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SPORTS PERFORMANCE

The effects of hip flexion angle on quadriceps femoris muscle hypertrophy in the leg extension exercise

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ABSTRACT

This study compared the effects of 90° versus 40° hip flexion in the leg extension exercise on quadriceps femoris muscle hypertrophy. Twenty-two untrained men completed a ten-week intervention comprising two resistance training sessions per week. A within-participant design was used, with the lower limb side randomly allocated to the 40 or 90° condition. Muscle thickness of distal and proximal rectus femoris and vastus lateralis was quantified via ultrasound. Data were analysed within a Bayesian framework including univariate and multivariate mixed effect models with random effects to account for the within participant design. Differences between conditions were estimated as average treatment effects (ATE) and inferences were made based on posterior distributions and Bayes Factors (BF). Results indicated a greater hypertrophic response in the rectus femoris for the 40° condition, with "extreme" evidence supporting a hypertrophic response favouring the 40° hip angle for the rectus femoris ($BF > 100$; $p(\text{Distal/ATE} \ \& \ \text{Proximal/ATE} > 0) > 0.999$), and "strong" evidence supporting no difference in hypertrophic response for the vastus lateralis ($BF = 0.07$). Therefore, both conditions could be viable options for increasing quadriceps femoris hypertrophy. However, when training for maximizing rectus femoris hypertrophy among untrained men, we suggest training with a reduced hip flexion in the leg extension exercise.

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Knee extension; vastus lateralis; rectus femoris; hypertrophy

Introduction

Resistance training is a popular method to increase skeletal muscle hypertrophy (Roberts et al., 2023). Regional or inhomogeneous muscle hypertrophy, characterized by an increase in the size of a specific muscle region relative to others, has been documented to occur from resistance training (Zabaleta-Korta et al., 2023). For instance, different selections of resistance exercise have been observed to impact regional hypertrophy (Maeo et al., 2021, 2023).

One muscle group that has been reported to be influenced by the selection of resistance exercises on regional muscle hypertrophy is the quadriceps femoris (Zabaleta-Korta et al., 2021). Substantial muscle growth has been noted in the monoarticular vastii muscles from multi-joint lower-body exercises (Kubo et al., 2019; Larsen et al., 2022). The rectus femoris is the only muscle of the quadriceps that is a biarticular muscle, functioning as both a hip flexor and knee extensor (Kojic et al., 2022). Due to the biarticular nature of the rectus femoris, it has been postulated that closed-chain multi-joint exercises like the back squat mainly induce muscle growth of the monoarticular vastii muscles (Kojic et al., 2022). Several previous studies using the squat exercise with different protocols, measuring quadriceps femoris growth, have reported minimal hypertrophy of the rectus femoris following weeks of squat training (Kojic et al., 2022; Kubo et al., 2019; Zabaleta-Korta et al., 2021). Moreover, Zabaleta-Korta et al. (2021) compared the effects of smith machine squats and the leg extensions on distal, central, and proximal hypertrophy of the rectus femoris and vastus lateralis during five weeks of resistance training. The researchers observed that all three regions of the rectus femoris hypertrophied for the leg extension group, whereas muscle growth was only observed at the central measurement site in the vastus lateralis among the squat group.

Findings may, however, be influenced by contraction type. Eccentric leg extensions have been observed to preferentially train the rectus femoris and result in minimal hypertrophy of the vastus muscles (Maeo et al., 2018), and previous studies suggest that eccentric movements may result in increased hypertrophy at the distal portion of the quadriceps femoris (Franchi et al., 2014). Thus, the differences in eccentric lifting duration, standardized to two seconds by Zabaleta-Korta et al. (2021) but not mentioned in the studies by Kojic et al. (2022) and Kubo et al. (2019) may limit the ability to draw clear conclusions. In addition, previous studies have employed different protocols, with these differences able to influence findings. For example, the participants in Kojic et al. (2022), trained parallel squats twice a week for seven weeks in which exercises increased from 60 to 70% with 3 to 4 sets over the period, while the participants in Kubo et al. (2019) squatted for ten weeks starting with the same intensity, but more repetitions to a higher intensity. Zabaleta-Korta et al. (2021) conducted only a 5-week resistance training programme with 4 sets of 12

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repetitions, but training three times per week, with each set taken to momentary failure. Thereby, due to these differences in intervention duration, proximity-to-failure, training volume, and frequency between these studies, it is difficult to compare their results with each other.

Besides factors like training volume, intensity and training frequency which may impact the hypertrophic stimuli (Pelland et al., 2024; Robinson et al., 2023), it is also postulated that the angle at which resistance training is performed is of influence for hypertrophy. So did Mitsuya et al. (2023) used magnetic resonance imaging to compare the impact of 40 vs. 80° hip flexion angle on distal, middle, and proximal transverse relaxation time of the rectus femoris during the leg extension exercise. The authors observed that a hip flexion angle of 40° led to significantly more muscle activation in the proximal and mid-belly rectus femoris compared to 80° of hip flexion (Mitsuya et al., 2023). This finding may have implications for longitudinal adaptations, including hypertrophy, as previous investigations have suggested that the transverse relaxation time is associated with regional/non-uniform intra-muscular hypertrophy after a training intervention (Wakahara et al., 2013, 2017)

The mechanisms underlying the potential benefits of training at longer-muscle length remain unclear (Wolf et al., 2023). However, the proposed factors include enhanced muscle deoxygenation (Kooistra et al., 2008) and increased IGF-1 levels (McMahon et al., 2014). Also, the quadriceps femoris do appear to function within both the ascending limb, plateau region and the descending limb of the length–tension-relationship (Cutts, 1988, 1989; Son et al., 2018), suggesting that training the quadriceps femoris at longer muscle lengths could be beneficial when training for muscle growth (Ottinger et al., 2023). For example, Pedrosa et al. (2022) compared regional muscle hypertrophy in the rectus femoris and vastus lateralis in the leg extension exercise when training with different ranges of motion (ROM) with a standardized eccentric and concentric duration of two seconds. The researchers observed that training in the initial ROM (100–65° of knee flexion) resulted in superior hypertrophic outcomes in both the distal rectus femoris and vastus lateralis compared to the groups training with both a full ROM (100–30°), in the final partial ROM (65–30°), and with a variable ROM.

