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Does longer-muscle length resistance training cause greater longitudinal growth in humans? A systematic review.

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ABSTRACT

The purpose of this paper was to systematically review the literature regarding the effects of resistance training (RT) performed at longer-muscle length (LML) versus shorter-muscle length (SML) on proxy measurements for longitudinal hypertrophy. We included studies that satisfied the following criteria: (1) be a resistance training intervention with a comparison of LML vs SML-RT; (2) assess both fascicle length (FL) and muscle size pre- and post-intervention; (3) involve healthy adults aged ≥ 18 years; (4) be published in an English-language journal, and; (5) have a minimum training intervention duration of 4 weeks. Three databases were searched in February 2024 (Google Scholar, PubMed/Medline, Scopus) for relevant articles, alongside 'forward' and 'backward' citation searching of articles included and additions via authors' personal knowledge.

Study quality was assessed using the 'Standards Method for Assessment of Resistance Training in Longitudinal Designs' (SMART-LD). Results of studies were described narratively, compared, and contrasted. Eight studies met inclusion criteria, totaling a sample size 120. Our results suggest that both muscle size and fascicle length increases may be greater following LML-RT versus SML-RT, suggesting LML-RT may lead to greater longitudinal hypertrophy than SML-RT. Notably, evidence is largely mixed, no studies to date have attempted to estimate serial sarcomere number changes from LML versus SML-RT, and all but one study used linear extrapolation methods to estimate FL, which has questionable validity. Therefore, the structural adaptations underlying hypertrophy from LML-RT remain undetermined. In conclusion, results suggest that LML-RT may be superior to SML-RT for inducing muscle hypertrophy, and, more specifically, longitudinal growth, though evidence is mixed. This systematic review was pre-registered (https://osf.io/3d9ez) and no funding was used for completion of this review.

INTRODUCTION

Resistance training (RT) is the primary exercise strategy used to enhance muscular size in humans (Krzysztofik et al., 2019). Though a consensus is still developing, RT is thought to induce hypertrophy primarily through mechanical overload and possibly other mechanisms (Roberts et al., 2023). Repeated mechanical overload leads to transient increases in mammalian target of rapamycin complex 1 (mTORC1) signaling, as well as mTOR-independent pathways, eventually causing muscle growth via elevations in protein synthesis (Roberts et al., 2023). Of note, both active and passive tension have been shown to similarly elevate p70S6K, a downstream effector of mTOR, suggesting that tension per se drives the anabolic response to mechanical stimuli (Rindom et al., 2020). These findings raise the possibility that the combination of active and passive tension may confer a synergistic effect on RT-induced hypertrophy.

One variable that may modulate the muscle hypertrophy response from RT is range of motion (ROM), defined as the degree of movement that occurs at a specific joint during the execution of a RT exercise. A meta-analysis by (Wolf et al., 2023) indicated that a full ROM appears superior to a partial ROM for eliciting whole muscle hypertrophy. However, this finding may be mediated by the muscle length at which RT is performed, such that longer-muscle length RT (LML-RT) is superior to RT performed at shorter-muscle lengths (SML-RT) for inducing muscle hypertrophy. Indeed, three studies within this meta-analysis compared a full ROM to a partial ROM performed at longer-muscle lengths or a "lengthened partials" approach. Generally, greater hypertrophy was found with lengthened partials compared to a full ROM (Goto et al., 2019; Pedrosa et al., 2023; Werkhausen et al., 2021).

Since publication of the Wolf et al., (2023) meta-analysis, a study by Kassiano et al. (2022) also found greater hypertrophy in both the medial and lateral gastrocnemius when performing lengthened partial plantarflexion vs full ROM plantarflexion. Therefore, lengthened partials appear to be a promising strategy to maximize muscle hypertrophy. However, a substantial limitation of existing data lies in its inability to inform us about the pattern of hypertrophy that occurs in response to LML-RT, thus restricting generalizability. Indeed, most measurements of muscle hypertrophy in these studies were based on B-mode ultrasonography measurements of muscle thickness (Wolf et al., 2023). While ultrasound-derived muscle thickness can reliably reveal changes in muscle size, it cannot distinguish between radial and longitudinal hypertrophy.

Increases in measured fascicle length may give an indication as to the degree of longitudinal hypertrophy, whereas increases in measured fascicle angle may provide a representation of radial hypertrophy. This distinction is critical because the structural patterns may conceivably differ based on the range of motion used and resistance challenge within a given range of motion. Thus, it remains unclear to what extent longitudinal hypertrophy - an increase in fascicle length potentially stemming from an increase in the number of sarcomeres in series and/or the lengthening of existing sarcomeres (Pincheira et al., 2022) - may also play a role in the hypertrophy response to LML-RT.

Serial hypertrophy, or the creation and serial addition of new sarcomere units in series, is a common adaptation to limb lengthening, surgical limb/muscle lengthening, and chronic stretching protocols (Warneke et al., 2022; Williams et al., 1988). Importantly, much of the foundational evidence for stretching protocols initiating sarcomerogenesis has been conducted in animal models (Alway, 1994; Williams et al., 1988). However, as it pertains to humans, direct evidence linking RT to serial sarcomere number increases remains elusive. More recently, Damas et al. (2018) hypothesized that Z-band streaming, a proposed component of the muscle damage process, would lead to the addition of sarcomeres in series, resulting in reduced strain per sarcomere when muscle is lengthened after this adaptation has taken place. Therefore, exercise protocols that elicit greater muscle damage conceivably have the potential to enhance sarcomerogenesis, however it is hard to distinguish between remodeling and damage at present.

