerns", or "low" risk of bias.

Statistical analysis

Software and packages

All statistical analyses were conducted using R version 4.5.1 (39) within a custom shiny application (40) developed for interactive meta-analysis and between-limb cross-education correlation analyses. Primary *packages* included: *metafor* (41) for meta-analytic calculations and modeling; clubSandwich (42) for robust variance estimation in sensitivity analyses; *dplyr* (43) and *tidyr* (44) for data manipulation; *ggplot2* (45), ggtext (46), and viridis (47) for visualisation with customisable aesthetics; *readxl* (48) for data import; *plotly* (49) for interactive graphics; and *DT* (50) for interactive data tables. The Shiny application interface employed *shiny* (40), *shinydashboard* (51), *shinyWidgets* (52), and *colourpicker* (53) packages. The application includes an advanced filtering interface for dynamic data subsetting by categorical variables and provides comprehensive export functionality for data, effect sizes, statistical results, and publication-ready graphics in multiple formats (PNG, PDF) with customisable dimensions and resolution. The complete meta-analysis pipeline is publicly available at https://jandrushko.shinyapps.io/Easy_Meta-Analysis/.

Effect size calculation

Standardised mean change using raw score standardisation (SMCR) served as the primary effect size metric, representing within-group change from pre- to post-intervention (54). SMCR for each group and measure was calculated using the formula:

$$SMCR = \frac{M_{post} - M_{pre}}{SD_{pre}}$$

where M_{post} and M_{pre} represent post- and pre-intervention means, respectively, and SD_{pre} is the standard deviation from the pre-immobilisation timepoint. Given that all included studies had group sizes below 20, Hedges' g was calculated with the Hedges' correction factor (*J*) to adjust for small-sample bias (55). Effect sizes were calculated using the *escalc()* function from the *metafor* package with measure = "SMCR". While the Hedges' correction was applied to all effect sizes in this meta-analysis due to small sample sizes, the analysis pipeline allows users to optionally disable this correction for analyses of larger samples.

Pre-post correlation

Pre-post correlations were calculated directly from available pre-intervention, post-intervention, and change score standard deviations (56):

$$r = \frac{SD_{pre}^2 + SD_{post}^2 - SD_{chang}^2}{2 \times SD_{pre} \times SD_{post}}$$

This approach derived the actual within-subject correlation from reported descriptive statistics without relying on estimated or assumed correlation values. When change score standard deviations were unavailable, pre-post correlations were extracted from study-reported correlation coefficients. After contacting corresponding authors to obtain missing data, no studies in the final analysis required estimated correlations.

Sampling Variance

Sampling variance for each effect size was calculated, accounting for the pre-post correlation structure inherent in repeated measures designs (54):

$$Var = \left(\frac{1}{n}\right) + \left(\frac{SMCR^2}{2n}\right) \times (1 - r)$$

where n represents the sample size and r is the pre-post correlation. This formula appropriately adjusts variance estimation for the dependency between pre- and post-intervention measurements.

Meta-analysis model

To account for the statistical dependency arising from multiple outcome measures within studies, a three-level hierarchical random-effects meta-analysis was conducted using Restricted Maximum Likelihood (REML) estimation with Knapp-Hartung adjustments for uncertainty in heterogeneity (τ^2; (57)), with test statistics and *p*-values calculated using the

Knapp-Hartung method throughout all analyses. The analysis pipeline also provides an option for z-tests as an alternative inference method for sensitivity analyses. The nested structure incorporated sampling variance within individual outcome measures, nested within study groups, nested within studies. Control and intervention groups were treated as independent observations.

Random-effects models were used to accommodate expected heterogeneity in study populations, intervention protocols, and outcome measures. Overall effect estimates, 95% confidence intervals (CI), and associated *p*-values were extracted from model outputs. The alpha level for statistical significance was set at $\alpha = 0.05$.

Effect sizes were interpreted using conventional thresholds: g(SMCR) < 0.2 indicating negligible effects, 0.2 ≤ g(SMCR) < 0.5 indicating small effects, 0.5 ≤ g(SMCR) < 0.8 indicating moderate effects, and g(SMCR) ≥ 0.8 indicating large effects. SMCR effect sizes will hereafter be reported as 'g'.

When three-level models failed to converge due to limited data (k < 6 studies), effect sizes were aggregated to one per study (mean across outcomes) and analysed using simplified two-level random-effects models. This approach provides valid estimates but limits subgroup analyses. This was applied to proximal muscle size outcomes (k = 5 studies).

Heterogeneity assessment

Between-study heterogeneity was quantified using Cochran's Q statistic, with statistical significance assessed at $\alpha = 0.05$. For the three-level model, variance components (σ^2) were estimated at Level 2 (within study-groups, representing variation between different outcome measures) and Level 3 (between study-groups, representing variation between studies). Total heterogeneity (τ^2) was calculated as the sum of Level 2 and Level 3 variance components. The magnitude of total heterogeneity was evaluated using I^2 statistics, with values decomposed to show the proportion of variance attributable to each level (58). I^2 values of approximately 25%, 50%, and 75% were interpreted as representing low, moderate, and high heterogeneity, respectively (58).

Cross-education between-limb relationships

To examine relationships between adaptations in trained and immobilised limbs, linear regression analyses were performed separately for muscle strength and size outcomes.

Analyses employed two metrics: (1) percentage change from baseline, calculated as [(post – pre-testing) / pre-testing] × 100; and (2) standardised mean change raw scores

(SMCR effect sizes). This dual-metric approach examined whether the trained-immobilised limb relationship varied as a function of measurement scale (59). Model assumptions (linearity, normality of residuals, homoscedasticity, and independence) were assessed through visual inspection.

Publication bias

Publication bias was assessed through multiple approaches. Visual inspection employed funnel plots of effect sizes against standard errors (60), with contour-enhanced funnel plots displaying significance regions at α levels of 0.10, 0.05, and 0.01 (61). For statistical evaluation of funnel plot asymmetry, Egger's test (62) was used via the *regtest()* function in *metafor*, with $p < 0.05$ indicating evidence of small-study effects. Since a hierarchical random effects model was used for the Meta-Analysis, and Egger's test is incompatible with these models, Egger's test was run using aggregated effect sizes (one effect size per study-group, calculated as the mean effect size and mean variance across outcomes). If Egger's test was significant, then the Duval and Tweedie's trim-and-fill procedure (63) was applied to estimate the potential impact of publication bias on effect size estimates.

Subgroup analyses

Subgroup analyses were conducted using meta-regression with categorical moderators to examine potential sources of heterogeneity. Separate analyses examined: (1) proximal versus distal upper limb immobilisation models, reflecting differential innervation ratios between corticospinal and reticulospinal pathways; and (2) measurement specificity, with trained homologous muscle groups only versus combined trained homologous and untrained heterologous muscle groups. Untrained muscle groups were not examined independently due to insufficient sample size. Importantly, proximal versus distal immobilisation location comparisons were pre-specified as exploratory subgroup analyses given the limited number of studies available for each stratum; these analyses are intended to generate hypotheses and provide preliminary effect size estimates for future adequately powered studies, rather than to yield definitive conclusions. Separate meta-analyses were conducted within each subgroup level, with between-group differences assessed using Q-tests for moderator effects.

Results

Literature search

<<Figure 1>>

The systematic literature search identified 394 articles, with an additional six records obtained through manual reference screening, Google Scholar citation tracking, and AI-assisted generative search. All records were imported into the Rayyan platform, where they were independently and blindly screened by two reviewers (M.R. and L.C.). A total of 159 duplicate articles were removed, leaving 235 records for further assessment, of which 21 were initially selected.

Of these 21 articles, one was excluded due to the inability to retrieve the full text. The remaining 20 articles underwent title and abstract screening for an initial assessment of the eligibility criteria. Thirteen studies were excluded: seven due to the absence of immobilization data, four because they were not experimental studies, and two for involving an orthopaedic clinical population. One additional study was identified and included through alternative methods; this study was known to one of the authors (J.A.), who was a co-author of the recently published work (34). No disagreements arose regarding study inclusion. Ultimately, eight studies met the eligibility criteria and were included in this review and meta-analysis (Figure 1).

Included study characteristics

Characteristics of the eight included studies are presented in Table 2. Immobilisation duration ranged from 3 to 4 weeks, with daily immobilisation periods varying from 8 to 24 hours. Immobilisation models included wrist casts (n = 3 studies), shoulder sling and swathe (n = 3 studies), a standardised arm sling (n = 1 study), and an elbow cast (n = 1 study). Training interventions comprised isometric, eccentric, concentric, and combined concentric-eccentric protocols targeting upper limb musculature.

Participants across included studies

There was a total of 189 participants across the eight included studies, comprising 101 females and 88 males (Table 3).

Further participant characteristics of the included studies can be found in table 4.

Risk of bias assessment

<<Figure 2>>

Risk of bias was assessed using the Cochrane RoB 2 tool across five domains (Figure 2). The overall risk of bias profile was mixed: four studies were rated as high risk overall and four as having some concerns, with no studies rated as low risk overall. These findings indicate a non-trivial risk of bias across the included literature, and all results should be interpreted with this in mind. For randomisation (D1), no studies were rated as low risk, with five studies rated as having some concerns, and three studies were rated as having high risk. Risk of bias due to deviations from intended interventions (D2) was generally low, as immobilisation and training protocols were well-defined and adherence was typically monitored. Carr et al. (34) was the only study to be rated as having high risk in this category. Missing outcome data (D3) presented low risk across studies, with minimal attrition reported, with Carr et al. (34), again being the only study to be rated as having high risk. Measurement of outcomes (D4) was rated as low risk across all eight studies. Selection of reported results (D5) was rated as some concerns for all studies except for Carr et al. (34), which was rated as low risk. Four studies were rated as high risk of bias overall and the remaining four studies were rated as having some concerns overall. Notably, no included study was rated as low risk overall, and the primary source of high-risk ratings was the randomisation domain (D1), which has direct implications for the internal validity of the pooled estimates reported below.

Publication bias assessment

<<Figure 3>>

Publication bias was assessed using funnel plots and Egger's regression test for both strength and muscle size outcomes (Figure 3). For strength, visual inspection of the funnel plot revealed a reasonably symmetric distribution of effect sizes around the pooled estimate. Egger's regression test indicated no significant funnel plot asymmetry ($z = 1.71$, $p = 0.086$). Similarly, for muscle size outcomes, the funnel plot appeared symmetric, and Egger's test was not significant ($z = 1.83$, $p = 0.068$). These findings suggest the pooled estimates for both strength and muscle size preservation are unlikely to be substantially influenced by publication bias, however all subsequent meta-analytic results should be interpreted with appropriate caution due to the near significant *p*-values with both tests.

Meta-analyses

The below meta-analytic reporting includes the primary statistical outputs, but a full comprehensive overview of all meta-analyses statistical reporting including variance components can be found in table 5.

Primary meta-analyses – including all outcomes in the immobilised limb

Cross-education of neuromuscular strength in the immobilised limb

<<Figure 4>>

A three-level random-effects meta-analysis was conducted to examine the effects of cross-education on strength outcomes in the immobilised limb compared to immobilisation alone. The analysis included 25 effect sizes from eight studies, with training types including isometric, eccentric, concentric, and concentric-eccentric protocols (Figure 4). Cross-education produced a significant moderate effect for attenuated losses in strength for the immobilised limb compared to immobilised controls (k = 25; g = 0.53, 95% CI [0.34 to 0.73], $p < 0.001$). Further analysis splitting the data by training type revealed that both eccentric (k = 11; g = 0.57, 95% CI [0.16 to 0.98], p = 0.012) and concentric-eccentric (k = 7; g = 0.69, 95% CI [0.19 to 1.18], p = 0.01) training produced significant effects, whereas isometric (k = 4; g = 0.41, 95% CI [-0.05 to 0.87], p = 0.07) and concentric training (k = 3; g = 0.54, 95% CI [-0.46 to 1.54], p = 0.14) were non-significant.

Cross-education of muscle size in the immobilised limb

<<Figure 5>>

The meta-analysis of muscle size outcomes in the immobilised limb included 16 effect sizes from eight studies (Figure 5). Cross-education produced a significant small effect for muscle size preservation in the immobilised limb compared to immobilised controls (k = 16; g = 0.19, 95% CI [0.05 to 0.33], p = 0.01). Subgroup analysis by training type revealed no significant effects for any individual training protocol: eccentric (k = 6; g = 0.20, 95% CI [-0.08 to 0.49], p = 0.13), concentric-eccentric (k = 4; g = 0.33, 95% CI [-0.34 to 1.01], p = 0.22), isometric (k = 4; g = 0.12, 95% CI [-0.33 to 0.57], p = 0.46), and concentric training (k = 2; g = 0.39, 95% CI [-3.45 to 4.23], p = 0.42).

Subgroup analyses

Muscle group specificity: Trained homologous muscles

Immobilised limb strength

<<Figure 6>>

To examine whether cross-education of strength effects were specific to the trained homologous muscle group, subgroup analyses were conducted including only outcomes measured in muscles corresponding to those trained in the contralateral limb. This analysis included 19 effect sizes from eight studies (Figure 6). For strength outcomes in the immobilised limb, cross-education produced a significant moderate-to-large effect when examining trained muscles only (k = 19; g = 0.66, 95% CI [0.38 to 0.93], $p < 0.001$; Figure 6). Subgroup analysis by training type revealed significant effects for both eccentric (k = 7; g = 0.75, 95% CI [0.02 to 1.49], p = 0.046) and concentric-eccentric training (k = 6; g = 0.83, 95% CI [0.16 to 1.51], p = 0.024), whereas isometric (k = 4; g = 0.41, 95% CI [-0.05 to 0.87], p = 0.07) and concentric training (k = 2; g = 0.90, 95% CI [-4.08 to 5.88], p = 0.26) were non-significant. The larger overall effect size for trained muscles (g = 0.66) compared to all muscles combined (g = 0.53) suggests a degree of homologous specificity in the attenuation of muscle strength with cross-education.