Yet, to our knowledge, the effect of hip flexion angle on rectus femoris and vastus lateralis muscle hypertrophy in the leg extension remains unstudied. Thus, this study aimed to examine the effect of training recumbent with 40° versus sitting upright at 90° of hip flexion angle in the leg extension exercise on muscle hypertrophy in the rectus femoris and the vastus lateralis during a ten-week resistance training programme among untrained men. Our hypothesis was that ten weeks of resistance training with a 40° hip flexion angle in the leg extension would lead to greater muscle hypertrophy of the rectus femoris but not vastus lateralis compared to the 90° hip flexion angle.

Methods

Experimental approach to the problem

This study used a within-participant repeated-measures design, as cross-education has been observed to impact muscle strength (Manca et al., 2017) rather than muscle size (M. Lee & Carroll, 2007; Manca et al., 2017). The left and right lower limbs were randomly assigned (using www.randomizer.org) to one of the two hip flexion angles in the leg extension exercise: 40° hip flexion angle, or 90° hip flexion angle (See Figure 1), where 0° was defined as no flexion in the hip joint (i.e., standing upright in an anatomical position). The study was conducted between January and March 2024 in Levanger, Norway. The same five researchers (S.L, N.Ø.S, B.S.F, A.B.F, and H.N.F) with at least a bachelor's degree in sports science supervised all resistance training sessions. Importantly, the supervisors were carefully instructed about the research procedure by the lead researcher and met at the training facilities twice for pilot testing to learn the resistance training procedures and standardize resistance techniques before the training intervention started.

Two pre-intervention measurements and two post-intervention measurements were made to increase the precision of the results obtained with ultrasound imaging of the distal and proximal rectus femoris and vastus lateralis (P. P. Swinton, 2024). To familiarize the participants with the techniques, a familiarization session was conducted in week one, where the participants gradually worked up with two to three sets to test their 10-20RM on each leg. Thereafter, the participants trained the

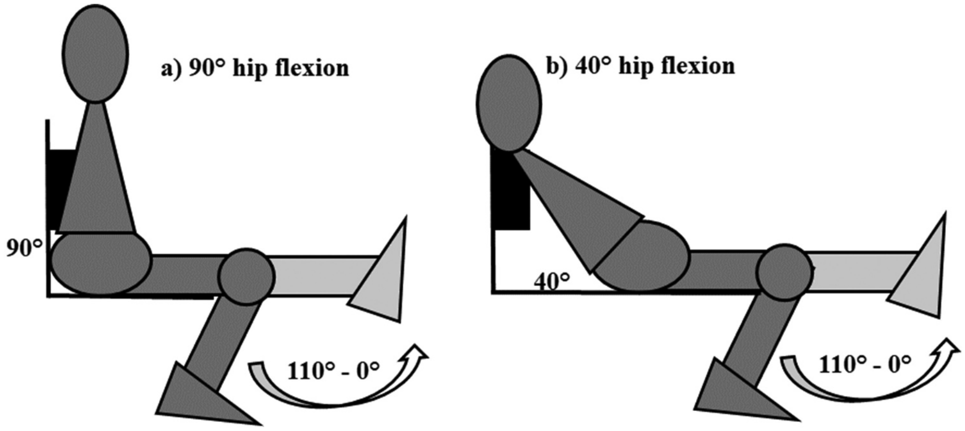


Figure 1. Illustration of the two hip flexion angles the participants trained with.

leg extension exercise for ten weeks. All participants trained twice a week, totalling 20 training sessions. Each training session consisted of three sets of 10–20 repetitions in weeks one to five, and four sets of 10–20 repetitions in weeks six to ten in the unilateral leg extension exercise. The participants trained to momentary concentric failure, defined as the inability to complete the concentric portion of a given repetition with a full range-of-motion and without deviation from the prescribed form of the exercise (Steele et al., 2017).

Risk of bias

This study followed the Standards Method for Assessment of resistance training in Longitudinal Design (SMART-LD) checklist (Schoenfeld et al., 2023). This was done to reduce the chance for potential biases (see supplementary file 1). After conducting the study, the final grading was 19/20 points (>80%), which is deemed "good quality" (Schoenfeld et al., 2023). We also made every effort to standardize repetition number, sets, proximity-to-failure, knee flexion ROM, concentric and eccentric duration, and rest intervals as these variables may influence the stimuli within a resistance exercise (Coratella, 2022). In addition, this study and hypotheses were pre-registered prior to the data collection on the Open Science Framework (OSF: https://osf.io/8x2gc).

Participants

This study's sample consisted of healthy, untrained adult men between 18 and 50 years. A total sample of 30 untrained and healthy adult men were recruited for the study. The inclusion criteria were a) no previous resistance training experience, defined as less than one resistance training session a week in the last six months, b) no previous self-reported use of anabolic steroids or other muscle-enhancing illegal agents, c) no musculoskeletal or cardiorespiratory disorders that could compromise the results of this current study. Participants who failed to participate in at least 85% of scheduled training sessions were excluded from the analyses. A total of 22 participants were included in the statistics (body mass: 84.1 ± 13.6 kg, age: 33.0 ± 5.8 years, height: 179.2 ± 5.7 cm; see Figure 2). All participants were instructed to maintain their daily routines and nutrition habits during the training intervention. However, all participants were provided with protein recommendations of a daily protein intake of 1.6-gram per kg of body mass (Morton et al., 2018). After a detailed description of the study and procedures, the participants signed a written

