Resistance training beyond momentary failure: The effects of lengthened supersets on muscle hypertrophy in the gastrocnemius

Supplementary materials: https://osf.io/by8ke/

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Abstract

The purpose of this study was to assess whether performing additional partial repetitions beyond momentary failure increased muscle hypertrophy. A total of 23 untrained men completed a 10-week within-participant intervention study comprising two weekly resistance training sessions of 3-4 sets of standing smith machine calf raises. One limb was randomly allocated to the control condition performing sets to momentary failure and the other limb allocated to the test intervention that included additional partial repetitions in the lengthened position. Muscle thickness of the medial gastrocnemius muscle was measured pre- and post-intervention via ultrasound and an a priori hypothesis of greater hypertrophy with additional partial repetitions made. Data were analysed within a Bayesian framework using a mixed effect model with random effects to account for the within participant design. The average treatment effect (ATE) was measured to assess any difference in condition and inferences made based on the ATE posterior distribution and associated Bayes Factor (BF). The results identified an ATE favouring the inclusion of additional partial repetitions (0.62 [95%CrI: 0.21 to 1.0 mm; $p(>0)=0.998$]) with 'strong' evidence (BF = 13.3) supporting the a priori hypothesis. Thus, when the goal is to train for maximum gastrocnemius hypertrophy over a relatively short time period, we suggest performing sets beyond momentary failure as a likely superior option.

Introduction

Resistance training is often used to increase skeletal muscle mass and strength. In resistance training, the repetitions performed lie on a continuum. Typically, the most extreme termination point of a cluster of uninterrupted repetitions, referred to as a "set", is considered to be momentary failure (Refalo et al., 2024). Momentary failure has been be defined as the set ending when the athlete reaches the point where, despite attempting to do so, they cannot complete the concentric portion of a repetition without any deviation from the prescribed form of the exercise (Steele et al., 2017). Other set failure definitions exist, such as volitional failure, which may be defined as the point at which an individual perceives they have reached the set termination criteria (Refalo et al., 2022). Despite differences in set failure definitions, when sufficient proximity-to-failure is achieved, a progressive recruitment of high-threshold motor units occurs that exposes type II myofibers to mechanical tension (Refalo et al., 2022). Although the underlying mechanisms of hypertrophy are not fully understood, mechanical tension currently appears as the most likely and influential stimulus responsible for inducing muscle hypertrophy (Wackerhage et al., 2019).

Proximity-to-failure has been observed to acutely influence several physiological responses during resistance training, such as muscular damage and neuromuscular fatigue (Pareja-Blanco et al., 2017). Such physiological responses following resistance training may reduce the muscle's capability to contract in subsequent training sessions (Refalo et al., 2022), potentially limiting mechanical tension and the resulting muscle hypertrophy. Recently, Robinson et al. (2023) conducted an exploratory meta-regression, observing that training to, or close to, momentary failure meaningfully improved hypertrophic outcomes compared with training further from momentary failure. The joint angles at which momentary failure occurs, however, may vary across exercises as the internal moment arm and length-tension relationships likely influence the maximal possible muscle torque generation at a joint (Kipp et al., 2022;

Ottinger et al., 2023). In addition, the chosen range of motion (ROM) in the resistance exercise may influence the hypertrophy stimulus due to a variety of factors, such as the length-tension relationship, internal moment arm, and activation of the muscle (Kassiano et al., 2023; Ottinger et al., 2023), potentially influencing the mechanical tension experienced by the target musculature during resistance training. For example, several studies have reported that a full ROM enhances hypertrophy compared to partial ROM (Bloomquist et al., 2013; Kubo et al., 2019). Especially when the partial ROM is performed at shorter-muscle lengths in relation to the average muscle length achieved during full ROM training (Wolf et al., 2023). Whilst some studies have observed greater muscular adaptations for training with full ROM compared with partial ROM at shorter muscle lengths, a recent meta-analysis by Wolf et al. (2023) reported favorable effects of partial ROM performed at longer muscle lengths. For example, Pedrosa et al. (2022) observed larger distal quadriceps femoris hypertrophy in a cohort of untrained women when performing the leg extension exercise in a lengthened partial ROM (100-65° of knee flexion) compared with full ROM (100-30°) and shortened partial ROM (65-30°) conditions. Therefore, though the mechanisms remain largely unclear, it has been hypothesised that resistance training at longer-muscle lengths is beneficial when the desired outcome is hypertrophy, potentially due to the muscle reaching the plateau or descending limb increasing mechanical tension experienced at the sarcomere level (Ottinger et al., 2023). Additionally, it has been proposed that a partial ROM may enhance muscle deoxygenation and blood lactate accumulation (Goto et al., 2019), which could mechanistically explain divergent physiological adaptations to resistance training (Wolf et al., 2023). Neither of these explanations currently have sufficient evidentiary basis to justify a high degree of confidence, highlighting the need for further research. More recently, Kassiano et al. (2023) compared muscle thickness changes in young women performing calf raises with a full ROM (-25° dorsiflexion to +25° plantarflexion), a lengthened partial ROM (-25 to 0°), or a shortened partial ROM (0 to +25°). The investigators observed larger increases in medial gastrocnemius muscle thickness for the lengthened partial ROM compared to the other conditions. However, the full ROM group reached momentary failure at around 0° to +25° plantar flexion. Mechanistically, this may indicate that the sets were terminated when the muscle was at a weaker force production position as the gastrocnemius has been suggested to produce lower torque at plantarflexion angles (10-30° plantarflexion) compared to dorsiflexion angles (-20°-10° dorsiflexion) with an extended knee (Maganaris, 2003). Even when the same study reported larger internal gastrocnemius moment arms at the plantarflexion angles (Maganaris, 2003). These findings indicate that if the set is terminated at momentary failure, the gastrocnemius is operating at the ascending limb and therefore could be in a weaker force position, potentially limiting the mechanical tension achieved by the muscle. Thus, continuing the set past the inability to achieve peak plantarflexion at a given load, combining full repetitions with subsequent partial repetitions could constitute a superior strategy to increase both the intra-set volume and the mechanical tension experienced by the gastrocnemius muscle. In turn, this could plausibly increase hypertrophic adaptations experienced by the gastrocnemius muscle.