Sarcomerogenesis may not be limited to stretching interventions alone. Mechanistically, muscle damage can occur as a consequence of RT, particularly when the trainee has not yet been exposed to a given protocol. Foundational work by Lieber & Fridén (1993) suggested that muscle length or “strain”, as opposed to force, determines the degree of muscle damage caused by contraction. Consistent with this early research, a study by Nosaka et al. (2005) showed that eccentric RT performed at LML resulted in greater muscle damage than eccentric RT performed at SML in the elbow flexors. Notably, both SML- and LML- eccentric RT appeared to confer a protective effect, such that recovery from the second exposure to eccentric RT at LML resulted in lower elevations in creatine kinase activity and faster recovery of force production capabilities. Given that unaccustomed LML-RT appears to lead to a greater degree of muscle damage, it is possible that LML-RT - or RT performed with greater resistance at LML - would also, therefore, lead to greater sarcomerogenesis in the early phase of training. Importantly, while the stimuli underlying longitudinal growth remain unclear, the degree to which it takes place in response to SML- vs LML-RT carries important practical implications. Since individual studies assessing sarcomerogenesis or its proxy measurements (e.g., fascicle length changes) from such interventions exist, a systematic synthesis of the literature appears important in developing a better understanding of the potential hypertrophic adaptations underlying LML-RT. This systematic review aims to examine the data comparing LML- and SML-RT and their respective effects on sarcomerogenesis, or the addition of sarcomeres in series, alongside their effect on measures of muscle hypertrophy.

METHODS

Search Syntax

The search was performed using the following combination of terms: (“resistance training” OR “resistance exercise” OR “resistive exercise” OR “strength training” OR “strength exercise” OR “weight training” OR “weight lifting” OR “weightlifting” OR “range of motion” OR “muscle length” OR “resistance profile“ OR “resistance curve“) AND ("fascicle length" OR “sarcomere“ OR “longitudinal hypertrophy“) AND (“muscle thickness” OR “cross-sectional area” OR “cross sectional area“ OR “muscle growth” OR “muscle volume” OR “hypertrophy“ OR “muscle size” or “muscle area”).

Three databases were searched from inception to February 2024 to locate relevant studies: PubMed/MEDLINE, Scopus, and Google Scholar. We also performed secondary “forward” and “backward” citation searches on included studies in Google Scholar as well as considered studies from the authors’ personal knowledge on the topic. Two researchers (MW and PAK) screened titles and abstracts to assess if a study met inclusion criteria. If a paper was deemed potentially relevant, the full text was evaluated to determine whether it should be included for analysis, with any disagreement settled by a third researcher (BJS). Screening of abstracts and management of included studies was performed using RAYYAN (https://www.rayyan.ai/).

The methods and reporting of results followed guidelines set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Additionally, this study was pre-registered (see https://osf.io/3d9ez).

Inclusion criteria

We included studies that satisfied the following criteria:

a) Involved a resistance training intervention with the only independent variable being:
    i) The average joint angles at which RT is performed;
    ii) A difference in resistance curve of RT
b) Participants were free from cardiovascular, respiratory or musculoskeletal conditions that would alter RT capacity
c) Included a measure, pre- and post-intervention, of either:
    i) Fascicle length (FL) measured via B-Mode Ultrasonography; and/or
    ii) Sarcomere length (SL) measured via microendoscopy
d) Included a direct measure of muscle size (muscle thickness, muscle cross-sectional area or muscle volume), pre- and post-intervention
e) Was conducted in adults aged 18 years or older
f) Was published in an English-language journal
g) Had a minimum duration of 4 weeks

Data coding and analysis

From each study, two researchers (MW and PAK) independently extracted the following data into a predefined coding sheet using Microsoft Excel software (Microsoft Corporation, WA, USA):

a) Lead author name and year of publication
b) Sample size
c) Participant's characteristics (e.g., sex, age, training status)
d) Intervention characteristics (e.g., duration, whether ROM/muscle length and/or resistance curve were manipulated, training volume, frequency, exercise(s) performed, proximity to failure, ROM used by the different groups/condition)
e) Imaging measurements (e.g., method and muscle group)
f) Measurement type (e.g., fascicle length, serial sarcomere number)
g) Measurement points (e.g., at which specific muscle length or region)
h) Mean pre-post study results for the LML-RT and SML-RT group/conditions at each measured point with corresponding standard deviations (SD).

In the case of missing data, we contacted the authors to obtain this information directly. If we were unable to acquire data directly from the authors, we extracted values from figures using WebPlotDigitizer online software (https://apps.automeris.io/wpd/) where applicable. Where a range of values was reported (e.g. the number of reps performed varied throughout the training intervention), an average was calculated. Any disagreements between the two researchers (MW and PAK) were resolved through discussion and mutual consensus. If consensus between the two researchers could not be reached, a third researcher (BJS) resolved the dispute. The data used in this systematic review can be found in the supplementary materials here.