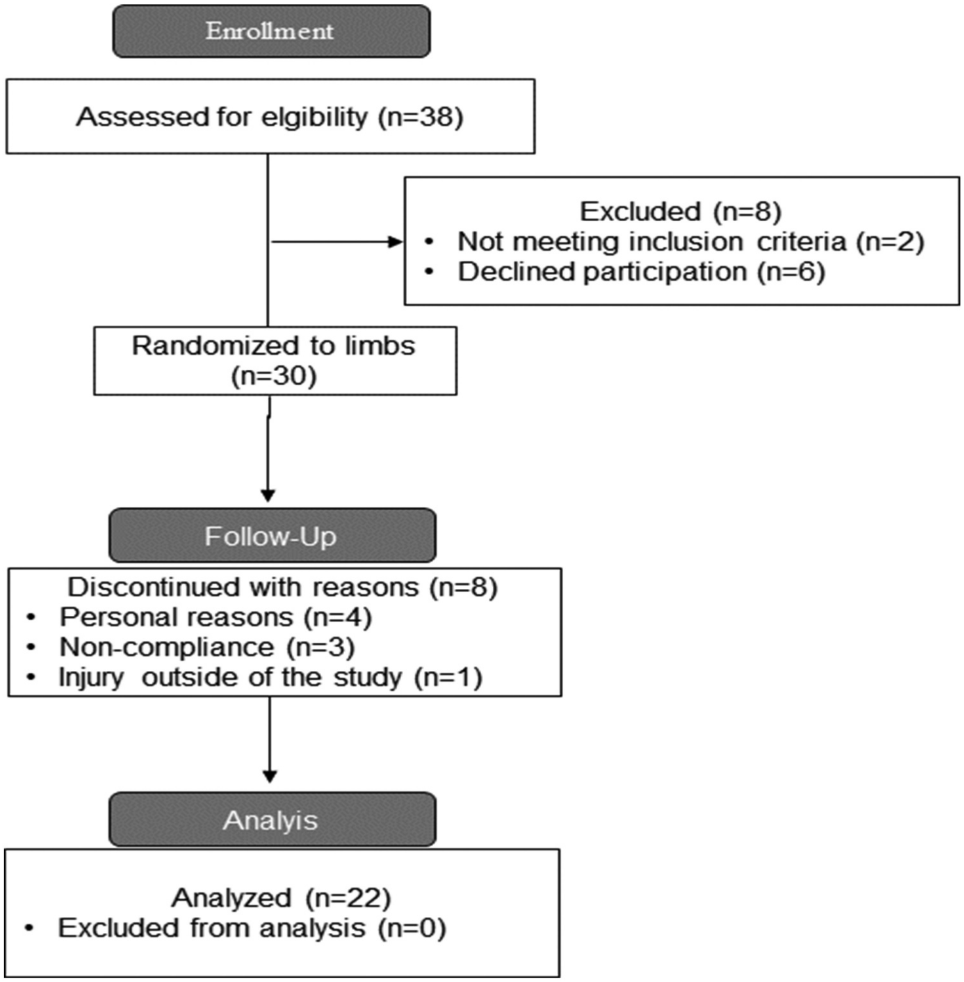


Figure 2. Consort flow chart.

informed consent form. This project was performed according to the latest revision of the Declaration of Helsinki, and the project was submitted and approved by SIKT (ref number: 125855). Also, the study was submitted to the Regional Committees for Medical and Health Research Ethics and deemed exempt from presentation (application number 696,927).

Sample size rationale

While a priori power analyses are often conducted to establish a sample size that would achieve a “desirable” level of statistical power for detecting the smallest effect size of interest, the true bottleneck to recruitment is inevitably based on resource constraints (Lakens, 2022). Consequently, we endeavoured to enlist as many participants as our resources would allow, to achieve the highest statistical power possible, alongside the use of a within-participant study to further bolster power. Ultimately, we managed to recruit 30 volunteers.

Procedures

Vastus lateralis and rectus femoris muscle thickness measurements were taken by b-mode ultrasonography (Echo Wave 2 Software; Telemed, Latvia) with a 60-mm probe size and 9 MHz scanning frequency, and Chemolan transmission gel (Chemodis, DA Alkmaar, The Netherlands). Transverse images were captured for both the distal and proximal part of the rectus femoris muscle and the vastus lateralis muscle (See supplementary file 1). When a participant arrived at the laboratory, the participant was placed in a supine position on a bench and rested for ten minutes before the data collection began. A mark with a pen was made on 50 and 70% of the femur length, measured between greater trochanter and lateral epicondyle. Individual adjustments were made for several of the participants on the distal rectus femoris since only a tendon was observed at 70% length. In these cases, ultrasound was used to detect the most distal part of the rectus femoris. The marks for the vastus lateralis muscle were placed 40–60 mm medially for the rectus femoris with individual adjustments to ensure correct placement. Pictures and measurements were taken of the marks for each participant at the pre-intervention assessment and stored in a password-locked external flash drive to ensure reliable measurements during both the pre- and post-intervention measurement. The same two sonographers performed the measurement procedures, where one researcher was tasked with handling the probe, while the other researcher captured the images. When the ultrasound images clearly displayed the muscle boundaries, allowing for accurate measurement, three images were taken at each site. Muscle thickness was averaged across these three images and used as the muscle hypertrophy measurement to increase validity. The participants were instructed not to engage in any type of training in the 96 hours preceding the pre- and post-intervention test. In addition, the participants were instructed to avoid caffeine for eight hours or food for two hours before the pre- and post-intervention tests. The intraclass correlation coefficient (ICC) was calculated for all participants between pre-intervention test one and two, and post-intervention test one and two. The ICC for distal and proximal vastus lateralis was 0.96 and 0.98 between pre-intervention tests and 0.98 and 0.99 between post-intervention tests. The ICC for distal and proximal rectus femoris was 0.96 and 0.97 between pre-intervention tests and 0.99 and 0.98 between post-intervention tests.

The resistance training programme was performed twice per week, for 10 weeks with at least 48 hours between each session (see Figure 3). The leg extension exercise was performed unilaterally in an Impulse seated leg extension machine (Impulse Fitness, Jimo, Qingdao, China) loaded with weight magazines, with 3 (or 4 sets from week 5, session 2) sets of 10–20 repetitions performed to momentary concentric failure. A double progression method was employed, with micro-loading used to ensure progressive overload. When a participant reached 20 repetitions in the first set, the load was increased by 0.25–0.5 kg to ensure the repetitions performed per set were within the given repetition range in each set (see supplementary file 1). Additionally, the participants performed three sets of biceps curls and three sets of calf raises for other studies by our research group. Training intensity was standardized by having both conditions terminate sets at momentary failure for each set, with around 30 seconds rest between limbs and 2 minutes between sets (Steele et al., 2017). The limb order varied in each session to ensure that the resistance training order did not confound results. Importantly, performing precisely 40° hip

