The Effect of Resistance Training Proximity to Failure on Muscular Adaptations and Longitudinal Fatigue in Trained Men

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ABSTRACT

Purpose: This study examined the effect of proximity to failure on hypertrophy, strength, and fatigue. We hypothesized strength gains would be superior in non-failure groups compared to those that include sets to momentary failure, while hypertrophy would be similar in all groups. Methods: 38 men were randomized into four groups (4–6 rating of perceived exertion-RPE per set, 7–9 RPE per set, 7–9+ RPE [last set taken to momentary failure], and 10 RPE per set) and completed an eight-week program. Back squat and bench press strength, muscle thickness, subjective fatigue, muscle soreness, and biomarkers (creatine kinase-CK and lactate dehydrogenase-LDH) were assessed. Results: Bench Press strength gains were comparable between the 4–6 RPE (9.05 kg [95% CI: 6.36, 11.76]) and 7–9 RPE (9.72 kg [95% CI: 7.03, 12.42]) groups, while outcomes in the 7–9+ (5.07 kg [95% CI: 2.05, 8.1]) and 10 RPE (0.71 kg [95% CI: -4.51, 5.54]) groups were slightly inferior. Squat strength gains were comparable between 4–6 RPE (13.79 kg [95% CI: 7.54, 19.92]) and 7–9 RPE (18.05 kg [95% CI: 12.28, 23.99]) groups, but data for 7–9+ RPE and 10 RPE are difficult to interpret due to poor feasibility of the protocols. For muscle hypertrophy, our data do not provide strong conclusions as to the effects of proximity to failure due to the large variability observed. The indices of fatigue were largely comparable between groups, without strong evidence of the repeated bout effect. Conclusion: These data suggest strength outcomes are comparable when taking sets to either a self-reported 4–6 RPE or 7–9 RPE, while training that includes sets to momentary failure may result in slightly inferior outcomes (i.e., 7–9+ and 10 RPE). However, the influence of proximity to failure on hypertrophy remains unclear and our data did not reveal clear differences between groups in any measure of fatigue.

Key Words: RESISTANCE TRAINING, PROXIMITY TO FAILURE, MUSCULAR ADAPTATIONS, LONGITUDINAL FATIGUE

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1 INTRODUCTION

The necessity of performing resistance training sets to failure to maximize muscle hypertrophy and strength remains unclear. Recently, meta-analyses from Grgic et al. [1] and Vieira et al. [2] found that increases in strength and muscle hypertrophy were not significantly different ($p = 0.237–0.860$, SMD = 0.01–0.59) between training to or not to failure when volume is equated. However, these meta-analyses examine proximity to failure in binary (i.e., training to or not to failure) rather than investigating dose-response relationship (i.e., how does training to a 1 repetition in reserve [RIR] influence strength and hypertrophy outcomes compared to 2 RIR, and 3 RIR, etc.); thus, the minimum proximity to failure needed to maximize adaptations is unknown. Additionally, training to failure has been shown to elongate acute recovery time courses [3]; possibly compromising training performance. Thus, in addition to examining the dose-response relationship between RIR with and training outcomes, more information is needed regarding how a given proximity to failure influences recovery over time.

Recent studies [4–6] that have examined multiple submaximal proximities to failure reported that non-failure training may lead to superior strength gains due to better maintenance of barbell velocity. For example, Pareja-Blanco et al. [4] reported trivial to small effect sizes ($d = 0.10–0.35$) for Smith machine squat strength improvement over eight weeks in favor of trained men who did not train to failure (i.e., 0, 10, and 20% velocity losses) versus a group that trained with a high-velocity loss (i.e., 40% velocity loss) which likely resulted in most sets reaching failure [7]. Importantly, the proximity to failure (i.e., repetitions in reserve-RIR) on each set was not directly quantified; however, the 0, 10, and 20% velocity loss groups had faster average concentric velocities (ACV) across all sets (0.74 ± 0.11, 0.71 ± 0.07, 0.64 ± 0.06 $m \cdot s^{-1}$, respectively) compared to the 40% velocity loss group (0.58 ± 0.06 $m \cdot s^{-1}$). However, a limitation of this study was that total repetition volume was not equated, with a range of 181–637% more repetitions performed in the high-velocity loss group (i.e., 40% velocity loss). Thus, it is unclear which factor (i.e., proximity to failure or repetition volume) mediate the differential strength gains.

Regarding hypertrophy, most recent data have reported either comparable muscle growth between conditions training to and not to failure [8–10], with a minority of studies favoring training to [11,12], or not to failure [13]. However, despite the mixed findings of most studies, similar to strength, proximity to failure has not been directly quantified making it difficult to infer the RIR required to maximize hypertrophy. For example, using a within-participants design, Santanielo et al. 2020 [10] reported no significant difference in vastus lateralis cross-sectional area between limbs training to or not to failure over ten weeks on the unilateral leg press and knee extension at 75–80% of 1RM. Further, Santanielo et al. [10] reported that the participants performed 12.0 ± 2.1 repetitions per set when training to failure versus 10.4 ± 2.8 repetitions per set in the limb not training to failure; however, RIR was not directly quantified. Carroll et al. [13] also reported effect sizes in favor of not training to failure for type I (g = 0.27) and type II (g = 0.99) fiber hypertrophy of the vastus lateralis, but did not directly quantify the number of RIR after each set. However, the prescription of the group not training to failure suggests a wide range of per set RIR (estimated ~1–8 RIR); thus, the minimum proximity to failure to maximize muscle hypertrophy remains unclear.

Although training to failure may be a viable option, a recent meta-analysis [3] has shown that recovery time courses are elongated by 24–48 hours and are associated with greater session rating of perceived exertion (sRPE) [8]. Consequently, if training a muscle group 2-3 times per week, weekly volume load could be negatively affected. However, all studies included in the Vieira et al. meta-analysis examined recovery time course following a single training session. Therefore, it is unknown if the repeated bout effect (RBE) would manifest following chronic exposure to failure training and the recovery differences would be inconsequential over time. If the longer recovery time courses are not mitigated over time, then training to failure may lack long-term feasibility [14].

Therefore, the purpose of this study was to compare muscle hypertrophy and strength outcomes among trained men using four different volume-equated resistance training protocols with a different number of self-reported RIR per set (i.e., 4-6 RIR, 1-3 RIR, 0-3 RIR, 0 RIR). A secondary aim was to assess the change in acute fatigue (i.e., indirect markers of muscle damage, barbell velocity, and subjective fatigue scales) over the course of the eight-week protocol. We hypothesized larger strength gains in both submaximal training groups compared to the groups that included some sets to failure, but similar hypertrophy between groups.

2 METHODS

2.1 Participants. Thirty-eight males between the ages of 18–40 were recruited. For inclusion, participants needed to have at least 2 years of resistance training experience as determined by a physical activity questionnaire. Participants were required to have a 1RM squat of at least 1.25 times body mass, and 1RM bench press of at least 1 times body mass. Further, participants with contraindications to exercise (i.e., heart disease, hypertension, diabetes, etc.) as determined via a health history questionnaire were excluded. Prior to participation, all participants provided written consent and the University's Institutional Review Board approved this investigation. Six participants dropped out of the study (n = 3 in 7–9+ RPE and n = 3 in 10 RPE) due to training related discomfort and/or injury. At the investigators' discretion, the 10 RPE group was terminated due to safety concerns. Data of participants that completed the 10 RPE protocols was analyzed, but the small sample size warrants extreme caution. Similarly, the lower body training protocol of the 7–9+ RPE group was altered mid-intervention (i.e., participants trained with the 4–6 RPE protocol for over half of the intervention) at the investigator's discretion. Therefore, the 7–9+ group was not analyzed for any lower body or systemic outcomes; however all raw data is provided in supplementary file 0. Additionally, one participant in the 4–6 RPE group was removed from lower body and systemic outcomes due to training related discomfort that required significant modification to the squat training. Another participant in the 4–6 RPE group was uncomfortable with blood draws and thus was removed for systemic outcomes. Participant characteristics for all 4 groups can be seen in Table 1.