Quality of evidence

The methodological quality of the included studies was assessed using the "Standards Method for Assessment of Resistance Training in Longitudinal Designs" (SMART-LD) scale (Schoenfeld et al., 2024). The scale is composed of 20 items that refer to study quality, statistical analysis, study reporting and methodological rigor. Each item on the SMART-LD scale is answered “yes” or “no” if the criteria are satisfied or not satisfied, respectively. The maximum number of possible points is therefore 20. Based on the summary scores, we classified studies as “good quality” (16-20 points), “fair quality” (12-15 points), or "poor quality” (0-11 points). Two authors independently assessed the methodological quality. 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.

Potential Bias in the review process

In order to minimize the potential for bias in the search, screening, extraction, and interpretation of results, the following steps were taken. First, methods were pre-registered to avoid selective reporting of outcomes or unjustified changes in methods to alter outcomes. Second, the search, screening, SMART-LD rating, and extraction of data were performed in a blinded fashion by two investigators (MW and PAK). Following this, disagreements were discussed and resolved. Third, we followed the PRISMA guidelines for systematic reviews, strengthening the confidence in conclusions.

RESULTS

The search string identified 535 publications/theses for potential inclusion, while 2 others were identified through websites and citation searching. Once duplicates were removed, 298 studies remained. The titles and abstracts were screened, and, where deemed appropriate, full-text versions were sought to determine eligibility. Ultimately, seven studies were included in the review, in addition to the two studies identified through citation searching and personal databases. One study (Noorkõiv et al., 2015) was eventually excluded during the data extraction due to containing the same dataset as another already included study (Noorkõiv et al., 2014). Figure 1 details the search process. Table 1 provides summary data of the 8 studies that were finally included for review.

Fig. 1 PRISMA Flow Chart

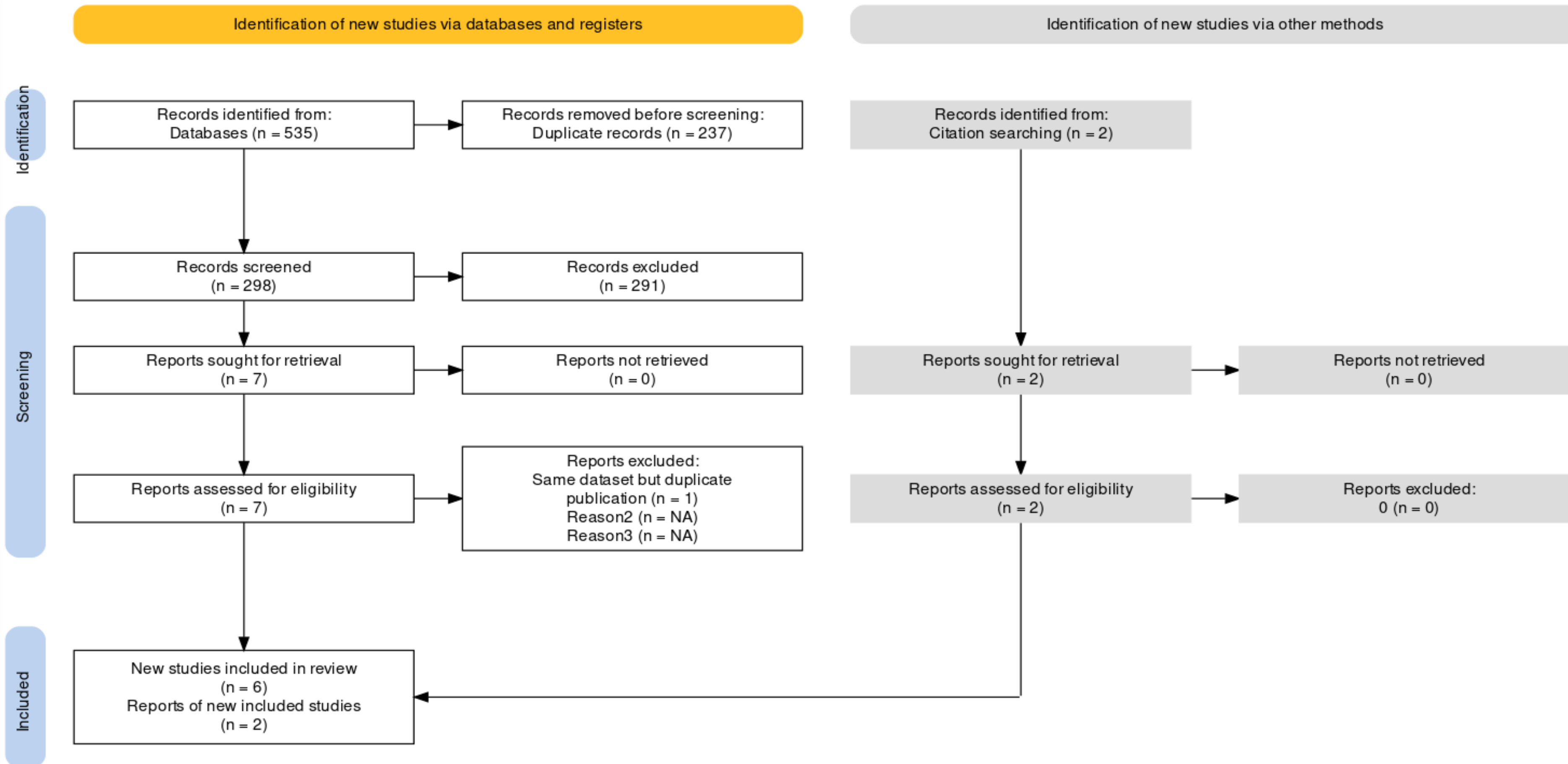

Table 1. Summary of studies on fascicle length, pennation angle, and muscle size adaptations from lengthened versus shortened training.