Immobilised limb size

<<Figure 7>>

For muscle size outcomes in the trained homologous muscle group, the analysis included 15 effect sizes from eight studies (Figure 7). Cross-education produced a significant small effect (k = 15; g = 0.19, 95% CI [0.04 to 0.33], p = 0.01; Figure 7). Subgroup analysis by training type revealed no significant effects for any training protocol: eccentric (k = 5; g = 0.20, 95% CI [-0.11 to 0.51], p = 0.15), concentric-eccentric (k = 4; g = 0.33, 95% CI [-0.34 to 1.01], p = 0.22), isometric (k = 4; g = 0.12, 95% CI [-0.33 to 0.57], p = 0.46), and concentric training (k = 2; g = 0.39, 95% CI [-3.45 to 4.24], p = 0.42).

Immobilisation model: Proximal versus distal musculature

Subgroup analyses examined whether cross-education effects differed between proximal (shoulder sling and long arm cast) and distal (wrist cast) immobilisation models, with both trained homologous and untrained heterologous muscle groups included.

Strength: proximal immobilisation

<<Figure 8>>

For strength outcomes after proximal immobilisation, the meta-analysis included 17 effect sizes from five studies (Figure 8), considering only trained homologous muscles. Cross-education resulted in a significant moderate to large effect on strength preservation (k = 17; g = 0.62, 95% CI [0.35 to 0.88], p < 0.001). Subgroup analysis by training type showed significant effects for eccentric training (k = 5; g = 0.82, 95% CI [0.25 to 1.38], p = 0.02) and for combined concentric-eccentric training (k = 7; g = 0.68, 95% CI [0.19 to 1.18], p = 0.01). In contrast, no significant effects were observed for isometric (k = 2; g = 0.30, 95% CI [-2.10 to 2.70], p = 0.36) or concentric training (k = 3; g = 0.54, 95% CI [-0.46 to 1.54], p = 0.14).

Size: proximal immobilisation

<<Figure 9>>

For muscle size outcomes following proximal immobilisation, the analysis included seven effect sizes from five studies (Figure 9). Due to limited data preventing three-level model convergence, effect sizes were aggregated to one per study, and a simplified random-effects meta-analysis was conducted. Cross-education produced a significant small-to-moderate effect (k = 7; g = 0.40, 95% CI [0.14 to 0.66], p = 0.01). Subgroup analysis by training type was not conducted due to the simplified modelling approach.

Strength: distal immobilisation

For strength outcomes following distal (wrist cast) immobilisation, the analysis included eight effect sizes from three studies (Supplementary Figure 1). Given that only three studies contributed to this subgroup, the following findings should be cautiously interpreted as exploratory. Cross-education produced a significant small-to-moderate effect for strength preservation (k = 8; g = 0.42, 95% CI [0.17 to 0.66], p = 0.005). Only two training types were represented in distal immobilisation studies. Subgroup analysis revealed that both eccentric (k = 6; g = 0.34, 95% CI [0.05 to 0.64], p = 0.03) and isometric training (k = 2; g = 0.63, 95% CI [0.20 to 1.06], p = 0.03) produced significant effects. Comparison between immobilisation sites revealed anatomical specificity, with proximal immobilisation (g = 0.62) showing larger effects than distal immobilisation (g = 0.42).

Size: distal immobilisation

For muscle size outcomes following distal (wrist cast) immobilisation, the analysis included five effect sizes from three studies (Supplementary Figure 2). Given the small number of contributing studies, this analysis should be considered exploratory. Cross-education did not

produce a significant effect on muscle size preservation (k = 5; g = 0.06, 95% CI [-0.16 to 0.29], p = 0.48). Only two training types were represented in distal size studies; neither eccentric (k = 3; g = 0.12, 95% CI [-0.03 to 0.27], p = 0.08) nor isometric training (k = 2; g = -0.01, 95% CI [-1.91 to 1.89], p = 0.97) produced significant effects. The absence of significant size preservation for distal immobilisation (g = 0.06, p = 0.48) contrasts markedly with proximal immobilisation (g = 0.40, p = 0.01), suggesting a potential anatomical specificity wherein cross-education size preservation is notable for proximal muscles but negligible for distal wrist musculature.

Relationship between non-immobilised and immobilised limb adaptations

Unilateral resistance training produced significant improvements in both strength and size in the trained (non-immobilised) limb compared to immobilised controls (Supplementary Figures 3 and 4; full results reported in Supplementary Material). These trained-limb adaptations provide the dose-response context for the between-limb correlation analyses presented in this section.

<<Figure 10>>

To examine whether the magnitude of adaptation in the trained limb was associated with preservation of the immobilised limb, correlation analyses were conducted between effect sizes for the trained and immobilised limbs across included studies (Figure 10A and 10B).

Strong positive correlations were observed for both strength (r = 0.79, R^2 = 0.63, p < 0.001, n = 16) and muscle size (r = 0.81, R^2 = 0.65, p < 0.001, n = 16), indicating that studies demonstrating larger adaptations in the trained limb for both strength and size also exhibited better preservation in the immobilised limb for strength and size respectively (i.e., attenuated losses compared to immobilisation alone). For both outcomes, cross-education training groups clustered in the upper-right quadrant of the scatterplots, demonstrating positive adaptations in the trained limb alongside near-zero or positive changes in the immobilised limb. Immobilised control groups occupied the lower-left region, exhibiting minimal change in the non-exercised limb and negative effect sizes in the immobilised limb reflecting disuse-induced losses.

Within-group correlations were generally weaker and non-significant for strength (immobilised control: r = 0.11, p = 0.79; training: r = 0.63, p = 0.10), though a significant within-group correlation emerged for muscle size in the immobilised control group (r = 0.80,

493 p = 0.017). These regression results must be interpreted cautiously, because there are only
494 eight included studies that all have relatively small sample sizes (64).

495 **Discussion**

496 This systematic review and three-level meta-analysis demonstrate that cross-education
497 attenuates losses in both muscle strength and size during short-term unilateral upper-limb
498 immobilisation, with strength preservation representing the more robust and consistent
499 effect. The comparatively smaller effect on muscle size is consistent with the mechanistic
500 basis of hypertrophic adaptation, which is fundamentally dependent on direct mechanical
501 loading of the muscle (65). The finding that any degree of size preservation is observed
502 without direct mechanical loading of the immobilised limb is nonetheless notable, and
503 whether bilateral neural activation can meaningfully modulate muscle protein turnover in
504 this context remains an open question warranting direct mechanistic investigation (6-8).
505 Even small attenuation of size loss during immobilisation may carry practical significance for
506 the trajectory of strength recovery. Whether the mechanisms underlying these differential
507 effects are neural, hypertrophic, or both cannot be determined from the present data and
508 warrants direct investigation in future work. Of note, the overall muscle size preservation
509 effect was only significant when all training types were combined; no individual training
510 protocol produced a significant effect in isolation. This pattern likely reflects the limited
511 number of effect sizes available per protocol subgroup rather than a true absence of protocol-
512 specific effects and should be interpreted accordingly.

513 The subgroup analyses reveal that these effects are moderated by both training
514 modality and anatomical location. Eccentric and combined concentric-eccentric protocols
515 produced the largest strength preservation effects, particularly under proximal
516 immobilisation, while effects were attenuated under distal immobilisation and with isometric
517 training. Importantly, the proximal versus distal comparisons were based on a limited
518 number of studies and should be interpreted as exploratory and hypothesis-generating
519 rather than definitive. The observed gradients between proximal and distal immobilisation
520 for strength and muscle size, provides the first quantitative – albeit underpowered and
521 exploratory - basis for powering future confirmatory studies examining whether
522 immobilisation location systematically moderates the magnitude of cross-education. The
523 basis for these apparent differences cannot be established from the current evidence base,

and adequately powered trials examining both proximal and distal immobilisation models are needed.

From a clinical perspective, these findings support the incorporation of unilateral eccentric or combined resistance training of the non-immobilised limb as a strategy to preserve neuromuscular function during immobilisation, particularly where proximal joints are affected. However, given the varying risk of bias across included studies and the limited number of studies available for several subgroup comparisons, these recommendations should be interpreted with appropriate caution.

Comparison to previous literature

The present findings are broadly consistent with, but more precisely quantified than, previous reviews examining cross-education during immobilisation. Hendy et al. (66) and Andrushko et al. (67) narratively synthesised evidence from up to five studies, concluding that cross-education could attenuate strength losses during immobilisation. Haggert et al. (68) conducted the first formal meta-analysis of this topic but was limited to five studies and did not employ multilevel modelling to account for dependent effect sizes. The current analysis, with eight studies and multi-level statistical handling of multiple outcomes within studies, provides up to date results and more in-depth insights into the muscle strength and size sparing effects compared to the previous literature.

The strong positive correlations observed between trained and immobilised limb adaptations for both strength and muscle size support the notion that maximising training adaptations in the exercising limb is critical for optimising the cross-education effect (18). This dose-response relationship is consistent with findings from non-immobilised populations, where the magnitude of contralateral strength transfer scales with the strength gains achieved in the trained limb (17), where following cross-education the untrained limb has a relative gain ~52% of the strength improvement in the trained limb. Notably, the strength preservation effect in the immobilised limb exceeded that observed in the trained limb, likely reflecting the combination of training-induced preservation in the cross-education groups against a backdrop of disuse-induced losses in the immobilised control groups. This pattern suggests that cross-education may be particularly efficacious during immobilisation, when the alternative is unmitigated neuromuscular decline. Notably, the same pattern observed for muscle size in the immobilised limb, where a significant overall effect with no protocol-specific effects, was also evident in the trained limb (no individual protocol was significant). This parallel suggests the absence of protocol-specific size effects

557 is a feature of the available evidence base rather than a true null finding, and that the limited
558 number of effect sizes per training type subgroup constrains the detection of protocol-
559 specific morphological adaptations.

560 ***Mechanistic considerations***

561 The different effects observed for strength and muscle size outcomes have important
562 mechanistic implications. The larger effect for strength preservation compared to muscle size
563 suggests that cross-education primarily operates through neural mechanisms rather than
564 direct muscular adaptations in the immobilised limb. This interpretation is consistent with
565 the leading candidate mechanistic hypotheses including the cross-activation, and the
566 bilateral access hypotheses (69). The cross-activation hypothesis posits that unilateral motor
567 training produces bilateral activation of motor cortices and descending pathways, facilitating
568 neural adaptations in both hemispheres (69-71), whereas the bilateral access hypothesis
569 proposes that the site of adaptation remains within the 'trained' hemisphere and is accessible
570 for the 'untrained' hemisphere via transcallosal pathways (69).

571 The finding that strength losses during immobilisation are predominantly neural in
572 origin, occurring within days before substantial muscle atrophy develops (6-8), provides a
573 compelling explanation for why cross-education, a predominantly neural phenomenon, is
574 effective at preserving strength. By maintaining neural drive and corticospinal excitability to
575 the immobilised limb through bilateral cortical activation, cross-education may counteract
576 the neural decrements that would otherwise occur during disuse (68).

577 The observation of significant, albeit smaller, effects on muscle size preservation
578 presents a more complex mechanistic picture. In healthy populations without
579 immobilisation, cross-education produces minimal morphological effects in the untrained
580 limb (72), yet during immobilisation, some degree of muscle size preservation is consistently
581 observed (28-34)**.** Several potential explanations warrant consideration. The muscle size
582 preservation observed may reflect attenuation of atrophy (i.e., reduced muscle loss) rather
583 than true hypertrophy, representing different underlying processes, and the sustained neural
584 activation through cross-education may modulate local signalling pathways involved in
585 muscle protein synthesis and muscle protein breakdown, even without direct mechanical
586 loading (73). Of potential relevance, Jameson et al. (74) observed that when maximal
587 eccentric muscle actions were performed prior to leg immobilisation, an attenuated decline
588 in muscle protein synthesis was observed after two and seven days of immobilisation. This

attenuation was accompanied by a reduction in the amount of muscle atrophy after two days. However, whether the sparing effects observed with cross-education during limb immobilisation have a shared mechanistic underpinning remains to be determined.

Anatomical specificity of cross-education effects

The subgroup analyses revealed an intriguing dissociation between proximal and distal musculature for muscle size, but not strength. Cross-education produced a significant muscle size preservation following proximal immobilisation but negligible effects following distal (wrist cast) immobilisation. In contrast, strength preservation was significant for both proximal and distal models. This pattern suggests that the mechanisms underlying strength and size preservation may operate somewhat independently, depending on the muscle group being investigated. To quantify this anatomical gradient, proximal effects were ~1.5 times larger than distal effects for strength, but a striking ~6.7 times larger for size. This order-of-magnitude difference in the proximal-distal gradient between outcomes underscores the distinct mechanistic pathways: strength preservation appears relatively robust across the limb, consistent with broadly distributed neural adaptations, whereas size preservation is almost exclusively observed for proximal musculature.