Characteristic	**4-6 RPE** (n=10)	**7-9 RPE** (n=10)	**7-9+ RPE** (n=9)	**10 RPE** (n=3)
Age (years)	22.50 ± 3.21	23.30 ± 3.09	21.33 ± 2.78	21.67 ± 2.08
Height (cm)	177.51 ± 5.75	174.95 ± 6.14	173.19 ± 6.23	168.03 ± 3.57
Pre Body Mass (kg)	81.33 ± 12.04	82.05 ± 12.82	78.24 ± 7.46	78.68 ± 14.37
Post Body Mass (kg)	82.61 ± 12.19	83.15 ± 13.14	79.33 ± 9.05	77.98 ± 15.49
Δ Body Mass (kg)	1.28 ± 1.64	1.10 ± 0.69	1.09 ± 2.87	-0.70 ± 2.08
Pre Sum of Skinfolds (mm)	32.20 ± 8.98	31.40 ± 11.16	29.94 ± 9.52	31.50 ± 12.49
Post Sum of Skinfolds (mm)	35.32 ± 7.18	33.70 ± 13.51	33.44 ± 9.77	35.50 ± 14.00
Δ Sum of Skinfolds (mm)	3.12 ± 3.86	2.30 ± 3.70	3.50 ± 2.59	4.00 ± 5.29
Pre Estimated Body Fat (%)	15.42 ± 3.41	15.24 ± 4.60	14.35 ± 3.18	14.90 ± 5.34
Post Estimated Body Fat (%)	16.42 ± 3.02	15.94 ± 5.31	15.46 ± 3.36	16.15 ± 5.94
Δ Estimated Body Fat (%)	1.00 ± 1.25	0.70 ± 1.16	1.11 ± 0.82	1.25 ± 1.68

Table 1: *Participant descriptive data. Data are mean ± standard deviation*

2.2 Experimental Design. The purpose of this study was to compare hypertrophy, strength gains, and markers of both subjective and objective fatigue over eight weeks between four training groups. Participants were counterbalanced by relative strength into four training groups in which each set's proximity to failure was controlled by an RIR-based RPE rating: 4–6 RPE, 7–9 RPE, 7–9+ RPE, 10 RPE. This intended groups to train at an average of 4–6 RIR, 1–3 RIR, 1–3 RIR with the last set of each session taken to failure on each exercise, and all sets taken to failure, respectively. All groups trained the squat and bench press three times per week on non-consecutive days (i.e., Monday, Wednesday, and Friday). Participants reported to the laboratory a total of 25 days over eight consecutive weeks. Pre- and post-study testing for 1RM squat and bench press, MT of the quadriceps and chest, and anthropometrics took place 48–72 hours prior to and after weeks 1 and 8; respectively. In week 1, following baseline testing, participants performed a group-specific introductory microcycle. Weeks 2–7 served as the main training program followed by a group-specific taper during week 8 to prepare for post-study testing. To examine temporal recovery and the occurrence of the RBE, blood was collected, and muscle soreness was assessed immediately before and after training on days 1 and 2 (i.e., Monday and Wednesday) of weeks 1, 2, and 7. Readiness, motivation to train and acute global fatigue were assessed before and after each training session using the perceived recovery status (PRS), motivation to train (MTT), and session RPE (sRPE) scales; respectively. Additionally, average concentric velocity (ACV $m \cdot s^{-1}$) was assessed on every repetition of every training session to verify different proximities to failure between conditions.

To control for pre- and post-exercise nutrient timing, participants ingested a Branched Chain Amino Acid (BCAA) (BCAA, Core Nutritionals, LLC, Arlington, Virginia, United States of America, 22203) supplement containing 3.5g of leucine, 1.75g of Isoleucine, 1.75g of Valine (Ratio of 2:1:1), and 2.5g of glutamine 30 minutes prior to each testing and training session. Immediately following each training session 30g of whey protein (Core Pro, Core Nutritionals, LLC, Arlington, Virginia, United States of America, 22203), containing 3.5g of leucine, was ingested by each subject. These nutrient portions were selected as 3.5g of leucine is the threshold to maximally stimulate the process of muscle protein synthesis (MPS) [15]. Stimulating MPS prior to and following high intensity resistance training significantly augments performance [16]. Both BCAA and whey protein were consumed in powdered form with 10 oz. of water. Participants were also instructed to discontinue all other supplementation for the duration of the study.

2.3 Training Program. All groups trained three times per week on non-consecutive days and the number of sets and repetitions were the same with only a set's proximity to failure (4–6 RPE, 7–9 RPE, 7–9+ RPE, or 10 RPE) differing between groups, as seen in supplementary file 1. Further, rest periods of 3–5 minutes were administered between all sets for all groups. During week 1 all groups performed group-specific introductory training with reduced volume and RPE targets. Investigators selected all loads during week 1 using subject-reported RIR-based RPE of previous sets in addition to barbell velocity and apparent set difficulty. The investigators explained their load selection decisions to participants to further familiarize them with protocol expectations since participants selected their own training loads for the rest of the training program. The main training program occurred between weeks 2–7. For weeks 2 and 3, an undulating periodized repetition pattern of 10, 8, and 6 was followed on session 1, 2, and 3 (e.g., Monday, Wednesday, Friday), respectively. In weeks 4 and 5, the undulation pattern was 9, 7, and 5 repetitions. In weeks 6 and 7, the undulation pattern decreased, again, to 8, 6, and 4 repetitions. The final training week was a taper microcycle where each participant performed sets with the average load lifted throughout the training program within that session (e.g., 7 weeks of session 1 loads averaged). 2 sets of 4 repetitions and 2 sets of 2 repetitions were performed in session 1 and session 2, respectively. At the completion of each set, participants were asked to report an RIR-based RPE value. The above protocol was performed on the back squat and bench press exercises. Additionally, to aid in participant recruitment and train more muscle groups, all participants performed assistance exercises (barbell overhead press, barbell row, barbell lying triceps extension, barbell curl, and dumbbell lateral raise) to an 8 RPE and with the same exact prescription. All repetitions were performed with a controlled eccentric tempo and habitual concentric intended velocity. Failure was defined as the inability to perform a repetition through its full range of motion despite maximal effort to do so or the point at which a subject did not feel comfortable attempting another repetition. However, a distinction was made in record keeping between sets that reached momentary failure as defined by Steele et al. [17] (i.e., 11 RPE) and those that were terminated volitionally (i.e., 10 RPE).

2.4 Training Load Instruction and Adjustments. The following script was read to each participant while being shown the RIR-based RPE scale before each testing and training session:

"*Please view this scale to remind you of how RPE is scored. Today, working sets should fall within the RPE range of insert RPE range assigned for the week. Use your knowledge of your prior performances* *and how the warm-up sets felt to select a load you believe will fall within the assigned RPE range. The goal is to maintain your loads in a subsequent fashion, therefore, if the load you select falls above or below the target RPE range, an increase or decrease in load will occur on the next set. If you fall within the target RPE range, you have the freedom to increase or decrease load as you see fit so long as you believe this modified load will still fall within the target RPE range. Avoid being overly conservative or aggressive in your load selection and expect your RPE to rise with each set as fatigue accumulates.*"

In terms of the specific intra-session set-to-set load adjustments, if the 4–6 and 7–9 RPE groups either under- or over-shot the desired RPE range, load was increased or decreased by 2% for every 0.5 RPE value from the middle of the range in accordance with Helms et al. 2018 [18]. For all sets except the final set of each session in the 7–9+ RPE group, if the subject-reported RIR-based RPE was under or over the desired RPE range of 7–9, load was increased or decreased by 2% for every 0.5 RPE value from the range for the subsequent set in accordance with Helms et al. [18]. Prior to the final set of each session of weeks 2–7, participants were informed that the goal of the final set was to select a load that would lead to failure after reaching the session's repetition target (e.g., failing repetition 11 if the repetition target is 10). If the second-to-final set was in the RPE 7–9 range, the participant selected the load for the final set based on these instructions. If the RIR-based RPE for the previous set was under or over the desired RPE range of 7–9, load was maintained or increased by 2% for every 0.5 RPE value from the desired 10 RPE on the upcoming set.

For the 10 RPE group, load adjustments were made based upon repetitions performed compared to the prescribed number of repetitions. Pilot testing was conducted on five individuals prior to data collection to determine the appropriate set-to-set loading changes with the goal that following a set to failure the participant would be able to complete the prescribed number of repetitions during the next set to failure. Pilot testing revealed that a 2% reduction in load should be made from set 1 to 2 to account for fatigue from training to failure no matter if the target repetition number was met or not. However, this 2% fatigue adjustment was not applied in sets thereafter. Further, pilot testing revealed that a 1% loading change (increase or decrease) should be applied from set-to-set for the difference in repetitions performed and the prescribed number of repetitions. If the target repetitions were completed on the first set, load was changed by 2%. If target repetitions were completed from sets 2–4, then the load was kept the same.

For example, if a participant in the 10 RPE group chose to squat 100kg for their first of 3 sets with a target of 10 repetitions and performed 9 repetitions on the first set, then the load was reduced by 3% (2% automatic reduction for training to failure on set 1 and a 1% reduction performing one less repetition than prescribed) to 97kg. If this same individual then performed 12 repetitions on set 2, the load was increased (+2% for 2 repetitions over the prescribed number) to 99kg for set 3.

