Without fail: Muscular adaptations in single set resistance training performed to failure or with repetitions-in-reserve

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ABSTRACT

This study compared the effects of single-set resistance training performed with maximal effort (failure) vs submaximal effort on muscular adaptations. Forty-two young, resistance-trained men and women were randomly assigned to 1 of 2 parallel groups: A group that trained to failure on all exercises (FAIL) or a submaximal effort group (RIR-2) that trained with two repetitions in reserve for the same exercises. Participants performed a single set of 9 exercises targeting all major muscle groups per session, twice weekly for 8 weeks. We assessed pre-post study changes in muscle thickness for the biceps brachii, triceps brachii, and quadriceps femoris, along with measures of muscular strength, power, endurance, and ability to estimate RIR in the bench press and squat. Results indicated that both FAIL and RIR-2 elicited appreciable gains in most of the assessed outcomes. Several measures of hypertrophy tended to favor FAIL, although absolute differences between conditions were generally modest. Increases in countermovement jump height favored FAIL, but with no clear statistical support for either the null or alternative hypothesis. Increases in strength and local muscular endurance were similar between conditions. Participants demonstrated greater accuracy in estimating RIR for the bench press compared to the squat and improved their accuracy over the intervention, particularly for the bench press. These findings suggest that single-set routines can be a time-efficient strategy for promoting muscular adaptations in resistance-trained individuals. Training to failure in single-set routines may modestly enhance some measures of muscle hypertrophy and power, but not strength or local muscle endurance.

Keywords: time-efficient training; minimum effective dose; set end point; proximity to failure; muscle hypertrophy; strength

INTRODUCTION

A compelling body of evidence indicates that regimented resistance training (RT) promotes a wide array of health- and fitness-related benefits (1). To achieve beneficial effects, RT programs are often implemented using multi-set protocols, which frequently exceed an hour per session across several weekly sessions (2). However, research shows that a lack of time is a primary barrier to exercise adherence (3), which may discourage some individuals from participating in long-duration RT programs. Indeed, only 28% of the United States population regularly engages in RT at least 2 days-per-week as recommended by the Federal Physical Activity Guidelines for muscle-strengthening (4). Thus, identifying time-efficient training strategies has important implications for long-term RT engagement and hence public health and wellness.

Evidence suggests that single-set RT, defined as performing one set of each exercise per session, can be a viable time-efficient strategy to promote muscular adaptations (5). To achieve optimal effects, it is generally proposed that single-set RT must be carried out to momentary muscular failure (described hereafter as “failure”) (6), defined as the point at which an individual cannot complete the concentric portion of a repetition, despite attempting to do so, without deviation from the prescribed form of the exercise (7). However, this can be problematic for some individuals as reaching failure causes high levels of perceived discomfort and negative post-exercise feelings (8), which may be a deterrent to long-term exercise adherence. Furthermore, emerging research in multi-set RT protocols suggests that performing RT to failure may not be necessary to optimize strength development and muscle hypertrophy (9) (10). Accordingly, the repetitions in reserve (RIR) scale was developed to help provide an accurate measure for determining RT proximity to failure (11). For example, a proximity-to-failure of 1-RIR indicates a single additional repetition could be completed, while 0-RIR indicates the next attempted repetition would result in failure. Indeed, an individual may attempt to control the proximity-to-failure reached by performing repetitions with a given load until they perceive a given RIR target has been reached, known as self-reported prediction of RIR.

Recent research in trained men has shown that terminating RT sets with a self-reported prediction of 1- to 2-RIR can promote similar quadriceps hypertrophy to reaching failure (12), supporting general recommendations that speculate 2-RIR would likely be sufficient to elicit optimal hypertrophic outcomes (13). However, this recommendation is specific to evidence derived from multi-set protocols. It remains unclear whether training to failure is necessary to achieve satisfactory results in single-set protocols; if not, this would be of practical importance for removing barriers to RT participation. Therefore, this study aimed to compare the effects of single-set RT performed either with 2-RIR or to failure on muscular adaptations in young, resistance-trained adults. We hypothesized that reaching failure would induce greater strength and hypertrophy under the assumption that a lack of accumulated intersession fatigue in single set protocols would mitigate detrimental effects observed in multi-set protocols (e.g., less or similar volume load completed when RT is performed to failure versus with RIR) (8).