Although speculative, several factors may contribute to this proximal-distal dissociation for muscle size outcomes. Classically, the reticulospinal tract has been considered to control proximal and axial muscles, while the corticospinal tract mediates fine distal movements, particularly of the hand (75-77). Recent evidence confirms that in human upper extremities, reticulospinal drive is enhanced to proximal compared to distal muscles (78), while corticospinal projections show stronger effects on motoneurons innervating forearm and hand muscles compared to upper arm muscles (79). Cross-education may involve, at least in part, cortico–reticulospinal pathways. The supplementary motor area contributes descending drive to corticoreticular circuits (80) and has been implicated in the cross-education effect (81). Evidence from a unilateral resistance training intervention in non-human primates supports this notion (82), as diffuse bilateral adaptations have been observed within reticulospinal projections.

No evidence of publication bias despite limited statistical power

Publication bias was assessed using funnel plots and Egger's regression test. For strength outcomes, Egger's test indicated no significant funnel plot asymmetry. Similarly, for muscle size outcomes, Egger's test was not significant. As no significant asymmetry was detected,

trim-and-fill analysis was not warranted. These findings suggest the pooled estimates are unlikely to be substantially influenced by publication bias.

Nevertheless, the relatively small number of included studies (k = 8) limits the statistical power of tests for funnel plot asymmetry, and results should be interpreted with this in mind. Three unpublished papers (two thesis documents and one short report) were identified through additional search strategies (83-85). Although these papers were too limited for inclusion in the meta-analysis, this is the first time each has been identified through a systematic search process, as none are mentioned in previous reviews on this topic (66-68). Particularly noteworthy is the work by Rozier and Elder (84) and Hlavacek and Koszalinski (85), as these both pre-date the earliest reports of cross-education with limb disuse (29).

Clinical implications

The consistent direction of effects across studies and the plausible mechanistic basis suggest that cross-education represents a viable adjunct intervention during limb immobilisation or for individuals with unilateral impairment (86). From a practical standpoint, cross-education offers several advantages over alternative countermeasures such as neuromuscular electrical stimulation or localised heat therapy: it requires no specialised equipment, can be self-administered, maintains fitness in the non-injured limb, and carries minimal risk of adverse effects.

Based on the current evidence, several recommendations for clinical implementation can be offered. Cross-education interventions should emphasise high-intensity resistance exercise, as the magnitude of cross-education is dose-dependent and near-maximal intensities produce the greatest contralateral effects (14, 18). The use of eccentric muscle actions should be prioritised where feasible, given their superior capacity to induce neuroplastic adaptations and enhance cross-education magnitude (20, 87). The exercise should target the homologous muscle group or should be implemented across multiple muscle groups in contralateral non-immobilised limb, as cross-education exhibits muscle-specificity (26, 28). Although the current analyses focus on healthy upper limb immobilisation, it is important to acknowledge meaningful cross-education effects have been observed in clinical models such as stroke (88, 89), wrist fracture (90), and following knee injury (87, 91-96), and the general points of recommendation mentioned above generally align with the clinical cross-education data. It should be noted, however, that these

recommendations are based on evidence with a non-trivial risk of bias: no included study was rated as low risk overall, and four were rated as high risk, primarily due to limitations in the randomisation process. Clinical implementation of these recommendations should therefore be considered provisional until confirmed by adequately powered, well-randomised trials.

Limitations

Several limitations should be acknowledged. All included studies employed experimental immobilisation models in healthy young adults, and the observed magnitude of preservation is unlikely to occur over longer disuse periods often required in clinical populations undergoing immobilisation following actual injury. Injury-induced inflammation, pain, and psychological factors may modulate the response to cross-education in ways not captured by these 'healthy' experimental models. The evidence base remains relatively small (eight studies, 189 participants), limiting statistical power for subgroup analyses, and this is especially evident with only three studies in the distal limb meta-analyses reported in this manuscript. The inability to examine contraction type as a moderator due to insufficient studies employing comparable protocols represents a notable gap. Additionally, all included studies examined upper limb immobilisation; no eligible studies of lower limb immobilisation were identified, limiting generalisability to common clinical scenarios such as ankle fractures or knee surgery. This absence of lower limb evidence represents perhaps the most critical gap in the literature, given that lower limb immobilisation following ankle fractures, knee surgery (including anterior cruciate ligament reconstruction and meniscectomy), and Achilles tendon repairs are among the most common clinical scenarios requiring prolonged immobilisation. The quadriceps in particular are highly susceptible to rapid atrophy following knee injury and surgery, with deficits persisting for years post-operatively; whether cross-education can attenuate this decline remains unknown. Future research should prioritise lower limb immobilisation models as a matter of clinical urgency.

Future directions

Several priorities for future research emerge from this analysis. First, adequately powered randomised controlled trials in clinical populations undergoing immobilisation following orthopaedic injury or surgery are needed to establish external validity, particularly in lower limb immobilisation models where evidence remains limited. In parallel, mechanistic work integrating neuroimaging (functional Magnetic Resonance Imaging, Transcranial Magnetic

Stimulation) with molecular analyses could elucidate the relative contributions of neural and muscular factors to cross-education effects during immobilisation. To translate these findings into practice, dose-response studies systematically varying training intensity, volume, and contraction type would optimise exercise prescription. The application of cross-education for attenuating neuromuscular decline in older adults is also an area that remains to be investigated. Older adults have a greater incidence of fractures (97), and exhibit rostral atrophy in the corpus callosum (98), which might impact the efficacy of cross-education. Finally, longer-term follow-up examining whether cross-education during immobilisation accelerates post-immobilisation rehabilitation and return to function would strengthen the clinical rationale for implementation.

Conclusion

This systematic review and meta-analysis provide the most comprehensive synthesis to date of cross-education effects during limb immobilisation. Cross-education training produces moderate-to-large effects on strength preservation and small effects on muscle size preservation in the immobilised limb, with effects consistently favouring the intervention across studies. The larger effects on strength compared to size are consistent with a primarily neural basis for cross-education, though this inference requires direct mechanistic investigation. Subgroup analyses suggest that muscle size preservation may be anatomically specific, favouring proximal over distal musculature, however the limited amount of data in the distal musculature greatly limits the strength of this interpretation. Future research should prioritise clinical populations, lower limb models, and mechanistic investigations to optimise implementation and understand the physiological basis for these effects. It should be noted that these findings are based on a body of evidence with a non-trivial risk of bias. No included study was rated as low risk overall, and four were rated as high risk, and all conclusions should be interpreted accordingly.

Data availability

The data file compiled for this meta-analysis, along with additional analyses of the non-immobilised limb have been made available as supplementary materials at https://doi.org/10.5281/zenodo.19383506. Further, the meta-analysis pipeline has been compiled into a Shiny application and published to the web (https://jandrushko.shinyapps.io/Easy_Meta-Analysis/), and the code is available on GitHub

716 (https://github.com/jandrushko/Easy_Meta_Analysis) for further data investigation and/or
717 replication of findings.

718 **Declaration**

719 ***Conflict of interest***

720 The authors have no conflicts of interest to declare.

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723 ***Author contributions***

724 Matías Rodríguez-Coloma, Luke D. Scott, Claudio I. Bascour-Sandoval, and Laura Castillo-
725 Vejar carried out the literature search, Luke D. Scott and Justin W. Andrushko carried out
726 the meta-analysis, Matías Rodríguez-Coloma, Luke D. Scott, Joshua C. Carr, and Justin W.
727 Andrushko contributed to writing the manuscript, and all authors reviewed, edited and
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998

Figure Captions

Figure 1. PRISMA flow diagram illustrating the systematic literature search and study selection process. The left pathway shows records identified through database searching across eight sources (PubMed, EMBASE, Scopus, Web of Science, CINAHL, Epistemonikos, and LILACS; total n = 394). The right pathway shows records identified through supplementary methods (citation searching, generative AI, Google Scholar citations, and collaboration on a later published study; total n = 6). Yellow header boxes denote the identification stage; blue side labels indicate the stages of identification, screening, and inclusion. Following removal of 159 duplicate records, 235 records were screened. After full-text eligibility assessment, 8 studies were ultimately included in the review. Source: Page MJ et al. *BMJ* 2021;372:n71. doi:10.1136/bmj.n71. This work is licensed under CC BY 4.0.

Figure 2. Cochrane Risk of Bias (RoB) 2 assessment for the eight included studies. **A) Traffic light plot** displaying judgements across five domains for each study: D1 = bias arising from the randomisation process; D2 = bias due to deviations from intended interventions; D3 = bias due to missing outcome data; D4 = bias in measurement of the outcome; D5 = bias in selection of the reported result. Judgements are indicated by coloured symbols: red circle with X = high risk; yellow circle with dash = some concerns; green circle with plus = low risk. The Overall column represents the study-level summary judgement. **B) Summary bar chart** displaying the proportion of studies rated as low risk (green), some concerns (yellow), or high risk (red) for each domain and overall. Figure created using *robvis* (https://mcguinlu.shinyapps.io/robvis/).

Figure 3. Contour-enhanced funnel plots for **A)** immobilised limb muscle strength and **B)** immobilised limb muscle size, used to assess potential publication bias. The y-axis represents standard error (inverted, with 0 at the apex) and the x-axis represents the observed effect size (Hedges' g). The dotted vertical line indicates the pooled effect estimate. Shaded regions indicate significance thresholds: white = $p > 0.10$; amber = $0.05 < p \leq 0.10$; blue = $0.01 < p \leq 0.05$. Individual aggregated effect sizes are shown as black points. Points within the blue region or outside of the triangle are consistent with statistically significant effects.

Figure 4. Forest plot of between-group differences (training vs. immobilised control) for muscle strength in the immobilised limb (25 effect sizes from 8 studies; three-level random-effects model). Individual effect sizes are displayed as filled circles, with horizontal lines indicating 95% confidence intervals; circle size is proportional to study weight. Points are colour-coded by training type: orange = Concentric; light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds below the individual studies represent subgroup pooled effects by training type using the same colour scheme. Weights (%) reflect the contribution of each effect size to the pooled estimate.

Figure 5. Forest plot of between-group differences (training vs. immobilised control) for muscle size in the immobilised limb (16 effect sizes from 8 studies; three-level random-effects model). Individual effect sizes are displayed as filled circles proportional in size to their study weight, with horizontal lines indicating 95% confidence intervals. Points are colour-coded by training type: orange = Concentric; light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds represent subgroup pooled effects by training type. Note that the Concentric subgroup diamond extends substantially beyond the x-axis range due to wide confidence intervals resulting from only two effect sizes.

Figure 6. Forest plot of between-group differences (training vs. immobilised control) for muscle strength restricted to trained homologous muscle groups in the immobilised limb (19 effect sizes from 8 studies; three-level random-effects model). Individual effect sizes are displayed as filled circles proportional in size to their study weight, with horizontal lines indicating 95% confidence intervals. Points are colour-coded by training type: orange = Concentric; light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds represent subgroup pooled effects by training type. The Concentric subgroup diamond extends beyond the displayed x-axis range due to wide confidence intervals from only two contributing effect sizes.

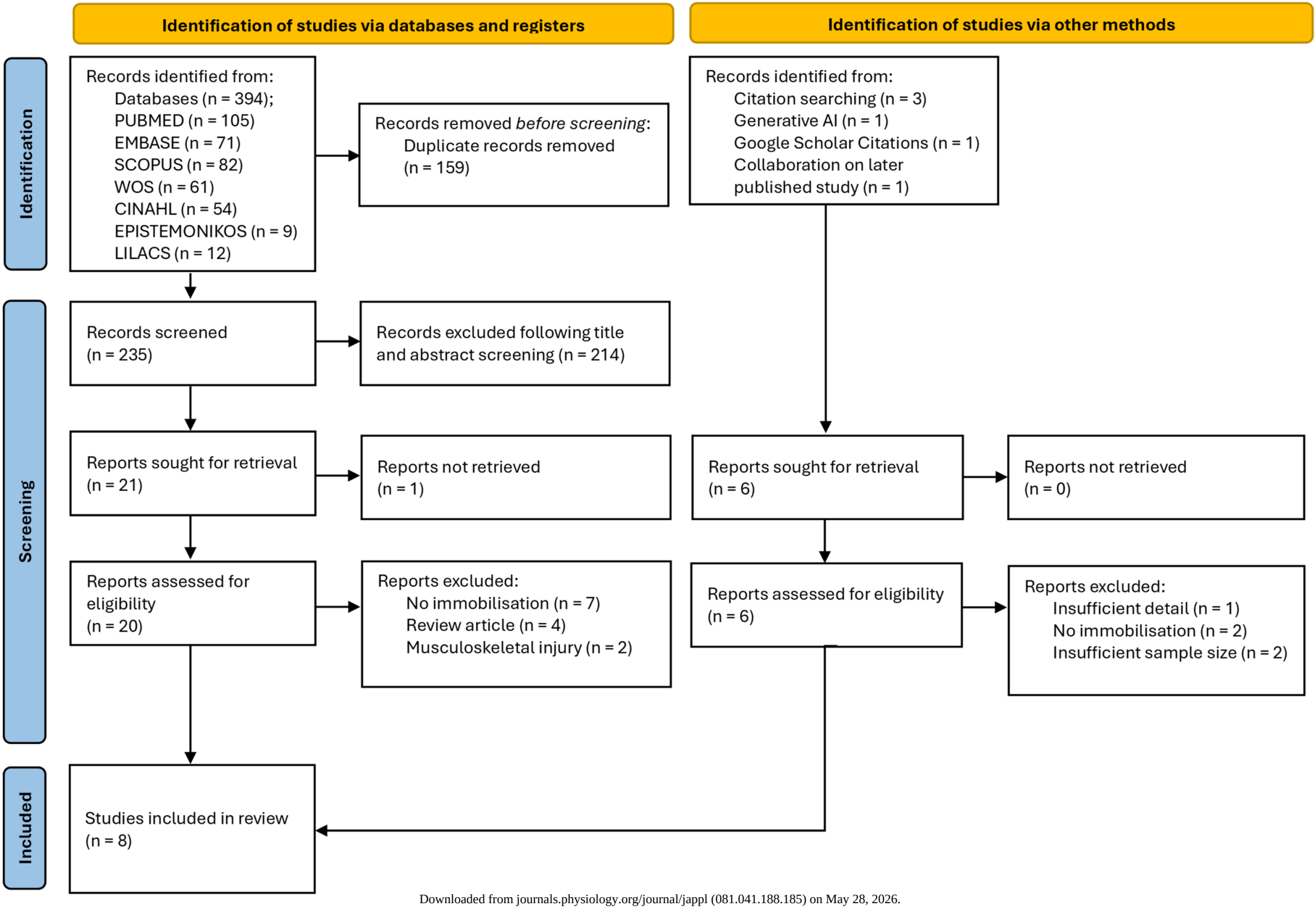
Figure 7. Forest plot of between-group differences (training vs. immobilised control) for muscle size restricted to trained homologous muscle groups in the immobilised limb (15 effect sizes from 8 studies; three-level random-effects model). Individual effect sizes are displayed as filled circles proportional in size to their study weight, with horizontal lines indicating 95% confidence intervals. Points are colour-coded by training type: orange = Concentric; light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds represent subgroup pooled effects by training type. The Concentric subgroup diamond extends substantially beyond the displayed x-axis range due to wide confidence intervals from only two contributing effect sizes.