2.5 Anthropometric Assessments. Total body mass (kg) was assessed by a calibrated digital scale (Mettler-Toledo, Columbus, Ohio, USA) and subject's height (cm) was measured via a wall-mounted stadiometer (SECA, Hamburg, Germany). Body-fat percentage was estimated using the average of two skinfold thickness measurements acquired from three sites (chest, abdomen, anterior thigh) which were then summed. If any measurement was >2mm different than the previous measure, a third thickness was taken. The Jackson and Pollock equation [19] was used to estimate body-fat percentage, and the same investigator took all measurements.

2.6 Back Squat and Bench Press Technique. Both the back squat and bench press were performed in accordance with International Powerlifting Federation standards [20]. Specifically, for the squat, participants stood straight with the hips and knees locked, and the barbell placed across the upper back/shoulders. Upon the investigator's command of "squat" participants descended by bending the knees until the hip joint was below the top of the knee. Then participants returned to the starting position upon their own volition. Participants waited until a rack command was issued to re-rack the barbell. During the bench press, participants laid supine on a weight bench, maintaining five points of contact (head, butt, and shoulders in contact with the bench, both feet flat on the floor throughout the movement). Participants removed the barbell from the rack and held it with arms extended in a stable position. Investigators issued a start command upon which participants lowered the barbell until it contacted the chest and then pressed upwards until the arms were once again fully extended. No pause was required during the bench press. Participants waited until a rack command was issued to re-rack the barbell.

2.7 One-Repetition Maximum (1RM) Testing. All 1RM testing was performed in accordance with previously validated procedures [21]. Specifically, all participants completed a 5-minute dynamic warm-up followed by a squat-specific warm-up consisting of as many repetitions as desired with an empty barbell. Next, participants performed 5 repetitions with 20% of their estimated 1RM, followed by 50% for 3 repetitions, 70% for 2 repetitions, and 80% of 1RM for 1 repetition. Following the 80% of estimated 1RM warm-up, participants were given 3–5 minutes of rest before a final warm-up at a load determined by the investigators (between 85–90% of estimated 1RM). Following the final warm-up, participants took 5–7 minutes of rest while the investigators determined the load for the first 1RM attempt. Load was increased on each subsequent attempt until a 1RM was reached and 5–7 minutes of rest was given between each attempt. On every warm-up and 1RM attempt, RIR-based RPE and ACV were collected to aid in attempt selection. Following 1RM testing on the back squat, 10 minutes of rest was given and then an identical protocol was followed for the bench press. A 1RM was accepted as valid if one of 3 conditions are met: (a) participant reported a "10" on the RPE scale and the investigators determined an additional attempt with increased load would be unsuccessful, (b) participant reported a "9.5" RPE and then proceeded to fail the subsequent attempt with a load increase of 2.5 kg or less, and (c) participant reported an RPE of 9 and failed the subsequent attempt with a load increase of 5 kg or less. Finally, Eleiko barbells and lifting discs (Chicago, Ill., USA) calibrated to the nearest 0.25 kg were used for all 1RM testing. At post-study back squat testing for the 7–9+ RPE group, the investigators had already determined the group would be excluded from the lower body and systemic outcomes due to the change in protocol mid-intervention to decrease risk of injury. However, to ensure all groups performed the bench press 1RM in a similar state of fatigue, a back squat 1RM was still performed by the 7–9+ group, albeit with conservative load selection. Specifically, weight jumps were limited to 5 kg or more; thus, the test was concluded if the investigators believed the next attempt would potentially result in a missed attempt within those constraints.

2.8 Velocity Assessment. The Open Barbell System Version 3 (OBS3): (Squats & Science, New York, N.Y., USA) was used to assess ACV during every repetition of every testing and training session. During testing, ACV was used to aid in 1RM attempt selection. During training sessions, ACV was collected to be compared across sets between groups. In other words, a difference between groups in mean ACV of each training session verifies that per set proximity to failure was different between groups. The OBS has a velocity sensor and a display unit. The OBS was set on the floor to the right side of the participant and attached to the barbell using a Velcro strap, via a cord, just inside of the "sleeve". The OBS has been previously validated for ACV against a gold-standard 3D motion capture system [22]. Data from the OBS was transmitted via Bluetooth to an Apple iPad (Cupertino, California, USA) and data was gathered and stored in the Open Barbell phone application for later assessment.

2.9 Ultrasonography Assessment. Pectoralis major and vastus lateralis muscle thickness were assessed via ultrasonography (Bodymetrix Pro System, Intelemetrix Inc., Livermore, Calif., USA) prior to 1RM pre- and post-study testing on the right side of the body. This method of testing was previously used to assess the growth response to resistance training [23] and has been validated with magnetic resonance imaging [24]. Scans were performed with the participant in the supine position. Sites were scanned from the lateral border of the vastus lateralis to the medial border of the vastus lateralis with the transducer perpendicular to the skin. Sites were scanned twice and an average of the two scans was recorded. The site for the chest was designated as half the distance between the nipple and the anterior axillary line. Vastus lateralis scans were performed in the supine position. Sites were marked and measured at 50 and 70%, respectively, of the distance from the greater trochanter to the lateral epicondyle of the femur [25,26]. For each scan, an average of the muscle thickness values was quantified. Due to the COVID-19 pandemic, 12 participant's pre- and post-test scans were performed by a different investigator (4–6 RPE [n = 5], 7–9 RPE [n = 3], 7–9+ RPE [n = 1], 10 RPE [n = 3]). Given the unique circumstance, inter-rater reliability was not able to be determined. For each participant, the same investigator took the scan at pre and post study testing, with the exception of 4 total scans (4–6 RPE [n = 1], 7–9+ RPE [n = 3]). All scans were analyzed by the same investigator prior to analysis.

2.10 Perceived Recovery Status Scale (PRS). The PRS scale was completed by each participant prior to each training session. It is a 0–10 scale, which asks participants to rate subjective recovery [27].

2.11 Motivation to Train Scale. Prior to each training session participants completed a 1–10 Likert scale assessing their "motivation to train" on that specific day [28]. This scale has the following anchors: 1 – Not Motivated at All, 5 – Somewhat Motivated, and 10 – Highly Motivated.

2.12 Session Rating of Perceived Exertion (sRPE) Scale. The sRPE scale was completed by participants immediately following each training session to gauge the difficulty and fatigue of the entire training session [29]. This scale is 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”.

2.13 Blood Collection and Analysis. Blood was collected via the antecubital vein using serum venipuncture techniques and serum separating tubes. Once collected, samples were set at room temperature for 20–30 minutes for clotting and then were centrifuged at 1,600 x G for 10 minutes to obtain serum. Both biomarkers (creatine kinase – CK and lactate dehydrogenase – LDH) were measured in duplicate using the Epoch microplate spectrophotometer (BioTek Instruments, Winooski, VT, USA) through commercially available colorimetric assay kits (cat. no. K726, Lactate Dehydrogenase Activity Colorimetric Assay Kit, and cat. no. K777, Creatine Kinase Activity Colorimetric Assay Kit; BioVision, Milpitas, Calif., USA). Blood collection occurred immediately before and after training on day 1 (i.e., Monday) of weeks 1, 2, and 7 and immediately before training on day 2 (i.e., Wednesday) of weeks 1, 2, and 7. The CK and LDH analysis was used to assess the temporal muscle damage response in each group.

2.14 Delayed Onset Muscle Soreness. Pressure-pain threshold was used to assess delayed onset muscle soreness (DOMS) and was defined as the minimal amount of pressure needed to induce pain [30,31]; thus, a decrease in pressure-pain threshold indicates an increase in DOMS. Participants were tested in a relaxed standing position using the probe of an algometer (Pain Diagnostic & Treatment Inc.; Great Neck, NY, USA) with a 0.9 cm diameter stimulation area. Palpations occurred at the midline of the vastus lateralis at the midpoint between the iliac crest and the superior border of the patella and into the midline of the biceps femoris at the distal 40% point between the articulate interline of the knee and the head of the femur. For the upper body, algometer palpations occurred on the pectoralis major just medial to the anterior point of the axillary line. For all palpations, force started at 0 kPa and gradually increased at a constant rate of 50 to 60 $kPa \cdot s^{-1}$ until the participant indicated the presence of pain. All pressure-pain threshold assessments were tested on each subject’s non-dominant side and participants were instructed to say “now” the instant pain was felt rather than pressure and this point was recorded. Assessments were completed three consecutive times with a 30-second interval between measurements. The assessment of DOMS occurred immediately before training in weeks 1, 2, and 7. Pressure-pain thresholds were used to assess the temporal muscle soreness response in each group.

Scores were recorded in kilograms per centimeters squared and converted to kilopascals (98.1 $kPa = \frac{kg}{cm^2}$) and the mean score of the three trials were used for analysis. To maintain reliability between assessments, each DOMS assessment site was marked by a semi-permanent pen to maintain homogeneity in repeated assessments. The outlined protocol for DOMS assessment is in accordance with previously validated measures [30,31].