METHOD

Participants

We recruited a total of 50 volunteers, irrespective of sex, from a university population. To qualify for inclusion in the study, participants were required to be: (a) between the ages of 18-40 years; (b) free from existing cardiorespiratory or musculoskeletal disorders; (c) self-reported as free from use of anabolic steroids or any other illegal agents known to increase muscle size currently and for the previous year; and, (d) considered as resistance-trained, defined as consistently lifting weights targeting all major skeletal muscles at least 3 times per week (on most weeks) for at least 1 year. Participants were asked to refrain from the use of creatine products throughout the course of the study period, as this supplement has been shown to enhance muscle-building when combined with RT (14).

Participants were randomly assigned to 1 of 2 experimental, parallel groups: A group that trained to failure on all exercises (FAIL) or a group that performed the same exercises at a RIR of 2 (2-RIR). Randomization into groups was carried out using block randomization, with 2 participants per block, via online software (www.randomizer.org.); group allocation was concealed from the researcher who determined whether a subject was eligible for inclusion.

Approval for the study was obtained from the Lehman College Institutional Review Board (#2022-0762-Lehman). Written informed consent and completion of the 2023 PAR-Q+ was obtained from all participants prior to enrollment in the study. The methods for this study were preregistered prior to recruitment at: https://osf.io/un8k4. Supplemental Figure S1 provides a CONSORT flowchart of the data collection process.

Sample Size Justification

Our sample size was justified by *a priori* precision analysis for the minimum detectable change at the 68% level ($MDC_{68\%}$; i.e., 1 standard deviation [SD], which is conservative in that it requires a larger sample to produce a narrow interval) for mid-thigh hypertrophy (i.e., SEM2=2.93 mm), such that the compatibility interval (CI) of the between-group effect would be approximately ± $MDC_{68\%}$. Based on data from previous research [13], along with their sampling distributions, Monte Carlo simulation was used to generate 90% CI widths for 5000 random samples of each sample size. To ensure a conservative estimate, as literature values may not be extrapolatable, the sum of each simulated sample size's 90% CI's mean and SD were used, and the smallest sample that exceeded $MDC_{68\%}$ was chosen; that is, 18 participants per group (1:1 allocation ratio). Additional participants were recruited to account for the possibility of dropouts.

Resistance Training Procedures

The RT program worked both the upper and lower body musculature in each workout, with sessions performed twice weekly on nonconsecutive days for 8 weeks. As previously described (15), the protocol was directly supervised by the research team with each participant trained by at least one research assistant to monitor the proper performance of the respective routines and ensure participant safety. Exercises consisted of the front lat pulldown, seated cable row, machine shoulder press, machine chest press, cable triceps pushdown, supinated dumbbell biceps curl, Smith squat, plate-loaded leg press, and machine leg extension. The duration of each session was approximately 30 minutes.

Prior to commencement of the training program, participants underwent a 10RM testing session to determine their initial training loads for each exercise. The RM testing was consistent with recognized guidelines as established by the National Strength and Conditioning

Association (16). During this testing session, participants were instructed how to perform each exercise in the manner specified in the protocol.