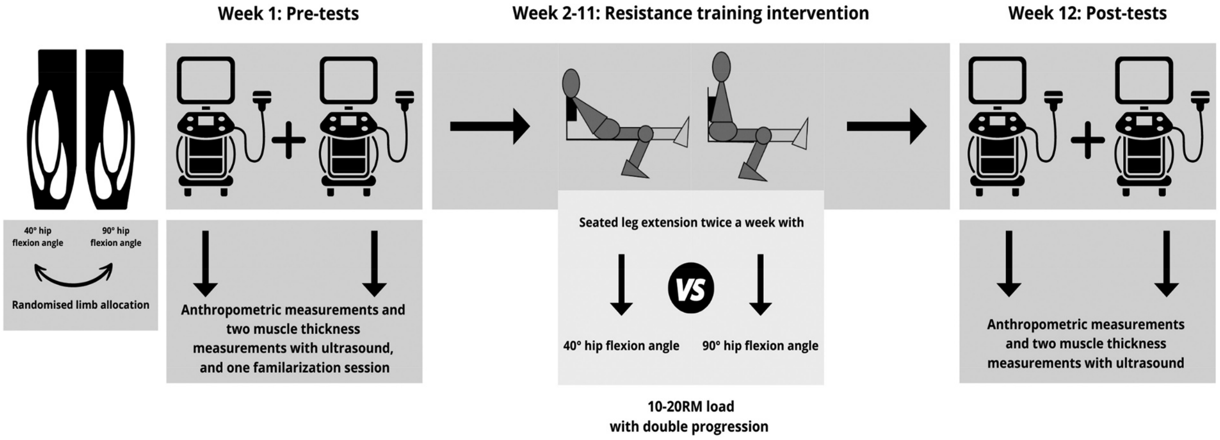


Figure 3. A schematic overview of the study design. RM: repetition-maximum. The graphics is inspired by Refalo et al. (2024).

flexion for each participant was not possible. Therefore, individual adjustments were made. This resulted in a mean hip flexion angle of 40.8 ± 6.9° (see supplementary file 2 for individual values). Knee flexion angle was similar between limbs (110° knee flexion to 0° knee flexion; see Figure 1). An electric goniometer (Easyangle, Stockholm, Sweden) was used to ensure the correct hip flexion angle for each participant. Figure 1 illustrates the two experimental conditions. Volume load, descent duration (instructed to 2 seconds), and ascent duration (as fast as possible) were controlled by personal trainers who supervised all training sessions. Additionally, participants were instructed to have a controlled stop at both the bottom and top of the lift. The same five researchers (S.L, N.Ø.S, B.S.F, A.B.F, and H.N.F) with at least a bachelors' degree in sports science and a Norwegian personal trainer certification supervised all resistance training sessions. Importantly, the supervisors were carefully instructed about the research procedure by the lead researcher and met at the training facilities twice for pilot testing to learn the resistance training procedures and standardize resistance techniques before the training intervention started. The personal trainers supervised (1:1, 1:2, 2:3 supervisor: participant ratio) the participants to ensure an adequate execution of the exercise. Every training session was documented, including the individual settings on the leg extension machine, load, and repetitions on each set. Moreover, volume load was calculated as sets x repetitions x load lifted to compare volume load between the conditions. Verbal encouragement and feedback were given to ensure motivation and full range of motion in every repetition. All training sessions were performed at the same gym using the same apparatus.

Statistics

All analyses were conducted in R (version 4.4.0) within a Bayesian framework. Bayesian statistics represents an approach to data analysis and parameter estimation based on Bayes' theorem and can provide several advantages over frequentist approaches (van de Schoot et al., 2021). Within the context of this study, a Bayesian approach enabled formal inclusion of information regarding likely differences between interventions based on knowledge from previous studies through the use of informative priors. The approach also enabled inferences to be based on intuitive probabilities and to assess the strength of evidence in support of the existence or non-existence of an intervention effect (Schad et al., 2022). Analyses were conducted using univariate and multivariate linear mixed effects models, with random effects included to account for both the repeated measures and within participant design (Magezi, 2015). The effect of the hip angle (40° vs 90°) on muscle thickness was the focus of the analyses and quantified through the Average Treatment Effect (ATE). Within-condition treatment effects were also quantified to assess the overall effectiveness of the different interventions separately and compared to thresholds specific to strength and conditioning (P. A. Swinton et al., 2022). Inferences were based on 1) posterior distribution of the ATE estimates and their associated credible intervals; and 2) Bayes factors (BF) to quantify the strength of evidence for either a non-zero ATE (alternative hypothesis H_1) or zero ATE (null hypothesis H_0) . Standard qualitative labels expressing the strength of evidence for the different hypotheses were adopted (M. D. Lee & Wagenmakers, 2014). All analyses were performed using the R wrapper package brms interfaced with Stan to perform sampling (Bürkner, 2017) and BFs estimated via the bridge sampling algorithm (Gronau et al., 2017). A full Bayesian workflow was adopted for the analyses and comprised: 1) use of informative priors obtained from meta-analyses in the discipline (P. A. Swinton et al., 2022, 2) assess appropriateness of priors using prior predictive checks; 3) run models and assess stability of estimates through repeated iterations with the same data; 4) assess appropriateness of posterior distributions using posterior predictive checks and sensitivity analyses with non-informative priors; and 5) perform simulation-based calibration of BFs (Schad et al., 2022). To improve accuracy, transparency and replication in the analyses, the WAMBS-checklist (When to worry and how to Avoid Misuse of Bayesian Statistics) was used (Depaoli & Van de Schoot, 2017) and summaries of the workflow are reported in supplementary file 3.

Results

Mean attendance was 19.1 of 20 resistance training sessions (95%). Twenty-two out of thirty participants completed the intervention. Four participants dropped out due to personal reasons, three participants dropped out due to non-compliance, and one participant dropped out due to an injury obtained outside the study.

Muscle morphology

A descriptive summary of outcomes is displayed in Table 1. Increases in muscle thickness were observed at both regions for the rectus femoris and vastus lateralis across both the 40 and 90° conditions. Data illustrating individual pre- and post-intervention muscle thickness values are displayed in Figure 4, with group change values presented

Table 1. Descriptive summaries of data (mean ± SD).

