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Regional Hypertrophy with Resistance Training — Does Muscle Length Matter? A Systematic Review and Meta-Analysis

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Abstract

The aim of this systematic review and meta-analysis was to examine how mean muscle length during resistance training (RT) influences regional muscle hypertrophy. We included studies that manipulated muscle length through range of motion (ROM) or exercise selection and evaluated regional muscle hypertrophy (i.e., changes at proximal, mid-belly, and/or distal sites). After systematically searching through three databases with additional secondary searches 12 studies were included in a meta-analysis. The meta-analysis was performed within the Bayesian meta-analytic framework. Standardized mean changes indicated trivial hypertrophic effects estimated with relatively high precision between proximal (25% muscle length; SMD: 0.04 [95%QI: -0.07, 0.15]; Exponentiated lnRR: 0.48% [95%QI: -1.99%, 3.13%]), mid-belly (50% muscle length; SMD: 0.07 [95%QI: -0.02, 0.15]; Exponentiated lnRR: 1.14% [95%QI: -0.84%, 3.13%]), and distal (75% muscle length; SMD: 0.09 [95%QI: -0.01, 0.19]; Exponentiated lnRR: 1.8% [95%QI: -0.52%, 4.26%]) sites. While the effects of training at longer muscle lengths showed an increasing trend from proximal to distal

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sites, the percentage of posterior distributions falling within ROPE was high from proximal to distal sites suggesting that effects are practically equivalent when contrasting "shorter" and "longer" mean muscle lengths at the typical differences employed in the current body of literature (i.e., an average difference of 21.8% mean muscle length). In summary, our results indicate that training at longer mean muscle length does not seem to produce greater regional muscle hypertrophy compared to shorter mean muscle lengths. However, due to small contrast in muscle lengths employed between conditions/groups, our findings should be considered limited to the contrasts typically employed in the literature.

Keywords: *muscle hypertrophy; muscle length; range of motion; resistance training*

Introduction

Resistance training (RT) is an often-used intervention for promoting increases in muscle size (i.e., hypertrophy) (Kraemer & Ratamess, 2004). The preponderance of current evidence exploring the effects of RT variables on muscle hypertrophy focused on manipulating training load, volume, and rest intervals (B. Schoenfeld et al., 2021). One RT variable that has been increasingly gaining scientific attention in recent years is range of motion (ROM) (Bloomquist et al., 2013; Goto et al., 2019; Maeo et al., 2021, 2023; Nunes et al., 2020; Wolf et al., 2023a). Haff & Triplett (2016) define ROM as the degree of movement occurring at a given joint when performing an exercise. Training through both a full ROM (fROM) and partial ROM (pROM) has previously been shown to be effective for muscle hypertrophy. However, the impact of ROM on muscle hypertrophy may be moderated by the mean muscle lengths being trained through (i.e., shorter vs. longer muscle length) (Wolf et al., 2023a). The mean muscle length refers to the average muscle length at which muscle actions occur during a specific resistance exercise within a given ROM. A recent meta-analysis explored the effects of training with a fROM vs. pROM on muscle hypertrophy (Wolf et al., 2023a). Overall, their results indicated similar effectiveness of training with fROM and pROM on muscle hypertrophy, even when the pROM exercise was performed at shorter muscle lengths. However, when the pROM was performed at longer muscle lengths vs fROM, the data seemed to favor pROM (Hedges' g = -0.28) even though the 95% confidence interval was also wide (-0.81, 0.16).

Previous research has found that muscle hypertrophy can occur in a non-uniform manner, with growth varying along the length or different compartments of a muscle group, a physiological adaptation called regional hypertrophy (Antonio, 2000; Nunes et al., 2024; Wakahara et al., 2013; Zabaleta-Korta et al., 2020). Manipulation of certain RT variables such as exercise selection and muscle length may elicit such regional adaptations (Costa et al., 2021; Wolf et al., 2023a; Zabaleta-Korta et al., 2021). Due to the muscle length-tension relationship, which specifies that a muscle's ability to produce force changes depending on its length, training at longer muscle lengths might induce greater muscle hypertrophy compared to training at shorter muscle lengths because of greater amounts of passive and/or total tension (Brughelli

& Cronin, 2007; Linke, 2018). For example, Maeo et al. (2021) compared seated vs. lying leg curl exercises where the former trains biarticular heads of the hamstring muscles at longer, while the latter at shorter muscle lengths. Both exercises were performed through the same ROM at the knee joint (90°-0° knee flexion) but due to greater hip flexion in the seated leg curl exercise (~90° hip flexion), hamstrings were trained at longer muscle lengths. Employing a within-subject design, authors reported greater hypertrophy of semitendinosus, semimembranosus and biceps femoris long head muscles after performing seated leg curls. Conversely, greater growth of the sartorius muscle was observed in the lying leg curl exercise. Sartorius is a biarticular muscle involved in both knee and hip flexion. Therefore, when performing lying leg curl exercise, it was also trained at longer muscle lengths due to a lesser hip flexion angle (~30° hip flexion). These results highlight that moderating muscle length through exercise selection may influence hypertrophy outcomes even within a given muscle group.

While muscle length may produce differential hypertrophy adaptations within a given muscle group (e.g., hamstrings), this training variable may also produce site-specific (i.e., proximal, mid-belly, or distal) hypertrophy effects in one specific muscle. For example, several studies reported that training at longer muscle lengths produces greater hypertrophy at distal sites. Sato et al. (2021) compared hypertrophy of elbow flexors after training at longer (EXT: 0° - 50° elbow flexion) vs. shorter (FLEX: 80° - 130° elbow flexion) muscle lengths. Regional muscle hypertrophy was assessed at proximal, mid-belly and distal sites (50%, 60%, 70%). Following 5 weeks of training, authors reported similar growth at proximal and mid-belly sites between groups; however, greater increases at distal sites were found following training at longer muscle lengths than the mid-belly and proximal sites (12.8%, 7.1%, 5.4%, respectively). Still, these findings are not necessarily consistent in the literature. Stasinaki et al. (2018) reported that there was no significant difference in hypertrophy of the long head of the triceps brachii measured at 50% and 70% along the muscle's length when performing cable pushdowns (shorter muscle lengths) vs. cable overhead extension (longer muscle lengths). Elucidating this matter is of relevance as targeted hypertrophy of certain muscle regions may be of practical importance in sports performance but also to physique athletes and bodybuilders. For example, nonuniform changes of quadriceps femoris muscle after performing unilateral open- and closed kinetic chain RT have been reported to alter the distribution of mass within the quadriceps femoris, influencing its center of mass and moment of inertia (Earp et al., 2023). Greater proximal muscle mass might be indicative of better running economy and movement efficiency because the minimal increments in moment of inertia reduce the resistance to motion during the swing phase of running. Conversely, greater distal muscle mass might increase inertial resistance, and potentially hinder sports performance (Earp et al., 2023). Furthermore, understanding how to specifically target undeveloped muscle regions through exercise selection or varying ROM can be particularly relevant to bodybuilders who are aiming for maximal muscle development and symmetry, both of which are critical criteria in competitions (Antonio, 2000; Escalante et al., 2021; Rukstela et al., 2023).