3 Statistical Analyses

3.1 Sample Size Justification. Sample size was determined by feasibility [32] and no formal power analysis was performed. Because the sample size of this study is limited, efforts have been undertaken to ensure that data is as easy as possible to meta-analytically aggregate in the future.

3.2 Program Observations. To quantify the training completed by each group, descriptive statistics (mean ± standard deviation) were provided for I) total sets performed, II) total repetitions performed, III) mean load (% of pre-study 1RM), IV) total volume load, V) total relative volume load, VI) mean ACV, VII) mean last repetition ACV, VIII) mean intraset % ACV loss, and IX) mean RIR-based RPE, for both the bench press and back squat, respectively. Additionally, the number of accessory sets performed was included.

3.3 Primary Outcomes (Strength and Hypertrophy). To evaluate changes in strength (i.e., bench press and back squat) and muscle thickness (i.e., pectoralis major, and vastus lateralis), separate linear regression models fit in an analysis of covariance (ANCOVA) structure were utilized. For each model, the change from baseline was the dependent variable while group and the mean-centered pre-study value of the outcome being analyzed were included as fixed effects. For the model evaluating changes in vastus lateralis muscle thickness a main effect for region (i.e., 50% or 70% of VL), an interaction between region and group, random intercepts for participant (to account for multiple observations), and random slopes for region were also included in the model. For all models, marginal effects were estimated using the *marginaleffects* package [33]. Uncertainty intervals (i.e., 90 and 95% confidence intervals) for the marginal effects of all primary outcomes (i.e., strength and hypertrophy) were created via simulation based methods, similar to bootstrapping [34]. Specifically, 2000 samples were drawn from a multivariate normal distribution with a mean and variance equal to that of the original model estimates. Quantiles from the resulting distribution were then used to construct the confidence intervals and standard error.

Additionally, to investigate the practical implications of our findings, statistical equivalence was formally evaluated [35]. To do so, the uncertainty intervals of the marginal effects were compared against thresholds denoting the smallest effect size of interest (SESOI). For strength outcomes, the SESOI was defined as d = ± 0.25 by referencing the threshold for a small effect in highly trained samples from Rhea et al. [36] and for strength outcomes in Swinton et al. [37]. To allow for strength outcomes to be presented in raw units, this standardized effect threshold was divided by the pre-test standard deviation (Squat = ± 7.72kg; Bench = ± 5.03kg). For hypertrophy outcomes, the SESOI was defined as the typical error of measurement calculated by dividing the standard deviation of the difference between scans at the same time point by the square root of two [38,39] (Vastus Lateralis = ± 0.79mm; Pectoralis Major = ± 1.95mm).

Finally, a leave-one-out sensitivity analysis was performed for all primary outcomes by re-estimating all marginal effects after removing one participant at a time. All new estimates were then compared with the original to see if any single participant substantially influenced the magnitude and precision of the effects. Visualizations from these analyses can be seen in supplementary file 2.

3.4 Secondary Outcomes (Muscle Damage, Soreness, and Subjective Recovery). To explore the longitudinal effects (i.e., repeated measures) of proximity to failure on indirect markers of muscle damage (i.e., CK and LDH), perceived soreness (i.e., pectoralis major, quadriceps, and hamstrings), and ratings of subjective recovery (i.e., sRPE, PRS, and MTT), separate linear mixed effect models were utilized. For the models examining muscle damage, fixed effects and interactions thereof were included for group, week, and session. For the model examining soreness fixed effects and interaction thereof were included for group, session, and muscle. For the models examining subjective ratings of recovery, fixed effects and interaction thereof were included for group and session. Random intercepts per participant were introduced in all models to account for repeated measures. Initially, a maximal random slope structure was attempted [40], but subsequently reduced until the model did not result in a convergence error. The final CK model included a random slope for session, the LDH model included a random slope for week, and all of the other models included a random slope for session. Each model investigating time as a continuous variable (i.e., soreness and subjective proxies of fatigue) included a first order autoregressive covariance matrix. From each model, marginal effects and 95% confidence intervals were examined to explore differences between groups and the occurrence of the RBE for each outcome.

Prior to the extraction of estimates from all models the data were visually examined for violation of model assumptions using the *performance* package [41]. Finally, in addressing our research questions we have opted to avoid dichotomizing our findings and therefore did not employ traditional null hypothesis significance testing which has been extensively critiqued [42]. Instead, all outcomes compatible with the data were considered, with the greatest emphasis placed on the point estimates [43]. All analysis was conducted in the R environment and language for statistical computing (v 4.3.1; R Core Team, https://www.r-project.org/). All raw data utilized, model outputs, and visualizations are presented in the supplementary materials.

4 RESULTS

4.1 Program Observations. Descriptions of the training completed by each group can be found in files 3 and 4 in the supplementary materials. Importantly, negligible differences were observed in all proxies of training volume (i.e., sets, repetitions, volume load, relative volume load), while all indices of proximity to failure (i.e., ACV, last repetition ACV, intraset % ACV loss, and RIR-based RPE) showed meaningful differences between groups. Finally, load (% of pre-study 1RM) was marginally different in the bench press, but likely meaningfully different in the back squat between groups.

4.2 Back Squat Strength. Increases in back squat strength were observed in the 4–6 (13.79kg [95% CI: 7.54, 19.92]), 7–9 (18.05kg [95% CI: 12.28, 23.99]), and 10 RPE (5.45kg [95% CI: -5.49, 16.24]) groups (Figure 1A). However, the 90% confidence intervals of the 10 RPE (90% CI: -3.74, 14.48) but not the 4–6 (90% CI: 8.47, 18.91) and 7–9 RPE (90% CI: 13.31, 22.97) groups suggest that the strength gains were compatible with values less than the SESOI. Contrasts between groups favored the non-failure conditions, but the width of the 90% confidence intervals were compatible with differences less than the SESOI (Figure 1C). The leave-one-out sensitivity analysis revealed that one participant influenced the magnitude and precision of model estimates. Specifically, upon removing this subject, the contrast of changes in strength between the 4–6 and 7–9 RPE (-0.78kg [90% CI: -5.06, 3.37]) was considered equivalent at the stated SESOI.

4.3 Bench Press Strength. Increases in bench press strength were observed in the 4–6 (9.05kg [95% CI: 6.36, 11.76]), 7–9 (9.72kg [95% CI: 7.03, 12.42]), 7–9+ (5.07kg [95% CI: 2.05, 8.1]), and 10 RPE (0.71kg [95% CI: -4.51, 5.54]) groups (Figure 1B). However, the 90% confidence intervals of the 7–9+ (90% CI: 2.53, 7.5) and 10 RPE (90% CI: -3.72, 4.8) but not the 4–6 (90% CI: 6.83, 11.31) and 7–9 RPE (90% CI: 7.45, 11.98) groups suggest that the strength gains were compatible with values less than the SESOI. Contrasts between groups favored the non-failure conditions, but the width of the 90% confidence intervals were compatible with differences less than the SESOI (Figure 1D). Moreover, the strength gains observed in the 4–6 and 7–9 RPE groups were considered equivalent at the stated SESOI (-0.66kg [90% CI: -3.79, 2.62]). The leave one out sensitivity analysis did not meaningfully change the interpretation of the model estimates.