Outcome (mm)	Baseline 40°	Post-test 40°	Δ%	Baseline 90°	Post-test 90°	Δ%
Rectus femoris proximal	18.6 ± 3.1	20.8 ± 3.2	12.4	19.1 ± 3.1	20.0 ± 3.4	4.6
Rectus femoris distal	10.2 ± 2.4	11.8 ± 2.8	15.8	9.8 ± 2.6	10.9 ± 2.7	10.9
Vastus lateralis proximal	22.8 ± 3.9	25.2 ± 4.1	10.8	22.9 ± 4.5	24.9 ± 4.4	9.7
Vastus lateralis distal	16.5 ± 3.9	17.9 ± 3.8	9.9	16.4 ± 3.9	18.1 ± 3.7	11.8

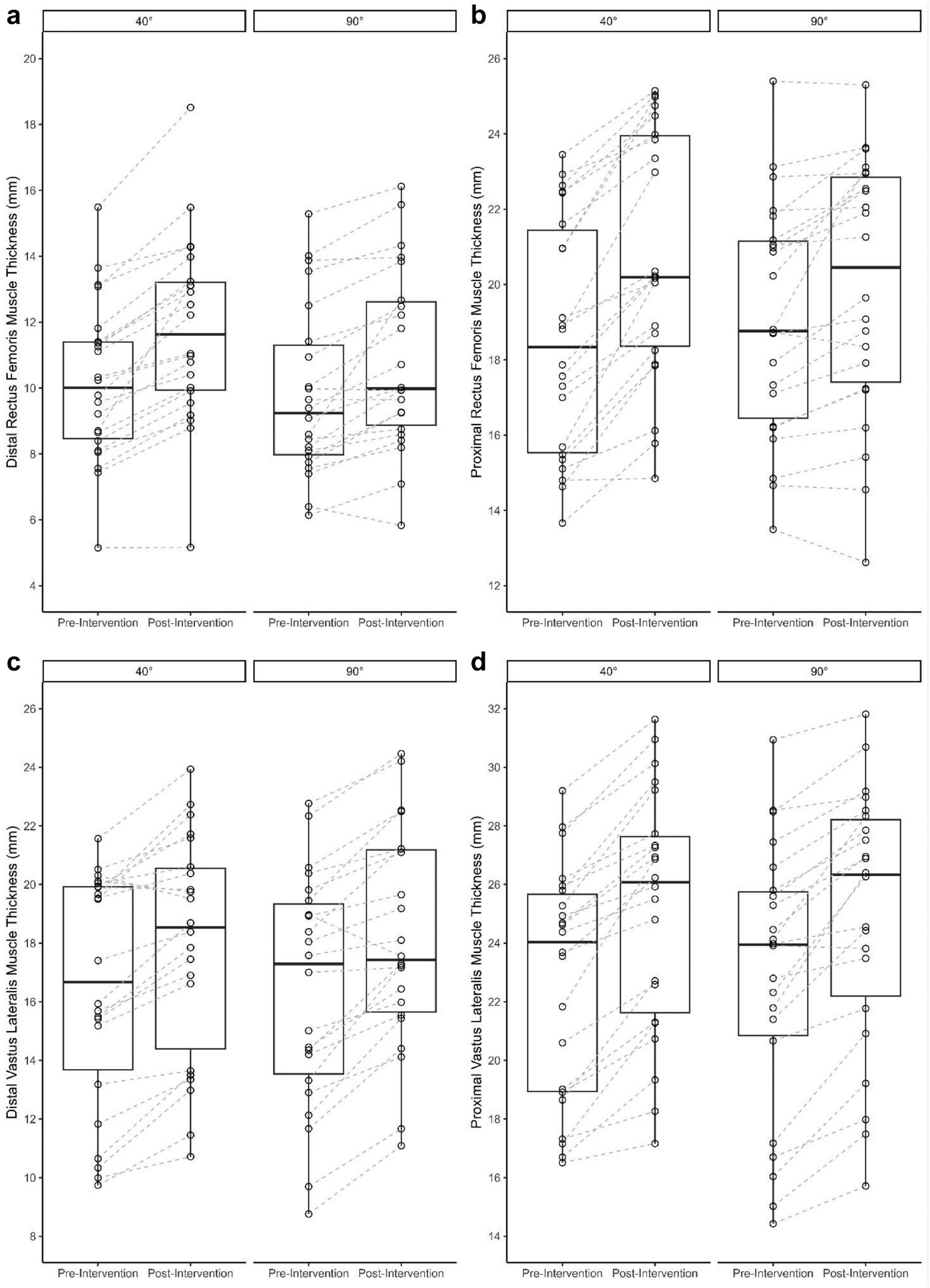


Figure 4. Box plots with individual pre- and post-intervention muscle thickness values for the rectus femoris (A/B) and vastus lateralis (C/D). individual data points are calculated from the average of the two measurements taken at that time period and separated by the two conditions (40° and 90° hip flexion).

as standardized mean differences in Figure 5. The results show that the interventions generally produced medium to large changes.

Univariate analyses of between condition comparisons identified “very strong” and “extreme” evidence in support of a different hypertrophic response in the distal (BF = 88.4) and proximal regions of the rectus femoris (BF > 100), respectively. For both regions, an intervention effect favouring the 40° condition (Distal/ATE: 0.64 [95%CrI: 0.29 to 0.99 mm], *p* (ATE >0)>0.999, Proximal/ATE: 1.1 [95%CrI: 0.65 to 1.6 mm], *p* (ATE >0)>0.999) were identified. Combining the regions within a multivariate analysis