Although several studies explored how training at different muscle lengths via the manipulation of ROM or exercise selection affects regional muscle hypertrophy, inconsistencies in findings might have been affected by the small sample sizes in these studies (e.g., 10 participants

(Stasinaki et al., 2018)). This warrants the need for a meta-analytical approach to synthesize the available data and provide a clearer understanding of how muscle length during RT affects regional hypertrophy. Therefore, the aim of this systematic review and meta-analysis was to examine how mean muscle length during RT manipulated through ROM or exercise selection influences muscle hypertrophy at distinct measurement sites (i.e., proximal, mid-belly, and distal regions).

Methods

We performed a systematic review in accordance with the guidelines of the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA). This study was pre-registered on the Open Science Framework (https://osf.io/gxtk6) on April 7th, 2024.

Search strategy

We searched through three databases that index published articles (PubMed/MEDLINE, Scopus, and Web of Science) from inception to April 2024 using the following search syntax: ("resistance training" OR "resistance exercise" OR "resistive exercise" OR "strength training" OR "strength* exercise" OR "weight training" OR "weight lifting" OR "weightlifting") AND ("range of motion" OR "muscle length*") AND ("muscle hypertrophy" OR "muscular hypertrophy" OR "muscle mass" OR "muscle size" OR "muscular size" OR "muscle thickness" OR "muscle development" OR "muscular development" OR "cross-sectional area" OR "cross sectional area" OR "muscle growth" OR "muscular growth") to locate relevant studies. We performed secondary "forward" and "backward" citation searches by examining papers that cited the included studies in Google Scholar as well as in the included studies' reference lists. In addition, authors' personal libraries were screened for any additional papers that might meet the inclusion criteria. Two researchers (DV and MW) individually screened titles and abstracts to assess if a study met inclusion criteria using an online software (https://www.rayyan.ai/). If a study was deemed potentially relevant, the full text was evaluated to determine whether it should be included for further analysis. Any disputes that could not be resolved by the two researchers (DV and MW) were settled by a third researcher (BJS). The search was finalized in April 2024.

Inclusion criteria

To be included in the review, studies had to meet the following criteria: (a) including apparently healthy young men and women as participants, (b) RT intervention lasting a minimum of 4 weeks, (c) directly comparing at least two groups or conditions training at different joint angles (isometric training), or through different joint angles (isotonic training), or muscle lengths, (d) randomized experimental design (within- or between-subjects), (e) assessed muscle hypertrophy outcomes via direct imaging methods (ultrasound, computerized tomography [CT], MRI), (f) assessed regional changes through at least two measurement points along the length of a muscle, (g) published in an English-written peer-reviewed journal. We made an addendum to pre-registration as we did not include the following inclusion criteria in our original submission:

(1) both groups performed RT using the same muscle actions[1], (2) we included studies that compared exercises with different resistance curves.

Data extraction and analysis

Two researchers (DV and MW) independently extracted the following data into a predefined coding sheet using Google Sheets: lead author name(s), article title, and year of publication; sample size; participant characteristics (e.g., weight, height, sex, age, training status), intervention characteristics (e.g., duration, ROM used by the fROM and pROM group/condition, muscle length, volume, repetitions, frequency, resistance exercises, intensity, rest intervals, muscle action, modality); method for muscle size assessment (e.g., MRI, ultrasound); assessment locations and distality (i.e., specific muscle group and at what section of the muscle was measurement taken[2]); mean pre- and post-study values for muscle size with corresponding standard deviations or if a study reported standard error of the mean (SEM), they were converted to standard deviations (SD) via following equation: SEM $\times \sqrt{n}$. In cases where the data for muscle hypertrophy were not reported, we contacted the corresponding author(s) to obtain the data. If we were unable to acquire data directly from the authors, we extracted the values from figures using WebPlotDigitizer online software (https://apps.automeris.io/wpd/). Any disagreements between the two researchers were resolved through discussion and mutual consensus. If consensus between the two researchers could not be reached, a third researcher (BJS) resolved the dispute. To assess potential coder drift, a third researcher (BS) re-coded 30% of the studies that were randomly selected for assessment (G. McMahon et al., 2014; Pedrosa et al., 2023; Valamatos et al., 2018; Zabaleta-Korta et al., 2023).

Muscle length estimation

To operationally define muscle length, it is important to note that joint angle and muscle length likely do not correlate perfectly (Raiteri et al., 2021). However, as mean muscle length was one of the primary predictors, we followed specific procedures to estimate muscle length used within each group or conditions. First, calculations of muscle length were based on several assumptions: a) when biarticular muscles were explored, both joints would contribute equally and linearly to the muscle length; and b) previously established anatomical ranges of motion for each joint were used. Procedures differed on whether one or two joints were involved in movement. For example, if only one joint was involved, we would first define a maximum joint ROM[3]. Then, the joint angle at the start of the concentric phase was divided by maximum

[1]The rescaling was in order to have the values for coefficients in the model on a similar scale as the intercept values so that when setting initial values for Monte Carlo Markov Chain sampling these could be set to similar values.

[2]Though some of the authors here were those who had been involved in eliciting the smallest effect size of interest used for a currently pre-registered trial examining the effects lengthened partial training upon hypertrophy (see https://osf.io/9sgjk).

[3]We obtained priors from studies in the dataset of Wolf et al. (2023b) by firstly calculating the within arm pre- to post-intervention changes for the partial range of motion groups only (both SMD and lnRR effect sizes as detailed above) for only muscle size outcomes. We excluded any studies that were already included in the present dataset. Muscle length categorised as short or long was then recoded to be -0.5 and 0.5 respectively such that the predictor was centred; we assumed that the typical difference between short and long was similar to the ~21.8% as noted above in extracting slopes for reporting and so these codes corresponded to ~32.4% and ~54.2% muscle length respectively. Measurement site was also centred at 50%. We then fit a model with the same parametrization as the present pre-

joint ROM to obtain muscle length start point (SML) value. Similarly, to obtain muscle length end point (EML) value, we would divide the joint angle at the end of the concentric phase by maximum joint ROM. Finally, mean muscle length (MML) was calculated as an average of muscle length start and end point values. To calculate muscle length of biarticular muscles we repeated the same steps as mentioned above, but for each joint individually (i.e., hip and knee joints). Values of both joints were summed and divided by two per following equations:

$$\begin{aligned} SML &= \left(\frac{\mathrm{J}^1_{startCON}}{\mathrm{J}^1_{maxROM}} + \frac{\mathrm{J}^2_{startCON}}{\mathrm{J}^2_{maxROM}} \right) \div 2 \\ EML &= \left(\frac{\mathrm{J}^1_{endCON}}{\mathrm{J}^1_{maxROM}} + \frac{\mathrm{J}^2_{endCON}}{\mathrm{J}^2_{maxROM}} \right) \div 2 \end{aligned} \tag{1}$$

where J^1 is joint 1, J^1 is joint 2, and the subscripts $startCON$ indicate the start of the concentric phase, $endCON$ the end of the concentric phase, and $maxROM$ the maximum joint ROM. MML was calculated as an average of muscle length start and end point values. All estimations of muscle lengths were performed by DV and MW.