Figure 8. Forest plot of between-group differences (training vs. immobilised control) for muscle strength following proximal upper-limb immobilisation (shoulder sling and long arm cast; 17 effect sizes from 5 studies; three-level random-effects model).

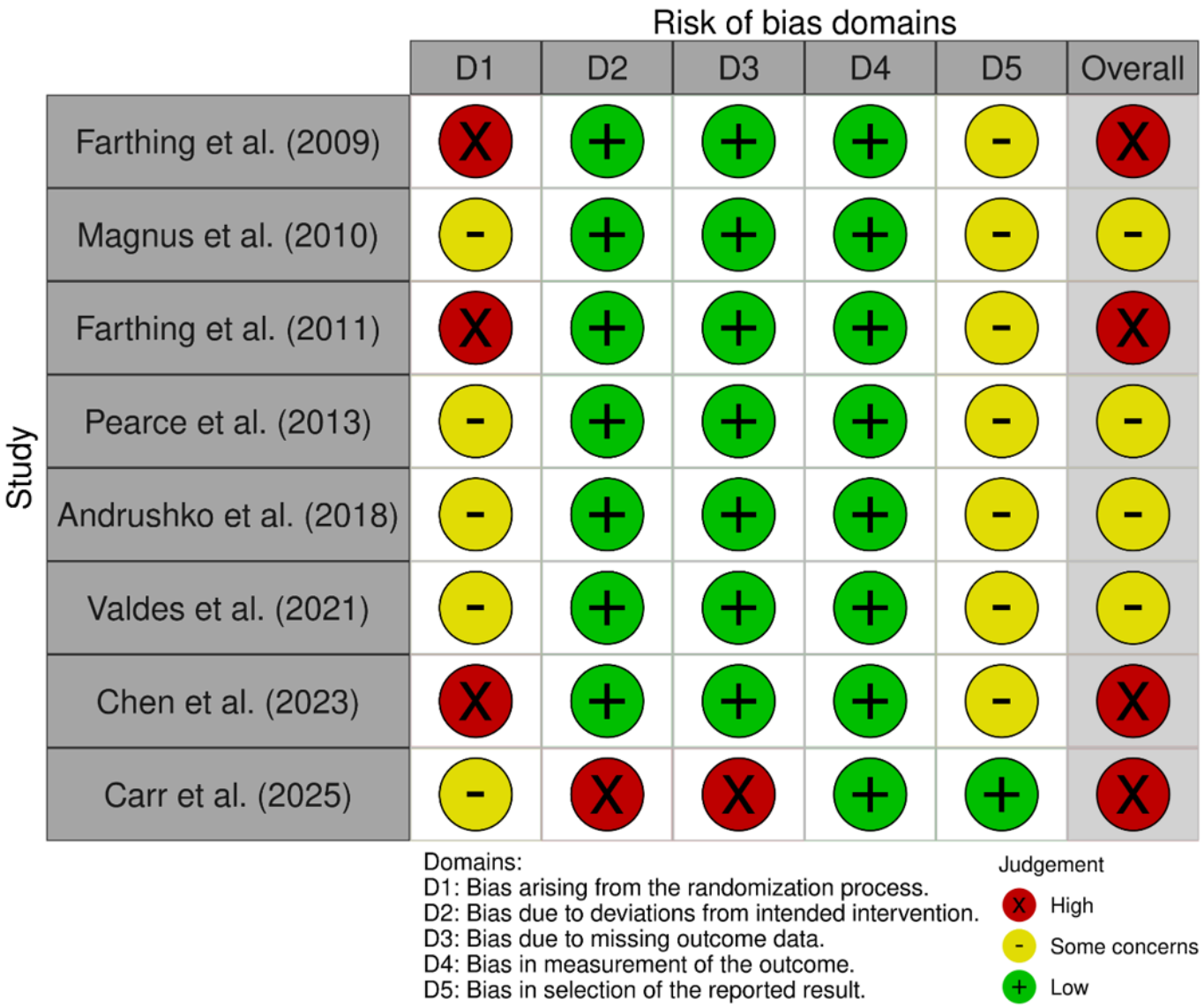
Individual effect sizes are displayed as filled circles proportional in size to their study weight, with horizontal lines indicating 95% confidence intervals. Points are colour-coded by training type: orange = Concentric; light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds represent subgroup pooled effects by training type. These analyses should be interpreted as exploratory given the limited number of contributing studies.

Figure 9. Forest plot of between-group differences (training vs. immobilised control) for muscle size following proximal upper-limb immobilisation (shoulder sling and long arm cast; 7 effect sizes from 5 studies; simplified random-effects model). Individual effect sizes are displayed as filled circles proportional in size to their study weight, with horizontal lines indicating 95% confidence intervals. Points are colour-coded by training type: light blue = Concentric-Eccentric; teal = Eccentric; yellow = Isometric. The solid teal vertical line and shaded band represent the overall pooled effect and its 95% confidence interval; the dotted vertical line represents the null effect (zero). The overall pooled effect is shown as a green diamond with a black border. Coloured diamonds represent subgroup pooled effects by training type. Due to limited data preventing three-level model convergence, effect sizes were aggregated to one per study and a simplified random-effects model was employed; note that subgroup analyses by training type should therefore be interpreted with additional caution.

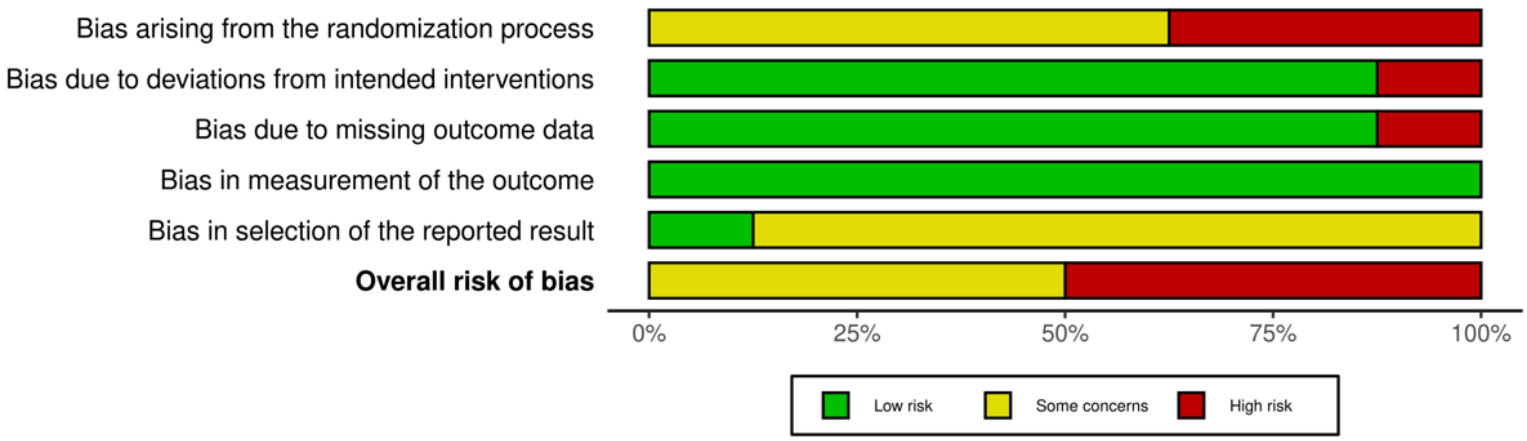
Figure 10. Scatter plots with separate linear regressions for **A)** muscle strength and **B)** muscle size, displaying the relationship between the pre-post effect size (SMCR, Hedges' *g*) for the non-immobilised limb (x-axis) and the immobilised limb (y-axis) for each study included in the meta-analysis (n = 16 data points per panel). Orange circles with labelled study names represent cross-education training groups; blue circles represent immobilised control groups. Regression lines are displayed for each group with shaded bands indicating 95% confidence intervals. Overall correlation statistics (r, R^2, p) displayed in the upper left of each panel represent the model including both groups combined. Positive values on the y-axis indicate strength gains or size preservation in the immobilised limb relative to the control condition; negative values indicate losses.