During the training program, participants performed a single set of 8-12 repetition maximum (RM) for each exercise with ~2 minutes rest between exercises. The FAIL group was verbally encouraged to carry out all sets to momentary muscular failure, whereby participants continued to perform repetitions until they could not complete the concentric portion of a repetition, despite attempting to do so. Set termination for the 2-RIR group involved the participant subjectively terminating each set (without the supervisor's assistance) when they perceived to have reached the RIR target; they received no verbal encouragement from supervising researchers to avoid influencing their RIR estimate. Participants in 2-RIR were therefore provided with the following standardized instruction: "You will be required to stop the set when you perceive to have reached 2-RIR". For both groups, the cadence of repetitions was carried out in a controlled fashion, with a concentric action of approximately 1 second and an eccentric action of approximately 2 seconds as estimated by the research staff (i.e., without the use of a metronome). For both groups (FAIL and 2-RIR), if the participants performed more repetitions than the RM load range (8-12 repetitions), the load was adjusted the subsequent session by a minimal load to maintain the target repetition range. Participants were allotted a maximum of 2 nonconsecutive missed sessions and were expelled from the study if they missed an entire week of training. Video examples of participants performing both conditions on selected exercises can be found in the supplementary material.

Recovery Assessment

To assess recovery timelines across the study period, we employed both subjective and objective assessments. First, participants were asked to rate their recovery status immediately prior to the first, second, eighth, and final training sessions using the Perceived Recovery Scale (PRS) proposed by Laurent et al. (17). The scale gauges recovery along a spectrum from 0 to 10 (see Figure S2 in the supplementary material), with "0" indicating that the individual is "very poorly recovered/extremely tired" and "10" indicating that the individual is "very well recovered/highly energetic". A score between 0-2 suggests an expected reduction in

performance; a score between 3-7 suggests no expected changes in performance, and a score between 8-10 suggests an expected performance enhancement.

Immediately after completing the PRS, participants performed the CMJ test on the Just Jump mat as previously described. This assessed the extent of accumulated fatigue using a performance-based measure. The highest jump was recorded as the final value as previously described.

Measurements

The following measurements were conducted pre- and post-intervention. All measurements were taken in the same testing session. Participants reported to the lab at the time of their choosing between 10:00 AM and 2:00 PM, having refrained from any strenuous exercise for at least 72 hours prior to testing. Anthropometric and muscle thickness (MT) assessments were performed first in the session, followed by measures of muscle power, strength, and endurance. A 3-5-minute recovery interval separated each strength assessment to ensure adequate recovery, while a 10-minute recovery interval separated strength and endurance testing.

Anthropometry: To reduce the potential for confounding from lifestyle factors, participants were told to refrain from eating or drinking for 8 hours prior to anthropometric testing, eliminate alcohol consumption for 24 hours, and void their bladder immediately before assessment. As previously described (15), participants' heights were measured using a stadiometer and assessments of body mass and percent body fat were obtained by multifrequency bioelectrical impedance analysis (Model 770, InBody Corporation, Seoul, South Korea) as per the instructions of the manufacturer.

Muscle Thickness: As previously described (15), ultrasound imaging was used to obtain measurements of MT. A trained ultrasound technician performed all testing using a B-mode ultrasound imaging unit (MX7, Mindray Corporation, Shenzhen, China). The technician applied a water-soluble transmission gel (Aquasonic 100 Ultrasound Transmission gel, Parker Laboratories Inc., Fairfield, NJ) to each measurement site, and a 4-12 MHz linear array ultrasound probe was placed perpendicular to the tissue interface without depressing the skin. When the quality of the image was deemed to be satisfactory, the same technician saved the

image to a hard drive and immediately obtained MT dimensions by measuring the distance from the subcutaneous adipose tissue-muscle interface to the muscle-bone interface.

Measurements of 4 different muscle groups were taken on the right side of the body using identical procedures in pre- and post-study testing sessions: (1) elbow flexors, (2) elbow extensors, (3) mid-quadriceps (a composite of the rectus femoris and vastus intermedius), and (4) lateral quadriceps (a composite of the vastus lateralis and vastus intermedius). For the elbow flexors, assessments were conducted on the anterior surface of the upper arm at 60% of the distance between the antecubital fossa and the acromion process of the scapula. For the elbow extensors, assessments were obtained on the posterior surface of the upper arm at 50% between the olecranon tip and the acromion process of the scapula; mid- and lateral quadriceps measurements were obtained at 30%, 50%, and 70% between the lateral condyle of the femur and greater trochanter.