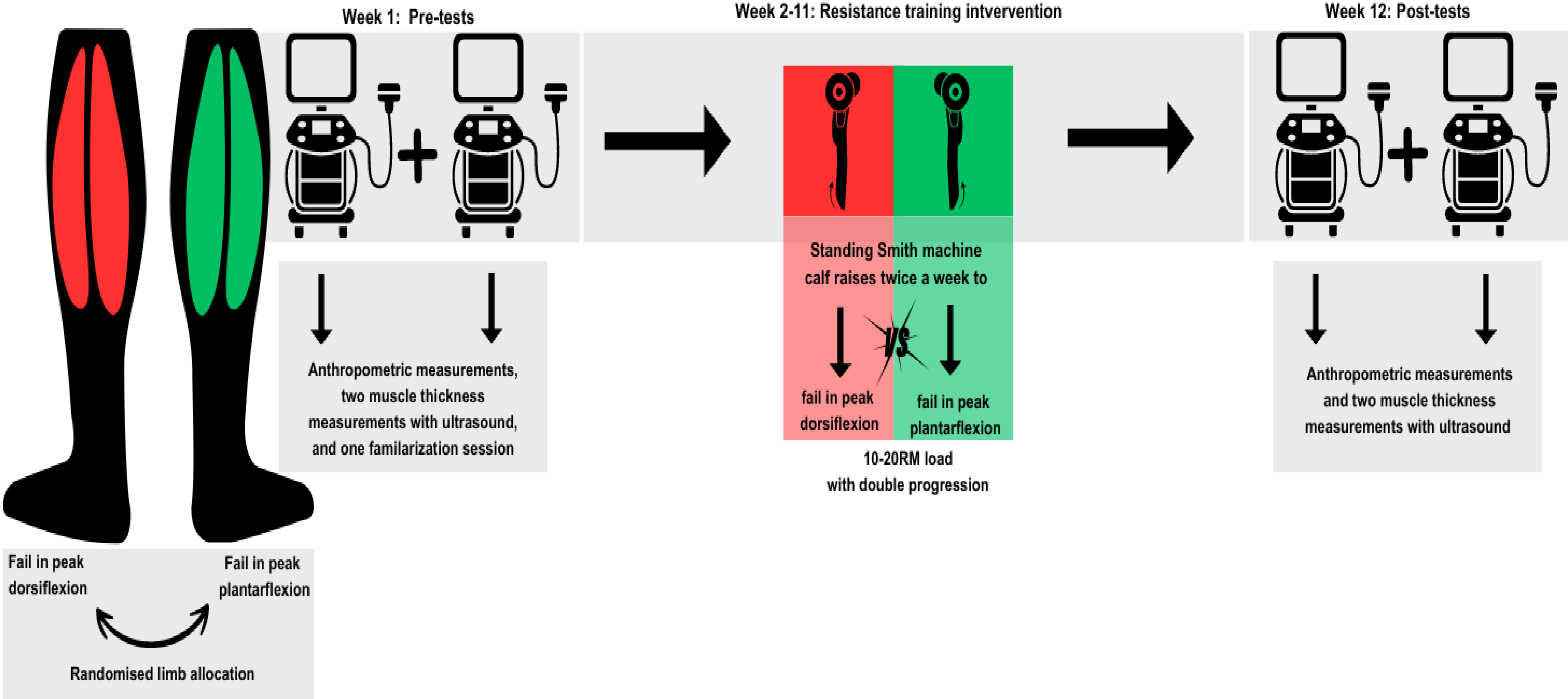
Importantly, several studies have compared different proximity-to-failure conditions on muscle hypertrophy (Robinson et al., 2023). To our knowledge, however, no studies have compared sets terminated at momentary failure with sets terminated beyond momentary failure comprising full then partial repetitions (hereafter referred to as "lengthened supersets") on muscle hypertrophy. As a result, the aim of this study was to compare standing calf raises with full ROM in a Smith machine to volitional failure in peak dorsiflexion (combining full repetitions with partial repetitions) with momentary failure in peak plantarflexion on medial gastrocnemius hypertrophy among untrained men. It was hypothesised that terminating the set around peak dorsiflexion would result in favorable hypertrophic outcomes of the medial gastrocnemius compared to terminating the set at peak plantarflexion.

Methods

Experimental approach to the problem

This study followed a within-participant repeated-measures design. Each participant had their right and left limb randomly allocated (using www.randomizer.org) to one of two failure conditions: momentary failure reached in peak plantar flexion ROM ($PLANTAR_{MF}$), or volitional failure reached in peak dorsiflexion ROM ($DORSI_{VF}$). Randomization and allocation procedures were performed prior to beginning the study and concealed from the investigators. All participants performed standing calf raises in a Smith machine (Smith machine N, GymSport AS, Trondheim, Norway) with an individualised ROM (see supplementary file 1) depending on the individual ankle dorsiflexion and plantarflexion flexibility, which was measured pre- and post-training intervention. The study lasted for 12 weeks, with two outcome measurement sessions performed both at the beginning of week one and end of week twelve. One familiarisation session was performed to introduce the participants to the respective techniques. In this session the participants worked up to their 10-20 RM on both legs unilaterally. Thereafter, all participants trained unilateral standing Smith machine calf raises for 10 weeks with a training frequency of twice per week, except for the first week and week 11, where only one resistance training session was performed. This led to a total of 18 training sessions. Between weeks 2-5 the participants trained each leg with 3 sets each workout with their 10-20 repetition maximum, whereas in weeks 6-11 all participants performed 4 sets during each workout. During the pre- and post-training intervention measurement sessions, medial gastrocnemius muscle thickness was assessed via b-mode ultrasonography (see supplementary file 1). The data collection was performed between January and March 2024 in Levanger, Norway.