Methodological quality

We decided to use the recently developed tool called Standards Method for Assessment of Resistance Training in Longitudinal Designs (SMART-LD), which was specifically designed to assess the quality (both in terms of risk of bias as well as transparency of reporting) of longitudinal RT research (B. J. Schoenfeld et al., 2023). The SMART-LD tool consists of 20 questions that address aspects of a study's methodology (potential bias and reporting quality) as follows: general (items 1-2); participants (items 3-7); training program (items 8-11); outcomes (items 12-16); and statistical analyses (17-20). Each item in the checklist is given 1 point if the criterion is satisfied or 0 points if the criterion is not satisfied. The values of all questions are summed, with the final total used to classify studies as follows: "good quality" (16-20 points); "fair quality" (12-15 points); or "poor quality" (≤ 11 points) (B. J. Schoenfeld et al., 2023). Two reviewers (DV and MW) independently rated each study using the SMART-LD tool; any disputes were resolved through discussion and mutual consensus.

Statistical Analysis

All code utilized for data preparation and analyses are available in either the Open Science Framework page for this project https://osf.io/c2657/ or the corresponding GitHub repository https://github.com/jamessteeleii/ROM_regional_hypertrophy. We cite all software and

registered model in Equation 2 with the primary difference being that muscle length was categorical and the coefficient in the model fit to the Wolf et al. (2023b) data reflected the slope of the difference i.e., comparison between ~32.4% and ~54.2% muscle length. We set weakly regularising priors of $student\ t(df = 3, \mu = 0, \sigma = 1)$ for the population parameters for this model as with default uninformative priors chains did not converge. Other priors were left as defaults. We then extracted, assuming $student\ t$ distributions, the hyperparameters df, μ, and σ for the following parameters: intercept, muscle length coefficient, measurement site coefficient, muscle length by measurement site interaction, and the random effects standard deviations for the study, arm, and effect level intercepts.

packages used in the analysis pipeline using the `grateful` package (Rodriguez-Sanchez et al., 2023) which can be seen here: https://osf.io/pgx6v. As noted, the project was previously pre-registered however in hindsight we realise that the details of our analysis plan were imprecise and left open many researcher degrees of freedom. Thus, we present the planned analyses as closely as possible given the pre-registration as written and our original intention, but note where we have deviated from this plan below. Further, given the ambiguity we have conducted several additional analyses, including varying the priors used and the model parametrization, the methods and results of which are described in full detail in the supplementary materials here https://osf.io/rqavs. In the main text here we report only the pre-registered main models.

All analyses have been conducted within a Bayesian meta-analytic framework and all posterior estimates and their precision, along with conclusions based upon them, will be interpreted continuously and probabilistically, considering priors, data quality, and all within the context of each outcome and the assumptions of the model employed as the estimator (Kruschke & Liddell, 2018). We deviate from the pre-registration in the number of sampling iterations (pre-registered as 6000) used as we include comparisons between all models fit in the supplementary materials using Bayes Factors and the Savage-Dickey ratio where it is recommended that at least 40000 iterations are used to obtain precise Bayes-Factors (Gronau et al., 2020). Trace plots were produced along with $\hat{R}$ values to examine whether chains had converged, and posterior predictive checks for each model were also examined to understand the model implied distributions.

Effect sizes

We explored effects calculated for within arm pre- to post-intervention (and for studies with multiple post baseline time points pre- to each time point) as the standardized mean change using raw score standardization with heteroscedastic population variances (SMD) (Bonett, 2008) given it is known that variances scale with mean values in RT study outcomes (Steele et al., 2023a) and so a pre-post intervention effect upon the mean will influence this. We also examined the log transformed response ratio (lnRR) (Lajeunesse, 2011), which was exponentiated back to the percentage change scale after model fitting (though note that all prior distributions were set on the lnRR scale directly) accounting for the total variance in the model when doing so for the meta-analytic predicted effects (Nakagawa et al., 2017; Spake et al., 2023), as this effect size statistic is unaffected (except in its sampling variance) by the estimates for standard deviations within individual studies which are likely underpowered in the typical sample sizes found in the RT literature (Steele et al., 2023a). The use of both additive and multiplicative effect sizes also allows us to explore the sensitivity of interaction effects to scaling as interactions, our primary estimand of interest, are very sensitive to this (Rohrer & Arslan, 2021; Spake et al., 2023). Effects were weighted in each model by their inverse sampling variance.

Models

The primary estimand of interest was the population level (i.e, fixed effect) muscle length by site of measurement interaction. In each model, as per the preregistration, muscle length and site of measurement were centred at 50%, and rescaled to be on the $(-0.5, 0.5)$ interval[4]. As such, the population level coefficients in each of the models corresponded to the overall average effect of RT on hypertrophy when at a muscle length of 50% at a site of measurement of 50% (i.e., the intercept: μ_{α_i} in each model below), the slope of the difference i.e., comparison between 0% and 100% muscle length at a site of measurement of 50% (i.e., muscle length coefficient: β_1 in each model below), the slope of the difference i.e., comparison between 0% and 100% site of measurement at a muscle length of 50% (i.e., site of measurement coefficient: β_2 in each model below), and the slope of the difference i.e., comparison between 0% and 100% site of measurement on the slope of the difference i.e., comparison between 0% and 100% muscle length (i.e., muscle length by site of measurement interaction coefficient: β_3 in each model below). Notably, the interpretation of continuous by continuous predictors can be quite challenging. As such, we present for each of these models draws from the posterior of the expectation of the predicted global grand mean across muscle length and at three levels of site of measurement (25%, 50%, and 75%) which shows the predicted effect size magnitudes at particular combinations of muscle length and site of measurement, in addition to the slopes for muscle length at three levels of site of measurement (25%, 50%, and 75%). The slopes for muscle length were transformed to reflect the average contrast in mean muscle length between "shorter" and "longer" conditions in the included studies which was $21.8 \pm 13.6\%$. Thus the slopes reflected a difference in muscle length of 21.8% e.g., the slope of the difference between 32.4% (the average "short" condition in the included studies) and 54.2% muscle length which shows the magnitude of the difference in effect size for a 21.8% difference in muscle length at different sites. We present the predicted values and slopes as mean and 95% quantile intervals. We also, whilst not pre-registered for this project, agreed upon a smallest effect size of interest on both the standardized mean change $(-0.1, 0.1)$[5] and the percentage change scales $(-3\%, 3\%)$ and thus set these as regions of practical equivalence (ROPE). This allows us to also examine the probability that the slopes for muscle length might produce a meaningful effect (i.e., greater than the smallest effect size of interest) by examining the mass of the posterior distribution exceeding the upper limits of the ROPE, and also the percentage of the posterior distributions mass that was within the ROPE thus reflecting the probability of practically equivalent effects.