Study	N	Design	Program duration (weeks)	Contraction Types	Manipulated variable	Angles	Intensity	Muscle	Summary of findings
(McMahon et al., 2014)	21	Between	8	ECC+ CON+ISO	Joint Angles	50-0° vs 90-40° of knee flexion	80 vs 55% of condition 1RM	Vastus lateralis	FL: Greater increases in LML-RT vs SML-RT at proximal (+36.5 vs +19.8%), central (+24.5 vs +8.7%) and distal (+22.9 vs +10.1%) sites. aCSA: Generally greater increases for LML-RT vs SML-RT at proximal (+30.5 vs +17.4%), central (+35.8 vs +21.6%) and distal (+50.7 vs +13.4%) sites; differences larger at more distal sites.
(Mcmahon et al., 2014)	16	Between	8	ECC+ CON+ISO	Joint Angles	50-0° vs 90-40° of	80% of condition 1RM	Vastus lateralis	FL: Greater increases in LML-RT vs SML-RT at proximal (+28.3 vs +18.1%), central (+24.7 vs +8.8%) and distal (+19.4 vs +10.1%) sites.

						knee flexion			aCSA: Substantially greater increases in LML-RT vs SML-RT at proximal (+33.8 vs +19%) and distal (+40.1 vs +7.5%) sites. Similar increase mid-belly (+18 vs +22%).
(Alegre et al., 2014)	19	Between	8	ISO	Joint Angles	50° vs 90° of knee flexion	60-80% MVC	Vastus lateralis	FL: Slight decrease in SML-RT (-1.1%); increase in LML-RT (+3.6%). MT: Slightly greater increase in LML-RT at proximal (+9.7 vs +5%), mid-belly (+12.8 vs 4.5%), and distal sites (+8.8 vs 7.6%), difference largest at mid-belly.
(Noorkõiv et al., 2014)	16	Between	6	ISO	Joint Angles	38.1° vs 87.5° of knee flexion	80% MVC at optimal angle	Vastus lateralis for FL; VL, VM, VI and RF for Muscle Volume /CSA	FL: Similar at proximal site (+3.3 vs +2.3%), greater for SML-RT at mid-belly (+3.9 vs +6%), greater for LML-RT at distal site (+6.7 vs -0.7%). Muscle Volume: No meaningful change in SML-RT, generally increase in LML-RT in VL, VM and RF but not VI. CSA: Only increase in LML-RT and not SML-RT.

(Stasinaki et al., 2018)	9	Within	6	ECC+ CON	Joint Angles, Resistance Curve	170-90° vs 110-30° of elbow extension	85% exercise 1RM	Triceps brachii long head	FL: Slight increase at 50% site for SML-RT (+7.7%), minimal change at 60% site (+1.8%). Minimal change at either site for LML-RT (+0.6% and -1.9% respectively). MT: Notable increases at both 50 (+13.2 vs + 8.9%) and 60% (+17.2 vs +14.8%) sites for both LML-RT and SML-RT, but slightly greater increases for LML-RT. CSA: Similar total increases in LML-RT vs SML-RT (+14.3 vs +14.7%). No change for LML-RT at proximal site, but notable increase for SML-RT (-1.1 vs +12.1%), Increases in distal CSA for both SML-RT and LML-RT, but slightly larger for LML-RT (+21.3 vs +17%).
(Valamatos et al., 2018)	11	Within	15	CON	Joint Angles	60-0° vs 100-0° of knee flexion	Maximal intent on IKD	Vastus lateralis	FL: No change in SML-RT, modest increase in LML-RT. pCSA: Lesser increase in LML-RT vs SML-RT (+2.4 vs +7.8%).

									aCSA: Similar increases at proximal and distal region; slightly greater increase for LML-RT at medial region. Muscle volume: Similar increase for LML-RT vs SML-RT (+7.6 vs +6.7%)
(Akagi et al., 2020)	13	Within	8	ISO	Joint Angles	0° vs 40° of ankle plantarflexion	Maximal intent on IKD	Tibialis Anterior (40% of leg length)	FL: Slight decrease for SML-RT (-2.1%), increase for LML-RT (+4.4%). MT 40% of leg length: Similar increases in both conditions, slightly larger for LML-RT (+1.4 vs +0.9%).
(Werkhausen et al., 2021)	15	Within	10	CON	Joint Angles	90-0° vs 90-81° of knee flexion	4-8RM (full ROM), adjusted by RPE <8	Vastus lateralis (60% of upper-leg length)	FL: Slightly larger increases for LML-RT vs SML-RT. MT 60% of leg length: No meaningful changes pre- to post for SML-RT or LML-RT.

