Mixing Up Muscle Lengths: The Effects of Manipulating Peak Torque at Different Muscle Lengths in the Elbow Flexors

Supplementary materials: https://osf.io/3v8ef/
For correspondence: shinson2021@fau.edu

Seth R Hinson[1], Jacob F Remmert[1], Zac P Robinson[1], Joshua C Pelland[1], Shawn Dinh[1], Ethan Elkins[1], Caitlyn M Meehan[1], David Diaz[1], Brian Benitez[1], Christian Macarilla[1], Michael W Morgan[1], Michael C Zourdos[1].

[1] Department of Exercise Science and Health Promotion, Florida Atlantic University

Please cite as: Hinson, S.R., Remmert, J.F., Robinson, Z.P., Pelland, J.C. ,Dinh, S., Elkins, E., Meehan, C.M., Diaz, D., Benitez, B., Macarilla, C., Morgan, M.W., Zourdos, M.C. (2024). Mixing Up Muscle Lengths: The Effects of Manipulating Peak Torque at Different Muscle Lengths in the Elbow Flexors. *SportRχiv.*

All authors have read and approved this version of the manuscript. This article was last modified in November 2024.

Abstract

PURPOSE: This repeated measures within-participant unilateral design study investigated the effect of resistance training with the peak torque occurring at only longer muscle lengths (LONG) to training with the peak torque occurring at a mixture of long and short muscle lengths (MIXED). **METHODS:** 7 recreationally trained males (n=5) and females (n=2) trained for eight weeks, with limbs randomized to either LONG or MIXED conditions. The repeated measures design required participants to repeat the 8 week training after a 6-8 week washout period, which effectively created observations equivalent to sample size of 14. In the LONG condition, participants performed six sets of seated lengthened cable curls to momentary failure with 3 minutes of interset rest each session. The MIXED condition performed three sets of seated lengthened cable curls and three sets of standing shortened cable curls to momentary failure with 3 minutes of interset rest each session. Elbow flexor cross-sectional area (CSA) and regional muscle thickness (MT) were assessed via panoramic b-mode ultrasonography at Pre and Post testing. Dynamic strength, isometric strength, and arm circumference were also assessed at Pre and Post testing. Session rating of perceived exertion (sRPE) and perceived soreness were assessed before and after every session. To compare changes in the primary training outcomes between conditions (i.e., elbow flexor cross-sectional area, muscle thickness, isometric force, dynamic strength, and arm circumference), Bayesian linear mixed effect models were constructed to mimic an analysis of covariance (i.e., ANCOVA) with an adjustment for the baseline score of the dependent variable. To compare longitudinal trends in the subjective perceptions of fatigue (i.e., session RPE and perceived elbow flexor soreness) between conditions Bayesian linear mixed effect models with a Gaussian response distribution were fit. For parameters of interest from each model (i.e., marginal effects for condition or the two-way interaction between condition and site, exercise, or session), draws were taken from the posterior distribution to construct a probability density function (i.e., mode and associated highest density intervals) that was used to make probabilistic inferences. The probability density functions related to the primary research questions were also compared to a region of practical equivalence (ROPE) defined by the typical error of measurement. **RESULTS:** Changes in total CSA for both LONG (6.01 cm^2 [95% HDI: -1.64, 14.66], 80.12% probability > ROPE) and MIXED (3.18 cm^2 [95% HDI: -5.66, 12.69], 55.51% probability > ROPE) were considered meaningful, but the contrast between conditions (2.58 cm^2 [HDI: -4.1, 9.01], 48.96% probability > ROPE) was not meaningful. Contrast estimates in arm circumference were meaningfully greater for the LONG condition at proximal (0.33 mm [95% HDI: -0.92, 1.95], 52.19% probability > ROPE), middle (0.46 mm [95% HDI: -1.06, 1.9], 54.39% probability > ROPE), and distal (0.89 mm [95% HDI: -0.74, 2.4], 74.26% probability >

ROPE) regions of the upper arm. Changes in dynamic strength for both conditions in the shortened cable curl (LONG=3.67 kg [95% HDI: -0.77, 7.65], 76.99% probability > ROPE; MIXED=5.44 kg [95% HDI: 0.59, 9.78], 92.31% probability > ROPE) and lengthened cable curl (LONG=6.93 kg [95% HDI: 2.37, 11.86], 97.86% probability > ROPE; MIXED=6.57 kg [95% HDI: 0.35, 11.77]; 93.86% probability > ROPE) were considered meaningful, but the contrast between conditions was not meaningful. Changes in regional MT, regional isometric force, total isometric strength, sRPE and perceived soreness were not considered meaningful for either condition. **CONCLUSIONS:** Given the lack of meaningful differences between conditions and the questionable relevance of circumference measurements, It seems that neither training condition provides clearly superior outcomes for hypertrophy, strength, or perceptual fatigue.

Introduction

Examining the influence of performing resistance training through various ranges of motion (ROM) for hypertrophy and strength outcomes is an emerging area of research; however, evidence regarding the efficacy of manipulated ROM to full length ROM is mixed. Specifically, for hypertrophy, Wolf et al. (39) reported that using various upper body exercises with partial ROM (lengthened position) or full ROM led to similar growth (BF_{h0}= .19 to .30) in the elbow flexors and extensors in trained individuals. Conversely, a meta-analysis by Wolf et al. (1), which included 24 studies, found that training through various partial ROM (shortened and lengthened positions) resulted in a trivial differences for muscle hypertrophy compared to full ROM training (SMD = 0.12 [-0.02,0.26]). For strength, Wolf et al. (1) reported that strength gains were greatest in the ROM that was trained. The findings for strength outcomes in ROM studies are not unexpected due to the principle of specificity; however, more nuance is needed regarding hypertrophy and resistance training ROM. Specifically, the muscle length (i.e., shortened or lengthened position) at which an exercise is performed (5,6,7,23,24) may affect muscle growth and temporal recovery (8,22). Additionally, the muscle length at which peak torque (i.e., the point in the ROM where force demand is highest due to the relationship between internal and external moments) is experienced in an exercise (25) may be crucial to consider.

Indeed, various studies (5,6,7,23,24) have compared training at different muscle lengths and found that training at long muscle lengths may enhance hypertrophy, with fewer studies (35,39) reporting no substantial differences in hypertrophy when training through different muscle lengths. Maeo et al. (6,7) observed greater hypertrophy in biarticular muscles when training through a full ROM at a longer muscle length compared to a shorter muscle length.

Moreover, Maeo et al. (6) reported additional hamstrings growth in healthy adults following 12 weeks of seated leg curl training (which expose the biarticular muscles of the hamstrings to longer muscle lengths) compared to prone leg curl training (+14.1% versus +9.3%, respectively, $p < 0.001$). Maeo et al. (7), also found that a mixed-sex sample of healthy adults experienced greater triceps brachii hypertrophy when training with the arms in an overhead position (exposing the biarticular muscles of the triceps to a longer muscle length) compared to arms at the sides (+19.9% versus +13.9%, respectively, $d = 0.54$, $p < 0.001$).

Importantly, regional hypertrophy within the same muscle (5,23) may also be affected by the length a muscle is trained. For example, Pedrosa et al. (5) found that performing partial ROM leg extensions for 12 weeks at a longer muscle length led to greater distal rectus femoris growth at 70% of femur length compared to training through only the final ROM or varied ROM (short and long) in untrained women. Further, Pedrosa et al. (23) reported that performing seated dumbbell preacher curls for 8 weeks at a longer muscle length (initial ROM 0°–68°) caused significantly greater distal biceps brachii growth (ES = 0.89; p = 0.001) at 70% of biceps length compared to training at a shorter muscle length (final ROM 68°–135°) in untrained women.

Additionally, Zabeleta-Korta et al. (25) found that regional hypertrophy is also affected when the greatest resistance in an exercise occurs in the ROM where the muscle is lengthened. Participants performed either a dumbbell preacher curl (more resistance at longer muscle length) or an incline dumbbell curl (more resistance at a shorter muscle length). Despite the incline dumbbell curl placing the elbow flexors at a longer muscle length, which is due to greater a greater degree of shoulder extension (36), only the group performing preacher curls experienced a significant increase in muscle thickness at 70% of the upper arm length (+9.8%, $p = 0.017$, ES = 0.623). Notably, there was no significant difference between groups and muscle thickness at 50% and 60% of upper arm length were not significantly different from pre testing. Conversely, there is evidence that performing exercises with greater resistance longer muscle lengths may not significantly benefit muscle growth. Nunes et al. (34) compared biceps brachii growth of a mixed sample of trained adults after 10 weeks of training preacher curls with a cable machine (torque emphasis at a short muscle length) or barbell (torque emphasis at a long muscle length) and reported similar growth at the midpoint of the biceps (Cable = +7%, Barbell= +8%, p=0.346). Although there is limited and mixed evidence on the topic, the muscle length where an exercise has the most resistance is likely important to consider, especially for regional hypertrophy outcomes.

Despite the possibility to enhance hypertrophy by manipulating the muscle length during training, the potential greater temporal fatigue cost should be considered. Nosaka et al. (8) found greater ratings of perceived muscle soreness and increases in plasma creatine kinase concentrations following eccentric training at long muscle lengths versus short muscle lengths. Importantly, excessive muscle damage may impair subsequent performance (25); thus, alternative strategies such as using mixed muscle lengths (long and short) should be investigated to gain the benefit of long muscle lengths without elongating recovery time courses.

Therefore, the purpose of this repeated measures within-participant study was to compare strength and hypertrophy (both whole-muscle and regional) between training with peak torque at longer muscle lengths (LONG) and training with peak torque at long and short muscle lengths (MIXED) over 8 weeks of biceps training. Additionally, we sought to examine the impact of training with peak torque at different muscle lengths on the time course of recovery while examining subjective proxies of fatigue. We hypothesized greater distal hypertrophy for LONG. We hypothesized greater isometric and dynamic strength gains for LONG at longer muscle lengths and greater isometric and dynamic strength outcomes for MIXED at shorter muscle lengths. Further, we predicted lower markers of perceived soreness and fatigue for MIXED.

Methods

Participants

Seven males (n = 5) and females (n =2) between the ages of 18-40 were recruited for this within-participant study with replication. Therefore, due to the repeated design of the present study, the number of observations is the same as 14 participants in a typical within-participant unilateral design. For inclusion, participants needed to have ≥2 consecutive years of resistance training experience as determined by a physical activity questionnaire, and no contraindications to exercise (e.g., heart disease, hypertension, diabetes, etc.) as determined by a health history questionnaire. Prior to participation, all participants provided written consent and the University's Institutional Review Board approved this investigation.