For the secondary predictor models we explored the muscle length by site of measurement by each additional predictor (e.g., upper or lower body OR muscle group OR muscle action) interaction respectively. For these models, we only present the predicted effect size magnitudes at particular combinations of muscle length and site of measurement similarly to the above.

[4] The rescaling was in order to have the values for coefficients in the model on a similar scale as the intercept values so that when setting initial values for Monte Carlo Markov Chain sampling these could be set to similar values.

[5] Though some of the authors here were those who had been involved in eliciting the smallest effect size of interest used for a currently pre-registered trial examining the effects lengthened partial training upon hypertrophy (see https://osf.io/9sgjk).

Pre-Registered Main Model

As noted, the pre-registered main model involved population level effects for the intercept, slope of muscle length, slope of measurement site, and the muscle length by measurement site interaction. The model also included random intercepts for study, arm, and effect levels. The model equation was as follows:

$$
\begin{aligned}
\hat{\theta}_{ijk} &\sim N\left(\mu, \sigma_{ijk}\right) \\
\mu &= \alpha_i + \alpha_j + \alpha_k + \beta_1(\text{muscle length}_{centred}) + \beta_2(\text{site}_{\text{centred}}) + \beta_3(\text{muscle length}_{\text{centred}} \times \text{site}_{\text{centred}}) \\
\alpha_i &\sim N\left(\mu_{\alpha_i}, \sigma_{\alpha_i}\right), \text{ for study i = 1, ... ,I} \\
\alpha_j &\sim N\left(0, \sigma_{\alpha_j}\right), \text{ for arm j = 1, ... ,J} \\
\alpha_k &\sim N\left(0, \sigma_{\alpha_k}\right), \text{ for effect k = 1, ... ,K}
\end{aligned}
\tag{2}
$$

where $\hat{\theta}_{ijk}$ is the kth effect size (k = 1, ... ,K), here the SMD or lnRR, from the jth arm (j = 1, ... ,J) for the ith study (i = 1, ... ,I), and α_i, α_j, and α_k are the random intercepts for study, arm, and effect respectively. Prior distributions[6] taken from Wolf et al. (2023b) for the SMD model were (note, values rounded; plots for the population level effect distributions can be seen in the supplementary materials here https://osf.io/uxhdj):

$$
\begin{aligned}
\mu_{\alpha_i} &\sim student\ t\left(df = 4.17, \mu = 0.16, \sigma = 0.53\right) \\
\sigma_{\alpha_i} &\sim half\ student\ t\left(df = 2.32, \mu = 0.79, \sigma = 0.60\right) \\
\sigma_{\alpha_j} &\sim half\ student\ t\left(df = 2.32, \mu = 0.62, \sigma = 0.46\right) \\
\sigma_{\alpha_k} &\sim half\ student\ t\left(df = 3.53, \mu = 0.14, \sigma = 0.10\right) \\
\beta_1 &\sim student\ t\left(df = 4.39, \mu = 0.40, \sigma = 1.15\right) \\
\beta_2 &\sim student\ t\left(df = 7.03, \mu = -0.02, \sigma = 0.91\right) \\
\beta_3 &\sim student\ t\left(df = 4.45, \mu = -0.09, \sigma = 1.95\right)
\end{aligned}
\tag{3}
$$

Prior distributions taken from Wolf et al. (2023b) for the lnRR model were (note, values rounded; plots for the population level effect distributions can be seen in the supplementary

[6]We obtained priors from studies in the dataset of Wolf et al. (2023b) by firstly calculating the within arm pre- to post-intervention changes for the partial range of motion groups only (both SMD and lnRR effect sizes as detailed above) for only muscle size outcomes. We excluded any studies that were already included in the present dataset. Muscle length categorised as short or long was then recoded to be -0.5 and 0.5 respectively such that the predictor was centred; we assumed that the typical difference between short and long was similar to the ~21.8% as noted above in extracting slopes for reporting and so these codes corresponded to ~32.4% and ~54.2% muscle length respectively. Measurement site was also centred at 50%. We then fit a model with the same parametrization as the present pre-registered model in Equation 2 with the primary difference being that muscle length was categorical and the coefficient in the model fit to the Wolf et al. (2023b) data reflected the slope of the difference i.e., comparison between ~32.4% and ~54.2% muscle length. We set weakly regularising priors of $student\ t(df = 3, \mu = 0, \sigma = 1)$ for the population parameters for this model as with default uninformative priors chains did not converge. Other priors were left as defaults. We then extracted, assuming $student\ t$ distributions, the hyperparameters df, μ, and σ for the following parameters: intercept, muscle length coefficient, measurement site coefficient, muscle length by measurement site interaction, and the random effects standard deviations for the study, arm, and effect level intercepts.

materials here https://osf.io/tvpes):

$$
\begin{aligned}
\mu_{\alpha_i} &\sim student\ t\,(df = 2.82, \mu = 0.04, \sigma = 0.39) \\
\sigma_{\alpha_i} &\sim half\ student\ t\,(df = 1.92, \mu = 0.55, \sigma = 0.47) \\
\sigma_{\alpha_j} &\sim half\ student\ t\,(df = 1.96, \mu = 0.43, \sigma = 0.35) \\
\sigma_{\alpha_k} &\sim half\ student\ t\,(df = 7.38, \mu = 0.06, \sigma = 0.04) \\
\beta_1 &\sim student\ t\,(df = 2.80, \mu = 0.10, \sigma = 0.80) \\
\beta_2 &\sim student\ t\,(df = 7.74, \mu = 0.10, \sigma = 0.48) \\
\beta_3 &\sim student\ t\,(df = 5.95, \mu = 0.08, \sigma = 1.70)
\end{aligned}
\tag{4}
$$

Secondary Predictor Models - Uninformed Priors

Although we noted these in the pre-registration we do not focus on them in the present manuscript instead focusing on the primary estimand noted above of the muscle length by measurement site interaction. We treat these secondary predictor models as highly exploratory given the amount of data available and the corresponding uncertainty of inferences, and present them only in the supplementary materials (see https://osf.io/tgzpk, https://osf.io/f86ng, and https://osf.io/gp2vr for the upper or lower body, muscle group, and muscle action SMD models respectively and https://osf.io/hxbv6, https://osf.io/w8mbg, and https://osf.io/9mhcu for the upper or lower body, muscle group, and muscle action lnRR models respectively). In addition, and not pre-registered either, we included a model comparing studies which manipulated mean muscle length by means of range of motion manipulation, or by means of exercise selection (see https://osf.io/pbqwe and https://osf.io/9snkh). For reference these models were the same parametrization as the pre-registered model using the same priors as noted above, with the exception of the additional categorical predictor of either upper or lower body OR muscle group OR muscle action added under a deviation coding scheme (i.e., such that the coefficients for each level were in comparison to the overall mean reflected by the intercept). The added predictors used default uninformative priors of $uniform(lb = -\infty, ub = \infty)$.