ECC: Eccentric-only. CON: Concentric-only. ISO: Isometric-Only. LML-RT: Longer-Muscle Length Resistance Training. SML-RT: Shorter-Muscle Length Resistance Training. IKD: Isokinetic Dynamometer. MVC: Maximal Voluntary Contraction. RPE: Rating of Perceived Exertion. RM: Repetition-Maximum. FL: Fascicle length. VL: Vastus Lateralis. VM: Vastus Medialis. RF: Rectus Femoris. VI: Vastus Intermedius. LBM: Lean Body Mass. MT: Muscle Thickness. CSA: Cross-Sectional Area. aCSA: anatomical Cross-Sectional Area.

Summary of study characteristics

All studies included were conducted in untrained individuals, with the exception of the study by Werkhausen et al. (2021), where participants were required to have at least 6 months of resistance training experience to participate. The total combined sample size of these studies was 120 participants. Four studies included a mixed-sex sample (Akagi et al., 2020; Alegre et al., 2014; McMahon et al., 2014; Mcmahon et al., 2014), one study included a female-only sample (Stasinaki et al., 2018), and three studies included a male-only sample (Noorkõiv et al., 2014; Valamatos et al., 2018; Werkhausen et al., 2021). Most studies examined morphological adaptations of the quadriceps muscle - the vastus lateralis muscle specifically (Alegre et al., 2014; Mcmahon et al., 2014; McMahon et al., 2014; Noorkõiv et al., 2014; Valamatos et al., 2018; Werkhausen et al., 2021). With the exception of the study by Stasinaki et al. (2020), which manipulated the exercise performed alongside the joint angles involved, all other studies manipulated joint angles. Interestingly, most operationalizations of LML-RT did not involve participants training near the extremity of joint ROM. For illustration, while full knee flexion can often exceed 150° of ROM, LML-RT joint angles for the quadriceps ranged from 87.5-100° of knee flexion, suggesting that LML-RT was generally not performed near maximal muscle lengths. In terms of muscle actions, three studies involved a combination of concentric and eccentric actions (Mcmahon et al., 2014; McMahon et al., 2014; Stasinaki et al., 2018), three involved isometric-only actions (Akagi et al., 2020; Alegre et al., 2014; Noorkõiv et al., 2014), and two examined concentric-only muscle actions (Valamatos et al., 2018; Werkhausen et al., 2021). Notably, no studies examined eccentric-only muscle actions, which generally appear to stimulate greater increases in fascicle length than concentric-only muscle actions (Franchi et al., 2014). Intensities of load were generally moderate to high, ranging from 55% of 1RM to maximal voluntary contractions performed using isometric dynamometry. Finally, LML-RT led to greater increases in fascicle angle in four studies (Alegre et al., 2014; McMahon et al., 2014; Stasinaki et al., 2018; Valamatos et al., 2018), similar changes in one study (Mcmahon et al., 2014) and SML-

RT led to greater increases in fascicle angle in two studies (Akagi et al., 2020; Werkhausen et al., 2021).

Assessment of fascicle length

With the exception of the study by Stasinaki et al. (2018), all studies estimated fascicle length using linear extrapolation equations. While this method allows estimation of fascicle length using only a linear transducer with a limited field-of-view, it presents several limitations. First, it assumes that fascicles are linear and does not account for curvature of fascicles, which is common. Second, extrapolation methods assume that fascicles are oriented homogeneously, which they usually are not (Sarto et al., 2021). Previous research has suggested the use of extrapolation methods may be particularly inaccurate for muscles such as the biceps femoris' long head, wherein the architectural arrangement of fascicles may be more heterogeneous (Franchi et al., 2020). Since all studies (with the exception of Stasinaki et al. (2018)) have used linear extrapolation methods, fascicle length results should be interpreted cautiously and with limited confidence (Franchi et al., 2020).