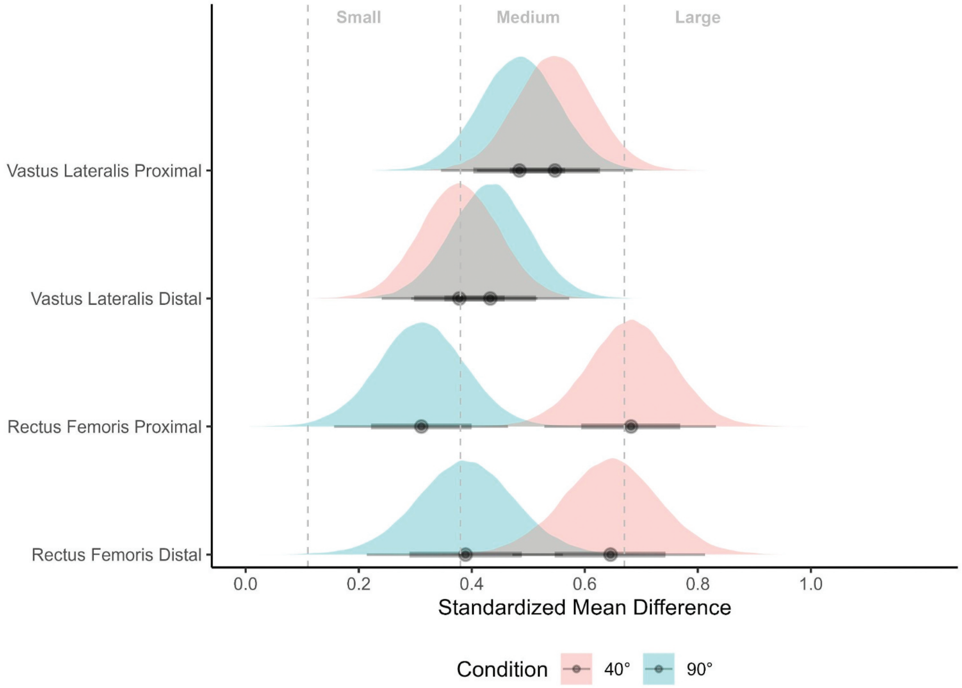


Figure 5. Standardized mean difference estimates of change in muscle thickness across the different intervention conditions. density plots illustrate posterior distribution of standardized mean differences estimated across the two conditions and muscle thickness outcomes. Circle: median, error bars represent 75% and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning.

resulted in similar ATE estimates and provided "extreme" evidence in support of a different hypertrophic response (BF > 100). The joint posterior distribution describing the simultaneous ATE for both regions returned a near maximum probability (*p*(Distal/ATE & Proximal/ATE >0)>0.999) favouring the 40° condition.

In contrast, univariate analyses of between condition comparisons identified "moderate" evidence in support of no hypertrophic difference between the conditions in both the distal (BF = 0.25) and proximal regions of the vastus lateralis (BF = 0.29). Posterior distributions of the ATE were close to zero (Distal/ATE: −0.21 [95%CrI: −0.84 to 0.42 mm], *p* (ATE <0) = 0.745, Proximal/ATE: 0.27 [95%CrI: −0.47 to 1.0 mm], *p* (ATE >0) = 0.768). Combining the regions within a multivariate analysis resulted in similar ATE estimates and provided "strong" evidence in support of no hypertrophic difference between conditions (BF = 0.07). The joint posterior distribution describing the simultaneous ATE for both regions showed low probabilities favouring either the 40° (*p* = 0.184) or 90° condition (*p* = 0.206). Output from the WAMBS checklist and BF simulation-based calibration are presented in the supplementary file and identified no concerns with the analyses.

Volume load

Volume load increased from 1220 ± 246 kg and 1101 ± 199 kg in the first resistance training session to 2446 ± 531 kg and 2322 ± 490 kg in the last resistance training session for the 40° and 90° hip flexion groups (see Figure 6). Total volume load during the entire training intervention was 38,405 kg and 37,027 kg for the 40° and 90° hip flexion groups, respectively.

Discussion

The main findings of this study were that: 1) all sites of the measured quadriceps femoris muscles showed hypertrophy following ten weeks of resistance training using the leg extension exercise; 2) greater hypertrophy occurred in both distal and proximal regions of the rectus femoris following training with 40° of hip flexion compared to 90° of hip flexion; and 3) no differences in hypertrophy occurred between the training conditions for distal and proximal regions of the vastus lateralis muscle. These findings support our a-priori hypotheses and highlight the potential for changes in posture to cause observable difference in muscular hypertrophy over a block of resistance training in untrained participants.

The observed changes in the rectus femoris thickness and the vastus lateralis thickness align with values from previous studies investigating the leg extension resistance training (rectus femoris: +8.8–24%, vastus lateralis: +2.8–15%) (Maeo et al., 2018; Pedrosa et al., 2022; Zabaleta-Korta et al., 2021). However, it should be noted that these studies did not manipulate hip flexion angle as an independent variable. Several training variables that can influence muscle hypertrophy differed between the protocols. For example, Zabaleta-Korta et al. (2021) employed the same training frequency and set termination criteria to the present study but only performed the intervention for half the duration. In contrast, Pedrosa et al. (2022) implemented a 12-week training protocol at a lower intensity

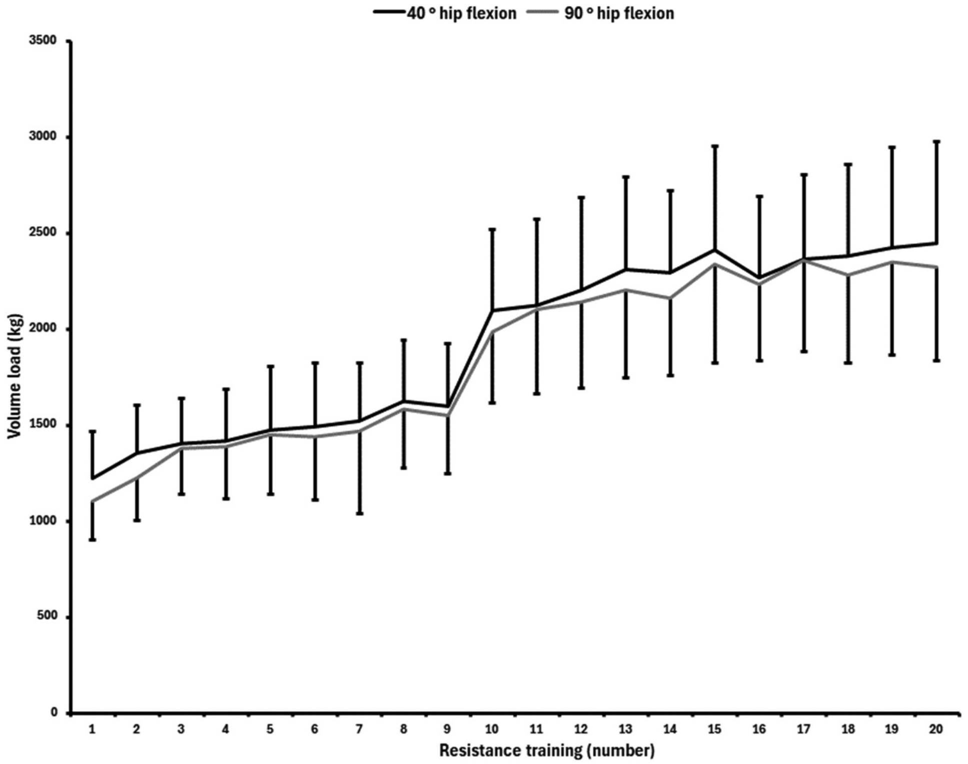


Figure 6. Mean (SD) volume load lifted each resistance training session for the 40° and 90° hip flexion group in the unilateral leg extension exercise.