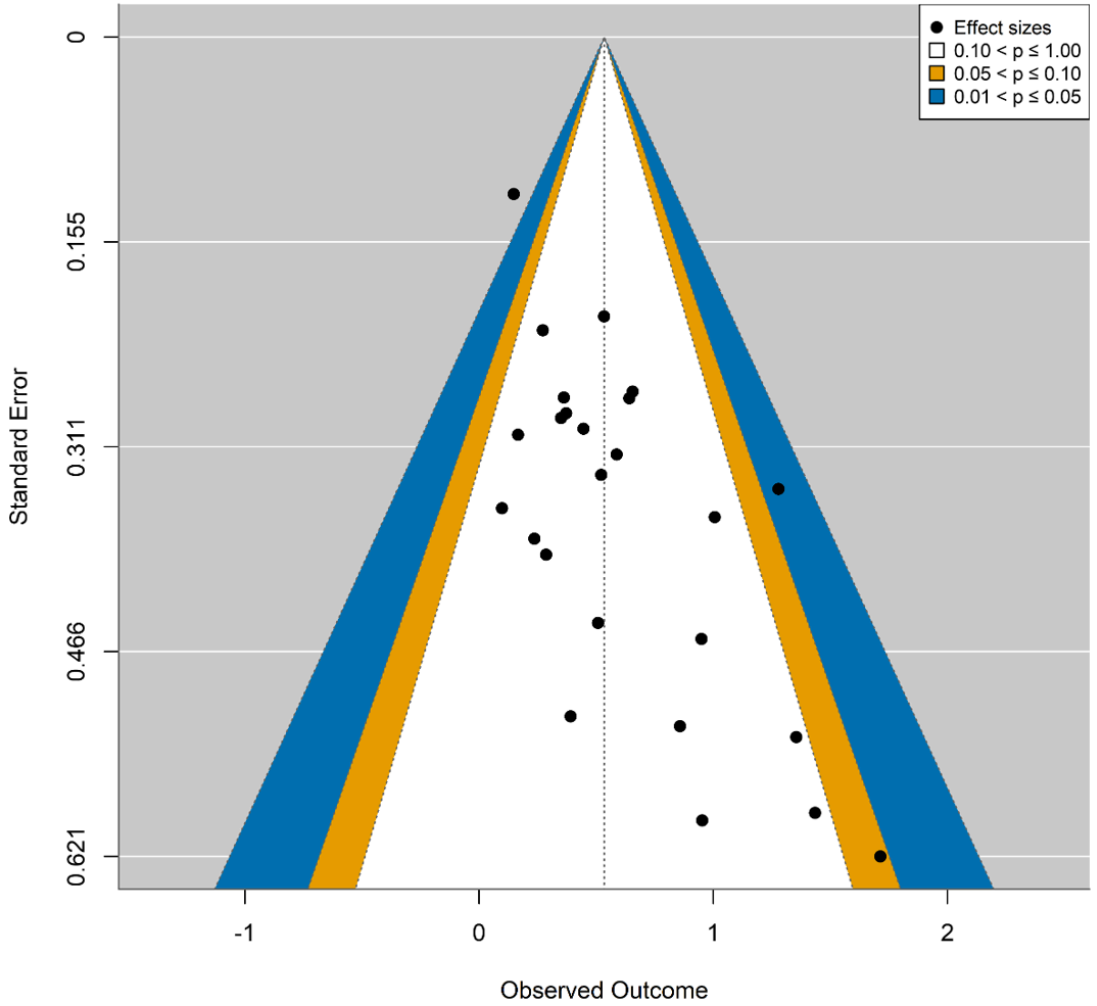
A) Traffic Light



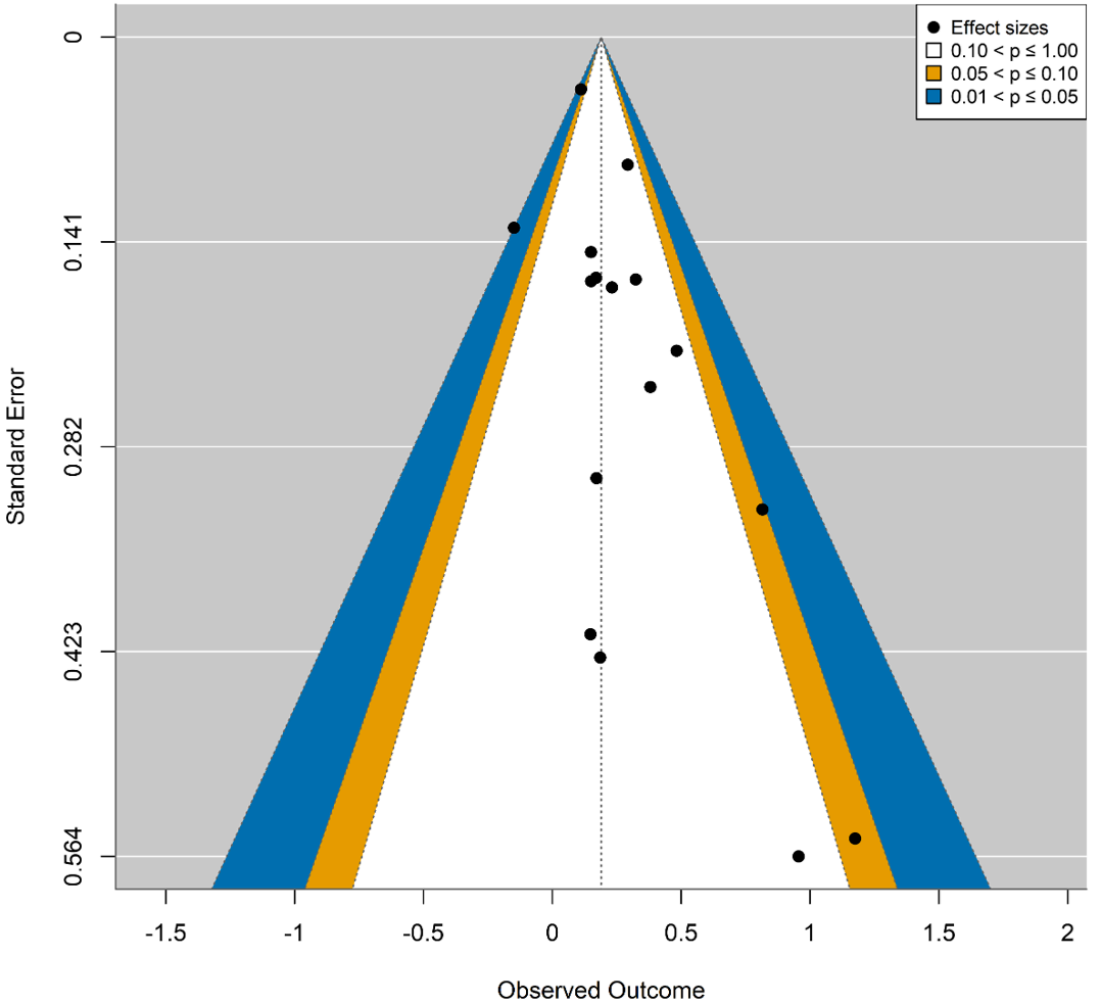
B) Summary

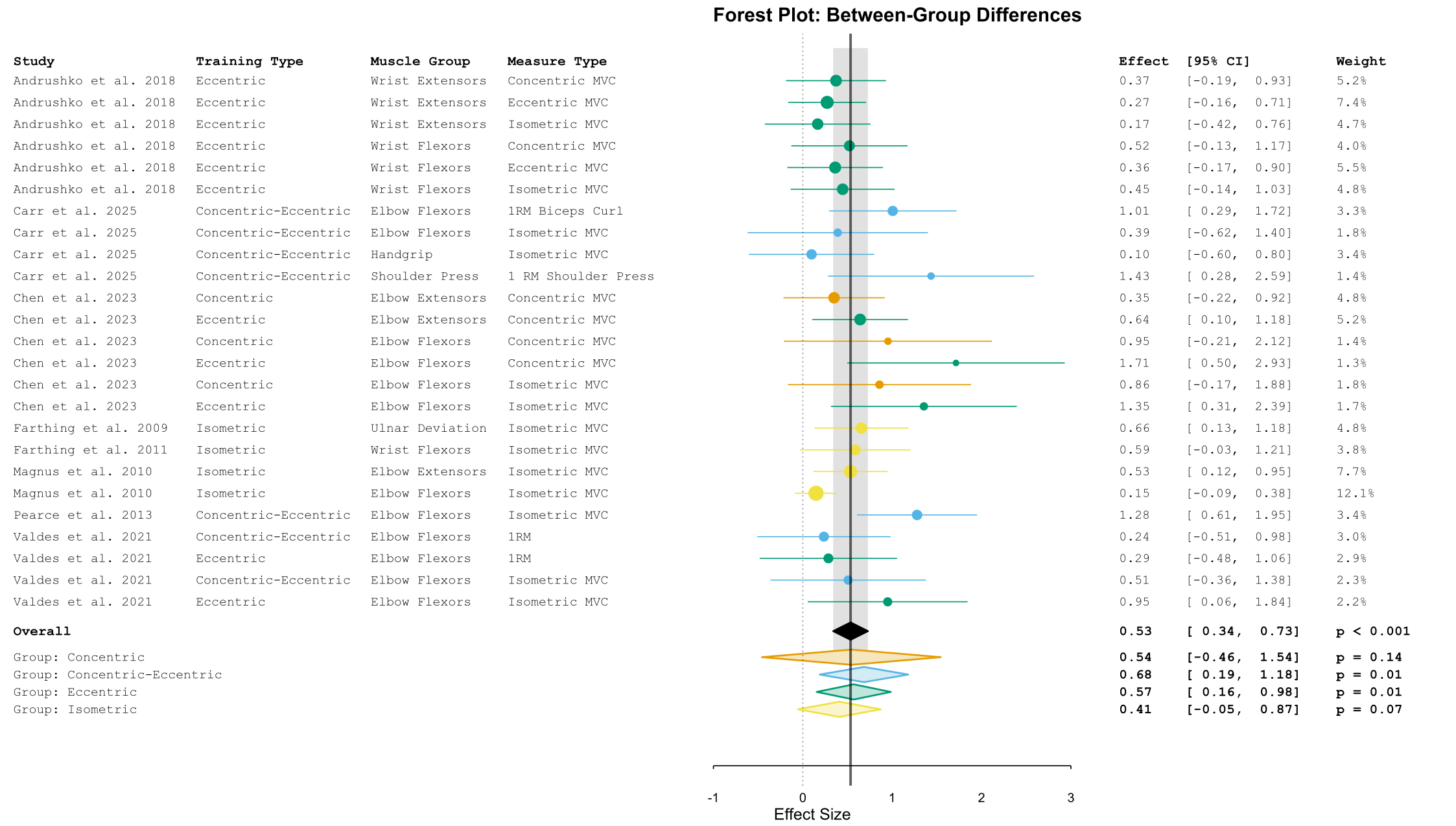


A) Immobilised Limb Strength



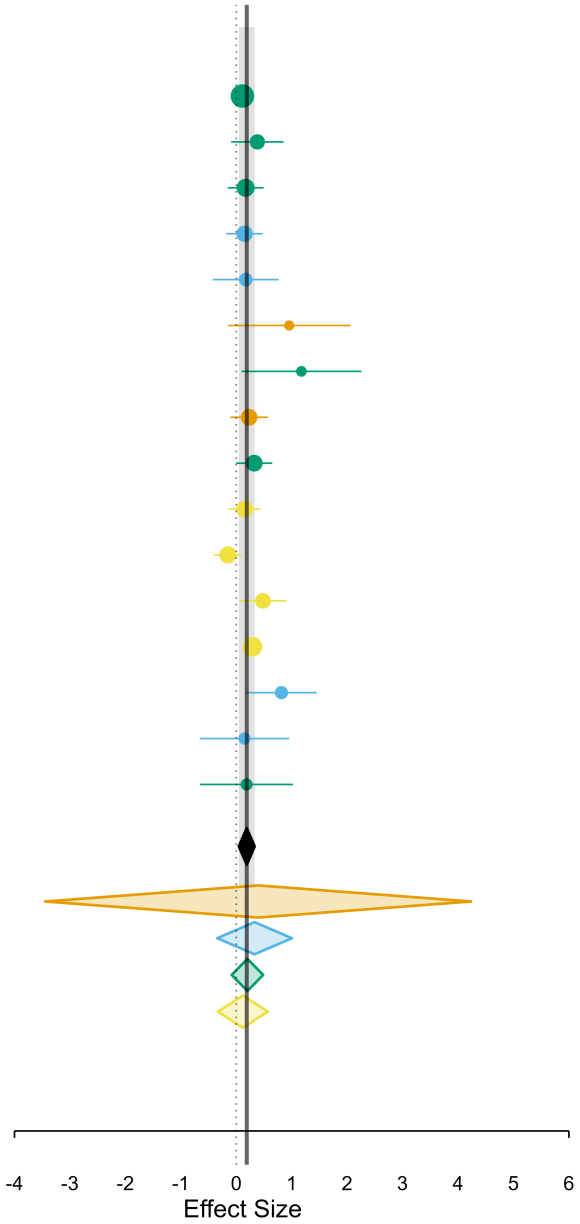
B) Immobilised Limb Size

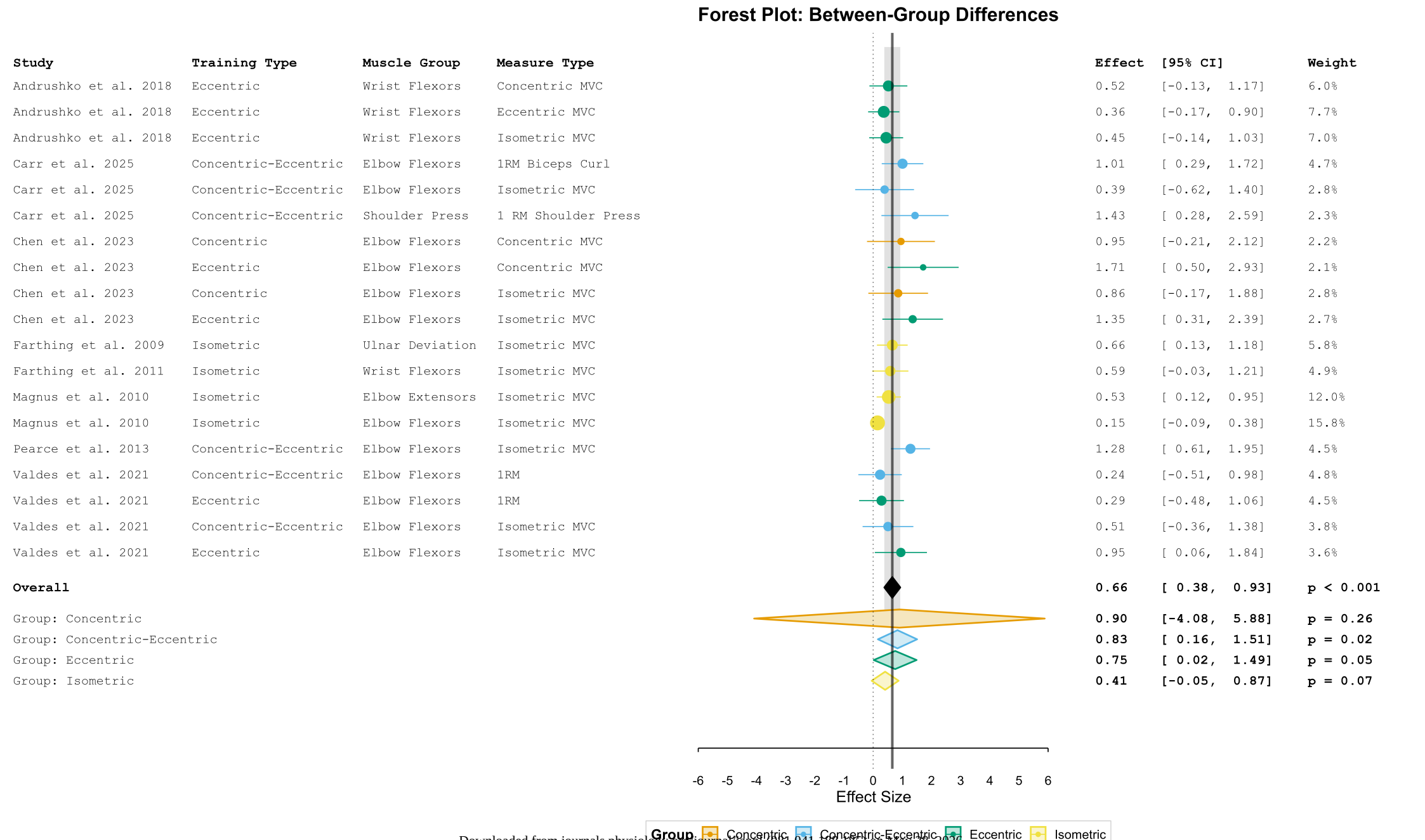




Forest Plot: Between-Group Differences

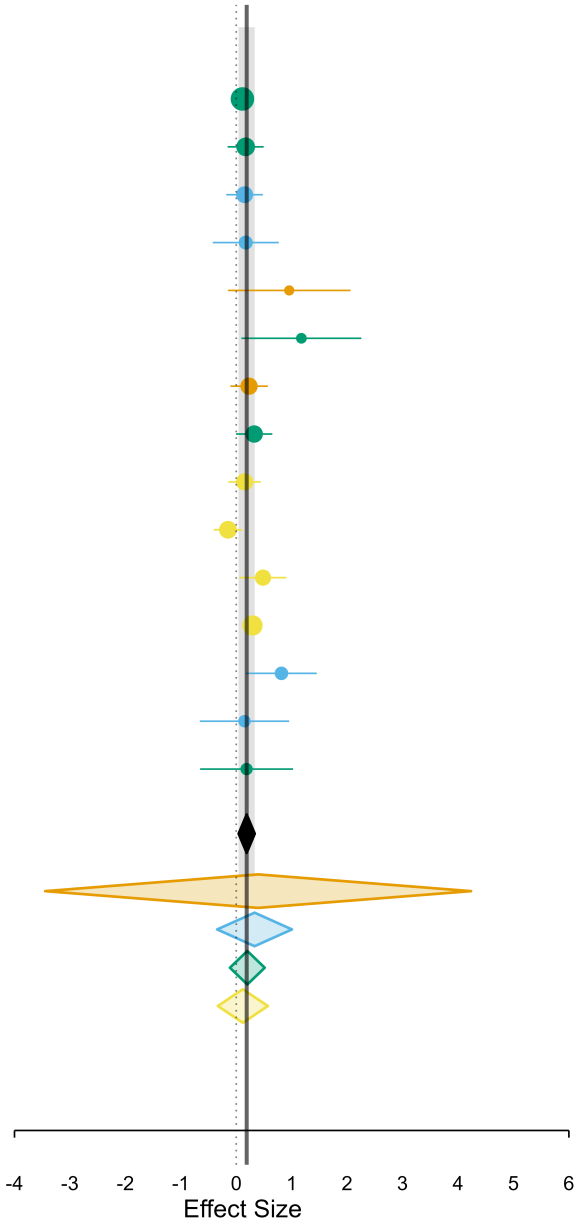
Study	Training Type	Muscle Group	Measure Type	Effect	[95% CI]	Weight
Andrushko et al. 2018	Eccentric	Forearm	MCSA	0.11	[0.04, 0.18]	25.4%
Andrushko et al. 2018	Eccentric	Wrist Extensors	Muscle Thickness	0.38	[-0.09, 0.85]	4.5%
Andrushko et al. 2018	Eccentric	Wrist Flexors	Muscle Thickness	0.17	[-0.16, 0.49]	9.2%
Carr et al. 2025	Concentric-Eccentric	Elbow Flexors	MCSA	0.15	[-0.18, 0.48]	6.1%
Carr et al. 2025	Concentric-Eccentric	Upper Body	Regional Lean Mass	0.17	[-0.42, 0.77]	2.6%
Chen et al. 2023	Concentric	Elbow Flexors	MCSA	0.96	[-0.15, 2.06]	0.8%
Chen et al. 2023	Eccentric	Elbow Flexors	MCSA	1.17	[0.09, 2.26]	0.8%
Chen et al. 2023	Concentric	Upper Arm	Circumference	0.23	[-0.11, 0.57]	6.6%
Chen et al. 2023	Eccentric	Upper Arm	Circumference	0.32	[-0.00, 0.65]	6.9%
Farthing et al. 2009	Isometric	Wrist Flexors	Muscle Thickness	0.15	[-0.14, 0.44]	6.7%
Farthing et al. 2011	Isometric	Wrist Flexors	Muscle Thickness	-0.15	[-0.41, 0.11]	7.5%
Magnus et al. 2010	Isometric	Elbow Extensors	Muscle Thickness	0.48	[0.06, 0.91]	5.1%
Magnus et al. 2010	Isometric	Elbow Flexors	Muscle Thickness	0.29	[0.12, 0.46]	12.8%
Pearce et al. 2013	Concentric-Eccentric	Elbow Flexors	Muscle Thickness	0.82	[0.18, 1.45]	2.1%
Valdes et al. 2021	Concentric-Eccentric	Upper Arm	Circumference	0.15	[-0.66, 0.95]	1.4%
Valdes et al. 2021	Eccentric	Upper Arm	Circumference	0.19	[-0.65, 1.02]	1.3%
Overall				**0.19**	**[0.05, 0.33]**	**p = 0.01**
Group: Concentric				**0.39**	**[-3.45, 4.23]**	**p = 0.42**