Muscle size

Muscle size increases were typically larger in the LML-RT group/condition versus the SML-RT group/condition. Mcmahon et al. (2014) noted greater increases in vastus lateralis anatomical CSA at proximal, medial, and distal sites for the LML group (40-90°) compared to the SML-RT group (50-0°), with differences being largest at the distal site. Notably, Mcmahon et al. (2014) used a complex protocol with a variety of exercises involving dynamic and isometric muscle actions training the quadriceps musculature, similar to what is commonly used in ecologically valid RT programs. A second investigation by the same research group (McMahon et al., 2014), using a similarly comprehensive training routine and involving the same joint angle excursions also found greater increases in VL anatomical CSA from LML-RT compared to SML-RT at proximal, medial, and distal measurement sites. In contrast, using concentric-only RT, Werkhausen et al. (2021) found similar hypertrophy following LML-RT (90-81°) and SML-RT (90-0°) leg press in the vastus lateralis using a within-participant design. Importantly, neither condition observed meaningful hypertrophy from pre- to post-intervention, suggesting the training intervention may have been insufficient to induce measurable hypertrophy. Since RT was performed in an explosive manner, the proximity-to-failure may have been insufficient to induce substantial muscle hypertrophy (Robinson et al., 2023). In partial agreement with these results, Valamatos et al. (2018) also observed similar muscle hypertrophy from SML-RT vs LML-RT when examining morphological adaptations to concentric-only RT in the vastus lateralis. Using the leg extension exercise, the SML-RT limb trained through 60-0° of knee flexion, whereas the LML-RT limb trained through 100-0° of knee flexion. Increases in anatomical CSA were similar between the LML-RT and SML-RT limb, with slightly greater hypertrophy at the medial site for the LML-RT limb. In contrast, the SML-RT limb observed greater increases in physiological CSA of the VL compared to the LML-RT limb. Noorkõiv et al. (2014) measured increases of the VL, VI, RF, an VM using MRI following unilateral isometric RT of the quadriceps at 37.1° of knee flexion in the SML-RT limb versus 87.5° of knee flexion for the LML-RT limb. Both in terms of muscle volume and CSA, the SML-RT limb failed to observe meaningful increases in muscle size. In contrast, the LML limb appeared to hypertrophy more substantially in the RF, VM, and VL, but not in the VI. These results may represent regional hypertrophy in response to RT, which is commonly observed (Nunes et al., 2024), especially with single-exercise interventions. Finally, Alegre et al. (2014) examined adaptations of the VL to isometric RT at SML (50°) or LML (90°) using a between-participant design. Increases in muscle thickness of the vastus lateralis were generally larger in the LML-RT group versus the SML-RT group, with the largest difference observed at the mid-belly/medially. Overall, studies in the VL appear to favor LML-RT for muscle hypertrophy, particularly at more distal measurement sites. Limited data exists in regard to the VI/VM/RF.

While most studies have examined architectural adaptations of the quadriceps/VL muscle in response to different muscle length RT, Stasinaki et al. (2018) examined the triceps brachii's long head. The SML-RT limb was trained using the cable pushdown exercise, with the shoulder in anatomical position, from 170-90° of elbow extension, with the external moment arm being largest at 90°. The LML-RT limb excursion was also 30-110° of elbow extension, but with the shoulder flexed to 180° overhead - as a result, the external moment arm may have been largest near the end of the concentric phase. As such, while the mean muscle length was likely greater in the LML-RT limb versus the SML-RT limb, the SML-RT limb likely strained against a greater external moment arm towards the start of the repetition, whereas the LML-RT limb strained against a greater external moment arm towards the end of the repetition. In terms of long head muscle thickness, both limbs observed increases in muscle size, though differences were slightly larger in the LML-RT limb. While care should be taken not to overinterpret statistically insignificant differences, it's worth noting that triceps brachii long head CSA increases were larger at the distal site with long-length training (25% vs 17%) yet larger at the proximal site with short-length training (14% vs 0%), tentatively supporting preferential distal muscle hypertrophy from long-length training. Finally, Akagi et al. (2020) examined changes in tibialis anterior architecture in response to isometric RT at SML (0° of plantarflexion from neutral) versus LML (40° of plantarflexion). Muscle thickness was only measured at 40% of shin length; both limbs saw an increase in tibialis anterior hypertrophy, though increases were larger in the LML-RT limb.

Overall, existing data suggests that LML-RT leads to greater increases in muscle size than SML-RT. Most longitudinal research on the topic has been conducted in the quadriceps - and the vastus lateralis more specifically - thus limiting the generalizability of findings for other muscles.

Fascicle length

Fascicle length increases generally appeared to be larger in the group/condition training at LML-RT than the group/condition training at SML-RT. Importantly, there is substantial variance in the changes observed – perhaps owing to some of the difficulties associated with measuring fascicle length using extrapolation methods - making it difficult to draw firm conclusions as to the presence and magnitude of the potential effect. Alongside observing greater hypertrophy from LML-RT versus SML-RT, McMahon et al. (2014) also reported greater increases in VL FL when estimated at 25, 50, and 75% of muscle length in the LML-RT group than the SML-RT group. Similarly, McMahon et al. (2014) found greater increases in VL FL when estimated at 25, 50, and 75% of muscle length in the LML-RT group compared to the SML-RT group. Notably, both of these investigations employed comprehensive training programs with a variety of exercises and involving concentric, isometric, and eccentric muscle actions. In line with these findings, Werkhausen et al. (2021) noted greater increases in fascicle length - even in the absence of appreciable muscle hypertrophy - when performing the leg press with the LML-RT limb (90-81°) versus the SML-RT limb (90-0°). Valamatos et al. (2018) also used a within-participant, concentric-only study design. In agreement with Werkhausen et al. (2021), greater increases in fascicle length were noted for the LML-RT condition, with no meaningful adaptation occurring in the SML-RT condition. In contrast, Noorkõiv et al. (2014) found mixed results; when isometric RT of the VL was performed at 37.1 or 87.5° of knee flexion, fascicle length adaptations were similar proximally, greater for SML-RT mid-belly, and greater for LML-RT distally. Finally, Alegre et al. (2014) compared the impact of isometric RT at 50 vs 90° of knee flexion on vastus lateralis FL. Interestingly, slight decreases in FL were noted in the SML-RT group, while the LML-RT group experienced modest increases in estimated FL.