Experimental Design

The purpose of this study was to compare changes in whole and regional muscle size, strength, and subjective markers of soreness and fatigue following a replicated within-participant unilateral design. All participants had their upper limbs randomized to the two conditions (LONG or MIXED), counterbalanced for limb dominance, and completed two pre-testing sessions, 8 weeks of training and finally two post-testing sessions. After the first 8 week training intervention and post-testing, participants completed a washout period of 6-8 weeks, then, each participant replicated the training intervention (i.e., performed another 8 weeks of training with pre- and post-testing). The duration of the washout period (6-8 wks.) was individualized depending on the availability of the participants, and participants were instructed to return to their habitual training (defined in their pre-training questionnaire). The second intervention was identical to the first, with each limb re-randomized to the intervention conditions.

Immediately following each training session 40g of whey protein containing 3.5g of leucine was ingested by each participant. Although the necessity of reaching a threshold of 3.5g leucine in a single meal to maximally stimulate muscle protein synthesis has been questioned recently (38), because nutritional control was limited to participants being asked to maintain normal eating habits, 40g of whey protein containing 3.5g leucine was ingested by each participant immediately following each training session to err on the side of caution and ensure optimal post-workout nutrition (11,12).

Training Program

The first session included initial paperwork, anthropometric measurements, muscle cross-sectional area assessment (CSA), muscle thickness , and isometric strength assessments. At least 48 hours later, the second pre-testing session involved 8-12 RM strength testing. At least 48 hours following the second pre-testing session, participants performed an introductory training week with reduced volume and proximity to failure. For the introductory training week participants performed two sessions separated by at least 48 hours as they would in the main training program, but completed 2 fewer sets per session and terminated sets further from momentary failure, at a self-rated 2 repetitions in reserve (RIR). The purpose of the introductory week was twofold: 1) to familiarize participants with standardized exercise techniques and procedures, and 2) to elicit the repeated bout effect (40). Following the introductory week, participants completed two training sessions per week, separated by at least 48 hours, for 7 weeks. During this main training program, participants completed 12 sets per limb per week, divided evenly between sessions (i.e., 6 sets per session). Participants completed all training volume using a lengthened cable curl exercise on the limb in the LONG condition (Figure 3AB). The limb randomized to the MIXED condition completed half of the training volume (3 sets per session) on the lengthened cable curl and the other half (3 sets per session) on the shortened cable curl performed in 90 degrees of shoulder flexion (Figure 4AB). At least 48 hours following the final training session, post-testing was conducted, repeating the exact protocols of pre-testing. Details of the training program and all assessments can be seen in Table 1.

Table 1

Phase	Week	Session 1	Session 2	Session 3	Session 4
Pre-testing	1	Paperwork Anthropometrics Muscle Size Isometric Strength	Dynamic Strength	N/a	N/a
Introductory week	2	Training (2 sessions per week separated by at least 48 hours)[#&] 8 sets per week (4 per session) @ 2 RIR			
Training Period	3 4 5 6 7 8 9	Training (2 sessions per week separated by at least 48 hours) 12 sets per week (6 per session) @ failure[&]			
Post-testing	10	Anthropometrics Muscle Size Isometric Strength	Dynamic Strength		

[#]= reduced volume and increased RIR (repetitions in reserve). [&]= session rating of perceived exertion (RPE), and perceived soreness were be collected each training session

Prior to each training session, participants completed a dynamic warm-up, followed by an exercise-specific warm-up. The exercise-specific warm-up consisted of 50% of the working load for 8 repetitions followed by 75% of the working load for 4 repetitions. After completing the warm-up on each limb, the designated first limb began the training session and alternated performing the prescribed training sets with the second limb. The limb designated to train first was alternated each session throughout the training intervention. Participants rested 90 seconds between each working set; therefore, the time between sets of the same limb was >3 minutes. For the limb in the MIXED condition, the exercise order was always lengthened cable curls followed by shortened cable curls. Each working set was performed until momentary muscular failure, defined as the inability to complete a repetition with the standardized technique (described in Exercise Procedures below) despite maximal effort to do so (13). Strong verbal encouragement was provided throughout all testing and training sessions. Both the LONG and MIXED conditions were performed after a Bench Press protocol (refer to supplementary materials). Also, back training was performed following both the LONG and MIXED training protocol to control for any indirect biceps training volume. Back training consisted of bilateral lat-pull downs or bilateral seated cable rows on alternating training days. These exercises were performed for three sets of 10 reps at 2 RIR.

The initially prescribed load was the exercise-specific 8-12 RM load determined at pre-testing, and a target repetition range of 8-12 repetitions was utilized for each working set. Set-to-set adjustments in load were completed similar to Helms et al. (16). However, due to the low absolute loads lifted in the present exercises the adjustment threshold was doubled. Specifically, if participants completed greater than 12 repetitions, load was increased for the next set by 4% for every repetition above 12. If participants completed less than 8 repetitions, load was decreased for the next set by 8% for every repetition below 8. For example, if 14 repetitions were completed the load was increased by 8% for the following set, while 6 repetitions completed led to a load decrease of 16% for the following set. The initial load used for the first set of a session (except for the first session) was the average load of all training sets of the previous session.

Testing Procedures

Training history

A custom training history questionnaire was completed by each participant that outlines weekly total training volume for the biceps, weekly sets taken to muscular failure, average repetition range, typical exercise selection, and habitual progression methods (Table 2).

Table 2: **Previous Training History**

Method	Weekly Sets	Repetitions Per Set	RIR Per Set	Interset Rest Periods (m)	Weekly Frequency
Direct	5.71 ± 7.02	9.75 ± 0.89	1.38 ± 0.69	1.88 ± 0.95	0.93 ± 0.92
Indirect	11.86 ± 6.65	9.73 ± 1.35	1.71 ± 1.17	2.42 ± 0.88	1.36 ± 0.74
Combined	17.57 ± 11.56	9.73 ± 1.20	1.78 ± 0.98	2.26 ± 0.88	1.64 ± 1.01

Anthropometrics

Total body mass (kg) was assessed by a calibrated digital scale (Mettler-Toledo, Columbus, Ohio, USA) and height (cm) was measured via a wall-mounted stadiometer (SECA, Hamburg, Germany). The circumference of the arm (mm) at 30, 50, and 70% of its length was also recorded. Arm length was defined as the distance between the acromion process of the scapula and the lateral epicondyle of the humerus, measured on the posterior side of the arm, as proposed by Miyatani et al. (15).

Ultrasonography

Elbow flexors CSA was assessed via panoramic b-mode ultrasonography (Phillips, Koninklijke Philips N.V., 2004). This method of testing biceps muscle size was previously reported as reliable (16), and ultrasound has been validated for measuring muscle hypertrophy against magnetic resonance imaging (37). Sites were scanned proximal to distal with the transducer perpendicular to the skin with no active pressure. A generous amount of transmission gel was utilized for each scan. Elbow flexors scans were performed in the supine position. To identify measurement sites, the investigator created marks using a permanent marker at 30%, 50%, and 70% of the distance between the acromion process of the scapula and the lateral epicondyle of the humerus on the posterior of the arm determined by palpation. Then, a second set of marks was made in line with the first set on the anterior side of the arm along the midline of the elbow flexors. Finally, a guideline was made that connects all three points in the middle of the elbow flexors. This guideline was extended proximally and distally to capture the entire length of the bicep as detectable by the ultrasound. Scans were performed along this guideline in a controlled but constant motion. Scans were extended both distally and stopped once the probe reached the antecubital fossa. Two scans were conducted at each timepoint; however, if upon visual inspection the two scans were notably different then a third scan was taken and the two scans which were most similar were used for analysis (Figure 1).

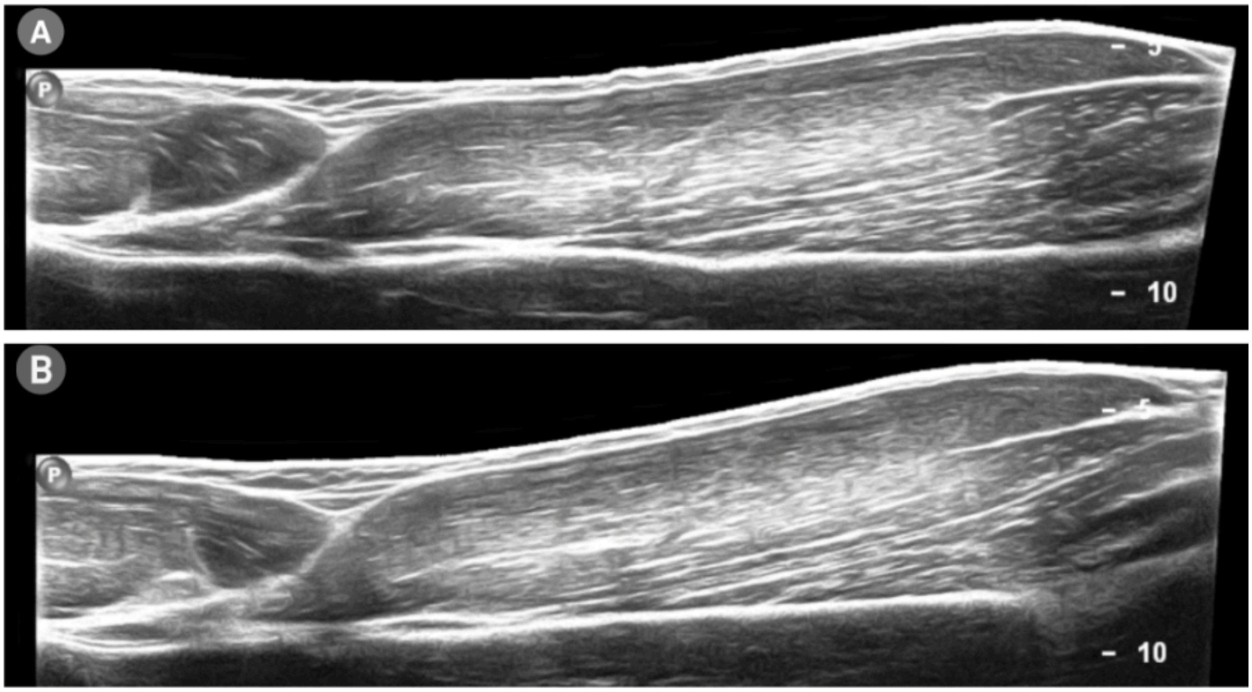

Figure 1: *Panoramic b-mode ultrasound scan of the elbow flexors. The left side of the images show the proximal region of the elbow flexors and the right side of the images show the distal region of the elbow flexors. The first (a) and second (b) scans were performed at the same time point but some variation in the scans is visible.*

Whole muscle CSA images were converted from DICOM to .jpeg format and then traced using the polygon tool in ImageJ (17). All scans were performed by the same investigator, and all scans were analyzed by another investigator. Regional hypertrophy was assessed via segmentation in ImageJ.