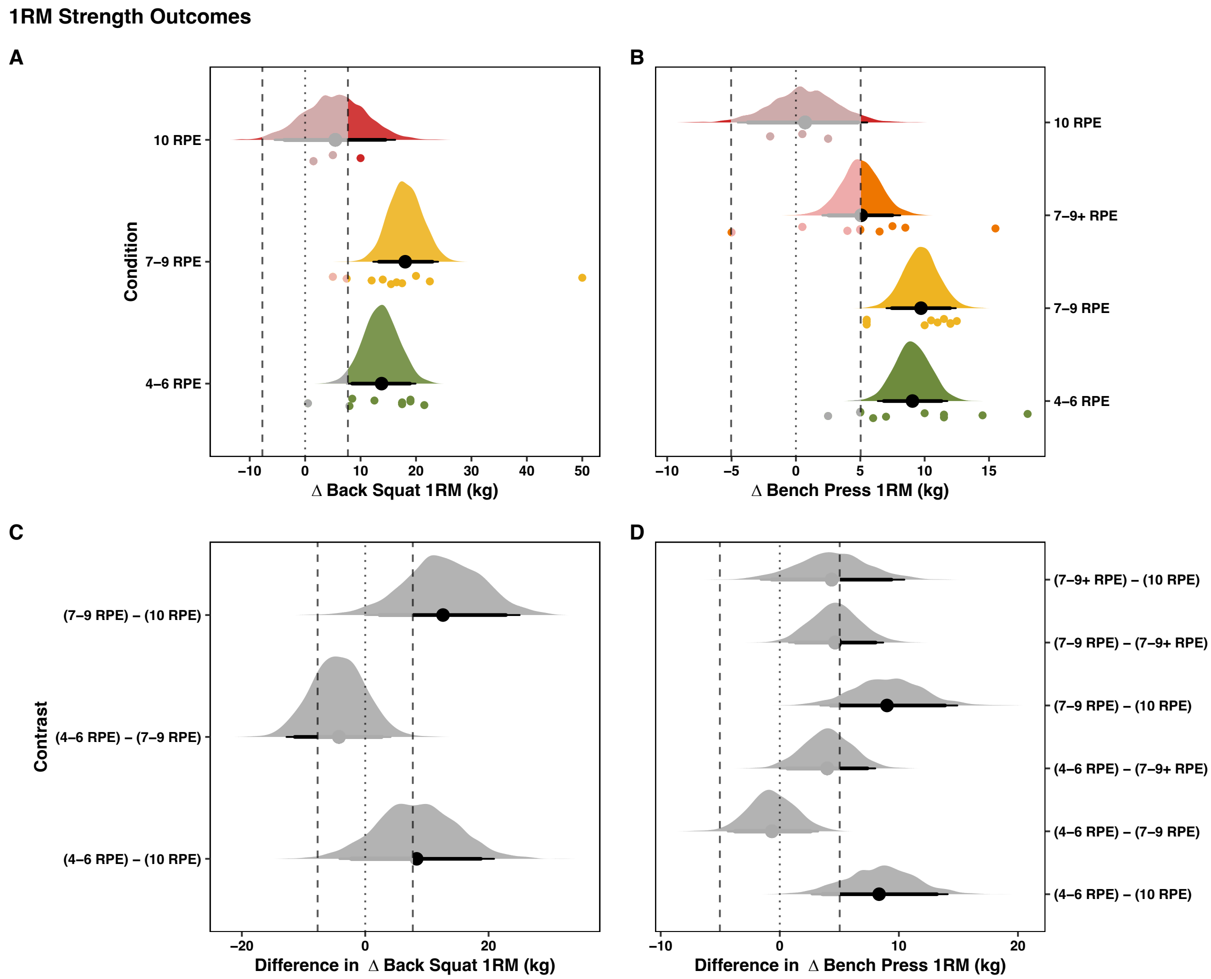

Figure 1: *Marginal effects for changes in back squat (A) and bench press 1RM strength (B), and contrasts thereof between groups (CD). Vertical dashed lines represent the smallest effect size of interest (SESOI) defined by converting a standardized mean difference of d ± 0.25 to raw units. Black dots and intervals represent the estimated marginal mean and simulated confidence intervals (90 and 95%). Brighter portions of the distributions are replications that exceed the SESOI. Finally, individual data are visualized below with solid circles. The marginal effects are adjusted for the mean centered pretest scores of the dependent variable.*

4.4 Vastus Lateralis Hypertrophy. Changes in vastus lateralis muscle thickness were compatible with values less than the SESOI for the 4–6 (0.07mm [95% CI: -1.25, 1.43]), 7–9 (-0.6mm [95% CI: -1.89, 0.64]), and 10 RPE (-1.64mm [95% CI: -3.81, 0.67]) groups. Moreover, for all contrasts between groups the width of the 90% confidence intervals were compatible with differences less than the SESOI. The leave one out sensitivity analysis did not meaningfully change the interpretation of the model estimates.

4.5 Pectoralis Major Hypertrophy. Changes in pectoralis major muscle thickness were compatible with values less than the SESOI for the 4–6 (1.83mm [95% CI: -0.96, 4.66]), 7–9 (0.52mm [95% CI: -2.28, 3.27]), 7–9+ (2.99mm [95% CI: -0.25, 6.24]), and 10 RPE (-5.54mm [95% CI: -10.88, -0.63]) groups. The contrasts between the 4–6 and 10 RPE groups (7.37mm [90% CI: 2.41, 12.41]) and the 7–9+ and 10 RPE (8.53mm [90% CI: 3.49, 13.63]) groups favored the conditions that included non-failure training. The 90% confidence intervals of the remaining contrasts were compatible with differences less than the SESOI. The leave-one-out sensitivity analysis revealed that two participants influenced the magnitude and precision of model estimates. Specifically, upon removing one subject, contrast between the 4–6 and 10 RPE (4.98mm [90% CI: -0.69, 10.61]), and 7–9+ and 10 RPE (5.67mm [90% CI: -0.26, 11.69]) groups became compatible with differences less than the SESOI. Additionally, upon removing another subject, the contrast between the 7–9 and 10 RPE (7.39mm [90% CI: 2.7, 12.21]) groups no longer was compatible with differences less than the SESOI and favored the non-failure condition.

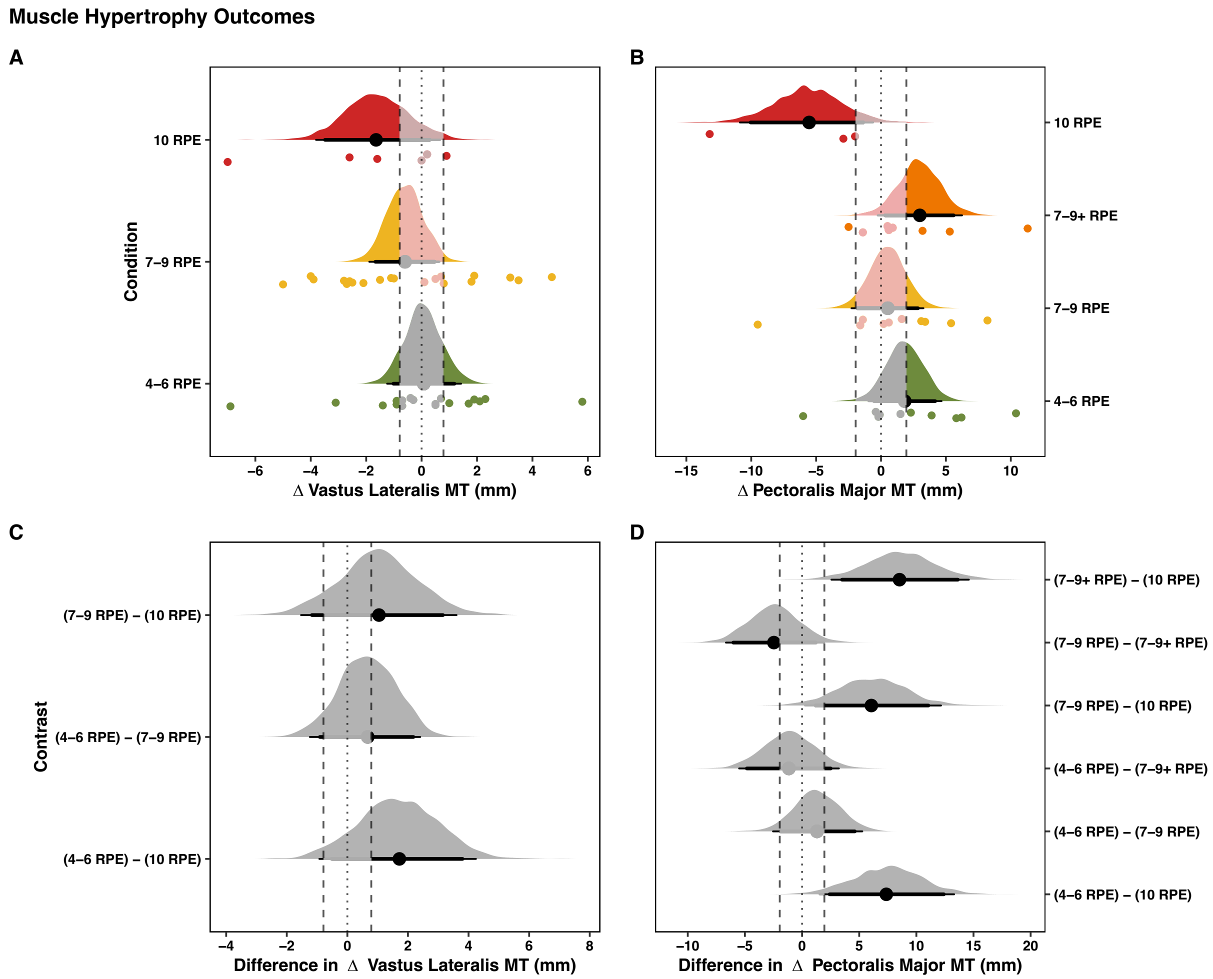

Figure 2: *Marginal effects for changes in vastus lateralis (A) and pectoralis major muscle thickness (B), and contrasts thereof between groups (CD). Vertical dashed lines represent the smallest effect size of interest (SESOI) defined by the typical error of measurement. Black dots and intervals represent the estimated marginal mean and simulated confidence intervals (90 and 95%). Brighter portions of the distributions are replications that exceed the SESOI. Finally, individual data are visualized below with solid circles. The marginal effects are adjusted for the mean centered pretest scores of the dependent variable for both outcomes and region (i.e., 50% or 70%) for the vastus lateralis outcomes*