Stasinaki et al. (2018) examined muscle architectural changes of the triceps brachii long head, comparing the effect of cable pushdowns (SML-RT) from 170-90° of elbow extension, with the shoulder in anatomical position to cable overhead extensions (LML-RT) from 30-110° of elbow extension, with the shoulder flexed to 180° overhead. Long head FL increased in the SML-RT limb at the 50% site, whereas FL at the 60% muscle length site and at both sites for the LML-RT limb remained largely unchanged. Of note, Stasinaki et al. (2018) was the only study to employ the extended field of view method for assessing FL, which is considered more accurate than extrapolation from conventional b-mode ultrasonography (Franchi et al., 2020). Finally, Akagi et al. (2020) examined changes in tibialis anterior architecture in response to isometric RT at SML versus LML. While the SML-RT limb experienced slight decreases in tibialis anterior FL, the LML-RT condition experienced substantial increases in FL. Overall, the literature remains equivocal regarding architectural changes when training at varied muscle lengths. Some studies suggest modestly greater increases in FL following LML-RT compared to SML-RT; however, given the uncertainty of evidence and limitations of the measurement techniques employed, these findings must be interpreted with circumspection.

Study quality

The SMART-LD scale was used to assess the quality of all studies included. A mean score of 11.4 ± 1.9 out of 20 points (range: 9 to 14 points). Four studies were deemed of poor quality (Alegre et al., 2014; Mcmahon et al., 2014; McMahon et al., 2014; Noorkõiv et al., 2014), and the remaining four studies were deemed of fair quality (Akagi et al., 2020; Stasinaki et al., 2018; Valamatos et al., 2018; Werkhausen et al., 2021). No studies were deemed to be of good quality.

DISCUSSION

This article aimed to systematically examine the effects of longer-muscle length RT versus shorter-muscle length RT on muscle hypertrophy and, specifically, proxy measures of longitudinal hypertrophy. The major findings from this systematic review and meta-analysis were that (1) LML-RT consistently leads to greater muscle hypertrophy than SML-RT, and (2) LML-RT may lead to greater increases in estimated fascicle length - or longitudinal hypertrophy - than SML-RT, although this finding remains equivocal.

The finding that longer-muscle length RT leads to greater increases in measures of overall muscle hypertrophy than shorter-muscle length RT is in agreement with prior preliminary findings by Wolf et al. (2023). Using an exploratory subgroup analysis, full ROM was compared to partial ROM at SML and partial ROM at LML. Although data were sparse and conclusions were tentative, training at LML appeared to confer a potential hypertrophic advantage. Similarly, in the present review, although muscle actions and the ROM excursion were matched for between groups/conditions, training at LML appeared superior to training at SML for muscle hypertrophy. With that said, most studies involved the vastus lateralis, potentially limiting generalizability to other muscles. Overall, for resistance trainees aiming to increase muscle hypertrophy, training at LML appears advantageous.

Similarly, most included studies observed somewhat greater increases in fascicle length from LML-RT compared to SML-RT. The magnitude of differences was generally small, and within the typical coefficient of variation of the measurements shown in the literature (Kwah et al., 2013). Moreover, these findings need to be interpreted cautiously for several reasons. First, as previously noted, LML-RT was generally performed at relatively moderate joint angles. In fact, the only study included that may have included excursions to particularly longer-muscle lengths was by Stasinaki et al. (2018), where the LML-RT condition used a partial ROM in the overhead extension from 30-110° of elbow extension, finding greater increases in FL in the SML limb, but similar hypertrophy between limbs. Since only one investigation has truly examined training at long-muscle lengths, it remains unclear whether adaptations to long-muscle length training would be similar to the operationalizations of "longer-muscle length" training used within the studies included. Second, while direct measurement of musculotendinous unit length during resistance training would be required to ascertain the true difference in muscle length trained, it is assumed that there is a relationship between joint angle excursion and the mean muscle length trained (Raiteri et al., 2021). Therefore, while discussion of results was predicated on this assumption, no attempt was made to quantify the exact differences in muscle length trained through between the longer- and shorter-muscle length conditions/groups. Third, as previously noted, the only study directly measuring fascicle length was performed by Stasinaki et al. (2018); all other studies used linear extrapolation methods, potentially introducing error. Notably, fascicle visibility in the triceps can be mixed, further impeding fascicle length assessment. Fourth, no study to date comparing SML- vs LML-RT has sought to measure sarcomere length and, subsequently, serial sarcomere number. The first instance of combined use of extended field-of-view ultrasonography and microendoscopy to measure these morphological adaptations is very recent (Pincheira et al., 2022) and has not yet been used when comparing SML- and LML-RT. As such, it remains unclear whether increases in fascicle length observed herein reflect an increase in the length of individual sarcomeres, an increase in the number of sarcomeres, or a combination thereof. Notably, Pincheira et al. (2022) observed an increase in sarcomere length, but not serial sarcomere number, casting doubt on previous hypotheses that increases in fascicle length largely reflect increases in serial sarcomere number.