ImageJ Segmentation Procedures

Regional muscle thickness at 33% and 66% of muscle length was computed from ultrasound scans of the elbow flexors using a custom ImageJ script designed to standardize segmentation. Regional thickness sites (33% and 66% of muscle length) were chosen to ensure reliability of muscle thickness measures, as visual differences between scans were occasionally observed in more distal and proximal regions due to measurement error. Once the ultrasound image was uploaded, the image was first scaled and leveled before a polygon tool was used to trace the aponeurosis of the elbow flexors. The image was then cropped, removing the background, and converted into an 8-bit image. Segmentation was then accomplished using a custom script designed to split the image into three distinct regions (refer to supplementary materials) (Figure 2).

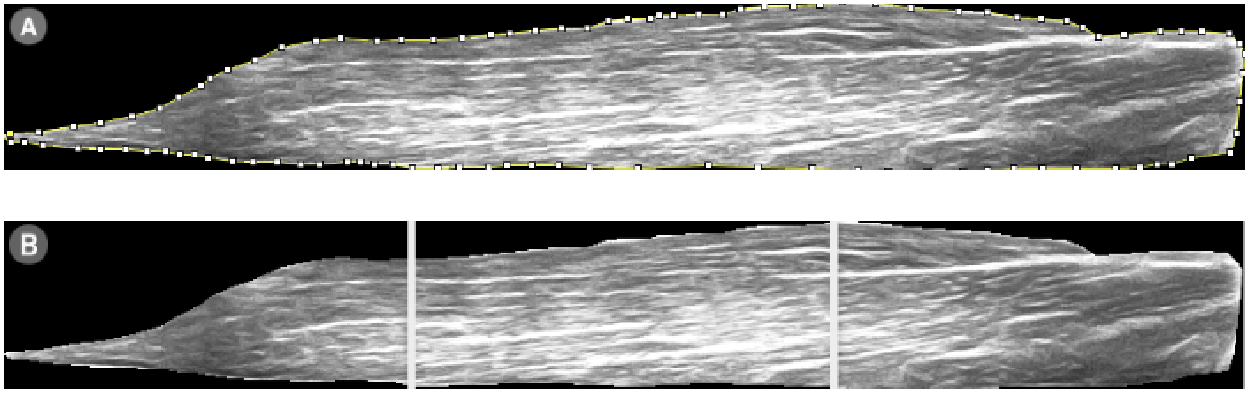

Figure 2: *The left side of the images show the proximal region of the elbow flexors and the right side of the images show the distal region of the elbow flexors. The total cross sectional area of the muscle (a) and the segmented ultrasound scan of the elbow flexors are shown above (b). Muscle thickness was measured at 33% and 66% of scan as indicated by white lines (b).*

Finally, Muscle thickness at 33% and 66% of muscle length was traced using the line tool and then quantified using the Measure function. All scans were performed and analyzed by the same investigator.

Dynamic Warm-up

Participants performed a dynamic whole-body warm-up before all strenuous exercise to ensure adequate preparation for the upcoming task. This warm-up consisted of various bodyweight movements designed to gradually increase core body temperature throughout extremely low intensity activity. The warm-up consisted of a total of 7 exercises all performed for 8 repetitions with no external load.

Exercise Procedures

Lengthened Cable Curl. The lengthened cable curl using a cable machine ((Titan Fitness, Item No. 400868)) was performed in the LONG and MIXED condition. Participants were seated on an incline bench facing away from the cable machine such that when grasping the cable machine handle with the palm facing away from the machine, the shoulder was extended to approximately 30 degrees as measured by a goniometer. At pre-testing, the distance between the incline bench and the cable machine that allowed for this shoulder extension angle was recorded for each arm for each participant, and kept constant throughout the intervention. The seat was placed so that the training limb was in line with the cable, and the cable was set at the level of the malleoli of the participant. The repetition was initiated by flexing the elbow and continuing until maximum elbow flexion was achieved before returning to the starting position. Participants were instructed to keep the forearm supinated, and to limit abduction of the humerus. The position of the cable relative to the hand was manipulated for participants to experience peak torque near the starting position but the angle of the cable relative to the hand was not standardized (Figure 3A). The feet remained on the floor, and the glutes, lower back, and shoulders maintained contact with the incline bench throughout the movement. The participant was allowed to use the opposite (non-exercising) limb to hold the seat of the bench for stability.

Figure 3: The starting position (a) and the ending position (b) of the lengthened cable curl.

Shortened Cable Curl. In the MIXED condition, participants performed half of the sets on the lengthened cable curl (as described above) and the other half on the shortened cable curl using a cable machine (Titan Fitness, Item No. 400868). For the shortened cable curl, participants were standing facing the cable machine such that when grasping the cable machine handle with the palm facing upward, the shoulder was flexed to approximately 90 degrees as measured by a goniometer. An incline bench was placed in front of the participant with the height adjusted so that the elbow of the exercising limb rests on top of the bench. At pre-testing, the incline of the bench and the height of the cable which allow for this position was measured and kept constant for each arm throughout the intervention. The repetition was initiated by flexing the elbow and continuing until maximum elbow flexion was achieved before returning to the starting position. Participants were instructed to keep the forearm supinated, and to limit abduction of the humerus. The position of the cable relative to the hand was manipulated for participants to experience the peak torque near the ending position but the angle of the cable relative to the hand was not standardized (Figure 4A). The feet remained on the floor and the elbow remained on the bench throughout the movement. The participant was allowed to hold the bench with their opposite (non-exercising) limb to aid with stability. For each participant, the cable was marked with a piece of tape at the point the individual reaches maximal elbow flexion. Thus, a failed repetition was defined as a repetition in which the portion of the cable that has been marked does not exit the pulley due to insufficient ROM being performed.

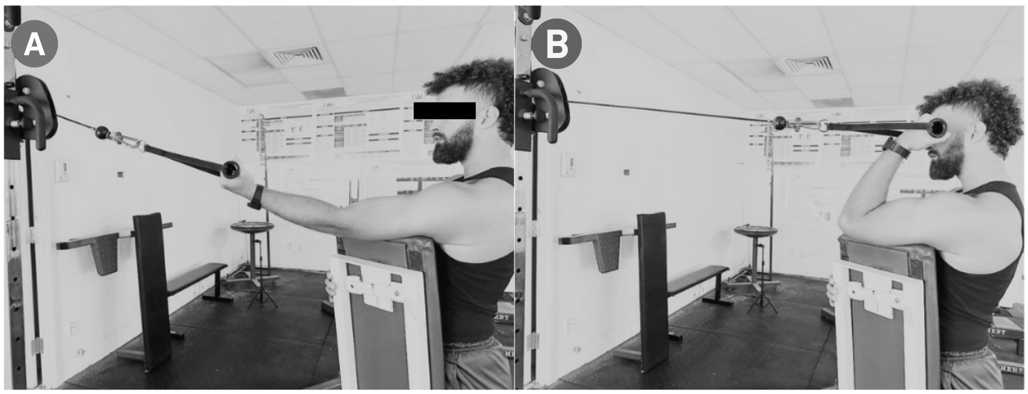

Figure 4: *The starting position of the shortened cable curl (a) and the ending position (b) of the shortened cable curl.*

Dynamic Strength Testing

Unilateral dynamic strength testing (8-12 RM) was performed for lengthened cable curl for both limbs then the shortened cable curl for both limbs. The limb performing the strength test first was randomized, with the same order performed for the same limb at both pre- and post-testing. All participants began with the dynamic warm-up described above, followed by an exercise-specific warmup. For the exercise-specific warm-up, 50% of participant-estimated 10RM was completed for 8 repetitions, followed by 75% of estimated 10RM for 4 repetitions. Then, participants were given 2 minutes rest before a final warm-up set of 100% of estimated 10RM for 2 repetitions. After the final warm-up, 3 minutes rest was given before the participant performed the dynamic strength test consisting of an 8-12 RM attempt. Participants rated RIR at the conclusion of each set. If multiple attempts were needed, load was increased with each attempt, using the investigator’s judgment along with participant-rated RIR, with 3 minutes of rest between each attempt. Following the 8-12 RM determination on the starting limb for the lengthened cable curl, 5 minutes rest were given before an identical protocol for the opposite limb. Then, another 5 minutes rest were given before an identical protocol for the shortened cable curl using the same limb that was tested first for the first exercise, followed by a final 5-minute rest period before an identical protocol for the opposite limb on the shortened cable curl. Eleiko lifting discs (Chicago, IL, USA) calibrated to the nearest 0.25kg were used for all testing.

Isometric Strength Testing

Unilateral Isometric strength testing consisted of performing two 3-second maximal isometric contractions at 70, 90, and 120 degrees of elbow flexion for each limb, with a two-minute rest between trials and a four-minute rest between limbs. A D-handle cable attachment was linked by a chain to an anchored load cell (Honeywell Model 125 S-type/z-beam Load Cell, (06-K627-03), Charlotte, NC, USA) with a sampling rate of 1kHz to measure isometric force. Participants were seated in a chair at a distance from the anchored load cell holding the D-handle such that the specific degree of elbow flexion (70 ,90, or 120 degrees) was achieved as measured by a goniometer. The elbow was braced against the arm of the chair. The highest value at each joint angle was used for further analysis. The limb performing the test first was randomized, but kept consistent at both pre- and post-testing for each participant. participants were instructed to curl the handle as fast and hard as possible for approximately 2 seconds after the cue, “Ready, set, go!”

Session Rating of Perceived Exertion (sRPE)

The sRPE scale was completed by participants immediately following the completion of each protocol on either limb to gauge the difficulty and fatigue for each limb individually (21). This scale was a 0-10 scale with “0” indicating the participants were at “rest” meaning they used no effort and a score of “10” indicating “maximal effort”. This rating was collected for each limb for each session.

Perceived Soreness

A subjective muscle soreness scale was completed by each participant prior to each training session for the biceps of each individual limb. This was a 0-6 scale with “0” indicating the participants had a complete absence of soreness and a score of “6” indicating a severe pain that limits their ability to move (22).

Statistical Analysis

All analyses were conducted in R language and environment for statistical computing (v 4.3.0; R Core Team, https://www.r-project.org/). In addressing our research questions, we avoided dichotomizing the findings and did not employ traditional null hypothesis significance testing, which has been extensively critiqued (26). Instead, we took an estimation-based approach within a Bayesian framework in which all outcomes compatible with the data were considered, with the greatest emphasis placed on the point estimates using the "brms", "tidybayes", and "marginaleffects" packages (27,28). Each model was fitted with the default uninformed priors and used four Monte Carlo Markov Chains with 2000 warmup and 2000 sampling iterations. Before extracting any estimates, each model was visually examined via trace plots to inspect chain convergence and posterior predictive checks to examine model validity. For the parameters of interest from each model (i.e., marginal effects for condition or the two-way interaction between condition and site, exercise, or session), draws were taken from the posterior distribution to construct a probability density function (i.e., mode and associated highest density intervals) that was used to make probabilistic inferences. The probability density functions related to the primary research questions were also compared to a region of practical equivalence (ROPE) defined by the typical error of measurement (29,30). For dynamic strength outcomes, the typical error of measurement was calculated from the differences between limbs at baseline, which assumes a negligible systematic bias between limbs.