Figure 1. A schematic overview of the study design. RM: repetition-maximum. Graphics inspired by Refalo et al. (2024).



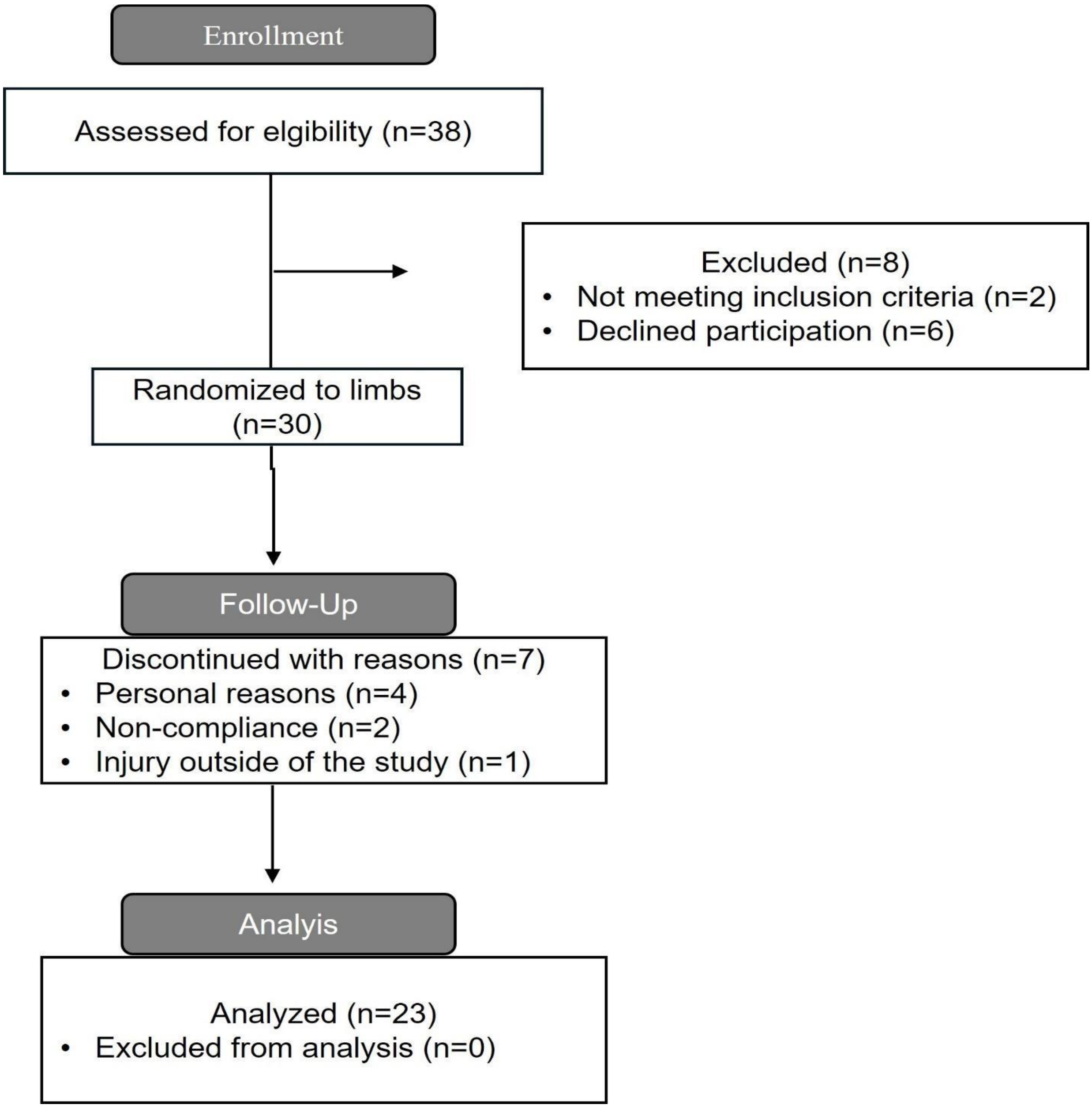
Risk of bias

This study aimed to follow the Standards Method for Assessment of Resistance Training in Longitudinal Design (SMART-LD) checklist for the items possible to reduce the chance for potential biases (Schoenfeld et al., 2023) (see supplementary file 1). This resulted in a final grading of 19/20 points (>80%), which is categorised as good quality (Schoenfeld et al., 2023). Additionally, a study protocol with a pre-registered hypothesis was registered prior to data collection on the Open Science Framework (OSF: https://osf.io/kyha9). Importantly, this study originally aimed to investigate the effect of momentary failure in peak dorsiflexion vs. peak plantarflexion. However, many of the participants were unable to perform all sets to momentary failure in peak dorsiflexion even with strong verbal encouragement. Therefore, momentary failure in peak dorsiflexion was changed to volitional failure around peak dorsiflexion after agreement within the research group.