4.6 Indirect Muscle Damage. Averaged across week, there were increases in CK immediately post exercise in the 4–6 (43.15$U\cdot L^{-1}$ [95% CI: 31.86, 54.44]), 7–9 (60.57$U\cdot L^{-1}$ [95% CI: 51.12, 70.01]), and 10 RPE (49.14$U\cdot L^{-1}$ [95% CI: 31.89, 66.38]) groups. CK then returned closer to baseline 48 hours post exercise in 4–6 (-51.68$U\cdot L^{-1}$ [95% CI: -64.99, -38.37]), 7–9 (-62.64$U\cdot L^{-1}$ [95% CI: -73.77, -51.5]), and 10 RPE (-55.66$U\cdot L^{-1}$ [95% CI: -75.99, -35.33]) groups. Averaged across session, CK decreased from week 1 to 2 (-1.29$U\cdot L^{-1}$ [95% CI: -11.9, 9.32]) and from week 2 to 7 (-6.47$U\cdot L^{-1}$ [95% CI: -17.07, 4.14]) in the 4–6 RPE group, but increased in the 7–9 RPE group

(Week 1 to 2: 10.1U·L^{-1} [95% CI: 1.22, 18.98]; Week 2 to 7: (2.59U·L^{-1} [95% CI: -6.29, 11.46])). The 10 RPE group saw an decrease from week 1 to 2 (-1.89U·L^{-1} [95% CI: -18.09, 14.32]) but a increase from week 2 to 7 (6.96U·L^{-1} [95% CI: -9.24, 23.17]). When examining the interaction contrasts (i.e., pre to post exercise change in CK compared between weeks 1 and 7) between groups, all were compatible with a null point estimate.

Averaged across week, there were increases in LDH immediately post exercise in the 4–6 (0.29U·L^{-1} [95% CI: -11.87, 12.46]), 7–9 (23.3U·L^{-1} [95% CI: 13.13, 33.48]), and 10 RPE (21.08U·L^{-1} [95% CI: 2.5, 39.67]) groups. LDH then returned closer to baseline 48 hours post exercise in 4–6 (-11.26U·L^{-1} [95% CI: -23.42, 0.91]), 7–9 (-20.15U·L^{-1} [95% CI: -30.33, -9.97]), and 10 RPE (-30.74U·L^{-1} [95% CI: -49.32, -12.16]) groups. Averaged across session, LDH decreased from week 1 to 2 in the 4–6 RPE group (-2.69U·L^{-1} [95% CI: -19.71, 14.32]), but increased for the 7–9 (9.54U·L^{-1} [95% CI: -4.69, 23.78]), and 10 RPE (3.58U·L^{-1} [95% CI: -22.41, 29.58]) groups. From week 2 to 7, LDH increased in the 4–6 (9.03U·L^{-1} [95% CI: -7.4, 25.45]), 7–9 (14.39U·L^{-1} [95% CI: 0.65, 28.13]), and 10 RPE (22.51U·L^{-1} [95% CI: -2.58, 47.6]) groups . When examining the interaction contrasts (i.e, pre to post exercise change in LDH compared between weeks 1 and 7) between groups, all were compatible with a null point estimate.

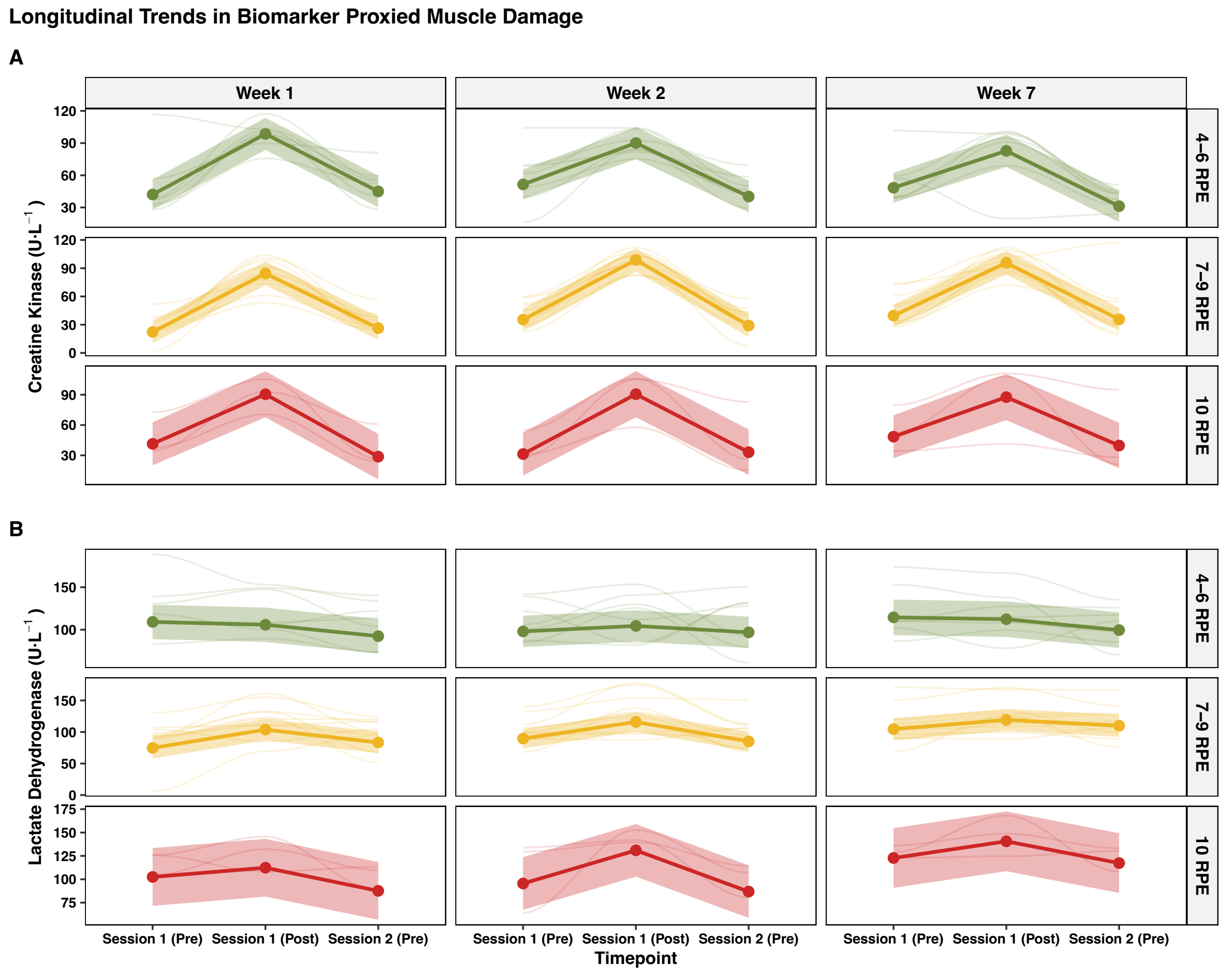

Figure 3: *Marginal effects for longitudinal trends in creatine kinase (A) and lactate dehydrogenase (B). Each panel contains three timepoints pre-exercise, immediately post-exercise, and 48 hours post-exercise. Columns represent the different weeks and rows for the different groups. Dots and intervals represent the estimated marginal means and confidence intervals (95%). Finally, individual data are visualized with faded lines.*

4.7 Soreness. Averaged across time and muscle, soreness was highest in the 4–6 RPE group (10.31kPa [95% CI: 8.47, 12.16]), followed by the 7–9 (10.03kPa [95% CI: 8.2, 11.86]), and 10 RPE (9.79kPa [95% CI: 6.44, 13.14]) groups. The 4–6 (0.21kPa [95% CI: 0.09, 0.33]), 7–9 (0.23kPa [95% CI: 0.12, 0.35]), and 10 RPE (0.24kPa [95% CI: 0.03, 0.46]) groups all exhibited a positive slope of soreness over the training program. The contrasts of these slopes between groups all contained a null point estimate.