To ensure that swelling in the muscles from training did not obscure MT results, images were obtained at least 72 hours after exercise/training sessions both in the pre- and post-intervention assessment. This is consistent with research showing that acute increases in MT return to baseline within 48 hours following a RT session (18) (19) and that muscle damage is minimal after repeated exposure to the same exercise stimulus over time (20) (21). To further ensure accuracy of measurements, 3 successive images were obtained for each site and then averaged to obtain a final value. The test-retest intraclass correlation coefficients (ICC) of our lab's ultrasound technician for MT measurements are excellent (>0.94) with coefficients of variation (CV) of ≤3.3%.

Lower Body Muscle Power: Lower body muscle power was assessed via the vertical jump test. As previously described (15), each participant was instructed on proper performance of the countermovement jump (CMJ) prior to testing. The test was carried out as follows: The participant began by assuming a shoulder-width stance with the body upright and hands on hips. When ready for the movement, the participant descended into a semi-squat position and then forcefully reversed direction, jumping as high as possible before landing with both feet on the ground.

Assessment of jump performance was carried out using a Just Jump mat (Probotics, Huntsville, AL) attached to a hand-held computer that records airtime and thereby ascertains the jump height. The participant stood on the mat and performed 3 maximal-effort CMJs with a 1-minute rest period between each trial. The highest jump was recorded as the final value.

Dynamic Muscle Strength: Upper and lower body strength were assessed in the bench press ($1RM_{BENCH}$) and back squat ($1RM_{SQUAT}$), respectively, performed on a Smith machine (Life Fitness, Westport, CT). All testing sessions were supervised by two research assistants to achieve a consensus for success on each attempt. Repetition maximum testing was consistent with recognized guidelines as established by the National Strength and Conditioning Association (16). As previously described (15), participants were allowed to perform a general warm-up prior to testing consisting of light cardiovascular exercise lasting approximately 5-10 minutes. Next, a specific warm-up set of the given exercise of 5 repetitions was performed at ~50% 1RM followed by one to two sets of 2-3 repetitions at a load corresponding to ~60-80% 1RM. Participants then performed sets of 1 repetition of increasing weight for 1RM determination. Three to 5 minutes rest was given between each successive attempt. All 1RM determinations were made within 5 attempts.

Successful performance in the $1RM_{BENCH}$ was determined as follows: Participants assumed a supine position on the bench with a five-point body contact position (head, upper back, and buttocks firmly on the bench with both feet flat on the floor) and grasp the bar at a comfortable distance and width. Participants removed the barbell from the rack (with assistance if desired), lowered the barbell until it touched the chest without bouncing, and then executed a full lock-out of the elbows without assistance. The test-retest ICC from our lab for the Smith machine bench press is 0.996 with a CV of 2.0%.

In the $1RM_{SQUAT}$, participants were required to reach parallel (i.e., upper thigh in line with the floor) and rise up until the hip and knees were fully extended for the attempt to be considered successful; confirmation of squat depth was obtained by a research assistant positioned laterally to the participant to ensure the thigh was parallel to the floor. The ICC from our lab for the Smith machine squat is 0.953 with a CV of 2.8%.