Elbow Flexor CSA, MT, Isometric Force, Dynamic Strength, and Arm Circumference

To compare changes in the primary training outcomes between conditions (i.e., elbow flexor cross-sectional area, muscle thickness, isometric force, dynamic strength, and arm circumference), Bayesian linear mixed effect models were constructed to mimic an analysis of covariance (i.e., ANCOVA) with an adjustment for the baseline score of the dependent variable. Specifically, the fixed effects included time, phase, sex, the interaction between time and condition, and the interaction between time and phase. For the models examining regional adaptations (i.e., MT, isometric force, and arm circumference) and dynamic strength, an additional categorical variable (i.e., site or exercise) and its interactions with time,phase, and the time by condition interaction were included in the model. As each model contained multiple observations per participant and limb, these variables were included as nested random intercepts. Each model was fit with a maximal random effect structure (32,33). Where possible, multiple measurements per occasion were included in the model to improve statistical precision (34).

Session RPE and Perceived Soreness

To compare longitudinal trends in the subjective perceptions of fatigue (i.e., session RPE and perceived elbow flexor soreness) between conditions Bayesian linear mixed effect models with a Gaussian response distribution were fit. Despite the ordinal nature of the scales, we chose to model their effects with an identity link function to maintain intuitive interpretation rather than reporting predicted probabilities of each response category. The fixed effects included session, phase, condition, and all of their corresponding two-way interactions. As each model contained multiple observations per participant and limb, these variables were included as nested random intercepts. Each model was fit with a maximal random effect structure.

Results

Descriptives

Descriptive summaries (i.e., mean ± standard deviation) of participant characteristics are located in Table 3. Details of the participants' previous training history and performance throughout the present training intervention are available in the supplementary materials .

Table 3: **Participant Characteristics**

Age (years)	Pre Body Mass (kg)	Post Body Mass (kg)	Height (cm)	Training Experience (years)
23.00 ± 2.00	83.18 ± 15.22	83.95 ± 15.44	171.29 ± 8.54	5.43 ± 2.14

Total CSA

The modal estimates of the posterior distributions suggest that both conditions demonstrated meaningful increases in total elbow flexor CSA. Specifically, the LONG condition observed an increase of 6.01 cm^2 [95% HDI: -1.64, 14.66] with 93.75% and 80.12% probabilities of the change being greater than a null effect and the ROPE, respectively. The MIXED condition observed a modal increase of 3.18 cm^2 [95% HDI: -5.66, 12.69] with 78.45% and 55.51% probabilities of the change being greater than a null effect and the ROPE, respectively. The modal estimate for the contrast between conditions was 2.58 cm^2 [HDI: -4.1, 9.01] with a 81.11% probability of the difference exceeding a null effect. The probability the difference between conditions exceeded the ROPE was 48.96%. These results are visualized in Figure 5

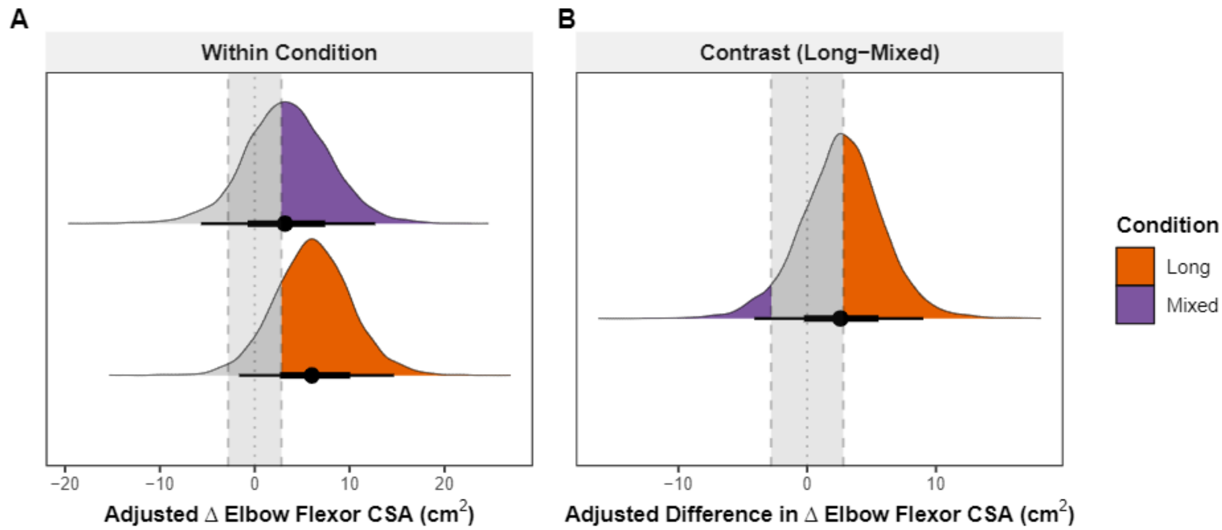

Figure 5: *Posterior distributions for A) within and b) between condition changes in total elbow flexor cross-sectional area. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by typical measurement error. Black dot and intervals represent the modal estimate and highest density intervals (66 and 95%) from the posterior distribution.*

Total Isometric Strength

The modal estimates of the posterior distributions suggest that both conditions demonstrated an increase in total elbow flexor isometric force. Specifically, the LONG condition observed a modal increase of 1.03 kg [95% HDI: -4.42, 7.39] with 70.03% and 33.52% probabilities of the change being greater than a null effect and the ROPE, respectively., The MIXED condition observed a modal increase of 0.69 kg [95% HDI: -4.94, 7.24] with a 62.45% and 28.51% probabilities of the change being greater than a null effect and the ROPE, respectively. The modal estimate for the contrast between conditions was 0.38 kg [HDI: -2.48, 3.61] with a 62.75% probability of the difference exceeding a null effect. The probability the difference between conditions exceeded the ROPE was 8.59%. These results are visualized in Figure 6.

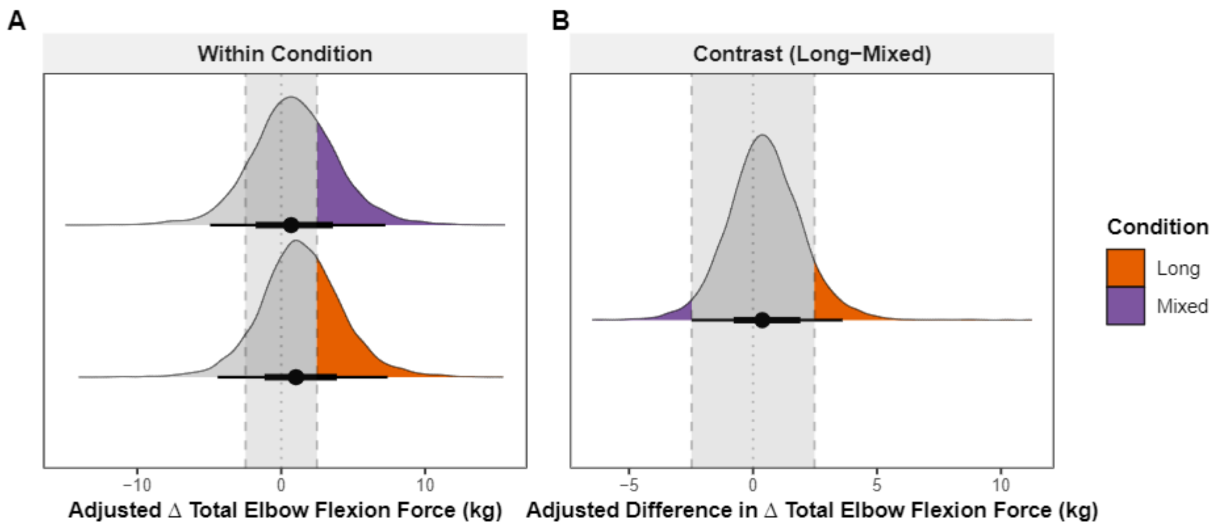

Figure 6: *Posterior distributions for A) within and b) between condition changes in total elbow flexor force. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by typical measurement error. Black dot and intervals represent the modal estimate and highest density intervals (66 and 95%) from the posterior distribution.*

Regional MT

The modal estimates of the posterior distributions suggest that both conditions demonstrated increases in both regions of elbow flexor MT. Specifically, the LONG condition observed modal changes of 0.07 cm [95% HDI: -0.25, 0.39] and 0.1 cm [95% HDI: -0.22, 0.45] for the proximal and distal regions, respectively. These changes resulted in 67.12% and 0% (proximal), and 75.64% and 0% (distal) probabilities of being greater than a null effect and the ROPE, respectively. The MIXED condition observed modal changes of 0.08 cm [95% HDI: -0.27, 0.49] and 0.1 cm [95% HDI: -0.28, 0.53] for the proximal and distal regions, respectively. These changes resulted in 74.66% and 0% (proximal), and 73.28% and 0% (distal) probabilities of being greater than a null effect and the ROPE, respectively. The modal estimates for the contrasts between conditions were -0.04 cm [95% HDI: -0.33, 0.23] and 0 cm [95% HDI: -0.31, 0.3] for the proximal and distal regions, respectively. These contrasts resulted in 65.26% and 53.42% probabilities the difference exceeded a null effect for the proximal and distal regions, respectively. The probability these differences between conditions exceeded the ROPE was 0% and 0% or the proximal and distal regions, respectively. These results are visualized in Figure 7.