Participants

A sample of 30 healthy, untrained adult males between 18-50 years were recruited for this study. Inclusion criteria were 1) age of 18-50 years, 2) no resistance training experience, which was defined as having performed less than one session a week in the last six months, 3) no previous self-reported use of illegal muscle-enhancing agents such as anabolic steroids, 4) and no cardiorespiratory or musculoskeletal disorders that could limit maximal performance on the training sessions. To be included in the analyses, participants had to complete at least 16 training sessions, which corresponded to attendance of 85 % (figure 1). This criterion resulted in a final sample of 23 participants who were included in the analysis (body mass: 84.6 ± 12.8 kg, age: 31.8 ± 6.1 years, height: 180.3 ± 5.7 cm; figure 2). Participants were instructed to maintain their daily nutritional habits during the training intervention; however, all participants were recommended to consume a daily protein intake of at least 1.6-gram protein for each kg of body mass (Morton et al., 2018). A detailed oral description of study procedures was provided before the start of the study. All participants signed a written informed consent form before the start of the study. The project was approved by SIKT (number: 125855) and followed the latest revision of the Helsinki Declaration. Additionally, ethical approval was obtained from the Regional Committees for Medical and Health Research Ethics which deemed the study exempt from ethical presentation (number: 696927).

Figure 2. Consort diagram showing the data collection process.



Sample size rationale

We tried to recruit as many participants as our resources would allow based on resource constraints (Lakens, 2022). In addition, we employed a within-participant design to achieve the highest possible statistical power possible. Thus, we ended up with recruiting 30 participants.

Procedures

The same procedures at two pre-intervention and two post-intervention tests for medial gastrocnemius muscle thickness measurements were conducted via b-mode ultrasonography (Echo Wave 2 Software, Telemed, Lativa). A 9 MHz scanning frequency with a 60-millimeter probe size, and Chemolan transmission gel (Chemodis, DA, Alkmaar, The Netherlands) were used for all measurements. The participants were placed in a supine position where they rested for 10 minutes before measurements began. After these measurements, the participant switched to a prone position and muscle thickness measurements of the medial gastrocnemius were performed. Images were obtained longitudinally (see supplementary file 1) in both legs with the probe positioned at the most prominent and thickest site of the leg from a posteroanterior view (Kassiano et al., 2023). The same two assessors performed all measurement procedures. One assessor handled the probe, whereas the other assessor was responsible for capturing the scan. When a satisfactory quality of the muscle thickness measures was obtained, three ultrasound images were obtained from both limbs during both pre- and post-intervention tests, totaling six images from each limb at both pre- and post-intervention testing (12 total). Averages of three measurements taken within a single testing session were used to perform subsequent analyses. A pen was used to draw reference lines on the medial gastrocnemius. Pictures of the reference lines for all participants were taken to enable accurate pre- and post-intervention test values. All reference line pictures, and muscle thickness measurements were saved and stored in a password-secured external flash drive, which only the two assessors had access to. Post-intervention test one was performed at least 120 hours after the last training session, whereas post-intervention test two was performed around 144-168 hours after the last training session. The participants were instructed to avoid food and caffeine consumption 2 and 8 hours prior to the measurement sessions, respectively. Importantly, the reliability of measurements was evaluated between pre-intervention test one and two, and post-intervention one and two using the intraclass correlation coefficient (ICC), coefficient of variation (CV), and typical error (TE). For the $DORSI_{VF}$ leg, an ICC, CV, and TE of 0.98, 1.91 %, and 0.39 mm were achieved between pre-intervention tests, while for the $PLANTAR_{MF}$ leg, the values were 0.97, 1.82 %, and 0.37 mm, respectively. Reliability measures between post-interventions yielded an ICC, CV, and TE of 0.98, 1.39 %, and 0.31 mm for the $DORSI_{VF}$ leg, and 0.99, 0.80 %, and 0.18 mm for the $PLANTAR_{MF}$ leg. In addition, all participants were asked two questions on the last post-intervention test: 1) would you prefer training the standing calf raise on your own to failure in the bottom position if you knew this would increase muscle growth compared to the condition of reaching failure in the top position?; 2) if yes, how much more relative muscle growth compared to the standing calf raise failed at the top position would be needed for choosing the condition reaching failure in the bottom position?

Resistance training was performed twice per week with a minimum of 48 hours rest between sessions for ten weeks. The calf raise was performed unilaterally in a Smith machine (Gymsport, Tiller, Norway) with the foot standing on a step with anti-skid tape added to increase friction (see supplementary file 1). All repetitions were executed with a full ROM repetition range between 10-20 repetitions until momentary failure. The $PLANTAR_{MF}$ terminated the set when reaching momentary failure, defined as being unable to reach the same barbell height on the failed repetition as the first repetition. The $DORSI_{VF}$ continued with partial repetitions after reaching momentary failure until the participant was unable to ascend over the point of peak dorsiflexion (meaning not able to plantarflex the talocrural joint from the deepest position) or upon reaching volitional failure around peak dorsiflexion. Importantly, joint angle ROM was individualised to reach both peak dorsiflexion and plantarflexion, achieving the greatest lengthened and shortened position achievable with an extended knee for each subject. Barbell load was increased in 0.25-0.5kg increments when the participant was able to perform 20+ repetitions with full ROM on the first set. To measure and count full ROM repetitions in the Smith machine calf raise participants were asked to plantarflex the ankle joint as much as possible on the first repetition while the personal trainer measured the peak barbell height during the first repetition of the calf raise and marked this height with a finger, which was kept in place throughout the set. Thereby, peak plantarflexion ROM was individualised on each set to the highest plantarflexion achievable. The $PLANTAR_{MF}$ set was terminated when the barbell did not reach the same barbell height as the first repetition, whereas partial repetitions were counted for the $DORSI_{VF}$. In addition, volume load was calculated as sets x repetitions x load.