Local Muscular Endurance: Absolute lower-body local muscular endurance was assessed by performing the leg extension exercise on a selectorized machine (Life Fitness, Westport, CT) using 60% of the participant's initial body mass. The smallest possible incremental increase in load for the unit was ~2.2 kg. As previously described (15), participants sat with their back flat against the backrest, grasping the handles of the unit for support. The backrest was adjusted so that the anatomical axis of the participant's knee joint aligned with the axis of the unit. Participants placed their shins against the pad attached to the machine's lever arm. Participants performed as many repetitions as possible (AMRAP) using a full range of motion (90-0 degrees of knee flexion) while maintaining a constant cadence of 1-0-1-0 as monitored by a metronome (i.e., is 1 second concentrically, no pause at full extension, 1 second eccentrically, and no pause at full flexion). The test was terminated when the participant could not perform a complete repetition with proper form in tempo. Local muscular endurance testing was carried out 10 minutes after assessment of muscular strength to minimize effects of metabolic stress potentially interfering with performance of the latter.

Repetitions-to-Failure Assessment

At least 2 days after completing initial measurements, participants were assessed for their ability to gauge RIR. As previously described (22), the assessment consisted of 2 sessions separated by 48 to 72 hours using the Smith machine bench press and squat. Participants began with a specific warm-up at 50%, 65%, and 85% of the 75% 1-RM load as determined in initial strength testing (for 6, 5, and 4 repetitions, respectively, with 2-minute inter-set rest periods). Researchers then explained the concept of intra-set RIR prediction, noting that a RIR of zero indicates the last repetition possible with proper form before reaching failure, as previously defined. Participants also were apprised of the difference between perceptions of discomfort versus proximity to failure given that participants may confuse these concepts (23). After acknowledgement of understanding the concepts, participants performed 1 set with a load corresponding to 75% of 1-RM and verbally assess the point at which they perceived reaching a 2 RIR before continuing the set to failure. This process was repeated in a single separate session after completion of the study, 48-72 hours after the final testing session.

As previously described (22), accuracy for RIR prediction was quantified as the difference between the predicted RIR and the actual RIR (i.e., the number of repetitions achieved after RIR prediction). We calculated both the raw RIR accuracy to assess the directionality of error (i.e., underestimation versus overestimation of RIR) and the absolute RIR accuracy to assess the magnitude of error independent of directionality.

Dietary Adherence

To avoid potential dietary confounding of results, participants were advised to maintain their customary nutritional regimen as previously described (15). Dietary adherence was assessed by self-reported five-day food records (including at least one weekend day) using MacroFactor (https://macrofactorapp.com/); similar applications have been shown to have good relative validity for tracking energy and macronutrient intake (24). Nutritional data was collected twice during the study: 1 week before the first training session (i.e., baseline) and during the final week of the training protocol. A researcher instructed participants on how to properly record all food items and their respective portion sizes consumed for the designated period of interest. Each item of food was individually entered into the program, and the program provided relevant information as to total energy consumption, as well as the amount of energy derived from proteins, fats, and carbohydrates for each time-period analyzed.

Blinding

To minimize the potential for bias, both the sonographer who conducted ultrasound testing and the statistician who analyzed data were blinded to group allocation.

Statistical Analyses

All analyses were conducted in R (version 4.2.0) (25) within a Bayesian framework, with descriptive values expressed in means ± SDs. Bayesian statistics represents an approach to data analysis and parameter estimation based on Bayes' theorem (26) and can provide several advantages over frequentist approaches including: 1) formal inclusion of information regarding likely differences between interventions based on knowledge from previous studies (i.e., through informative priors); 2) flexible model building to capture a range of complexities within the data; and 3) presentation of inferences based on intuitive probabilities (27) (26). Inferences were not drawn on baseline nor within-group change, as baseline testing is inconsequential

(28) and within-group outcomes are not the subject of our research question (29), although we descriptively presented within-group changes to help contextualize our findings.