Group: Concentric-Eccentric				**0.33**	**[-0.34, 1.01]**	**p = 0.22**
Group: Eccentric				**0.20**	**[-0.08, 0.49]**	**p = 0.13**
Group: Isometric				**0.12**	**[-0.33, 0.57]**	**p = 0.46**

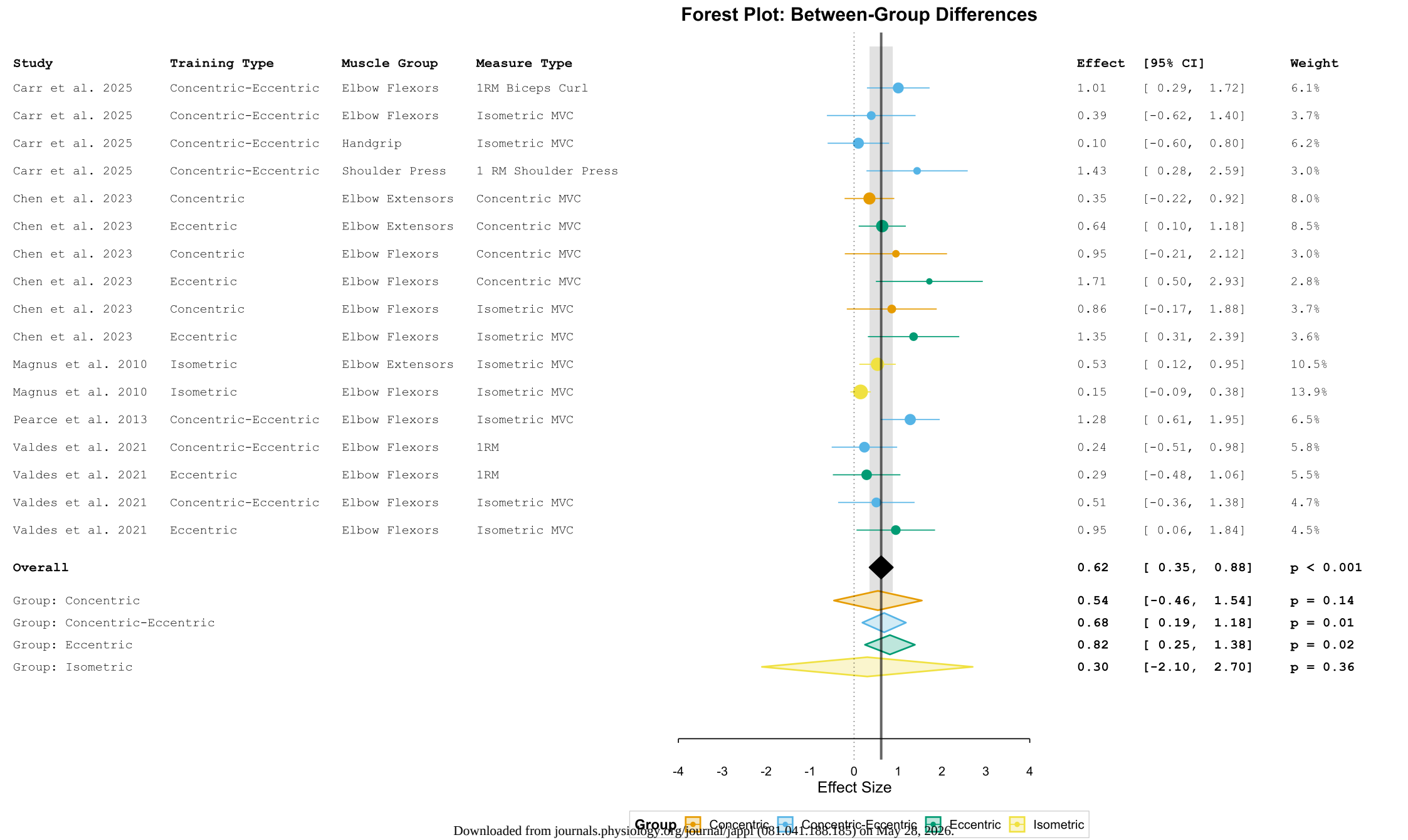




Forest Plot: Between-Group Differences

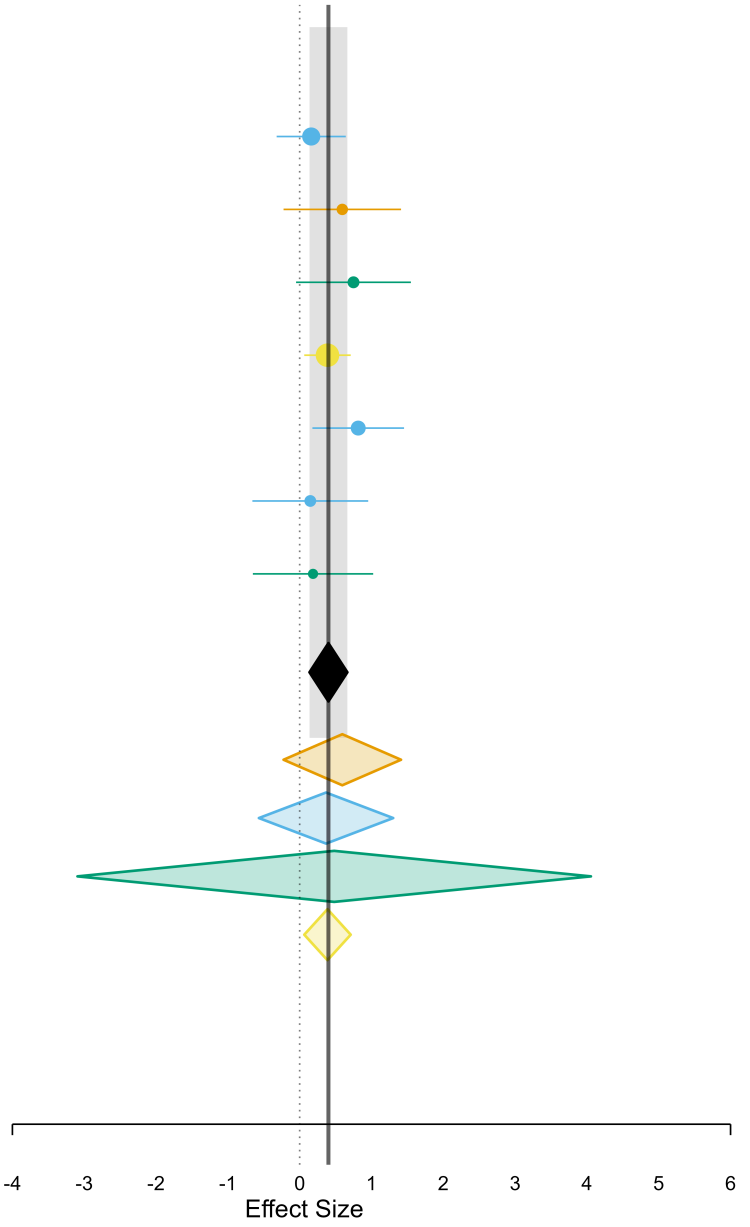
Study	Training Type	Muscle Group	Measure Type	Effect	[95% CI]	Weight
Andrushko et al. 2018	Eccentric	Forearm	MCSA	0.11	[0.04, 0.18]	23.6%
Andrushko et al. 2018	Eccentric	Wrist Flexors	Muscle Thickness	0.17	[-0.16, 0.49]	10.1%
Carr et al. 2025	Concentric-Eccentric	Elbow Flexors	MCSA	0.15	[-0.18, 0.48]	6.7%
Carr et al. 2025	Concentric-Eccentric	Upper Body	Regional Lean Mass	0.17	[-0.42, 0.77]	2.8%
Chen et al. 2023	Concentric	Elbow Flexors	MCSA	0.96	[-0.15, 2.06]	0.9%
Chen et al. 2023	Eccentric	Elbow Flexors	MCSA	1.17	[0.09, 2.26]	0.9%
Chen et al. 2023	Concentric	Upper Arm	Circumference	0.23	[-0.11, 0.57]	7.2%
Chen et al. 2023	Eccentric	Upper Arm	Circumference	0.32	[-0.00, 0.65]	7.6%
Farthing et al. 2009	Isometric	Wrist Flexors	Muscle Thickness	0.15	[-0.14, 0.44]	7.2%
Farthing et al. 2011	Isometric	Wrist Flexors	Muscle Thickness	-0.15	[-0.41, 0.11]	8.2%
Magnus et al. 2010	Isometric	Elbow Extensors	Muscle Thickness	0.48	[0.06, 0.91]	5.6%
Magnus et al. 2010	Isometric	Elbow Flexors	Muscle Thickness	0.29	[0.12, 0.46]	13.9%
Pearce et al. 2013	Concentric-Eccentric	Elbow Flexors	Muscle Thickness	0.82	[0.18, 1.45]	2.3%
Valdes et al. 2021	Concentric-Eccentric	Upper Arm	Circumference	0.15	[-0.66, 0.95]	1.6%
Valdes et al. 2021	Eccentric	Upper Arm	Circumference	0.19	[-0.65, 1.02]	1.5%
Overall				**0.19**	**[0.04, 0.33]**	**p = 0.01**
Group: Concentric				**0.39**	**[-3.45, 4.23]**	**p = 0.42**
Group: Concentric-Eccentric				**0.33**	**[-0.34, 1.01]**	**p = 0.22**
Group: Eccentric				**0.20**	**[-0.11, 0.51]**	**p = 0.15**
Group: Isometric				**0.12**	**[-0.33, 0.57]**	**p = 0.46**