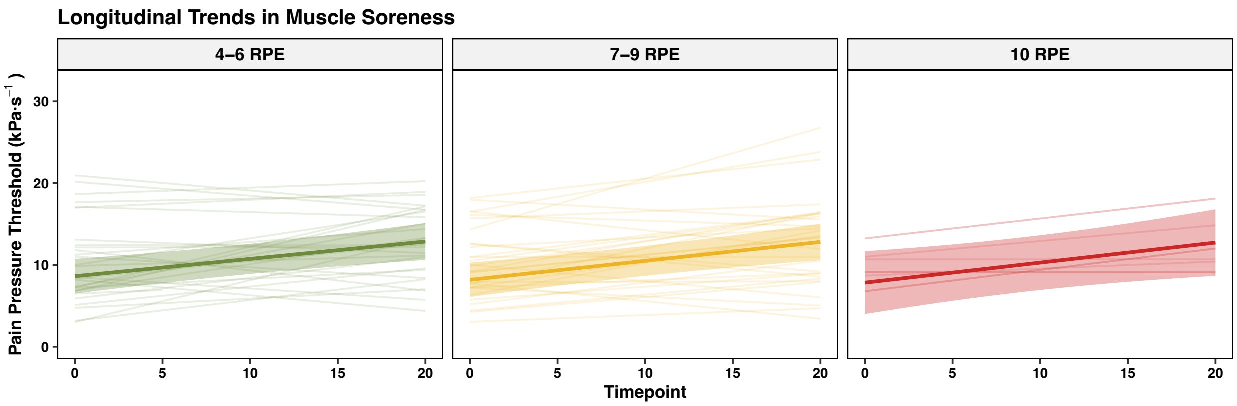

Figure 4: *Marginal effects for longitudinal trends in perceived muscle soreness. Each panel contains trends over the course of the training program. Columns represent trends for each of the different groups. Dark lines and intervals represent the estimated marginal means and confidence intervals (95%). Finally, individual data are visualized with faded lines.*

4.8 Subjective Recovery. Averaged across time, sRPE was lowest in the 4–6 RPE group (3.91a.u. [95% CI: 3.07, 4.74]) followed by the 7–9 (4.44a.u. [95% CI: 3.64, 5.23]), and 10 RPE (5.17a.u. [95% CI: 3.72, 6.62]) groups. The 4–6 (-0.08a.u. [95% CI: -0.13, -0.03]), 7–9 (-0.08a.u. [95% CI: -0.13, -0.04]), and 10 RPE (-0.08a.u. [95% CI: -0.15, 0]) groups all exhibited negative slopes of sRPE over the training program. The contrasts of these slopes between groups all contained a null point estimate.

Averaged across time, PRS was lowest in the 10 RPE group (5.93a.u. [95% CI: 4.65, 7.2]) followed by the 7–9 (6.76a.u. [95% CI: 6.06, 7.45]), and 4–6 RPE (6.81a.u. [95% CI: 6.07, 7.55]) groups. The 4–6 (-0.01a.u. [95% CI: -0.06, 0.04]), and 7–9 (-0.03a.u. [95% CI: -0.08, 0.01]) groups all exhibited negative slopes of PRS over the training program. However, the 10 RPE group (0.12a.u. [95% CI: 0.03, 0.21]) exhibited a positive slope of PRS over the training program. The contrasts between the 4–6 and 10 RPE (-0.13a.u. [95% CI: -0.23, -0.03]), and 7–9 and 10 RPE (-0.15a.u. [95% CI: -0.26, -0.05]) groups all did not contain a null point estimate.

Averaged across time, MTT was lowest in the 10 RPE group (7.05a.u. [95% CI: 5.72, 8.38]) followed by the 4–6 (7.54a.u. [95% CI: 6.77, 8.31]), and 7–9 RPE (7.58a.u. [95% CI: 6.85, 8.31]) groups. The 4–6 (-0.06a.u. [95% CI: -0.1, -0.01]), and 7–9 RPE (-0.06a.u. [95% CI: -0.1, -0.02]) groups all exhibited negative slopes of MTT over the training program. However, the 10 RPE group (0a.u. [95% CI: -0.08, 0.08]) exhibited a positive slope of MTT over the training program. The contrasts of these slopes between groups all contained a null point estimate.

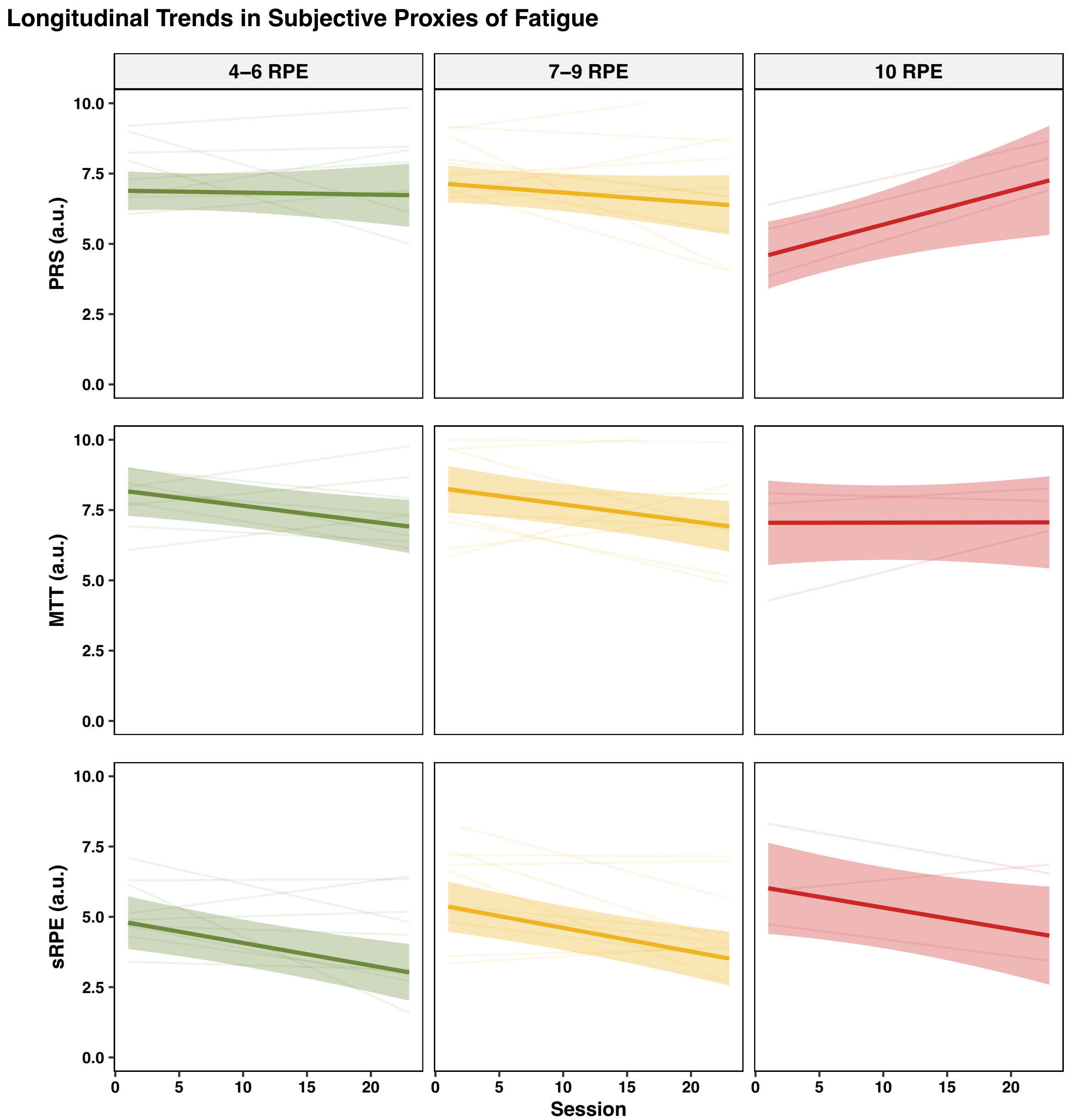

Figure 5: *Marginal effects for longitudinal trends in subjective markers of fatigue. Each panel contains trends over the course of the training program. Columns represent trends for each of the different groups while each row represents a different scale (i.e., PRS, MTT, sRPE). Dark lines and intervals represent the estimated marginal means and confidence intervals (95%). Finally, individual data are visualized with faded lines.*

5 DISCUSSION

To our knowledge, this is the first longitudinal study to quantify proximity to failure via RIR-based RPE, corroborate these ratings with objective barbell velocity (ACV), and assess longitudinal fatigue with varying resistance training proximities to failure. As hypothesized, strength outcomes were comparable between the 4–6 RPE and 7–9 RPE groups, while both groups saw marginally greater changes in strength compared to the 7–9+ and 10 RPE groups. Our hypothesis that hypertrophy would be similar between groups was partially supported as the changes in muscle thickness were not meaningfully different nor practically similar at all sites measured, with the width of the uncertainty intervals suggesting inconclusive findings. All secondary analyses of both objective and subjective markers of longitudinal fatigue resulted in negligible differences between groups and did not reveal strong evidence in favor of the RBE. Overall, these data suggest that when both repetition and set volume are equated, muscle strength outcomes are likely similar when taking sets to either 4–6 RIR or 1–3 RIR in trained men, while both approaches seem to be slightly more effective than training that includes sets performed to momentary failure (i.e., 7–9+ and 10 RPE groups). However, muscle hypertrophy outcomes remain inconclusive and markers of fatigue (objective and subjective) were comparable between groups.