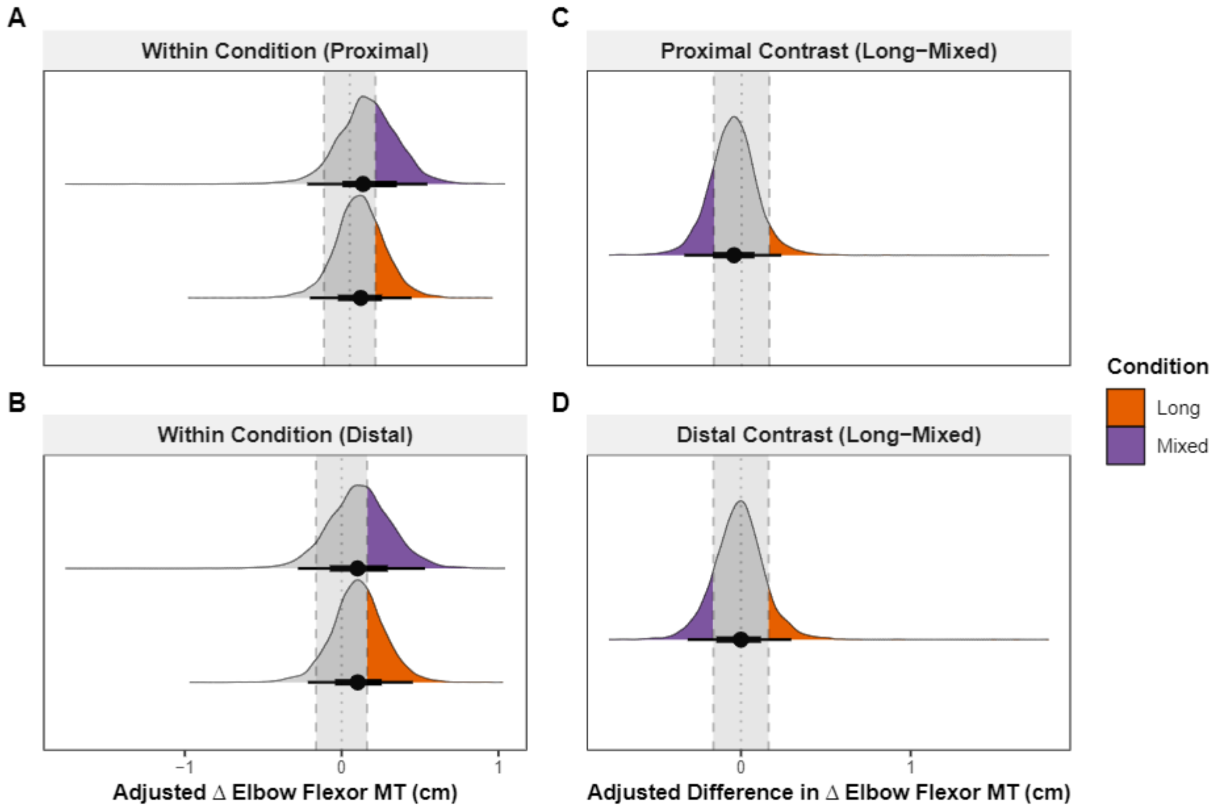

Figure 7: *Posterior distributions for changes in regional elbow flexor muscle thickness. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by typical measurement error. Black dot and intervals represent the modal estimates and highest density intervals (66 and 95%) from the posterior distribution.*

Regional Force

The modal estimates of the posterior distributions suggest that neither condition demonstrated consistent increases in isometric force. Specifically, the LONG condition observed modal changes of 0.88 kg [95% HDI: -1.49, 3.33], -0.46 kg [95% HDI: -2.9, 2.18], and 1.05 kg [95% HDI: -1.95, 3.82] for shortened, middle, and lengthened, respectively. These changes resulted in 78.61% and 32.45% (shortened), 63.44% and 19.4% (middle), and 77.11% and 38.11% (lengthened) probabilities of being greater than a null effect and the ROPE, respectively. The MIXED condition observed modal changes of 1.38 kg [95% HDI: -1.37, 3.78], 0.11 kg [95% HDI: -3.01, 2.74], and -0.52 kg [95% HDI: -3.71, 2.67] for shortened, middle, and lengthened, respectively. These changes resulted in 84.25% and 44.94% (shortened), 52.29% and 16.34% (middle), and 60.72% and 24.88% (lengthened) probabilities of being greater than a null effect and the ROPE, respectively. The modal estimates for the contrasts between conditions were -0.33 kg [95% HDI: -1.77, 1.19], -0.44 kg [95% HDI: -2, 1.46], and 1.36 kg [95% HDI: -0.49, 3.23] for shortened, middle, and lengthened, respectively. These contrasts resulted in 68.61%, 64.9%, and 93.56% probabilities of the difference exceeding a null effect for shortened, middle, and lengthened, respectively. The probability these differences between conditions exceeded the ROPE was 7.5%, 9.21%, and 49.41% or the for shortened, middle, and lengthened, respectively. These results are visualized in Figure 8.

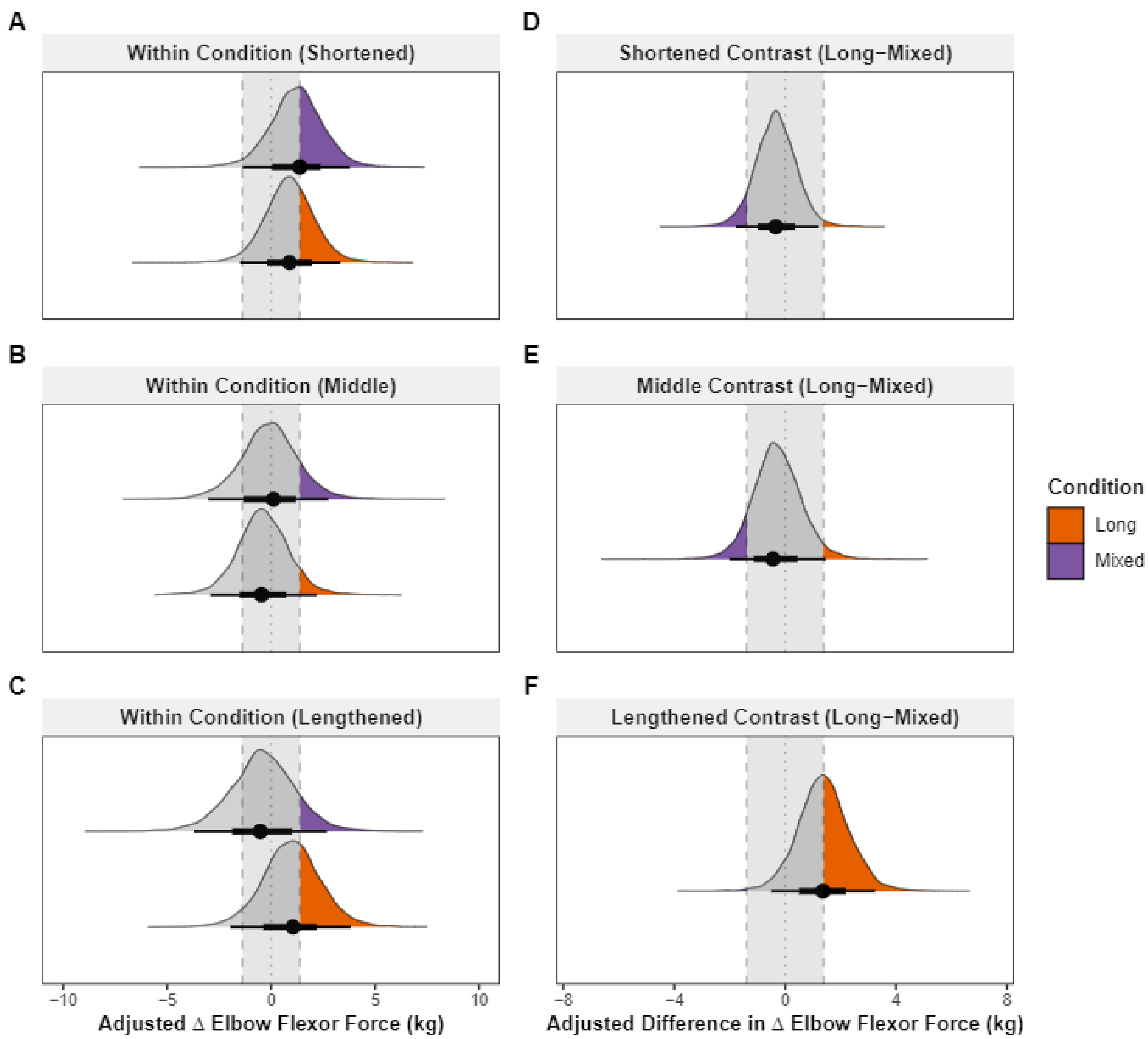

Figure 8: *Posterior distributions for changes in regional elbow flexor isometric strength. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by typical*

measurement error. Black dot and intervals represent the modal estimates and highest density intervals (66 and 95%) from the posterior distribution.

Dynamic Strength

The modal estimates of the posterior distributions suggest that both conditions demonstrated meaningful increases in dynamic strength. Specifically, the LONG condition observed modal changes of 3.67 kg [95% HDI: -0.77, 7.65] and 6.93 kg [95% HDI: 2.37, 11.86] for the shortened and lengthened cable curl, respectively. These changes resulted in 95.76% and 76.99% (shortened cable curl), and 99.51% and 97.86% (lengthened cable curl) probabilities of being greater than a null effect and the ROPE, respectively. The MIXED condition observed modal changes of 5.44 kg [95% HDI: 0.59, 9.78] and 6.57 kg [95% HDI: 0.35, 11.77] for the shortened and lengthened cable curl, respectively. These changes resulted in 98.52% and 92.31% (shortened cable curl), and 98.49% and 93.86% (lengthened cable curl) probabilities of being greater than a null effect and the ROPE, respectively. The modal estimates for the contrasts between conditions were -1.77 kg [95% HDI: -4.29, 0.82] and 0.52 kg [95% HDI: -3.1, 4.45] for the shortened and lengthened cable curl, respectively. These contrasts resulted in 91.27%, 65.5% probabilities of the difference exceeding a null effect for the shortened and lengthened cable curl, respectively. The probability the difference between conditions exceeded the ROPE was 35.27%, and 18.96% for the shortened and lengthened cable curl, respectively. These results are visualized in Figure 9.