We estimated the effects of group (FAIL vs. 2-RIR) on outcome variables using univariate and multivariate multilevel regression models (30). Use of multivariate models improves precision by modeling all outcome variables simultaneously, taking advantage of the correlations between outcomes (30) and avoiding limitations associated with separate inferences with related outcomes (31). Additionally, the multilevel component of the analysis accounted for the repeated measures made on each participant across outcomes and time points. Recent data quantifying comparative distributions and correlations across outcomes following interventions in strength and conditioning were used to obtain informative priors (32). Inferences were made based on estimates of the difference in change between FAIL and 2-RIR and their credible intervals along with Bayes factors that provided a 'level' of evidence (e.g., anecdotal, moderate, or strong) for either the null hypothesis (i.e., no difference between groups) or the alternative hypothesis (i.e., difference between groups). Secondary analyses were performed on nutritional variables and PRS values, which were analyzed using multilevel regression models. Accuracy of RIR estimates was modelled using ordinal regression with a cumulative logit link function. Based on observing the data post study, RIR estimates were entered as an ordered factor with levels -2, -1, 0, 1, 2, and >2.

All analyses were performed using the R wrapper package brms interfaced with Stan to perform sampling (33). There are three main areas where Bayesian analyses can be performed inappropriately and/or result in poor inferences. These areas include: 1) issues related to prior selection; 2) misinterpretation of Bayesian features and results; and 3) improper reporting (34). To improve accuracy, transparency and replication in the analyses, the WAMBS-checklist (When to worry and how to Avoid Misuse of Bayesian Statistics) was used and we incorporated sensitivity analyses of influential data points and priors, which has been shown to be important in all cases including when diffuse priors are used (35).

Results

Of the 50 participants that initially volunteered for the study, 42 completed the protocol (men = 34, women = 8; height = 172.5 ± 8.4 cm; weight = 79.9 ± 15.0 kg; age = 21.9 ± 3.8 years; body fat% = 21.4 ± 8.3%; training experience = 4.4 ± 3.8 years). Six participants dropped out of the study for personal reasons, 1 for non-compliance, and 1 for an injury unrelated to the training program. The final group sizes included for analyses were FAIL = 23 and 2-RIR = 19. Of those completing the study protocol, average session attendance was 94% and 92% for FAIL and 2-RIR, respectively. Prior to the study, 12 participants (29%) stated they were familiar with the concept of RIR and 5 (12%) stated they previously had employed RIR in their RT program. The only reported adverse event was an isolated incident of lightheadedness during a training session.

Table 1 presents a descriptive summary of pre- and post-intervention values for all outcomes. Table 2 presents univariate and multivariate estimates of between-group differences along with Bayes factors. Figure 2 presents posterior distributions illustrating RIR accuracy based on probabilities of the difference between predicted and actual repetitions.

Table 1: Descriptive summary of pre- and post-intervention values for all outcomes

	FAIL (n=23)			**2-RIR (n=19)**		
Variable	Pre	Post	Δ%	Pre	Post	Δ%
1RM squat (kg)*	103.2 ± 32.0	116.8 ± 31.4	13.2%	101.3 ± 31.6	113.9 ± 32.5	12.4%
1RM bench (kg)*	78.3 ± 27.7	83.7 ± 28.4	6.9%	72.2 ± 26.0	76.8 ± 25.0	6.4%
Countermovement Jump (cm)	46.7 ± 10.4	49.5 ± 10.1	6.0%	48.8 ± 9.1	49.5 ± 9.7	1.4%
Strength Endurance (reps)	16.7 ± 5.7	22.0 ± 8.0	31.7%	19.1 ± 6.7	23.4 ± 8.8	22.5%
Mid-quad 30% (mm)	52.3 ± 8.6	55.3 ± 9.0	5.7%	53.2 ± 9.3	55.0 ± 9.6	3.3%
Mid-quad 50% (mm)	44.9 ± 8.5	48.6 ± 9.1	8.2%	44.6 ± 8.9	46.3 ± 8.7	3.8%
Mid-quad 70% (mm)	34.9 ± 7.2	38.2 ± 7.2	9.5%	35.1 ± 7.2	36.7 ± 7.4	4.6%
Lateral quad 30% (mm)	33.3 ± 6.5	34.7 ± 6.6	4.2%	32.2 ± 6.5	33.0 ± 6.7	2.5%
Lateral quad 50% (mm)	38.4 ± 5.6	40.8 ± 5.6	6.3%	36.7 ± 5.3	38.4 ± 5.2	4.6%
Lateral quad 70% (mm)	36.7 ± 5.3	39.0 ± 5.2	6.3%	35.4 ± 5.0	37.6 ± 5.1	6.2%
Biceps brachii (mm)	37.4 ± 6.1	38.4 ± 6.8	2.7%	35.8 ± 5.7	37.4 ± 6.1	4.5%
Triceps brachii (mm)	45.2 ± 9.7	46.9 ± 8.7	3.8%	41.8 ± 8.6	42.3 ± 8.2	1.2%