Results

When searching the three databases there were 499 results. We excluded 478 references after reading their titles or abstracts. As a result, 21 full texts were read. Eleven studies satisfied the inclusion criteria (Alegre et al., 2014; Bloomquist et al., 2013; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014, 2015; Pedrosa et al., 2022; Sato et al., 2021; Valamatos et al., 2018; Zabaleta-Korta et al., 2023), while 10 were excluded because: eight did not assess regional changes (Akagi et al., 2020; Goto et al., 2019; Kassiano et al., 2023; Kinoshita et al., 2023; Maeo et al., 2023; Marušič et al., 2020; Nunes et al., 2020; Pinto et al., 2012), one did not manipulate ROM/muscle length (Earp et al., 2023), and one did not employ a relevant comparison group (Earp et al., 2015). Two additional studies were identified via citation searches (Pedrosa et al., 2023; Stasinaki et

al., 2018). Therefore, a total of 13 studies were included. However, 12 studies were meta-analyzed due to one study (Noorkõiv et al., 2015) using the same dataset as in a previous publication (Noorkõiv et al., 2014). Figure 1 provides a flow chart of the search process.

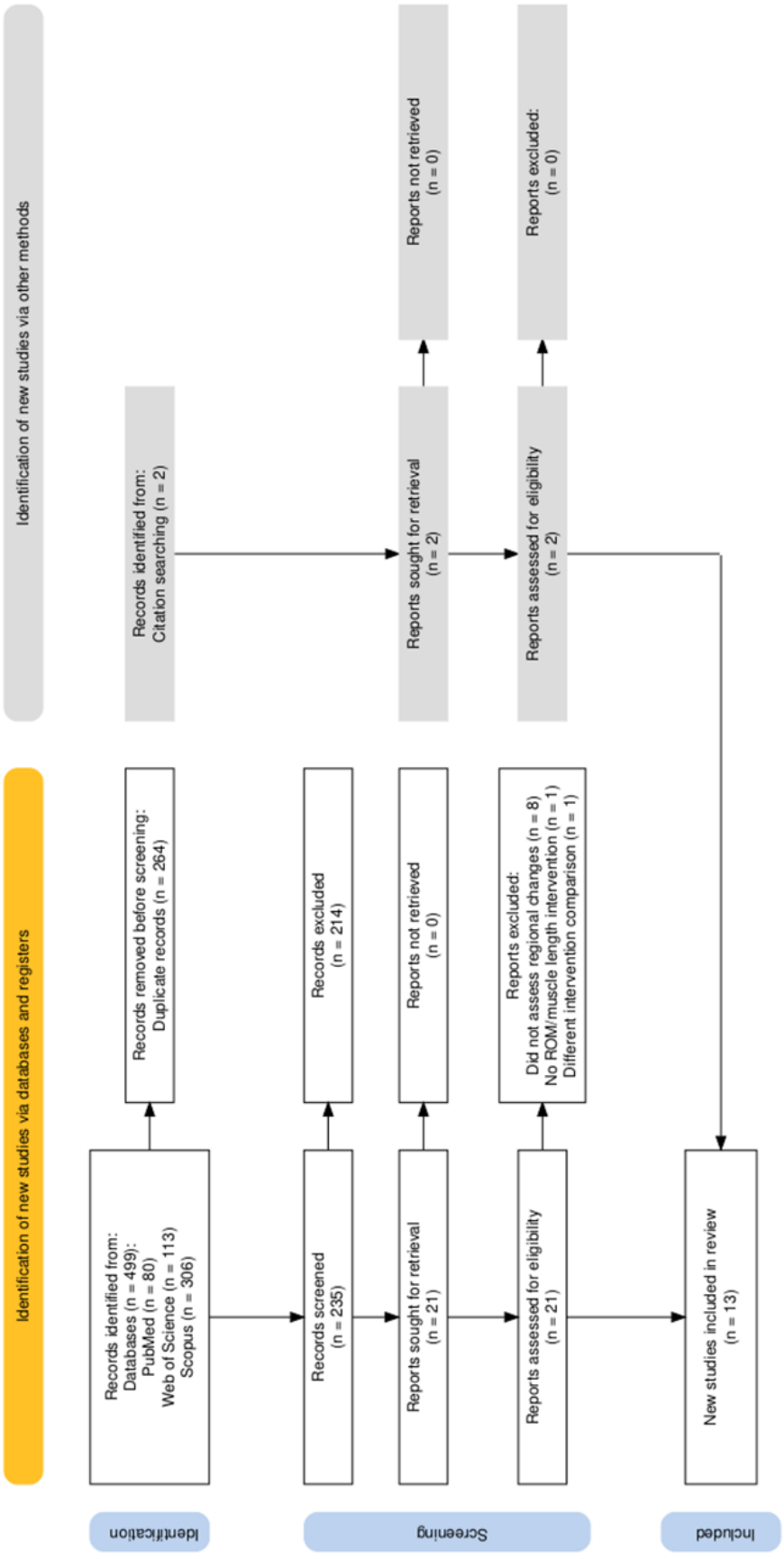


Figure 1: PRISMA 2020 flow diagram for new systematic reviews.