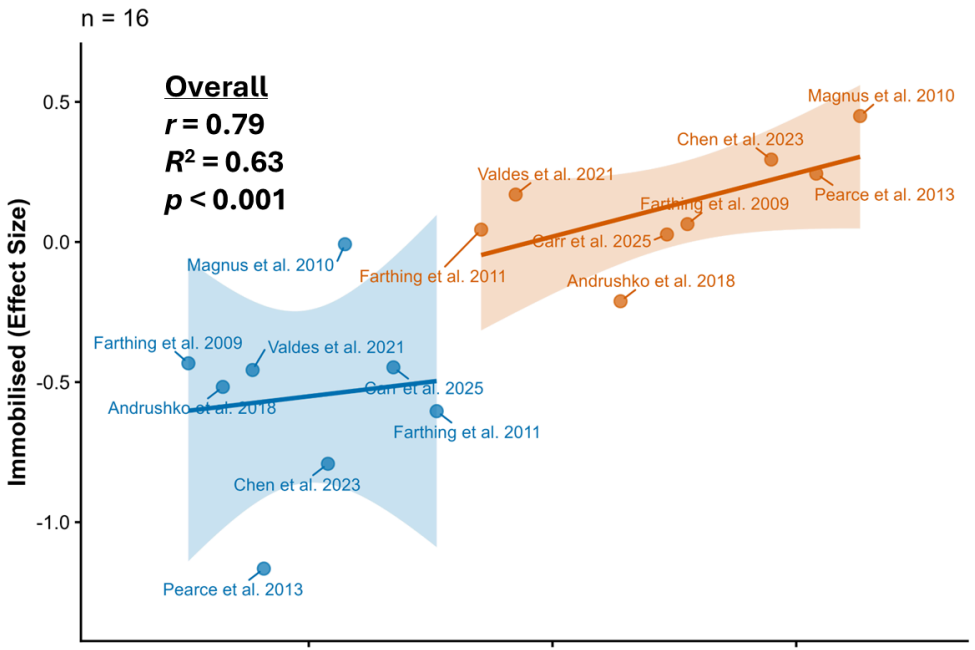




Forest Plot: Between-Group Differences

Study	Training Type	Effect	[95% CI]	Weight
Carr et al. 2025	Concentric-Eccentric	0.16	[-0.32, 0.64]	19.3%
Chen et al. 2023	Concentric	0.59	[-0.22, 1.41]	6.7%
Chen et al. 2023	Eccentric	0.75	[-0.05, 1.55]	7.0%
Magnus et al. 2010	Isometric	0.39	[0.06, 0.71]	42.8%
Pearce et al. 2013	Concentric-Eccentric	0.82	[0.18, 1.45]	11.0%
Valdes et al. 2021	Concentric-Eccentric	0.15	[-0.66, 0.95]	6.9%
Valdes et al. 2021	Eccentric	0.19	[-0.65, 1.02]	6.4%
Overall		**0.40**	**[0.14, 0.66]**	**p = 0.010**
Group: Concentric		**0.59**	**[-0.22, 1.41]**	**p = 0.15**
Group: Concentric-Eccentric		**0.37**	**[-0.57, 1.30]**	**p = 0.23**
Group: Eccentric		**0.48**	**[-3.09, 4.06]**	**p = 0.34**
Group: Isometric		**0.39**	**[0.06, 0.71]**	**p = 0.02**





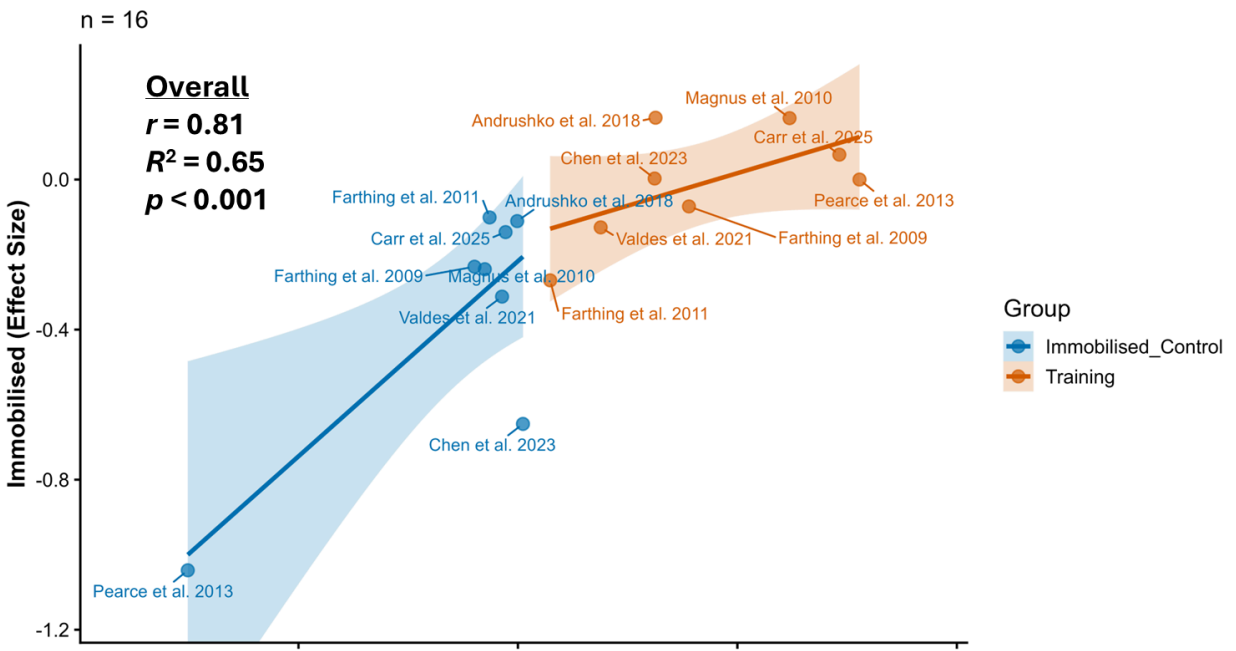


Table 1. Database search terms

Database	Search Terms
PubMed	("cross education" OR “cross-education” OR “unilateral-training” OR “unilateral training” OR “contralateral training” OR “unilateral strength training” OR “contralateral strength training” OR “interlimb transfer” OR “inter limb transfer” OR “strength transfer” OR “strength-transfer” OR “intermanual transfer” OR “cross training”) AND ("muscle mass" OR "muscle thickness" OR "lean mass" OR strength)
Scopus	
Web of Science	
Latin America and the Caribbean Literature on Health Sciences (LILACS)	"educação cruz" or "cross-education"
Epistemonikos	"cross education" OR "cross-education" OR "unilateral-training" OR "unilateral training" OR "contralateral training" OR "unilateral strength training" OR "contralateral strength training" OR "interlimb transfer" OR "inter limb transfer" OR "strength transfer" OR "strength-transfer" OR "intermanual transfer" OR "cross training" AND "muscle mass" OR "muscle thickness" OR "lean mass" OR "strength" OR "force" OR "power"
Embase (Elsevier)	'cross education'/exp OR 'cross education' OR 'cross-education' OR 'unilateral-training' OR 'unilateral training' OR 'contralateral training' OR 'unilateral strength training' OR 'contralateral strength training' OR 'interlimb transfer'/exp OR 'interlimb transfer' OR 'inter limb transfer' OR 'strength transfer' OR 'strength-transfer' OR 'intermanual transfer' OR 'cross training'/exp OR 'cross training' AND 'muscle mass' OR 'muscle thickness' OR 'lean mass' AND 'strength' OR 'force' OR 'power'
Cumulative Index to Nursing and Allied Health Literature	("cross education" or "cross-education") or interlimb transfer or "unilateral training") AND (muscle mass or muscle strength or muscle gains or muscle hypertrophy or muscle OR strength)

Table 2. Study characteristics

Authors	Subjects	Immobilisation method, Duration & Daily hours	Study & Intervention Design	Outcome Measures	Summary of findings
Farthing et al. 2009 (Journal Article)	Cross-Education: (n = 10) (M = 3, F = 7) Immobilised Control: (n = 10) (M = 2, F = 8) True Control: (n = 10) (M = 3, F = 7)	Immobilisation method: Wrist Cast Duration: 3 weeks Daily Hours: 24 hours	Study: Parallel group non-random assignment to 1 of 3 groups Intervention: Isometric Ulnar deviation 5 days per week. Sets × reps were 3 × 8 sets in the first session, to 6 × 8 by the 4th session.	Strength: Ulnar deviation; Isometric MVC Size: Wrist Flexor; Muscle thickness	No loss of strength or size in the cross-education group but a statistically significant decrease in the immobilised control group.
Magnus et al. 2010 (Journal Article)	Cross-Education: (n = 8) (M = 2, F = 6) Immobilised Control: (n = 8) (M = 2, F = 6) True Control: (n = 9) (M = 4, F = 5)	Immobilisation method: Sling & Swathe Duration: 4 weeks Daily Hours: Cross-Education = 13.4 hours Control = 12.6 hours	Study: Parallel group random assignment to 1 of 3 groups Intervention: Isometric Elbow flexion & Elbow extension 3 times per week. Sets × reps were 3 × 8 progressing to 6 × 8 by the fourth session. The final 2 sessions were 3 × 8 to provide a taper period.	Strength: Elbow Flexor, Elbow Extensor; Isometric MVC Size: Elbow Flexor, Elbow Extensor; Muscle thickness	The immobilised group lost statistically significantly more elbow flexor and extensor size than the cross-education group.
Farthing et al. 2011 (Journal Article)	Cross-Education: (n = 7) (M = 1, F = 6) Immobilised Control: (n = 7) (M = 1, F = 6)	Immobilisation method: Wrist Cast Duration: 3 weeks Daily Hours: 24 hours	Study: Parallel groups with assignment into 1 of 2 groups based on term time: (Cross-Education) academic term 1; (Immobilised Control) academic term 2	Strength: Wrist Flexor; Isometric MVC Size: Wrist Flexor; Muscle thickness	The cross-education group maintained wrist flexor isometric MVC strength unlike the immobilised control group which lost 11%.

			Intervention Isometric handgrip contractions performed 5 days per week. Sets × reps were 3 × 8 to begin progressing to 6 × 8 by session four. The final session was 2 × 8		
Pearce et al. 2013 (Journal Article)	Cross-Education: (n = 9) (M = 4, F = 5) Immobilised Control: (n = 9) (M = 4, F = 5) True Control: (n = 10) (M = 5, F = 5)	Immobilisation method: Standardised arm sling Duration: 3 weeks Daily Hours: 15 hours	Study: Parallel group random assignment to 1 of 3 groups Intervention: Dumbbell bicep curls were performed 3 times per week. Sessions were 4 × 6-8 with training weight increased by 5% when participants could complete 4 × 8 with the same weight in a session	Strength: Elbow Flexor; Isometric MVC, Dumbbell curl 1 rep max Size: Elbow Flexor; Muscle thickness	Participants in the Immobilised control group lost a statistically significant amount of 1RM & Isometric strength and Elbow flexor muscle thickness unlike the Cross-education group.
Andrushko et al. 2018 (Journal Article)	Cross-Education: (n = 8) (M = 1, F = 7) Immobilised Control: (n = 8) (M = 2, F = 6)	Immobilisation method: Wrist Cast Duration: 4 weeks Daily Hours: 24 hours	Study: Parallel group random assignment to 1 of 2 groups Intervention: Eccentric wrist flexion contractions were performed 3 times per week. Sets × Reps were 2 × 8 in the first session progressing to 6 × 8 by session five. The final two sessions were 2 × 8	Strength: Wrist Flexor, Wrist Extensor; Isometric MVC, Concentric MVC, Eccentric MVC Size: Wrist Flexor, Wrist Extensor; Muscle thickness Forearm; pQCT	Wrist flexion strength was preserved in the cross-education group unlike in the immobilised control however, strength was preserved in neither group for Wrist extensor strength following immobilisation. The immobilised control group also lost a statistically significantly more MCSA than the cross-education group.