During familiarisation, all participants gradually increased their workload to one set at around 20-repetition maximum. During the first training week all participants performed one session with three sets, each to momentary failure. From weeks 2-5, all participants completed two sessions with three sets each, totaling 6 weekly sets. In weeks 6-9, all participants completed two sessions with four sets each, with a total of 8 weekly sets. In week 10, only one session with four sets was performed. Rest periods were set around 30 seconds between legs, and more than 120 seconds between sets (new set = when both legs were trained). Limb training order was changed each week, meaning that week 1, 3, 5, 7, and 9, participants started exercising with the $DORSI_{VF}$ limb, whereas week 2, 4, 6, 8, and 10, participants started exercising with the $PLANTAR_{MF}$ limb. All participants were instructed to perform the eccentric component with around 2-second duration, whereas the concentric was instructed to be performed with maximal intended velocity.

Statistics

Statistics were performed in R (version 4.4.0) using a Bayesian framework. Within this study, a Bayesian approach enabled us to use formal inclusion of information regarding likely differences between interventions based on knowledge from former studies with the use of informative priors. This enables the use of inferences to be based on intuitive probabilities and, therefore, assess the strength of evidence in support of existence or nonexistence of an intervention effect (Schad et al., 2022). The main analysis was conducted using a linear mixed effects model with random effects to account for both the within participant design and repeated measures (Magezi, 2015). The effect of set termination criteria on muscle thickness was quantified through the Average Treatment Effect (ATE). Inferences were based on 1) a summary of the posterior distribution of the ATE estimate; and 2) Bayes factor (BF) to quantify the strength of evidence for either a non-zero ATE (alternative hypothesis H_1) or zero ATE (null hypothesis H_0). Also, standard qualitative labels that expresses the strength of evidence for the different hypotheses were used (Lee & Wagenmakers, 2014). The R wrapper package brms was used for all analyses interfaced with Stan to perform the sampling (Bürkner, 2017), and BFs were estimated via the bridge sampling algorithm (Gronau et al., 2017). We adopted a full Bayesian workflow for the analyses, which was comprised of: 1) the use of informative priors derived from meta-analyses within the field (Swinton et al., 2022); 2) assess appropriateness of priors using prior predictive checks; 3) run models and evaluate the stability of estimates through repeated iterations with the data; 4) determine the appropriateness of posterior distributions using posterior predictive checks and sensitivity analyses with non-informative priors; 5) conduct simulation-based calibration of BFs (Schad et al., 2022). To enhance transparency, accuracy, and replication for the analyses, we used the WAMBS-checklist (When to worry and how to Avoid Misuse of Bayesian Statistics) (Depaoli & Van de Schoot, 2017). Workflow summaries are reported in supplementary file 3.

Results

Mean attendance among the participants that finished the intervention was 17.3 of 18 (96.1 %) resistance training sessions. Twenty-three out of 30 participants finished the intervention. Four participants dropped out due to personal reasons, two participants dropped out due to non-compliance, and one participant dropped out due to injury outside the study.