Summary of the Included Studies

All studies employed young participants (18.8 – 27.2 years of age) (Alegre et al., 2014; Bloomquist et al., 2013; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022, 2023; Sato et al., 2021; Stasinaki et al., 2018; Valamatos et al., 2018; Zabaleta-Korta et al., 2023). Eleven studies employed untrained participants (Alegre et al., 2014; Bloomquist et al., 2013; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022, 2023; Sato et al., 2021; Stasinaki et al., 2018; Valamatos et al., 2018), and one study employed resistance-trained participants (Zabaleta-Korta et al., 2023). Three studies employed male participants (Bloomquist et al., 2013; Noorkõiv et al., 2014; Valamatos et al., 2018), four studies employed female participants (Pedrosa et al., 2022, 2023; Stasinaki et al., 2018; Zabaleta-Korta et al., 2023), and five studies employed both male and female participants (Alegre et al., 2014; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Sato et al., 2021). Four studies assessed upper-body measures of hypertrophy (elbow flexors and triceps brachii long head) (Pedrosa et al., 2023; Sato et al., 2021; Stasinaki et al., 2018; Zabaleta-Korta et al., 2023), and eight studies assessed lower body measures of hypertrophy (quadriceps femoris, biceps femoris, semitendinosus, front, and back thigh) (Alegre et al., 2014; Bloomquist et al., 2013; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022; Valamatos et al., 2018). Four studies assessed only relatively distal regions of the muscle groups (Pedrosa et al., 2023; Sato et al., 2021; Stasinaki et al., 2018; Zabaleta-Korta et al., 2023). Nine studies (Alegre et al., 2014; Bloomquist et al., 2013; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022, 2023; Sato et al., 2021; Valamatos et al., 2018) manipulated muscle length with ROM, while only three (Maeo et al., 2021; Stasinaki et al., 2018; Zabaleta-Korta et al., 2023) studies manipulated muscle lengths by performing different exercises. The duration of the included studies ranged from 5 to 15 weeks. The summary table in the supplementary materials provides a descriptive overview of each study's methodological design (see https://osf.io/zq2cr).

Methodological quality

The mean score on the SMART-LD tool was 11 ± 2 (range: 8-15 points). Six studies were judged to be of fair quality (Maeo et al., 2021; Pedrosa et al., 2023; Sato et al., 2021; Stasinaki et al., 2018; Valamatos et al., 2018; Zabaleta-Korta et al., 2023), and six studies were judged to be of poor quality (Alegre et al., 2014; Bloomquist et al., 2013; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022).

Meta-analysis results

The final models presented all included 184 effects nested within 22 intervention arms extracted from 12 studies.

Pre-Registered Main Model

For the main pre-registered model utilizing priors from Wolf et al. (2023b) the predicted effect size magnitudes across muscle length and at three levels of site of measurement (25%, 50%, and 75%) in addition to the slopes for muscle length (transformed to be the slope of a difference in muscle length of 21.8% e.g., the slope of the difference between ~32.4% and ~54.2% muscle length) at three levels of site of measurement (25%, 50%, and 75%) can be seen in Figure 2 for the SMD model, and Figure 3 for the lnRR model.

For the SMD model the magnitude of muscle length slope was 0.04 [95% quantile interval: -0.07, 0.15] at the 25% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 16.54% and percentage within the ROPE (i.e., -0.1,0.1) of 82.7%, 0.07 [95% quantile interval: -0.02,0.15] at the 50% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 22.3% and percentage within the ROPE (i.e., -0.1,0.1) of 77.68%, and 0.09 [95% quantile interval: -0.01,0.19] at the 75% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 40.96% and percentage within the ROPE (i.e., -0.1,0.1) of 59.02%. There was considerable heterogeneity of effects relative to the magnitude of the population level effects, particularly at the study level, with $\tau_{study} = 0.04$ [95% quantile interval: 0.03,0.35], $\tau_{arm} = 0.03$ [95% quantile interval: 0.01,0.26], and $\tau_{effect} = 0.01$ [95% quantile interval: 0,0.07].

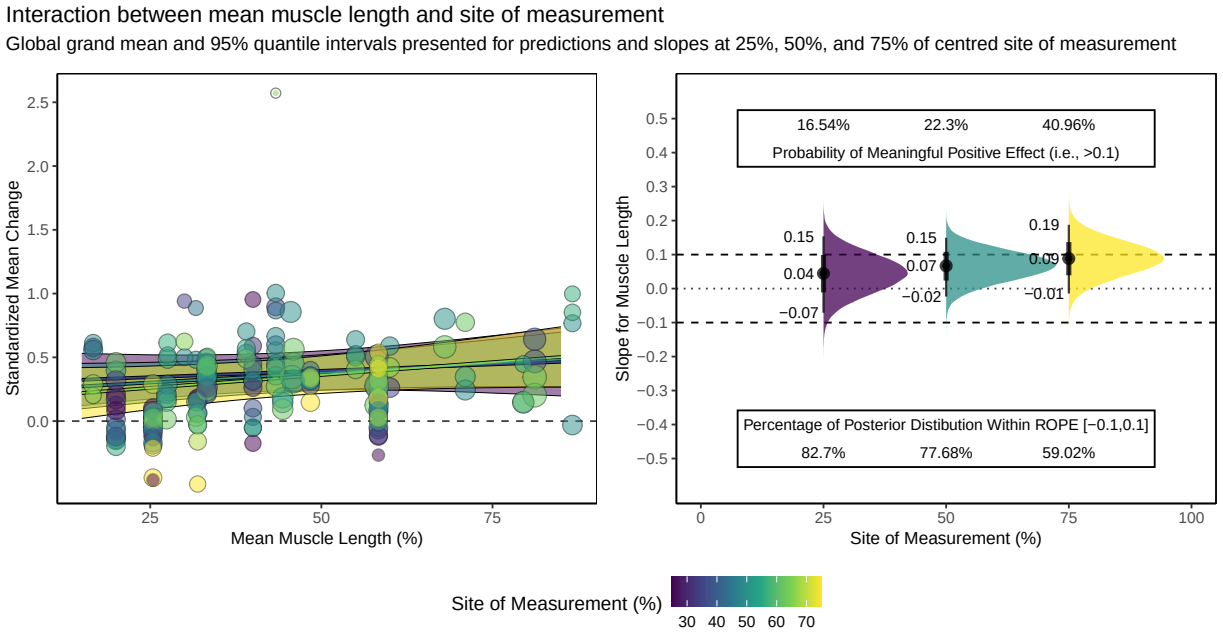
For the lnRR model the magnitude of muscle length slope was 0.48% [95% quantile interval: -1.99%, 3.13%] at the 25% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 3.09% and percentage within the ROPE (i.e., -0.1,0.1) of 96.66%, 1.14% [95% quantile interval: -0.84%,3.13%] at the 50% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 3.38% and percentage within the ROPE (i.e., -0.1,0.1) of 96.62%, and 1.8% [95% quantile interval: -0.52%,4.26%] at the 75% measurement site with probability of a meaningful positive effect (i.e., 0.1) of 16.55% and percentage within the ROPE (i.e., -0.1,0.1) of 83.45%. There was considerable heterogeneity of effects relative to the magnitude of the population level effects, particularly at the study level, with $\tau_{study} = 1.99\%$ [95% quantile interval: 3.6%,14.63%], $\tau_{arm} = 1.13\%$ [95% quantile interval: 1.71%,7.96%], and $\tau_{effect} = 0.45\%$ [95% quantile interval: 0.37%,1.67%].

Model diagnostics can be seen in the supplementary materials here: https://osf.io/3ybcs.