(60% of 1RM), with loads individualized to the ROM for each group and not to momentary failure. This distinction is notable, as proximity-to-failure is a factor known to influence hypertrophic adaptations (Robinson et al., 2023). Additionally, set volume varied between protocols, with the current study using eight weekly sets, whereas Zabaleta-Korta et al. (2021) used twelve weekly sets, and Pedrosa et al. (2022) increased set volume during the intervention. Recent findings by Pelland et al. (2024) suggest that weekly set volume significantly impacts muscle hypertrophy, further complicating direct comparisons.

Within the context of our study design, the results of the present study suggest that performing the leg extension exercise with 40° hip flexion resulted in superior increases in hypertrophy of the rectus femoris compared to performing the leg extension with 90° hip flexion. Muscle hypertrophy of the rectus femoris was likely to be between small and medium for the 90° condition, but medium to large for the 40° condition. This difference in hypertrophic response may be attributable to the longer-muscle lengths achieved in the biarticular rectus femoris when the exercise is performed with a greater degree of hip extension. This supports our pre-registered hypothesis, which asserted that, because the rectus femoris is more lengthened with 40° vs 90° hip flexion, it would experience greater muscle hypertrophy, whereas the vastus lateralis would not.

With regards to the differences in rectus femoris hypertrophy observed between the two conditions, one explanation could be a difference in sarcomere operating length. For example, Cutts (1988) compared the rectus femoris sarcomere length with combined 90° hip flexion and 13° knee flexion, with 0° hip flexion and 115° knee flexion. The estimates of the rectus femoris sarcomere length in the shortened condition were around 1.4 µm, meaning that the rectus femoris was operating in the ascending limb on the length–tension relationship (Cutts, 1988). In the lengthened condition, the estimated rectus femoris sarcomere length was 2.5 µm (Cutts, 1988), indicating that the rectus femoris may be capable of operating in the plateau region when being trained at longer muscle lengths. As mechanical tension is suggested to be an important stimulus of muscle hypertrophy in resistance training (Schoenfeld, 2010), the greater tension achievable in the plateau region compared to the ascending limb (Cutts, 1988) may be one potential explanation for the larger rectus femoris hypertrophic outcomes observed in the 40° hip flexion angle condition in our study. Nevertheless, other sarcomere estimations of the rectus femoris have reported the muscle to reach the descending limb (Cutts, 1989). The observed differences in rectus femoris hypertrophy may be partially explained by the influence of hip flexion angle on fascicle orientation and aponeurosis displacement within the muscle. For instance, Blazevich et al. (2006) demonstrated that even minor changes in fascicle angle could affect the aponeurosis and tendon displacement. Given that the rectus femoris fascicle angle is influenced by hip flexion angle (de Sousa et al., 2023), it is plausible that differential displacement of the tendon or aponeurosis occurs relative to the vastii muscles, potentially contributing to the observed differences in rectus femoris growth. Furthermore, the rectus femoris may generate greater maximum forces at a 40° hip flexion angle due to its more lengthened state, enabling it to handle a larger relative load compared to a 90° hip flexion angle, when the force output is maximized. With a constant external load applied across the leg extension conditions, the relative effort of the 40° hip flexion angle may actually be lower than that required at a 90° angle. This disparity in force demands, combined with the architectural differences noted by Blazevich et al. (2006) suggests that fascicles of the rectus femoris at different hip angles may be recruited in varying degrees along the muscle length, resulting in the observed region-specific adaptations.

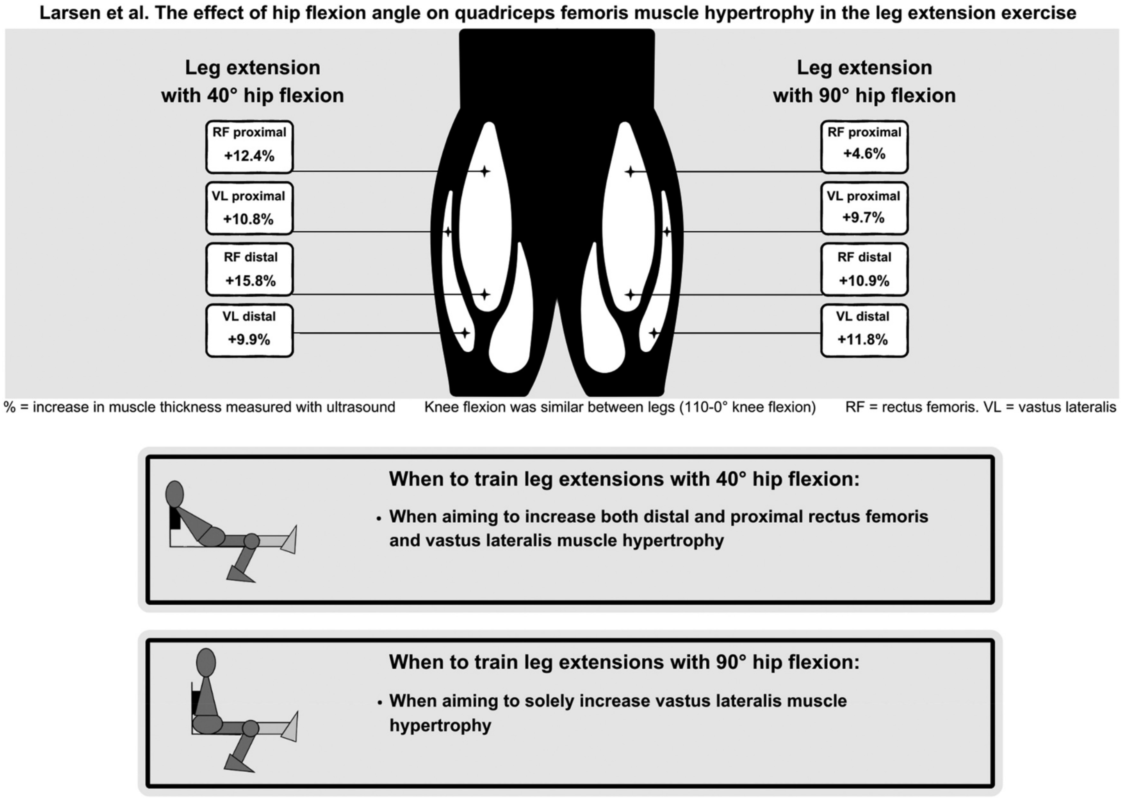
In addition, other potential stimulus proposed about the favourable hypertrophic outcomes when the muscle is trained at longer-muscle lengths are (but not limited to) greater increases in resting IGF-1 levels (McMahon et al., 2014) and greater muscle deoxygenation (Kooistra et al., 2008). Importantly, the mechanisms underlying the hypertrophic benefits of longer-muscle length training remain largely unexplored, as noted by Wolf et al. (2023).