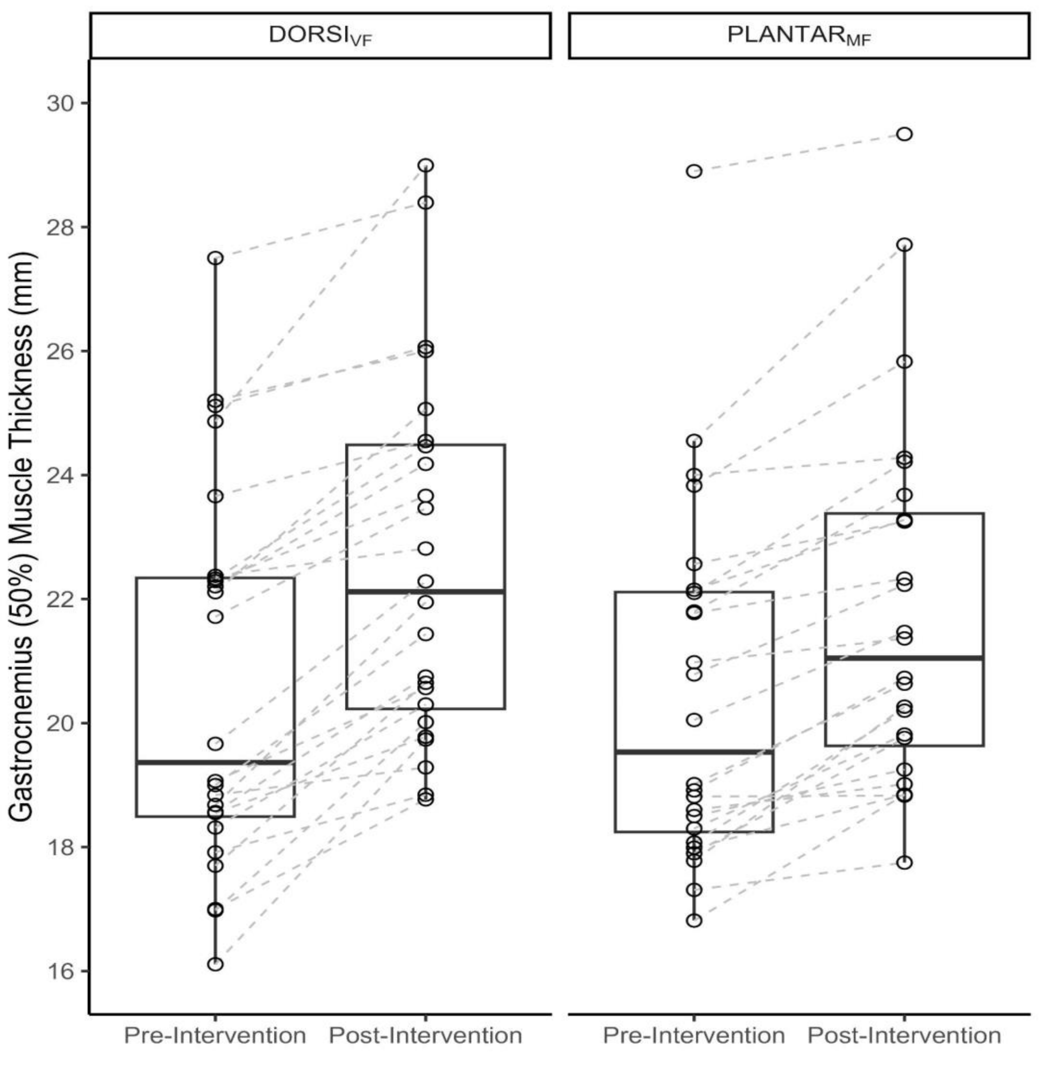
Muscle morphology

A descriptive summary of the training induced increases in muscle hypertrophy is presented in table 1 and individual participant data illustrated in figure 3. An increase in muscle thickness was observed for the gastrocnemius in both the $DORSI_{VF}$ and $PLANTAR_{MF}$ conditions. The linear mixed model provided 'strong' evidence in support of the a priori hypothesis that greater increases in muscle hypertrophy would occur with $DORSI_{VF}$ compared to $PLANTAR_{MF}$ (0.62 [95%CrI: 0.21 to 1.0 mm; $p(>0)=0.998$; BF = 13.3]).

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

Outcome	Baseline $DORSI_{vf}$	Post-test $DORSI_{vf}$	Δ%	Baseline $PLANTAR_{MF}$	Post-test $PLANTAR_{MF}$	Δ%
Medial gastrocnemius (mm)	20.7 ± 3.0	22.6 ± 2.9	9.8	20.5 ± 2.8	21.8 ± 2.9	6.6

Figure 3. Box plots with individual pre- and post-intervention muscle thickness values for the medial gastrocnemius.



Individual data points are calculated from the average of the two measurement sessions at that time-period and separated by the two conditions (DORSI$_{VF}$: beyond momentary failure and including partial repetitions in the dorsiflexed position; and PLANTAR$_{MF}$: to momentary failure in the plantarflexed position).

Questions

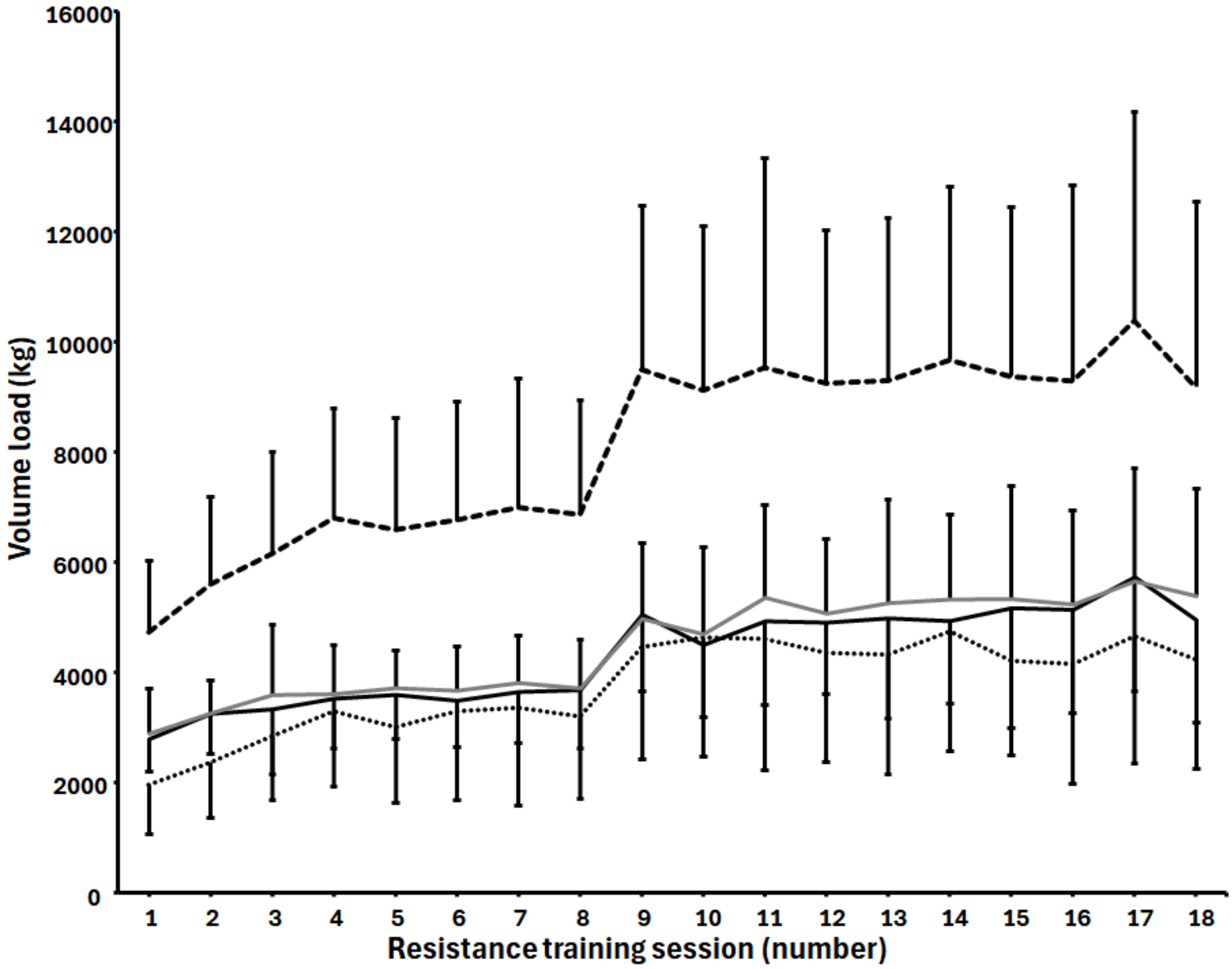
Eighteen participants (78.3 %) answered yes that they would prefer DORSI$_{VF}$ if this would lead to more muscle growth than training to PLANTAR$_{MF}$. On question two, participants answered that DORSI$_{VF}$ would have to be 32.2 ± 20.7% (range: 5-80%)