Discussion

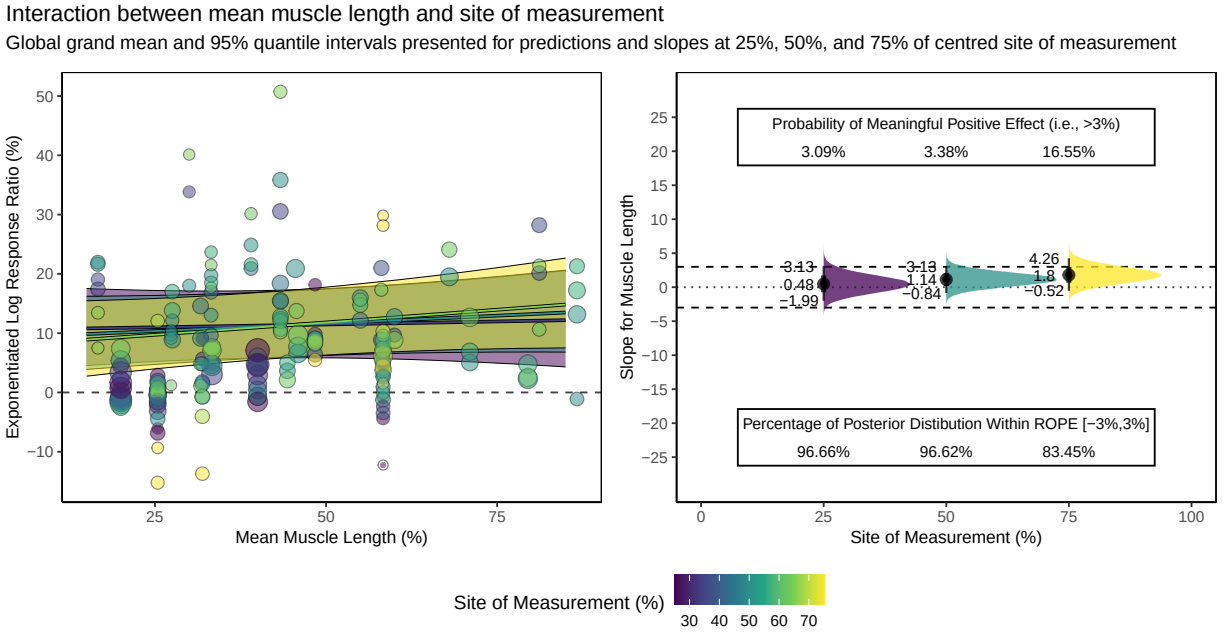
Main findings

We explored the effects of mean muscle length (manipulated through exercise ROM or exercise selection) during RT on regional muscle hypertrophy. Our main findings suggest trivial effects of mean muscle length, as indicated by point estimates and small differences between proximal (25% muscle length; SMD: 0.04 [95%QI: -0.07, 0.15]; Exponentiated lnRR: 0.48% [95%QI: -1.99%, 3.13%]), mid-belly (50% muscle length; SMD: 0.07 [95%QI: -0.02, 0.15]; Exponentiated lnRR: 1.14% [95%QI: -0.84%, 3.13%]), and distal (75% muscle length; SMD:



Note, the slopes have been transformed to the effect when increasing muscle length by 21.8% to reflect typical difference between short vs long lengths

Figure 2: Results from primary pre-registered main model for standardized mean difference effects.



Note, the slopes have been transformed to the effect when increasing muscle length by 21.8% to reflect typical difference between short vs long lengths

Figure 3: Results from primary pre-registered main model for exponentiated log response ratio effects.

0.09 [95%QI: -0.01, 0.19]; Exponentiated lnRR: 1.8% [95%QI: -0.52%, 4.26%]) sites. To help contextualize our findings, we agreed upon the smallest effect size of interest (SMD >0.1) and percentage changes (>3%) to ensure that any observed change in muscle hypertrophy was practically meaningful in the context of muscle development. The probability of finding a meaningful positive effect of training at longer mean muscle lengths at proximal, mid-belly and distal sites was 16.54%, 22.3%, and 40.96% respectively for SMDs and 3.09%, 3.38%, and 16.55% for exponentiated lnRRs. Instead, it was more probable that effects lay within the region of practical equivalence (ROPE) set by the smallest effect sizes of interest for proximal, mid-belly and distal sites with probabilities of 82.7%, 77.68%, 59.02% respectively for SMDs and 96.66%, 96.62%, and 83.45% for exponentiated lnRRs. Based on these data and our a priori thresholds, training at typically longer mean muscle lengths compared with shorter mean muscle lengths does not seem to clearly produce meaningfully greater regional muscle hypertrophy.

Results from our pre-registered model indicate that point estimate effects of mean muscle length on regional muscle hypertrophy were compatible with trivial effects (SMD point estimates: 0.04-0.09; Exponentiated lnRR point estimates: 0.48%-1.8%) with relatively precise interval estimates ranging trivial to small effects. This magnitude of effect for manipulating muscle length is perhaps not surprising given the magnitude of hypertrophy resultant from RT in general (SMD: 0.34; 95%CI: 0.29, 0.39; Exponentiated lnRR: 5.13%; 95%CI: 4.08%, 6.18%) (Steele et al., 2023b). Our point estimates showed trivial effects for mean muscle lengths when the contrast reflected the typical 21.8% difference between the shorter and longer muscle lengths used within the analyzed studies. The effects of training at longer muscle lengths showed a trend of increasing effect magnitude from proximal to distal muscle sites, though plausible effects were still trivial to small at all regions. In addition to our pre-registered model, we opted to present other models (see full results of these models at: https://osf.io/rqavs) using different informed priors and model specifications (i.e., the inclusion of random slopes). Across all models, the general effects of mean muscle length on regional muscle hypertrophy were trivial to small, similarly to the pre-registered main model lending robustness to our findings.

In addition to our main model, we pre-registered secondary predictor models. Specifically, we aimed to explore whether the effects of mean muscle length differ between upper- or lower-body muscle groups, individual muscle groups or the type of muscle action. For all secondary models, effects of additional predictors upon the effects of mean muscle lengths on regional muscle hypertrophy are largely inconclusive (see Secondary Predictor Models - Uninformed Priors section). This is primarily due to lack of studies included in each of the analyses for specific categories of each predictor, and high degree of uncertainty and imprecision as reflected by wide 95% quantile intervals in the majority of models which is to be expected given the complexity of exploring three-way interactions. Therefore, these analyses should be considered exploratory and interpreted with caution. However, one potentially worth noting is the model including the study level predictor for how muscle length was manipulated: studies that varied muscle length via alterations in exercise selection vs. alterations in ROM. Results indicated that when solely analyzing studies that manipulated ROM, the effect strengthened for greater

muscle hypertrophy at the distal site (SMD: 0.23, 95%QI [0.07, 0.35], https://osf.io/6ydrn); Exponentiated lnRR: 4.6% [95%QI: -0.08%, 8.02%], https://osf.io/3puzj). This suggests that performing repetitions at longer muscle lengths where muscle length is manipulated by means of increasing ROM (i.e., lengthened partials) may preferentially elicit greater distal muscle hypertrophy vs. more proximal sites. Alternatively, the effects of alteration of exercise selection were less clear. However, similarly to other secondary predictor models, these analyses should be interpreted cautiously given the limited number of studies that investigated the topic, and that this additional analysis was not pre-registered.