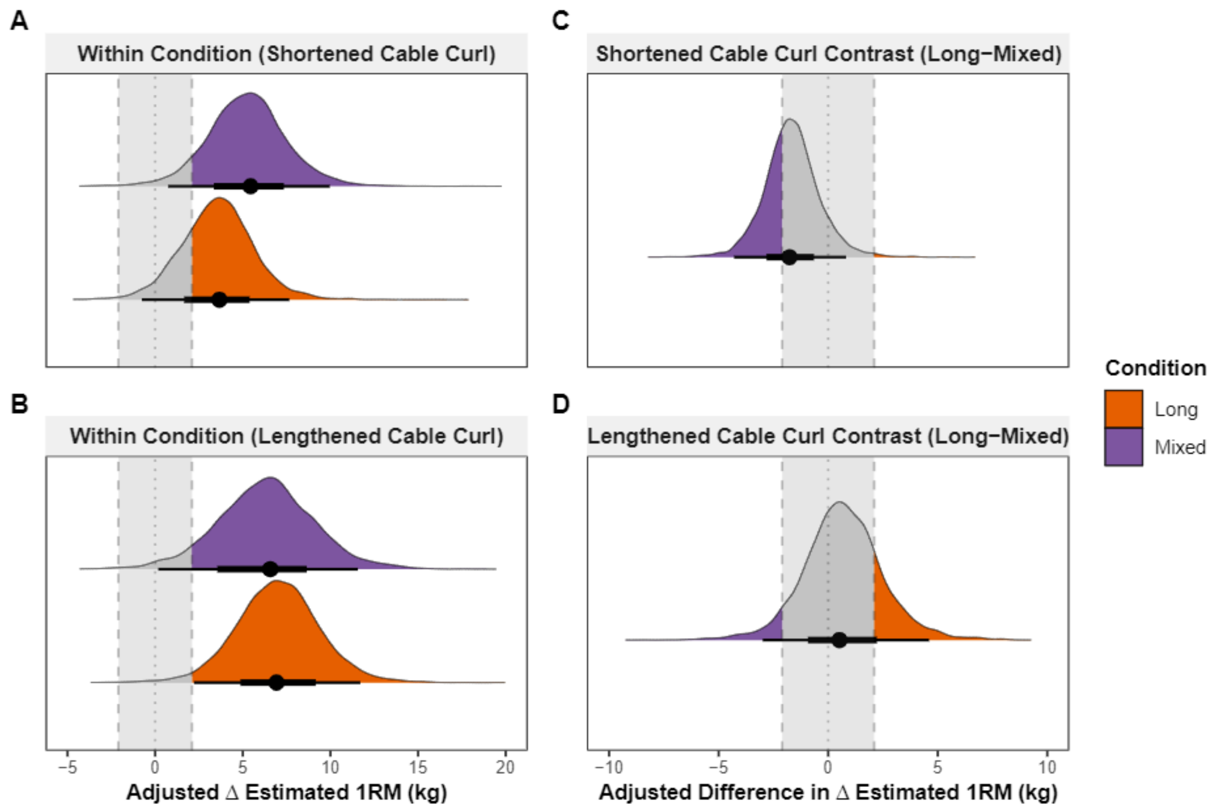

Figure 9: *Posterior distributions for changes in elbow flexor dynamic strength. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by the typical error of measurement. Black dot and intervals represent the modal estimates and highest density intervals (66 and 95%) from the posterior distribution*

Arm Circumference

The modal estimates of the posterior distributions suggest that gains in arm circumference seemed to be site-dependent. Specifically, the LONG condition observed modal changes of 0.14 mm [95% HDI: -1.45, 1.69], 0.58 mm [95% HDI: -1.2, 2.06], and 1.04 mm [95% HDI: -0.67, 2.85] for the proximal, middle, and distal regions, respectively. These changes resulted in 59.2% and 38.3% (proximal), 75.56% and 57.44% (middle), and 89.21% and 79.56% (distal) probabilities of being greater than a null effect and the ROPE, respectively. The MIXED condition observed modal changes of -0.28 mm [95% HDI: -2.18, 1.74], 0.08 mm [95% HDI: -1.99, 2.09], and 0.44 mm [95% HDI: -1.98, 2.31] for the proximal, middle, and distal regions, respectively. These changes resulted in 60.79% and 44.19% (proximal), 53.52% and 37.29% (middle), and 59.03% and 44.8% (distal) probabilities of being greater than a null effect and the

ROPE, respectively. The modal estimates for the contrasts between conditions were 0.33 mm [95% HDI: -0.92, 1.95], 0.46 mm [95% HDI: -1.06, 1.9], and 0.89 mm [95% HDI: -0.74, 2.4] for the proximal, middle, and distal regions, respectively. These contrasts resulted in 74.26%, 74.95%, and 87.06% probabilities of the difference exceeding a null effect for the proximal, middle, and distal regions, respectively. The probability these differences between conditions exceeded the ROPE was 52.19%, 54.39%, and 72.96% or the proximal, middle, and distal regions, respectively. These results are visualized in Figure 10.

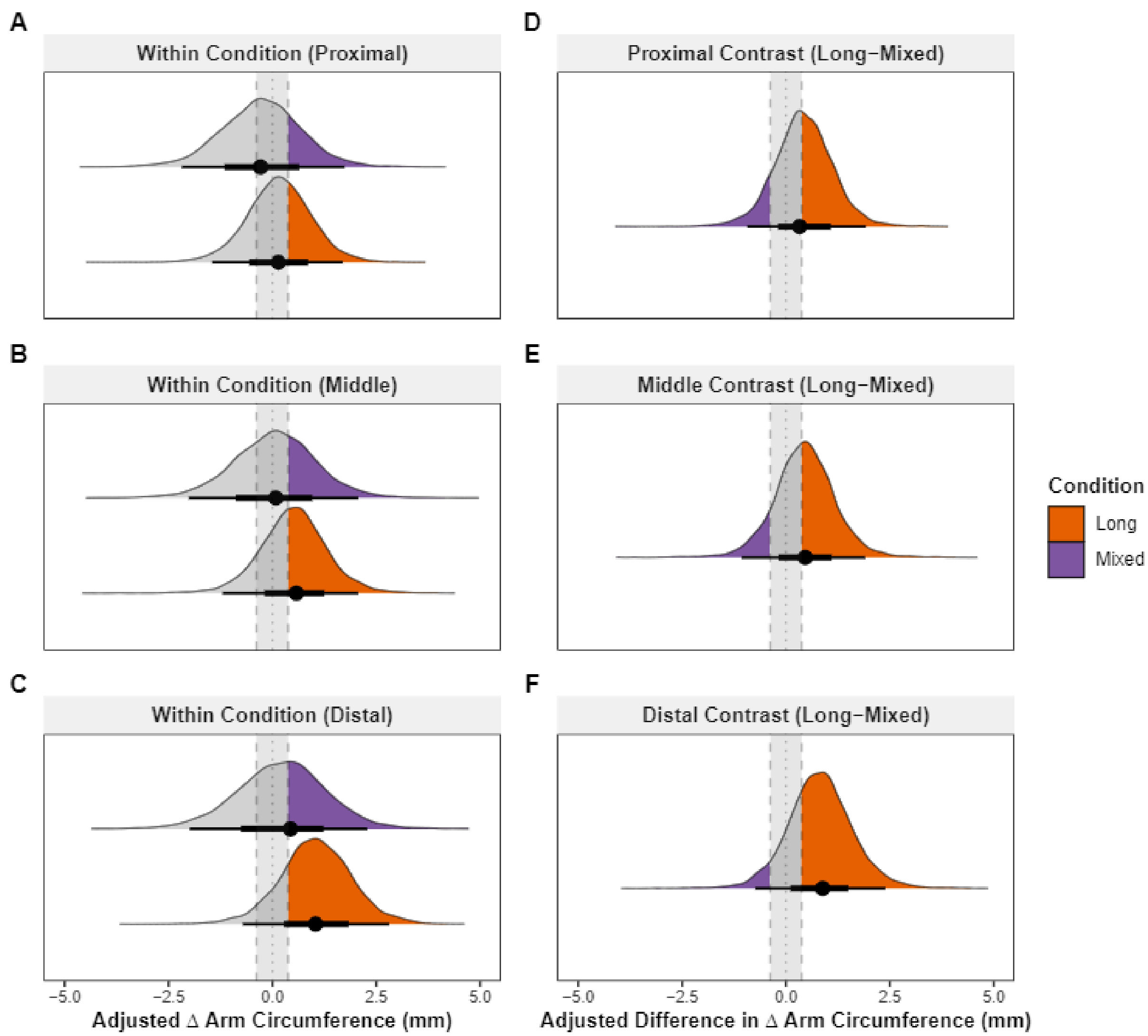

Figure 10: *Posterior distributions for changes in regional arm circumference. Vertical dashed lines represent the region of practical equivalence (i.e., ROPE) defined by typical measurement error.*

Black dot and intervals represent the modal estimates and highest density intervals (66 and 95%) from the posterior distribution.

Subjective Fatigue (sRPE and Soreness)

The modal estimates of the posterior distributions suggest that there were no meaningful differences in the perception of fatigue between conditions. Specifically, the modal estimate of session RPE was 4.87 a.u. [95% HDI: 3.38, 6.45] and 4.97 a.u. [95% HDI: 3.38, 6.47] for the Long and MIXED conditions, respectively. The modal estimate of the contrast in the change in session RPE over time between conditions was -0.15 a.u. [95% HDI: -0.77, 0.66] with an 57.34% probability of exceeding a null effect. Similarly, the modal estimate of soreness was 0.33 a.u. [95% HDI: -0.57, 1.24] and 0.26 a.u. [95% HDI: -0.63, 1.2] for the Long and MIXED conditions, respectively. The modal estimate of the contrast in the change in soreness over time between conditions was 0.16 a.u. [95% HDI: -0.16, 0.46] with an 81.51% probability of exceeding a null effect.

Discussion

The aim of this study was to compare changes in biceps strength and muscle size and temporal fatigue between training peak torque at longer muscle lengths (LONG) to training peak torque at both short and long muscle lengths (MIXED) in trained males and females. We hypothesized that participants would experience greater distal hypertrophy in the LONG condition. Additionally, we hypothesized that strength gains would be specific to the training style (i.e., greater strength gains at longer muscle lengths in LONG) and that temporal fatigue would be lower in MIXED. Our hypotheses were not supported and our main findings were: 1) there were no meaningful differences between conditions in regional or whole muscle hypertrophy (hypotheses not supported), 2) there were no meaningful differences in dynamic and isometric strength gains between conditions (hypothesis not supported), and 3) markers of fatigue were not different between conditions (hypothesis not supported). Overall, these findings suggest that performing exercises with the peak torque at only longer muscle length produces no meaningful difference in regional MT, whole muscle CSA, dynamic strength, isometric strength, and markers of fatigue compared to performing exercises with the peak torque at both shorter and longer muscle lengths.

Both the training conditions resulted in meaningful increases in total elbow flexor CSA (both >50% probability of exceeding ROPE). Participants in LONG experienced greater CSA increases than MIXED, but the difference was not considered meaningful due to a 48.96% probability of exceeding ROPE. The marginal difference favoring the LONG condition may be interpreted as evidence supporting the body of literature showing greater increases in whole muscle hypertrophy following training at long muscle lengths (5,6,7,23,24). Despite this, the absence of meaningful differences in total CSA is more closely aligned with previous research that has reported a small and non-significant difference between training with greater torque demand at longer muscle length and shorter muscle length (34). Further, It should be noted that although our analysis consisted of 14 observations per-condition in a within-participant design, a larger sample size is likely required to effectively detect the small effect for muscle growth that might be expected from manipulating the peak torque at different muscle lengths. Therefore, the present results should be interpreted with caution.