In our analyses, we estimated the largest relative differences between legs in rectus femoris growth to occur at the proximal site. Mitsuya et al. (2023) observed significantly higher rectus femoris proximal muscle activation with 40° hip flexion compared to 80° hip flexion in the leg extension exercise in a cohort of male bodybuilders. In addition, Wakahara et al. (2017) used magnetic resonance imaging to measure transverse relaxation time in the quadriceps femoris and had the participants performing the leg extension exercise for 12 weeks afterwards. The authors observed that the distal region of the rectus femoris had both the largest muscle activation when measured pre-training intervention and the greatest subsequent muscle growth during the training intervention, suggesting that muscle activation during the first training session was associated with regional rectus femoris hypertrophy (Wakahara et al., 2017). Therefore, since our results are in line with Mitsuya et al. (2023) and previous studies have reported transverse relaxation time to be associated with regional muscle hypertrophy within a muscle (Wakahara et al., 2013, 2017), our results supports that transverse relaxation time may be predictive of longitudinal hypertrophic outcomes, and especially rectus femoris muscle hypertrophy.

In support of our second hypothesis, we obtained moderate evidence for no difference in hypertrophic response of both distal and proximal vastus lateralis muscle thickness across conditions. This finding is logical as the vastus lateralis is a monoarticular muscle and the muscle length of the vastus lateralis was standardized and kept similar between conditions. Therefore, since the vastus lateralis is an important contributor to the knee net joint moment in squats, but not the rectus femoris (Kipp et al., 2022), we propose that athletes like powerlifters, for whom hypertrophy of the rectus femoris is not a primary concern, may choose the hip flexion angle in the leg extension exercise based on individual comfort and preferences.

Strength and limitations

We aimed to design both an internally and ecologically valid resistance training study. Since we combined: 1) pre-registration of all variables; 2) conducted two pre-tests and two post-tests; 3) blinded the statistical analysis to condition allocation; and 4) planned the study design based on the SMART-LD checklist to reduce potential biases (Schoenfeld et al., 2023), bias was reduced and precision enhanced such that observations likely occurred as a result of the manipulation of the independent variable (hip flexion angle). In addition, the resistance training intervention was designed to be ecologically valid with a moderate weekly set volume (Baz-Valle et al., 2022) aiming to achieve momentary failure, following a double progression method. There are, however, several limitations to this study that should be acknowledged. Firstly, we only measured muscle hypertrophy among untrained men due to resource constraints. Future studies should attempt to replicate the findings among more highly trained populations and in female participants. Secondly, it was not possible to ensure that participants performed the leg extension exercise with precisely 40° of hip flexion due to equipment limitations. Consequently, the hip flexion angle in the lengthened group ranged from 21 to 51°, with a mean hip flexion angle of 40.7°. This variability may have influenced our findings as a decreased hip flexion angle has been observed to reduce the fascicle pennation angle and increase the fascicle length of the rectus femoris (de Sousa et al., 2023). Changes in fascicle orientation and length can alter the force production and load distribution during the exercise, potentially affecting hypertrophic adaptations. This variability represents a significant limitation of our study, and future studies should aim to replicate these findings using the leg extension equipment that allows for precise standardization of the hip flexion angle at 40°. Thirdly, we assessed quadriceps femoris muscle thickness at four sites and not the cross-sectional area. Therefore, it is possible that our findings could have missed potential regional differences in muscle hypertrophy between the leg extension conditions. A fourth limitation was the absence of equipment to elucidate the mechanisms underlying the differences observed between the legs, which should be addressed in future studies. Lastly, a study comparing 90°, 40°, and 0° hip flexion angles is warranted to assess whether the 0° hip flexion results in even more favourable hypertrophic outcomes compared to 90° and 40° conditions.



When to train leg extensions with 40° hip flexion:

- When aiming to increase both distal and proximal rectus femoris and vastus lateralis muscle hypertrophy

When to train leg extensions with 90° hip flexion:

- When aiming to solely increase vastus lateralis muscle hypertrophy

Figure 7. A graphical overview of the main findings and potential practical applications. The graphics is inspired by Refalo et al. (2024).

Practical application of key findings

The practical application of our findings is that those who aim to maximise quadriceps femoris hypertrophy may do so by performing the leg extension while lying a bit backwards (around 40° hip flexion; Figure 7). Moreover, if aiming to isolate the vastus lateralis with minor rectus femoris growth, we recommend training the leg extensions with a 90° hip flexion angle.

Conclusion

In summary, we demonstrate that the rectus femoris muscle hypertrophy was greater with 40° hip flexion compared to 90° hip flexion with no differences between legs for vastus lateralis hypertrophy. Therefore, when the goal is to increase overall quadriceps femoris hypertrophy, we suggest training with reduced hip flexion targeting an angle close to 40° in the leg extension exercise.

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Contributions

Contributed to conception and design: SL, HNF, MW.
Contributed to acquisition of data: SL, NØS, BSK, ABF, HNF.
Contributed to analysis and interpretation of data: PAS, MW, SL.
Wrote the first draft of the manuscript: SL, NØS.
Revised the article: All authors.
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Data availability statement

Data and supplementary material are available on the Open Science Framework project page: https://osf.io/gvzfa/

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