more effective in increasing muscle growth to prefer training with this condition relative to $PLANTAR_{MF}$.

Volume load

Total volume load increased from 4742 ± 1283 kg and 2892 ± 821 kg in the first training session to 9170 ± 3370 kg and 5377 ± 1960 kg in the last session for the $DORSI_{VF}$ limb and $PLANTAR_{MF}$ limb, respectively (Figure 4). Partial volume load performed after reaching momentarily failure was 87.2 ± 7.8 % of the full repetitions volume load for the $DORSI_{VF}$ leg with a range from 70-103 %. Total volume load lifted during the training intervention was 145,141 kg and 80,417 kg for the $DORSI_{VF}$ limb and $PLANTAR_{MF}$ limb, respectively.

Figure 4. Mean volume load lifted each resistance training session for the $DORSI_{VF}$ and $PLANTAR_{MF}$ group in unilateral Smith machine calf raises.



Black solid line = volume load for full repetitions for $DORSI_{VF}$. Black dotted line = volume load for partial repetitions for $DORSI_{VF}$. Black dashed line = total volume load for all repetitions for $DORSI_{VF}$. Grey solid line = total volume load for full repetitions for $PLANTAR_{MF}$.

Discussion

In support of our a priori hypothesis, the primary finding of the study was that lengthened supersets were superior to training to momentary failure in inducing hypertrophy of the gastrocnemius following ten weeks of training among untrained men. Both training interventions resulted in average increases in hypertrophy

($DORSI_{VF}$: +9.8 % vs. $PLANTAR_{MF}$:+6.6 %). Moreover, participants were capable of performing an average of 87.2 % more volume load for the $DORSI_{VF}$ leg after reaching momentarily full range of motion failure, and the $PLANTAR_{MF}$ trained with only 55.4 % of the total volume load compared to the $DORSI_{VF}$ leg.

Notably, we observed an absolute and relative difference of 3.2 % and 45.6 % in favour of the $DORSI_{VF}$ condition. In absolute terms, the model estimate was that the $DORSI_{VF}$ condition could be expected to result in an additional 0.62 mm (95%CrI: 0.21 to 1.0 mm) increase in muscle thickness compared with $PLANTAR_{MF}$. Within the Bayesian framework, this result represents 'strong' evidence in support of our pre-registered hypothesis. The superior hypertrophic outcome for the $DORSI_{VF}$ leg may be related to several factors. Firstly, the $DORSI_{VF}$ leg trained with around 80.5 % larger intra-session volume load compared to the $PLANTAR_{MF,}$ and beyond what is often considered to be momentarily failure in the rest of the literature (Refalo et al., 2024; Robinson et al., 2023; Steele et al., 2017). The greater intra-set volume load observed for the $DORSI_{VF}$ was achievable since the set was not terminated when participants were no longer capable of ascending to the same barbell height as the first repetition, as was the case in the $PLANTAR_{MF}$ condition. The fact that participants could perform an average of 87.2 % more volume load when including partial repetitions after reaching what is traditionally considered momentary failure in that foot may indicate that the gastrocnemius and/or soleus are operating on the ascending part of their length-tension relationship during and around peak plantar flexion in Smith machine calf raises, as previously indicated by Maganaris (2003). Thus, our findings could suggest that terminating sets in the joint angle where the gastrocnemius is in a weaker force production position (possibly due to active insufficiency) may reduce hypertrophic outcomes, as participants achieved an average of 87.2% more volume load when performing partial repetitions after reaching what is often considered momentarily failure in the literature. Nevertheless, our results should be generalized to other muscle groups/exercises with caution, as other muscles may have different strength curves and other exercises may operate on different parts of the length-tension curve (Ottinger et al., 2023), resulting in varying amounts of partial repetitions being achievable after full range of motion failure. Importantly, our study design did not investigate the mechanisms of why performing lengthened supersets contributed to greater hypertrophy. Alternatively, our findings may partly be explained by the fact that the $DORSI_{VF}$ leg was trained at longer-muscle lengths, on average, as partial repetitions after full range of motion failure were performed in the lengthened portion of the calf raise exercise (Wolf et al., 2023). This explanation is supported by the previous findings of Kassiano et al. (2023) who also observed greater gastrocnemius hypertrophy when performing lengthened partials versus a full ROM. While the mechanisms underlying the potential benefit of lengthened partials remain unclear, previous investigations have found greater increases in resting levels of IGF-1 (McMahon et al., 2014), muscle deoxygenation, increases in blood lactate, and surface electromyography amplitude (Goto et al., 2019) when compared with a full range of motion. Another potential explanation for superior growth was that the lengthened superset was terminated after momentary failure, providing similar explanations as to why drop sets may be an time-efficient strategy when training for muscle growth (Coleman et al., 2022; Sødal et al., 2023).