These limitations in our understanding notwithstanding, the potential increase in fascicle length from LML-RT could be notable, particularly as it represents a means to further enhance muscle hypertrophy. Importantly, though, all studies - with the exception of Werkhausen et al. (2021) - were conducted in untrained participants, which could limit generalizability to more trained populations. Indeed, while fascicle length increases contribute to muscle hypertrophy, the time course of these changes and whether/to what extent they continue occurring in well-trained individuals remains unclear. The data on this topic are relatively mixed. On one hand, several studies examining different modes of resistance training that measured fascicle length at a variety of timepoints have found that adaptations diminish - if not halt altogether - after only 2-5 weeks (Blazevich et al., 2007; Carmichael et al., 2022; Timmins et al., 2016). The rapid increase in FL early in training could partly explain why untrained populations observe rapid and dramatic hypertrophy upon first engaging in RT. In contrast, a longer-duration, 12-week study by Baroni et al. (2013) showed continuous and nearly linear increases in FL during eccentric-only resistance training in the quadriceps during the first eight weeks of the training intervention. From weeks 8-12, increases in fascicle length appeared to diminish, but did not cease altogether. Similarly, two studies by the same research group found notable increases in FL (+8.5 to +12.3%) in highly trained, elite throwing athletes during certain phases of their training macrocycles (Anousaki et al., 2021; Zaras et al., 2016). As a result, the degree to which adaptations in fascicle length continue to contribute to muscle hypertrophy in trained populations remains unclear. To explain this discrepancy in findings, we hypothesize that the rate of adaptations in FL follows a similar pattern as that of muscle hypertrophy, such that increases in FL diminish as training experience increases, but do not cease altogether.

Importantly, as noted in the results section, most comparisons of SML- and LML-RT have also noted greater increases in fascicle angle from LML-RT (Alegre et al., 2014; McMahon et al., 2014; Stasinaki et al., 2018; Valamatos et al., 2018), though some studies have failed to find a meaningful difference (Mcmahon et al., 2014) or even found slightly greater increases in fascicle angle from SML-RT (Akagi et al., 2020; Werkhausen et al., 2021). In this regard, the literature on fascicle angle parallels the literature on fascicle length: while LML-RT may enhance adaptations, data are inconsistent. Since increases in fascicle angle have been hypothesized to represent increases in radial hypertrophy (Jorgenson et al., 2020), these results suggest that LML-RT may lead to both greater increases in longitudinal hypertrophy as well as radial hypertrophy. However, substantial variance is apparent in measurement of FL/fascicle angle, limiting inferential power. Moreover, all but one study employed the extrapolation technique to estimate changes in FL, the accuracy of which has been called into question (Franchi et al., 2020). Notably, though, these findings are in line with findings by Ema et al. (2016). When performing a linear regression analysis of existing studies measuring adaptations in muscle size measurements, fascicle angle measurements, and fascicle length measurements, statistically significant (but weak) correlations were found between fascicle angle adaptations and muscle size adaptations ($r=0.34$, $p<0.001$) and fascicle length adaptations and muscle size adaptations ($r=0.28$, $p=0.014$). While these associations were statistically significant, they only explain around 9-10% of covariance respectively, casting doubt on the practical significance of the findings.

Notably, this review also suffers from a few meaningful limitations. First, data are relatively sparse, and have predominantly been obtained in the vastus lateralis, potentially limiting generalizability. Second, while an effort was made to obtain as much of the data as possible, we were unable to acquire some of the data. Thus, it is possible that the results of this review could have been meaningfully different had all the data been available. Third, fascicle length was generally estimated using linear extrapolation methods, which is inferior to direct visualization and measurement of the entire fascicle using extended field-of-view ultrasonography (Franchi et al., 2020). Finally, no studies directly examined serial sarcomere number, making it impossible to draw any conclusions regarding the structural nature of the observed increases in fascicle length. Indeed, inferences about changes in serial sarcomere number cannot be drawn in the absence of the combined use of ultrasonography and micro endoscopy.

CONCLUSION

LML-RT appears to induce greater overall muscle hypertrophy than SML-RT; there is the suggestion of modestly greater longitudinal hypertrophy favoring LML as well, although evidence on the topic remains equivocal. Additionally, longer-muscle length RT may induce greater increases in fascicle angle/radial hypertrophy than shorter-muscle length RT. Therefore, trainees aiming to maximize muscle hypertrophy should aim to place a focus on longer-muscle length RT. With that said, many limitations of existing literature are noted. Future studies should aim to investigate LML-RT at longer-muscle lengths than have hitherto been examined, and use novel imaging methods (such as the combination of extended field-of-view ultrasonography and micro endoscopy) to gain insight into the structural adaptations underlying increases in FL from LML-RT. Finally, RT studies should seek to assess FL changes from LML-RT in more highly trained populations to gain a deeper understanding of the role of FL increases and how they relate to long-term muscle hypertrophy.

Contributions

Substantial contributions to conception and design: MW, PAK, MDR, DLP, MVF, BC, MH, BJS
Acquisition of data: MW, PAK, BJS
Analysis and interpretation of data: MW, PAK, MDR, DLP, MVF, BC, MH, BJS
Drafting the article or revising it critically: MW, PAK, MDR, DLP, MVF, MH, BJS
Final approval of the version to be published: MW, PAK, MDR, DLP, MVF, BC, MH, BJS

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Pre-registration and datasheet is available at
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