The regional MT outcomes of the present study did not support our prediction that the LONG condition would lead to greater changes in distal MT and that the MIXED condition would lead to greater changes in proximal MT. No difference was detected between conditions for the distal MT and there was a trivial difference in proximal MT that favored the MIXED condition but it was not considered meaningful. The lack of difference in regional MT did not reflect the small differences in total CSA that favored the LONG condition. We would expect the LONG condition's modal estimates of muscle thickness at one or either of the sites to be greater given the directionality of the total CSA modal estimates. Previous research has reported using more resistance at long muscle lengths when performing bicep curls leads to meaningful differences in distal hypertrophy of the biceps brachii (+9.8%, $p = 0.017$, ES = 0.623), although difference in distal hypertrophy between groups was not considered significant (25). Furthermore, previous research reports that distal portions of muscle may experience greater hypertrophy from longer muscle length training (5,23,24). The discrepancy between regional MT and total CSA outcomes could be due to limiting MT measurement to 2 sites (33% and 66% of muscle length) or measurement error. Also, It should be noted that our method for measuring regional MT is novel and has not been validated against magnetic resonance imaging; therefore, results should be interpreted with caution.

Arm circumference outcomes provided questionable support for the LONG condition. The difference of changes in distal circumference between conditions was considered meaningful in favor of the LONG condition (72.96% probability > ROPE). The differences at both the proximal and middle sites were also meaningful and favored the LONG condition but to a lesser extent than the distal site. The differences in arm circumference in favor of the LONG condition reflected the directionality of trivial changes in total CSA. It is important to note that the MIXED condition had a loss of circumference at the proximal site (-0.28 mm [95% HDI: -2.18, 1.74]), likely leading to the meaningful differences between the MIXED and LONG condition despite the changes in proximal circumference for the LONG condition not being meaningful (38.3% probability > ROPE). The lack of meaningful changes at the proximal site are interesting, but are consistent in changes of proximal hypertrophy reported in research using more resistance at longer muscle lengths as well as training at longer muscle lengths (5,23,25). Still, circumference measurements are a limited proxy of hypertrophy and do not account for changes in fat tissue, subcutaneous swelling, or other sources of measurement error. Therefore, arm circumference findings should be interpreted with caution and are of questionable relevance.

Dynamic strength outcomes were not meaningfully different between either condition on both the lengthened cable curl and shortened cable curl. The MIXED condition demonstrated marginally greater increases in strength compared to the LONG condition in the shortened cable curl. Still these results should be interpreted with caution as the differences in the lengthened cable curl (0.52 kg [95% HDI: -3.1, 4.45]) and shortened cable curl (-1.77 kg [95% HDI: -4.29, 0.82]) were not considered meaningful (18.96% probability > ROPE and 35.27% probability > ROPE, respectively). Our analysis would suggest there is no meaningful effect for using specific joint angles and different torque emphasis at specific muscle lengths to influence strength gains for a given exercise. Conversely, previous research reports that changes in strength reflect the specific ROM and even torque emphasis used while training (1,34).

Our investigation of isometric strength found that total changes in isometric strength marginally favored the LONG condition, but the difference between conditions was not considered meaningful (8.59% probability > ROPE). The changes in regional force were not substantial enough to be meaningful at a shortened (110° of elbow flexion), middle (90° of elbow flexion), lengthened (70° of elbow flexion) positions of elbow flexion for the LONG condition or for the MIXED condition. It is worth noting that despite no meaningful increase in regional force, the LONG condition was stronger at the lengthened position (1.36 kg [95% HDI: -0.49, 3.23], 49.41% probability > ROPE). The increase of lengthened isometric strength following training with greater resistance at longer muscle lengths has been reported in other research (34). Nunes et al. compared training preacher curls with a cable machine (torque emphasis at a short muscle length) or barbell (torque emphasis at a long muscle length) and found that isometric strength at 20° of elbow flexion was significantly greater for the group performing barbell preacher curls after 10 weeks of training (Cable: 30%; Barbell = 39%; $p = 0.046$). The results of the Nunes et al. align with the principle of specificity, but due to the paucity of research and the lack of meaningful differences in our study more research should be done to explore the relationship between training with greater resistance at long muscle lengths and isometric strength at longer muscle lengths.

There was no meaningful difference detected in session RPE and subjective soreness rating between conditions. The modal values for perceived soreness (0.33 a.u. [95% HDI: -0.57, 1.24] and 0.26 a.u. [95% HDI: -0.63, 1.2]) for the LONG and MIXED conditions suggest that participants experienced very little elbow flexor soreness throughout the training protocol. Also, the modal differences for session RPE showed virtually no difference in perception of difficulty for either condition. In contrast to our findings, previous evidence suggests training at longer muscle lengths leads to greater muscle damage than shorter muscle lengths (8). Nosaka et al. used a combination of subjective (perceived soreness) and objective markers (creatine kinase and isometric strength changes) which may be more sensitive to changes in soreness and fatigue. Also, the training protocol used by Nosaka et al. consisted of only eccentric actions which could lead to larger differences in perceptions of soreness. It is possible that the training protocol used in our study did not cause sufficient muscle damage or our subjective proxies of soreness and fatigue were not sensitive enough to detect differences. Therefore, we encourage caution in extrapolating the lack of between-group differences in soreness and fatigue to exercises that utilize more muscle mass (e.g., squatting pattern variations). Further, both conditions performed lengthened cable curls which could have mitigated any difference in perceptions of soreness or session RPE.

A small sample size may have caused our analysis to have insufficient power/precision for the detection of small effects. Given this limitation, interpretation of all outcomes should be made with caution. Further, the sample consisted of well-trained people which may explain small changes in hypertrophy outcomes marginalized over both 10 week training periods. The washout period (6-8 wks) was not controlled between-participants, but participants were asked to return to their habitual training being performed prior to the study (thus, within participant training was controlled), which could have contributed further to the lack of clear changes in hypertrophy outcomes. Further, the difference in the training programs between conditions was intentionally made to reflect an ecologically valid comparison. Consequently, the proportion of the training program that was different between conditions was modest, potentially reducing the expected effect size - making it harder to detect with small sample sizes.

Other limitations include possible measurement error from using panoramic b-mode ultrasonography to measure total CSA. The validity and reliability of panoramic ultrasound for measuring skeletal muscle can vary based upon the muscle site measured and the experience of the investigator (41). Using ImageJ to segment panoramic ultrasound scans is a novel method of measuring regional MT. Longitudinal changes in regional MT could have been attributed to differences in the segmentation process independent of muscle growth or other errors in measurement. Also, these results can not be extrapolated to other exercises or muscles.

Conclusion

In summary, regional muscle thickness at 33% and 66% of the elbow flexor length and isometric strength did not meaningfully increase for either condition. There was no meaningful difference in dynamic strength between the LONG and MIXED conditions, despite meaningful increases for both conditions. There was no meaningful difference in whole muscle CSA between LONG and MIXED conditions, despite meaningful increases in both training conditions. However, There were meaningful differences in arm circumference outcomes that favored the LONG condition at 30%, 50% and 70% of arm length. It is important to emphasize that the accretion of muscle mass is not the only potential contribution to arm circumference and is likely less sensitive to accurate training effects. Differences in session RPE and soreness were not meaningful between conditions, indicating similar fatigue and perceptual responses to the two training conditions. Given the lack of meaningful differences between conditions and the questionable relevance of circumference measurements, It seems that neither training condition provides clearly superior outcomes for hypertrophy, strength, or perceptual fatigue.

Disclosure

Supplementary Materials All data, code, and other supplementary files can be accessed at https://osf.io/3v8ef/.

Acknowledgements The authors would like to thank the participants for their time and effort.

Conflict of Interest Seth Hinson, Zac Robinson, Joshua Pelland, and Michael Zourdos are all coaches and writers in the fitness industry. Shawn Dinh, Ethan Elkins, Caitlyn Meehan, David Diaz, Brian Benitez, Christian Macarilla, and Michael Morgan declare that they have no conflicts of interest relevant to the content of this review.

References

1. Wolf, M., Androulakis-Korakakis, P., Fisher, J., Schoenfeld, B., & Steele, J. (2023). Partial Vs Full Range of Motion Resistance Training: A Systematic Review and Meta-Analysis. International Journal of Strength and Conditioning, 3(1). https://doi.org/10.47206/ijsc.v3i1.182
2. Costa, B. D. V., Kassiano, W., Nunes, J. P., Kunevaliki, G., Castro-E-Souza, P., Rodacki, A., Cyrino, L. T., Cyrino, E. S., & Fortes, L. S. (2021). Does Performing Different Resistance Exercises for the Same Muscle Group Induce Non-homogeneous Hypertrophy?. International journal of sports medicine, 42(9), 803–811. https://doi.org/10.1055/a-1308-3674
3. Kassiano, Witalo1; Nunes, João Pedro1; Costa, Bruna1; Ribeiro, Alex S.1,2; Schoenfeld, Brad J.3; Cyrino, Edilson S.1. Does Varying Resistance Exercises Promote Superior Muscle Hypertrophy and Strength Gains? A Systematic Review. Journal of Strength and Conditioning Research 36(6):p 1753-1762, June 2022. | DOI: 10.1519/JSC.0000000000004258
4. Zabaleta-Korta, A., Fernández-Peña, E., Torres-Unda, J., Garbisu-Hualde, A., & Santos-Concejero, J. (2021). The role of exercise selection in regional Muscle Hypertrophy: A randomized controlled trial. Journal of sports sciences, 39(20), 2298–2304. https://doi.org/10.1080/02640414.2021.1929736
5. Pedrosa, G. F., Lima, F. V., Schoenfeld, B. J., Lacerda, L. T., Simões, M. G., Pereira, M. R., Diniz, R. C. R., & Chagas, M. H. (2022). Partial range of motion training elicits favorable improvements in muscular adaptations when carried out at long muscle lengths. European journal of sport science, 22(8), 1250–1260. https://doi.org/10.1080/17461391.2021.1927199
6. Maeo, S., Huang, M., Wu, Y., Sakurai, H., Kusagawa, Y., Sugiyama, T., Kanehisa, H., & Isaka, T. (2021). Greater Hamstrings Muscle Hypertrophy but Similar Damage Protection after Training at Long versus Short Muscle Lengths. Medicine and science in sports and exercise, 53(4), 825–837. https://doi.org/10.1249/MSS.0000000000002523
7. Maeo, S., Wu, Y., Huang, M., Sakurai, H., Kusagawa, Y., Sugiyama, T., Kanehisa, H., & Isaka, T. (2022). Triceps brachii hypertrophy is substantially greater after elbow extension training performed in the overhead versus neutral arm position. European journal of sport science, 1–11. Advance online publication. https://doi.org/10.1080/17461391.2022.2100279
8. Nosaka, K., Newton, M., Sacco, P., Chapman, D., & Lavender, A. (2005). Partial protection against muscle damage by eccentric actions at short muscle lengths.