Valdes et al. 2021 (Journal Article)	Cross-Education (Eccentric): (n = 10) (M = 6, F = 4) Cross-Education (Concentric + Eccentric): (n = 10) (M = 6, F = 4) Immobilised Control: (n = 10) (M = 6, F = 4)	Immobilisation method: Shoulder Sling Duration: 4 weeks Daily Hours: 8 hours	Study: Parallel group random assignment to 1 of 3 groups with considerations to between-group parity of sex and hand dominance Intervention: Intensity was based on concentric dumbbell 1RM. Concentric-Eccentric: Dumbbell preacher curls were performed 3 times per week. The first week was 4 × 10 at an intensity of 60% with weeks two, three and four being 6 × 10 at intensities of 70%, 80%, and 90% respectively. Eccentric only: Dumbbell preacher curls with only the eccentric portion of the movement were performed 3 times per week. The first week was 3 × 10 at an intensity of 80% with weeks two, three and four being 4 × 10 at intensities of 100%, 110%, and 120% respectively.	Strength: Elbow Flexor; Isometric MVC, Dumbbell curl 1 rep max Size: Upper arm; Circumference	Losses in muscle strength and size were attenuated in both the concentric-eccentric and eccentric group unlike the immobilised control with a greater effect in the eccentric only group.

Chen et al. 2023 (Journal Article)	Cross-Education (Eccentric): (n = 12) (M = 12, F = 0) Cross-Education (Concentric): (n = 12) (M = 12, F = 0) Immobilised Control: (n = 12) (M = 12, F = 0)	Immobilisation method: Elbow Cast Duration: 3 weeks Daily Hours: 24 hours	Study: Parallel group assignment to 1 of 3 groups based on between-group parity in elbow flexor isometric MVC strength. Intervention (immobilisation phase): Dumbbell bicep curl and shoulder presses were performed during a total of 8 sessions throughout the	Strength: Elbow Flexor; Isometric MVC, Concentric MVC Elbow Extensor; Isometric MVC Size: Elbow Flexor; Muscle cross sectional area Upper arm; Circumference	Eccentric training attenuated decreases in neuromuscular function and muscle cross-sectional area of the immobilised arm greater than concentric training. Eccentric training also provided greater protective effects against muscle damage induced by maximal eccentric exercise following the period of immobilisation than concentric training, with both providing more protection than the immobilised control group.
Carr et al. 2025 (Journal Article)	Cross-Education: (n = 6) (M = 0, F = 6) Immobilised Control: (n = 4) (M = 0, F = 4)	Immobilisation method: Sling & Swathe Duration: 4 weeks Daily Hours: 10 hours	Study: Parallel group random assignment to 1 of 2 groups: (Cross-Education) & (Immobilised Control). Followed by 4 weeks of bilateral strength training. Intervention (immobilisation phase): Dumbbell bicep curl and shoulder presses were performed during a total of 8 sessions, twice weekly with at least 48 hours between each session. Participants began at 75% of their 1RM for both exercises with intensity adjusted as tolerated. 2-minute rests were given between sets. Three, four and five sets were performed for sessions	Strength: Elbow Flexor; Isometric MVC, Dumbbell bicep curl 1 rep max Shoulder abductors: Dumbbell shoulder press 1 rep max Wrist Flexors; Handgrip dynamometer Isometric MVC Size: Elbow Flexor; Muscle cross-sectional area	Unilateral resistance training attenuated bicep curl and shoulder press strength losses, although this did not significantly differ following the 4 weeks of bilateral strength training. Strength losses did not statistically differ in the untrained elbow flexor MVC and handgrip strength tests. The training group also lost less Biceps Brachii CSA, had statistically greater measures of echo intensity and greater measures of regional lean body mass, however again none differed following the retraining period.

			1, 2 and 3 with the set count remaining at five until sessions 7 and 8, during which it was reduced to three sets.		

Table 3. Biological sex distribution across studies

Groups	Female	Male	Total
Cross-Education	45	47	92
Immobilised Control	39	29	68
True Control	17	12	29
Totals	101	88	189

Table 4. Participant characteristics for included studies

Author	Group	Height (cm)	Weight (kg)	Age (Years)	Training (Years)	Handedness	
						Score	Method
Farthing et al., 2009	Training	171.6 ± 9.5	72.5 ± 12.0	20.9 ± 2.4	4.7 ± 4.5	16.3 ± 3.3	WHQ
	Immobilised Control	169.7 ± 8.8	72.5 ± 24.4	22.2 ± 2.8	2.5 ± 3.9	15.7 ± 4.2	WHQ
	True Control	169.9 ± 9.6	68.5 ± 15.6	25.4 ± 3.0	4.6 ± 4.3	17.4 ± 2.6	WHQ
Magnus et al., 2010	Training	171.7 ± 9.6	72.5 ± 18.3	20.9 ± 3.2	2.8 ± 4.0	14.1 ± 3.6	WHQ
	Immobilised Control	170.6 ± 10.3	83.2 ± 28.4	20.3 ± 1.8	2.0 ± 3.9	15.4 ± 5.0	WHQ
	True Control	175.3 ± 6.2	71.6 ± 11.8	24.9 ± 5.1	5.4 ± 5.2	16.2 ± 3.3	WHQ
Farthing et al., 2011	Training	167.3 ± 7.8	71.5 ± 20.7	20.6 ± 1.4	4.8 ± 3.5	16.4 ± 2.3	WHQ
	Immobilised Control	162.5 ± 9.3	65.8 ± 13.0	22.7 ± 4.4	3.9 ± 1.6	17.3 ± 4.1	WHQ
Pearce et al., 2013	Training	175.9 ± 12.5	68.3 ± 14.9	26.5 ± 7.6	n/a	91.5 ± 10.7	Laterality Index
	Immobilised Control	173.6 ± 9.1	62.5 ± 10.1	25.3 ± 8.7	n/a	89.5 ± 9.7	Laterality Index
	True Control	171.4 ± 7.3	66.6 ± 10.8	23.8 ± 6.0	n/a	90.2 ± 8.3	Laterality Index
Andrushko et al., 2018	Training	170.3 ± 10.1	77.2 ± 19.2	20.0 ± 2.0	2.3 ± 4.1	18.3 ± 2.4	WHQ
	Immobilised Control	169.3 ± 8.5	85.7 ± 22.7	23.0 ± 5.0	2.9 ± 4.3	17.1 ± 2.5	WHQ
Valdes et al., 2021	Training (Con-Ecc)	172.1 ± 8.3	74.3 ± 17.1	23.5 ± 5.0	n/a	n/a	
	Training (Ecc)	168.1 ± 10.1	73.0 ± 20.6	25.0 ± 1.9	n/a	n/a	
	Immobilised Control	169.1 ± 12.1	71.6 ± 17.4	25.1 ± 3.8	n/a	n/a	
Chen et al., 2023	Training (Con)	172.4 ± 6.5	73.7 ± 11.2	22.7 ± 1.7	n/a	n/a	
	Training (Ecc)	172.4 ± 6.5	73.7 ± 11.2	22.7 ± 1.7	n/a	n/a	
	Immobilised Control	172.4 ± 6.5	73.7 ± 11.2	22.7 ± 1.7	n/a	n/a	
Carr et al., 2025	Training	165.9 ± 10.1	58.7 ± 9.1	19.0 ± 0.5	n/a	n/a	WHQ
	Immobilised Control	159.4 ± 5.6	60.4 ± 13.9	19.0 ± 0.5	n/a	n/a	WHQ

Values presented as mean ± standard deviation; WHQ = Waterloo Handedness Questionnaire

Table 5. Summary of effect sizes, heterogeneity, and variance components across all meta-analyses.

Analysis	k	*g* (95% CI)	*p*	I^2 (%)	*Q* (df)	Q *p*	Level 2 variance (Within study)	Level 3 variance (Between study)
Primary Analyses — Immobilised Limb								
Strength (all training types)	25	0.53 [0.34, 0.73]	< 0.001	36.6	31.8 (24)	0.132	I^2 = 10.9%, σ^2 = 0.012	I^2 = 25.7%, τ^2 = 0.027
Eccentric	11	0.57 [0.16, 0.98]	0.012	—	—	—	—	—
Concentric-eccentric	7	0.69 [0.19, 1.18]	0.010	—	—	—	—	—
Isometric	4	0.41 [−0.05, 0.87]	0.070	—	—	—	—	—
Concentric	3	0.54 [−0.46, 1.54]	0.140	—	—	—	—	—
Muscle size (all training types)	16	0.19 [0.05, 0.33]	0.010	33.7	23.24 (15)	0.079	I^2 = 0%, σ^2 = 0	I^2 = 33.7%, τ^2 = 0.018
Eccentric	6	0.20 [−0.08, 0.49]	0.130	—	—	—	—	—
Concentric-eccentric	4	0.33 [−0.34, 1.01]	0.220	—	—	—	—	—
Isometric	4	0.12 [−0.33, 0.57]	0.460	—	—	—	—	—
Concentric	2	0.39 [−3.45, 4.23]	0.420	—	—	—	—	—
Primary Analyses — Non-Immobilised (Trained) Limb								
Strength (all training types)	25	0.42 [0.28, 0.56]	< 0.001	38.3	44.54 (24)	0.007	I^2 = 38.3%, σ^2 = 0.039	I^2 = 0%, τ^2 = 0
Eccentric	11	0.46 [0.25, 0.68]	< 0.001	—	—	—	—	—
Concentric-eccentric	7	0.47 [0.06, 0.88]	0.030	—	—	—	—	—
Isometric	4	0.45 [−0.27, 1.16]	0.140	—	—	—	—	—
Concentric	3	0.18 [−0.29, 0.65]	0.240	—	—	—	—	—
Muscle size (all training types)	15	0.24 [0.06, 0.42]	0.010	56.4	36.76 (14)	< 0.001	I^2 = 1.8%, σ^2 = 0.001	I^2 = 54.5%, τ^2 = 0.041
Eccentric	6	0.17 [−0.06, 0.39]	0.120	—	—	—	—	—
Concentric-eccentric	3	0.51 [−0.38, 1.41]	0.130	—	—	—	—	—
Isometric	4	0.21 [−0.08, 0.50]	0.110	—	—	—	—	—
Concentric	2	0.08 [−0.49, 0.64]	0.340	—	—	—	—	—
Subgroup Analyses — Muscle Specificity (Trained Homologous Muscles Only, Immobilised Limb)								

Strength	19	0.66 [0.38, 0.93]	< 0.001	52.4	28.35 (18)	0.057	I^2 = 7.3%, σ^2 = 0.012	I^2 = 45.1%, τ^2 = 0.072
Eccentric	7	0.75 [0.02, 1.49]	0.046	—	—	—	—	—
Concentric-eccentric	6	0.83 [0.16, 1.51]	0.024	—	—	—	—	—
Isometric	4	0.41 [−0.05, 0.87]	0.070	—	—	—	—	—
Concentric	2	0.90 [−4.08, 5.88]	0.260	—	—	—	—	—
Muscle size	15	0.19 [0.04, 0.33]	0.010	33.9	22.34 (14)	0.070	I^2 = 0%, σ^2 = 0	I^2 = 33.9%, τ^2 = 0.018
Eccentric	5	0.20 [−0.11, 0.51]	0.150	—	—	—	—	—
Concentric-eccentric	4	0.33 [−0.34, 1.01]	0.220	—	—	—	—	—
Isometric	4	0.12 [−0.33, 0.57]	0.460	—	—	—	—	—
Concentric	2	0.39 [−3.45, 4.24]	0.420	—	—	—	—	—
Subgroup Analyses — Immobilisation Model (Exploratory)								
Proximal — Strength	17	0.62 [0.35, 0.88]	< 0.001	49.9	29.24 (16)	0.020	I^2 = 39.4%, σ^2 = 0.063	I^2 = 10.5%, $\tau^2 = 0.017$
Eccentric	5	0.82 [0.25, 1.38]	0.020	—	—	—	—	—
Concentric-eccentric	7	0.68 [0.19, 1.18]	0.010	—	—	—	—	—
Isometric	2	0.30 [−2.10, 2.70]	0.360	—	—	—	—	—
Concentric	3	0.54 [−0.46, 1.54]	0.140	—	—	—	—	—
Proximal — Muscle size	7	0.40 [0.14, 0.66]	0.010	0.0	4.16 (6)	0.660	Simplified model (1 ES/study)	—
Distal — Strength †	8	0.42 [0.17, 0.66]	0.005	4.2	2.37 (7)	0.940	I^2 = 0%, σ^2 = 0	I^2 = 4.2%, τ^2 = 0.002
Eccentric	6	0.34 [0.05, 0.64]	0.030	—	—	—	—	—
Isometric	2	0.63 [0.20, 1.06]	0.030	—	—	—	—	—
Distal — Muscle size †	5	0.06 [−0.16, 0.29]	0.480	45.2	5.32 (4)	0.260	I^2 = 0%, σ^2 = 0	I^2 = 45.2%, τ^2 = 0.010
Eccentric	3	0.12 [−0.03, 0.27]	0.080	—	—	—	—	—
Isometric	2	−0.01 [−1.91, 1.89]	0.970	—	—	—	—	—

k = number of effect sizes; g = Hedges' g; 95% CI = 95% confidence interval; I^2 = total heterogeneity; Q = Cochran's Q statistic; Level 2 = within-study variance (σ^2); Level 3 = between-study variance (τ^2). Subgroup training type analyses report g and p only; full heterogeneity not modelled at subgroup level. † Distal analyses are exploratory given k = 2–3 studies. Rows highlighted in yellow indicate exploratory analyses.