To our knowledge this is the first study to observe the effects of performing repetitions beyond momentary failure in Smith machine calf raises and combining full and partial repetitions on muscle hypertrophy in the medial gastrocnemius. Therefore, it is not possible to draw direct comparisons between the results of the present study in the $DORSI_{VF}$ leg to hypertrophy observed in the gastrocnemius in previous studies. However, the changes in medial gastrocnemius muscle thickness ($DORSI_{VF}$: +9.6%, $PLANTAR_{MF}$: +6.6%) were comparable with the values reported in Kassiano et al. (2023) (full ROM: +6.7%, partial initial ROM: 15.2%) for the medial gastrocnemius. Participants in the initial partial ROM/lengthened partial group in the Kassiano et al. (2023) study increased muscle thickness from 1.58 ± 0.26 cm to 1.82 ± 0.27 cm after 8 weeks of resistance training. This resulted in around 8.5 % absolute and 126.9 % greater absolute and relative medial gastrocnemius growth for the lengthened partial group compared to the full ROM group. To compare, our $DORSI_{VF}$ group increased from 20.7 ± 3.0 mm to 22.6 ± 2.9 mm resulting in around 3.2 % absolute and 45.6 % greater relative growth in favour of the $DORSI_{VF}$ leg compared to the $PLANTAR_{MF}$ leg. Importantly, since the participants who trained calf raises through a full ROM and terminated the sets at short muscle lengths in both Kassiano et al. (2023) and in the present study at average increased medial gastrocnemius hypertrophy with 6.7 % and 6.6 %, we speculate that performing initial partial repetitions in calf raises may be more effective than lengthened supersets. However, this speculation requires further investigation, and a direct comparison of lengthened supersets and lengthened partials for muscle hypertrophy is warranted.

We observed that the participants frequently reported more discomfort when training to volitional failure around peak dorsiflexion during the training intervention. This raises the question of whether training beyond full ROM momentary failure and thereby experiencing additional discomfort is worth an expected average treatment effect of 0.62 mm in muscle hypertrophy. When the participants were asked if they would prefer training the standing calf raise on their own to failure in the bottom position if they knew this would increase muscle growth compared to the condition of reaching failure in the top position, eighteen out of twenty-three participants answered yes. The group also reported that they would prefer lengthened supersets if the training provided a relative growth benefit of 32.2 ± 20.7 % (range: 5 – 80 %). Using average values, the preferential threshold fell below the relative growth benefit of 45.6% that we observed when performing lengthened supersets. In addition to the five participants who would not prefer training with lengthened supersets even if this approach resulted in greater muscle growth, six of the twenty-three participants (26.1 %) reported that a larger growth benefit than 45.6 % was needed to create a preference for training lengthened supersets instead of regular sets. This resulted in twelve out of twenty-three participants (52.2 %) that would prefer training lengthened supersets based on the relative growth benefit we observed in the study. Notably, the questionnaire was only responded to by participants who completed the intervention, as seven participants discontinued participation during the intervention phase, adding more complexity when trying to draw conclusions. Nonetheless, we hypothesize that the additional muscle hypertrophy attained through training lengthened supersets with Smith machine calf raises may justify the additional perceived discomfort for around 50 % of individuals. Importantly, this speculation should be considered cautiously and further investigated as we did not use a validated tool to assess perceived discomfort or preferential thresholds, and participants reported a wide range on the question set.

Strengths, limitations, and further research

This training intervention aimed to be both internally and ecologically valid. We conducted two pre- and two post-intervention tests, pre-registered the study's methods, and hypotheses, and used the SMART-LD checklist to reduce potential biases. Additionally, the statistical analysis was performed blinded, with condition allocation concealed. These practices increase the robustness of our conclusions and limit the potential for bias. The most prominent limitation of the current study in terms of ecological validity and generalizability to more trained populations was that we only measured muscle hypertrophy among untrained men due to resource constraints. As this to our knowledge is the first study on the effects of lengthened supersets on muscle growth there is a need for several future studies to enhance the body of knowledge. Firstly, future studies should attempt to replicate the findings among women and more highly trained participants. Additionally, future studies should compare muscle hypertrophy from lengthened supersets versus traditional sets on other muscle groups, as our findings are perhaps not generalizable to other muscle groups due to differences in length-tension relationships and resistance curves of the exercises employed. Also, a study comparing lengthened supersets to initial partial ROM sets is warranted. Similarly, as we observed increased perceived discomfort among our participants, future studies should compare perceived discomfort with a validated tool between a lengthened superset vs. a traditional set terminated at momentary failure. Finally, future studies should compare the efficacy of one lengthened superset with a drop set, as a time-efficient modality, and 2-3 traditional sets, to compare the effectiveness between these training modalities

Conclusion

In summary, we demonstrated that medial gastrocnemius muscle hypertrophy was greater when Smith machine calf raises were performed to $DORSI_{VF}$ compared with $PLANTAR_{MF}$. Thus, when the goal is to increase medial gastrocnemius hypertrophy among untrained men, we suggest performing Smith machine calf raises to volitional failure in peak dorsiflexion.

Contributions

Contributed to conception and design: SL, HNF, MW, RT.

Contributed to acquisition of data: SL, NØS, BSK, ABF, HNF.

Contributed to analysis and interpretation of data: PAS, MW, SL.

Drafted the first draft: SL.

Revised the article: All authors.

Approved the submitted version for publication: All authors.

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Conflict of interest

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Data and Supplementary Material Accessibility

Data and supplementary material are available on the Open Science Framework project page:

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