As noted in supplementary files 3 and 4, the 7–9 RPE group trained at a higher percentage of 1RM (Bench Press: 83.44 ± 2.88%; Back Squat: 82.41 ± 4.40%) than the 4–6 RPE group (Bench Press: 79.50 ± 3.85%; Back Squat: 73.18 ± 3.95%). Given higher loads seem to be advantageous for strength development [8], it may be that the lower intraset velocity loss accumulated in the 4–6 RPE group (Bench Press: 30.80 ± 4.38%; Back Squat: 14.36 ± 4.58%) compared to the 7–9 RPE group (Bench Press: 41.63 ± 4.54%; Back Squat: 24.81 ± 5.88%) contributed to similar 1RM improvements [4]. Moreover, meta-analytic data suggest, training that includes sets performed to failure does not seem to further enhance strength outcomes [1,2], which also reflects our data with less strength gains observed in the 7–9+ and 10 RPE groups.

To explain these outcomes, it is possible that high loads (i.e., % of 1RM) and low intraset fatigue (i.e., velocity loss) have independent influences on strength outcomes, leading to the equivalent results in our study. Indeed, meta-analyses by Refalo et al. [44] and Jukic et al. [45]

suggest greater strength gains are expected with high loads and low velocity loss thresholds, respectively. Moreover, training to momentary failure results in high levels of intraset fatigue, and thus, greater decrements in performance would be expected [46,47]. Practically, greater reductions in performance would necessitate decreased loading to remain within a given repetition target, potentially reducing the potency for strength gain. Therefore, it seems that various program design variables may contribute to maximal strength gains and in the present study the 4–6 RPE and 7–9 RPE groups exhibited a favorable design in one of the aforementioned variables, while the groups that included sets to momentary failure (i.e., 7–9+ and 10 RPE) tended to observe inferior outcomes.

The findings for proximity to failure and muscle hypertrophy were inconclusive, as each group failed to experience hypertrophy greater than the SESOI defined by measurement error. Moreover, nearly all contrasts between conditions were compatible with the SESOI. The absence of a clear disadvantage, along with the lack of feasibility/safety we observed with regular momentary failure, may indicate that non-failure training is preferable for multi-joint lower-body exercises in trained individuals. Multiple studies [8,13,48] have observed training far from failure (i.e, >4 RIR) to be sufficient to maximize hypertrophy when using moderate to heavy loads (>60% of 1RM), as was done in the present study. Additionally, it seems that hypertrophy can be maximized far from failure in trained participants [13,18], as was done in the present study. Further, exercise selection may also be crucial to consider when determining the optimal per-set proximity to failure. Both Carroll et al. [13] and Helms et al. [18] used multi-joint exercise and observed a group training with ~4+ RIR achieved greater or similar hypertrophy, respectively, compared to a group training closer to failure (~0–3 RIR). Importantly, given we elected momentary failure (i.e., failing a repetition despite maximal effort to do so), our results (and lack of feasibility of the RT program) may not extrapolate to other, less strict definitions of failure [49].

A meaningful limitation of our study is the fact that multiple investigators performed ultrasound scans. Due to the COVID-19 pandemic, this limitation could not be avoided nor could inter-rater reliability be established. Considering the large amount of variability in our data, these results should be viewed as exploratory. While our study agrees with previous data that muscle hypertrophy does not seem to be meaningfully affected by proximity to failure when moderate to heavy loads are used in trained individuals using multi-joint exercises, extreme caution is warranted due to the aforementioned limitations.

As intended, the 4–6 RPE (Bench Press: 5.06 ± 0.28 RPE; Back Squat: 5.05 ± 0.79 RPE), 7–9 RPE (Bench Press: 7.51 ± 0.35 RPE; Back Squat: 7.34 ± 0.39 RPE), 7–9+ RPE (Bench Press: 8.39 ± 0.62 RPE; Back Squat: 6.04 ± 0.53 RPE), and 10 RPE (Bench Press: 10.07 ± 0.15 RPE; Back Squat: 10.06 ± 0.13 RPE) groups trained at different self-reported RPE in both the bench press and back squat; however, previous research has shown that trained lifters over-estimated RPE (i.e., under-estimated RIR) by ~5 and ~3 repetitions, when asked to estimate when they believed they had reached a 5 and 7 RPE during a set to failure at 70% of 1RM on the back squat [50]. A recent meta-analysis also confirmed that, on average, participants tend to under-estimate RIR [51]. Thus, these self-reported RPE values should be interpreted with caution.

To further inform per set proximity to failure, our lab established RIR/ACV relationships in the free weight bench press and back squat on the group-level [52]. In the current study, the average last repetition ACV of the 4–6 RPE group on the back squat was 0.55 ± 0.06 $m.s^{-1}$, which corresponds to approximately an 8 RIR (0.55 ± 0.02 $m.s^{-1}$) based on the data from our lab. This comparison may indicate that the 4–6 RPE group (target 5 RIR) may have actually trained with more RIR than intended, on average, for each set for the back squat. The average last repetition ACV's of the 7–9, 7–9+, and 10 RPE groups on the back squat (7–9 RPE = 0.43 ± 0.05 $m.s^{-1}$; 7–9+ RPE = 0.44 ± 0.08 $m.s^{-1}$; 10 RPE = 0.31 ± 0.06 $m.s^{-1}$) were close to the velocities associated with 3 RIR (0.42 ± 0.01 $m.s^{-1}$) and 0 RIR (0.35 ± 0.02 $m.s^{-1}$) from our lab, potentially verifying the desired proximity to failure. Finally, the average last repetition ACV of the 4–6 RPE (0.34 ± 0.04 $m.s^{-1}$), 7–9 RPE (0.25 ± 0.05 $m.s^{-1}$), 7–9+ RPE (0.24 ± 0.03 $m.s^{-1}$) and 10 RPE (0.19 ± 0.04 $m.s^{-1}$) groups were closest to RIR values within the desired range from our lab on the bench press (6 RIR: 0.35 ± 0.02 $m.s^{-1}$; 3 RIR: 0.26 ± 0.02 $m.s^{-1}$; 2 RIR: 0.23 ± 0.02 $m.s^{-1}$; 0 RIR: 0.17 ± 0.02 $m.s^{-1}$).

To date, multiple studies [46,47] have observed that training to failure on the squat and bench press elongates the time course of recovery compared to not training to failure. However, these studies have only examined temporal recovery over one week; thus, it's possible that the RBE mitigates this difference over time. In the present study, we observed largely comparable CK and LDH responses in all groups, without clear evidence of the RBE in either group. CK and LDH consistently elevated immediately post exercise and returned closer to baseline 48 hours later, but this pattern did not change meaningfully over the course of the program. Further, there were no meaningful differences between groups in measurements of muscle soreness.

When averaging across groups and muscles, soreness did tend to increase over the course of the program, but a meaningful limitation is that many participants demonstrated bruising from the repeated measurement that could have altered the pressure-pain threshold independent of the training intervention. Thus, these results should be interpreted cautiously.

Finally, subjective fatigue ratings of sRPE, MTT, and PRS were largely not meaningfully different between groups, with most having a similar trajectory over time. One explanation for the lack of convincing group differences in all indices of fatigue may be that the range of proximity to failure investigated (i.e., a difference of ~2–4 RIR) is considerably smaller than in previous research. Indeed, previous research has found significantly greater sRPE when comparing groups training to or not failure that likely differed substantially in the average RIR trained (i.e., >4 RIR) [8]; however, the current study is novel in comparing two different submaximal proximities to failure.

Another limitation of this study is a small sample size (n = 38) with deviation to the original research plan; thus, our findings should be interpreted cautiously. Data collection was first halted in the 10 RPE group (n = 3) due to safety precautions, then recruitment for the entire study was ceased in response to the COVID-19 pandemic. Recruitment then began again for the newly added 7–9+ RPE group (n = 9), which was constructed to safely investigate a group that included training to momentary failure, but then had to be modified for the lower body due to additional safety precautions.

6 CONCLUSION

In summary, these data suggest that muscle strength outcomes are similar when taking sets to either a self-reported 4–6 RIR or 1–3 RIR in trained men, while training that includes sets to momentary failure may result in slightly inferior strength development. However, our data do not provide robust conclusions as to the influence of proximity to failure on muscle hypertrophy due to the large variability observed. All indices of objective and subjective fatigue were comparable between groups, without strong evidence of the repeated bout effect. We urge future research to continue to use RIR-based RPE, a practical tool, while also tracking last repetition ACV, an objective tool, to report accurate proximities to failure [49].

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