Suggestions for future research

There are several potential avenues for future studies on the topic. Firstly, most studies comparing the effects of mean muscle length included here had relatively small differences between the "shorter" and "longer" mean muscle length conditions (average of 21.8% difference). The present model assumes a linear effect of mean muscle length on hypertrophy and thus greater contrasts between "shorter" and "longer" mean muscle length conditions imply greater effects might be possible. However, future studies should look to test multiple conditions across varying mean muscle lengths, including large contrasts (e.g., >21.8%), which might enable exploration of the possible presence of non-linear relationships both in primary studies and any future evidence synthesis by meta-analysis. If it seems plausible that there are indeed greater effects in the distal regions following training at longer muscle lengths, strengthened by evidence from studies employing greater contrasts in mean muscle length, it may be fruitful to explore whether different muscle lengths indeed cause distinct muscle activation patterns, as measured via T2 MRI (Wakahara et al., 2012, 2013, 2017). This would allow us to better understand potential underlying mechanisms. Researchers should also aim to increase the number of measurement points along the muscle, particularly at proximal sites. Instead of measuring only a few sites (i.e. proximal, mid-belly and distal), future studies could employ (if resources allow) advanced imaging techniques, such as MRI, extended field of view technique for panoramic B-mode ultrasound image acquisition or to collect multiple ultrasound images and stitch them together using contour matching (stitching images method) to better measure adaptations along the whole length of a muscle (Franchi et al., 2018, 2020; Stokes et al., 2021). Further research may be warranted to better understand the effects of all other secondary predictors examined: upper vs. lower body, specific muscle groups, muscle action performed, and different methods of manipulating muscle length on regional muscle hypertrophy. Current evidence might suggest isometric muscle actions performed at longer muscle lengths produce greater effects than isometrics at shorter muscle lengths (Oranchuk et al., 2019). However, only four studies (Akagi et al., 2020; Alegre et al., 2014; Kubo et al., 2006; Noorkõiv et al., 2014) have been published to date and none have compared performing isometric muscle actions at maximal muscle lengths, or to dynamic muscle actions (i.e., isokinetic/isotonic), which is something that future studies may consider. Studies examining the effects of manipulating muscle length through exercise selection are also far fewer than those manipulating ROM and thus further research is required examining this approach. Further investigation into the effects of training at longer muscle lengths and fROM, especially in

a trained population would fill a crucial gap in the literature as only one study (Zabaleta-Korta et al., 2023) on trained participants has been published in a peer-reviewed journal to date. Lastly, only Stasinaki et al. (2018) performed training at maximum muscle lengths, while other studies on the topic performed them at relatively shorter, or longer muscle lengths, respectively. Therefore, future studies should explore the effects of training at maximum muscle lengths on regional muscle hypertrophy.

Limitations

The present paper has several limitations that should be considered when drawing practical inferences. First, only 13 studies were included in systematic review, and only 12 studies were meta-analyzed due to one study (Noorkõiv et al., 2015) using the same dataset as in a previous publication (Noorkõiv et al., 2014). Even though we used an arm-based model, our analyses included only 184 effects nested within 22 intervention arms. Whilst the main effects from the pre-registered models were estimated with high precision, this lack of data rendered all secondary predictor models far less precise and limited our inferences about contrasts larger than those typically used in the studies included (i.e., an average 21.8% difference in mean muscle length). Second, the majority of the studies examined quadriceps femoris (Alegre et al., 2014; Bloomquist et al., 2013; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Pedrosa et al., 2022; Valamatos et al., 2018), while only three examined elbow flexors (Pedrosa et al., 2023; Sato et al., 2021; Zabaleta-Korta et al., 2023), two hamstrings/back thigh (Bloomquist et al., 2013; Maeo et al., 2021) and one elbow extensors (Stasinaki et al., 2018) and notably our secondary models exploring predictors such as muscle group were imprecise in their estimates. Therefore, future research should evaluate regional muscle hypertrophy across a broader range of muscle groups. Based on the SMART-LD checklist, the included studies were classified of poor to fair methodological quality. Majority of the studies were graded to be of lower quality due to either not specifying sample size justification, randomization methods and concealment, adequately reporting training adherence, training supervision, or provided exact outcome values pre- and post-study. While these aspects are more a limitation of the included studies, not this review *per se*, they should be addressed by future research. Finally, the majority of studies measured mid-belly and distal regions, however, only seven studies (Alegre et al., 2014; Bloomquist et al., 2013; Maeo et al., 2021; G. McMahon et al., 2014; G. E. McMahon et al., 2014; Noorkõiv et al., 2014; Valamatos et al., 2018) measured most proximal sites; therefore, future studies should endeavor to measure proximal regions to gain better understanding of changes in those regions following training at different muscle lengths.

Conclusion

We found trivial effects of mean muscle length on regional muscle hypertrophy estimated with relatively high precision. While the effects of training at longer muscle lengths showed an increasing trend from proximal to distal sites, the percentage of posterior distributions falling within ROPE was high from proximal to distal sites. This suggests it is more probable

that effects are practically equivalent when contrasting "shorter" and "longer" mean muscle lengths as opposed to being superior with longer mean muscle lengths. Our data does not seem to support that training at longer mean muscle length produces greater regional muscle hypertrophy compared to shorter mean muscle lengths. However, due to small contrast in muscle lengths employed between conditions/groups, our findings should be considered limited to the contrasts typically employed in the literature (i.e., a difference on average of 21.8% in mean muscle length between "shorter" and "longer" conditions).

Author Contributions

DV conceived the idea for the paper. DV, MW, BJS conceptualized the review. DV and MW conducted the study selection, data extraction, and methodological quality assessment. JS conducted the statistical analyses. DV drafted the initial manuscript. DV, MW, BJS, JS, JG, PM contributed to writing the manuscript. All authors read and approved the final manuscript.

Competing Interests

BJS serves on the scientific advisory board of Tonal Corporation, a manufacturer of fitness equipment. JS provides research and statistical consulting for organizations within the health and fitness field.

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Data and Supplementary Material Accessibility

All extracted data and code utilised for data preparation and analyses are available in either the Open Science Framework page for this project https://osf.io/c2657/ or the corresponding GitHub repository https://github.com/jamessteeleii/ROM_regional_hypertrophy. Other supplementary analyses and plots are also available there.

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