Medicine and science in sports and exercise, 37(5), 746–753. https://doi.org/10.1249/01.mss.0000162691.66162.00

9. Oranchuk, D. J., Hopkins, W. G., Nelson, A. R., Storey, A. G., & Cronin, J. B. (2021). The effect of regional quadriceps anatomical parameters on angle-specific isometric torque expression. Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme, 46(4), 368–378. https://doi.org/10.1139/apnm-2020-0565
10. Noorkõiv, M., Nosaka, K., & Blazevich, A. J. (2014). Neuromuscular adaptations associated with knee joint angle-specific force change. Medicine and science in sports and exercise, 46(8), 1525–1537. https://doi.org/10.1249/MSS.0000000000000269
11. Stark M, Lukaszuk J, Prawitz A, Salacinski A. Protein timing and its effects on muscular hypertrophy and strength in individuals engaged in weight-training. Journal of the International Society of Sports Nutrition [Internet]. 2012;9(1) Available from: https://doi.org/10.1186/1550-2783-9-54. doi:10.1186/1550-2783-9-54.
12. Tang JE, Moore DR, Kujbida GW, Tarnopolsky MA, Phillips SM. Ingestion of whey hydrolysate, casein, or soy protein isolate: Effects on mixed muscle protein synthesis at rest and following resistance exercise in young men. Journal of Applied Physiology. 2009;107(3):987–92.
13. Pelland, J. C., Robinson, Z. P., Remmert, J. F., Cerminaro, R. M., Benitez, B., John, T. A., Helms, E. R., & Zourdos, M. C. (2022). Methods for Controlling and Reporting Resistance Training Proximity to Failure: Current Issues and Future Directions. Sports medicine (Auckland, N.Z.), 52(7), 1461–1472. https://doi.org/10.1007/s40279-022-01667-2
14. Helms, E. R., Byrnes, R. K., Cooke, D. M., Haischer, M. H., Carzoli, J. P., Johnson, T. K., Cross, M. R., Cronin, J. B., Storey, A. G., & Zourdos, M. C. (2018). RPE vs. Percentage 1RM Loading in Periodized Programs Matched for Sets and Repetitions. Frontiers in physiology, 9, 247. https://doi.org/10.3389/fphys.2018.00247
15. Miyatani, M., Kanehisa, H., Ito, M., Kawakami, Y., & Fukunaga, T. (2004). The accuracy of volume estimates using ultrasound muscle thickness measurements in different muscle groups. European journal of applied physiology, 91(2-3), 264–272. https://doi.org/10.1007/s00421-003-0974-4
16. Jenkins, N. D., Miller, J. M., Buckner, S. L., Cochrane, K. C., Bergstrom, H. C., Hill, E. C., Smith, C. M., Housh, T. J., & Cramer, J. T. (2015). Test-Retest Reliability of Single Transverse versus Panoramic Ultrasound Imaging for Muscle Size and Echo

Intensity of the Biceps Brachii. Ultrasound in medicine & biology, 41(6), 1584–1591. https://doi.org/10.1016/j.ultrasmedbio.2015.01.017

17. Stokes, T., Tripp, T.R., Murphy, K., Morton, R.W., Oikawa, S.Y., Lam Choi, H., McGrath, J., McGlory, C., MacDonald, M.J. and Phillips, S.M. (2021), Methodological considerations for and validation of the ultrasonographic determination of human skeletal muscle hypertrophy and atrophy. Physiol Rep, 9: e14683. https://doi.org/10.14814/phy2.14683
18. Goldsmith JA, Trepeck C, Halle JL, et al. Validity of the open barbell and tendo weightlifting analyzer systems versus the optotrak certus 3D motion-capture system for barbell velocity. International Journal of Sports Physiology and Performance. 2019;14(4):540–3.
19. Laurent CM, Green JM, Bishop PA, et al. A practical approach to monitoring recovery: Development of a perceived recovery status scale. Journal of Strength and Conditioning Research. 2011;25(3):620–8.
20. Colquhoun RJ, Gai CM, Walters J, et al. Comparison of powerlifting performance in trained men using traditional and flexible daily undulating periodization. Journal of Strength and Conditioning Research. 2017;31(2):283–91.
21. Day ML, McGuigan MR, Brice G, Foster C. Monitoring exercise intensity during resistance training using the session RPE scale. The Journal of Strength and Conditioning Research. 2004;18(2):353.
22. Vickers, Andrew. (2001). Time course of muscle soreness following different types of exercise. BMC musculoskeletal disorders. 2. 5. 10.1186/1471-2474-2-5.
23. Pedrosa, G. F., Simões, M. G., Figueiredo, M. O. C., Lacerda, L. T., Schoenfeld, B. J., Lima, F. V., Chagas, M. H., & Diniz, R. C. R. (2023). Training in the Initial Range of Motion Promotes Greater Muscle Adaptations Than at Final in the Arm Curl. Sports (Basel, Switzerland), 11(2), 39. https://doi.org/10.3390/sports11020039
24. Kassiano, W., Costa, B., Kunevaliki, G., Soares, D., Zacarias, G., Manske, I., Takaki, Y., Ruggiero, M. F., Stavinski, N., Francsuel, J., Tricoli, I., Carneiro, M. A. S., & Cyrino, E. S. (2023). Greater Gastrocnemius Muscle Hypertrophy After Partial Range of Motion Training Performed at Long Muscle Lengths. Journal of strength and conditioning research, 10.1519/JSC.0000000000004460. Advance online publication. https://doi.org/10.1519/JSC.0000000000004460
25. Zabaleta-Korta, A., Fernández-Peña, E., Torres-Unda, J., Francés, M., Zubillaga, A., Santos-Concejero, J. (2023). Regional Hypertrophy: The Effect of Exercises at Long and Short Muscle Lengths in Recreationally Trained Women. Journal of Human Kinetics, 88, 259-270. https://doi.org/10.5114/jhk/163561

26. Amrhein V, Greenland S, McShane B. Scientists rise up against statistical significance. Nature [Internet]. 2019;567:305–7. Available from: https://doi.org/10.1038/d41586-019-00857-9
27. Kruschke JK, Liddell TM. The bayesian new statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a bayesian perspective. Psychonomic Bulletin & Review [Internet]. 2017;25:178–206. Available from: https://doi.org/10.3758/s13423-016-1221-4
28. Mengersen KL, Drovandi CC, Robert CP, Pyne DB, Gore CJ. Bayesian estimation of small effects in exercise and sports science. Chen CWS, editor. PLOS ONE [Internet]. 2016;11:e0147311. Available from: https://doi.org/10.1371/journal.pone.0147311
29. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. The Journal of Strength and Conditioning Research [Internet]. 2005;19:231. Available from: https://doi.org/10.1519/15184.1
30. Swinton PA, Hemingway BS, Saunders B, Gualano B, Dolan E. A statistical framework to interpret individual response to intervention: Paving the way for personalized nutrition and exercise prescription. Frontiers in Nutrition [Internet]. 2018;5. Available from: https://doi.org/10.3389/fnut.2018.00041
31. Barr DJ, Levy R, Scheepers C, Tily HJ. Random effects structure for confirmatory hypothesis testing: Keep it maximal. Journal of Memory and Language (Internet). 2013;68:255–78. Available from: https://doi.org/10.1016/j.jml.2012.11.001
32. Oberauer K. The importance of random slopes in mixed models for bayesian hypothesis testing. Psychological Science (Internet). 2022;33:648–65. Available from: https://doi.org/10.1177/09567976211046884
33. Swinton P. Adequate statistical power in strength and conditioning may be achieved through longer interventions and high frequency outcome measurement. 2024; Available from: http://dx.doi.org/10.51224/SRXIV.364
34. Nunes, J. P., Jacinto, J. L., Ribeiro, A. S., Mayhew, J. L., Nakamura, M., Capel, D. M. G., Santos, L. R., Santos, L., Cyrino, E. S., & Aguiar, A. F. (2020). Placing Greater Torque at Shorter or Longer Muscle Lengths? Effects of Cable vs. Barbell Preacher Curl Training on Muscular Strength and Hypertrophy in Young Adults. International journal of environmental research and public health, 17(16), 5859. https://doi.org/10.3390/ijerph17165859
35. Stasinaki A-N, Zaras N, Methenitis S, Tsitkanou S, Krase A, Kavvoura A, Terzis G. Triceps Brachii Muscle Strength and Architectural Adaptations with Resistance Training Exercises at Short or Long Fascicle Length. Journal of Functional

Morphology and Kinesiology. 2018; 3(2):28.
https://doi.org/10.3390/jfmk3020028

36. Landin, D., Thompson, M., & Jackson, M. R. (2017). Actions of the Biceps Brachii at the Shoulder: A Review. Journal of clinical medicine research, 9(8), 667–670. https://doi.org/10.14740/jocmr2901w
37. Scott, J. M., Martin, D. S., Ploutz-Snyder, R., Caine, T., Matz, T., Arzeno, N. M., Buxton, R., & Ploutz-Snyder, L. (2012). Reliability and validity of panoramic ultrasound for muscle quantification. Ultrasound in medicine & biology, 38(9), 1656–1661. https://doi.org/10.1016/j.ultrasmedbio.2012.04.018
38. Wilkinson, K., Koscien, C. P., Monteyne, A. J., Wall, B. T., & Stephens, F. B. (2023). Association of postprandial postexercise muscle protein synthesis rates with dietary leucine: A systematic review. Physiological reports, 11(15), e15775. https://doi.org/10.14814/phy2.15775
39. Wolf, Milo & Androulakis-Korakakis, Patroklos & Piñero, Alec & Mohan, Adam & Hermann, Tom & Augustin, Francesca & Sappupo, Max & Lin, Brian & Coleman, Max & Burke, Ryan & Nippard, Jeff & Swinton, Paul & Schoenfeld, Brad. (2024). Lengthened Partial Repetitions Elicit Similar Muscular Adaptations as a Full Range of Motion During Resistance Training in Trained Individuals. 10.51224/SRXIV.455.
40. Zourdos MC, Henning PC, Jo E, Khamoui AV, Lee SR, Park YM, Naimo M, Panton LB, Nosaka K, Kim JS. Repeated Bout Effect in Muscle-Specific Exercise Variations. J Strength Cond Res. 2015 Aug;29(8):2270-6. doi: 10.1519/JSC.0000000000000856. PMID: 25647658.
41. Hernández-Belmonte, A., Martínez-Cava, A., & Pallarés, J. G. (2022). Panoramic ultrasound requires a trained operator and specific evaluation sites to maximize its sensitivity: A comprehensive analysis of the measurement errors. Physiology & behavior, 248, 113737. https://doi.org/10.1016/j.physbeh.2022.113737