*Reflects the mass of the plates without including the mass of the bar

Table 2: Univariate and multivariate analyses of potential group pre to post differences for muscle growth and performance outcomes.

Variable	Univariate Group Difference (95%CrI)	Bayes factor for univariate analysis with interpretation	Bayes factor for multivariate analysis with interpretation
Mid-quad 30% (mm)	1.2 (-1.1 to 3.4)	0.56 (Anecdotal support of H_0)	0.17 (Moderate support of H_0)
Mid-quad 50% (mm)	1.9 (-0.17 to 3.9)	1.7 (Anecdotal support of H_1)	
Mid-quad 70% (mm)	1.6 (0.02 to 3.1)	2.1 (Anecdotal support of H_1)	
Lateral quad 30% (mm)	0.57 (-0.57 to 1.7)	0.37 (Anecdotal support of H_0)	0.04 (Strong support of H_0)
Lateral quad 50% (mm)	0.86 (-0.27 to 1.9)	0.83 (Anecdotal support of H_0)	
Lateral quad 70% (mm)	0.18 (-0.90 to 1.2)	0.27 (Moderate support of H_0)	
Biceps brachii (mm)	-0.67 (-1.9 to 0.57)	0.48 (Anecdotal support of H_0)	0.49 (Anecdotal support of H_0)
Triceps brachii (mm)	1.5 (-0.14 to 3.2)	1.2 (Anecdotal support of H_1)	
Bench press (kg)	1.0 (-2.8 to 4.7)	0.21 (Moderate support of H_0)	0.02 (Strong support of H_0)
Squat (kg)	1.1 (-4.3 to 6.6)	0.24 (Moderate support of H_0)	
Countermovement jump (cm)	1.8 (-0.72 to 4.2)	0.92 (Anecdotal support of H_0)	
AMRAP (#)	0.57 (-2.2 to 3.3)	0.62 (Anecdotal support of H_0)	

Positive values favor the train-to-failure intervention. CrI: Credible interval. H_0:Null hypothesis. H_1:Alternative hypothesis

Muscle Thickness

Both interventions promoted small-to-medium increases in muscle thickness from pre- to post-intervention. While the between-group estimates consistently favored FAIL over 2-RIR (Table 2), the modes of the posterior distributions were located at small values, with relatively wide credible intervals reflecting uncertainty. Summary Bayes factors for univariate models generally indicated 'anecdotal' or 'moderate' support for no difference between groups (i.e., null hypothesis). Exceptions included 'anecdotal' support for superior mid-quadriceps thickness changes for FAIL versus 2-RIR (i.e., alternative hypothesis) measured at 50 and 70% (BF = 1.7 and 2.1, respectively), and triceps brachii thickness (BF = 1.2). Multivariate analyses pooling outcomes for the quadriceps and upper arms provided increased support for the null hypothesis, with Bayes factors of 0.17, 0.04, and 0.49, respectively (Table 2).

Strength

Between-group estimates for both the $1RM_{BENCH}$ and $1RM_{SQUAT}$ were close to zero, with wide credible intervals. These results yielded summary Bayes factors indicating 'moderate' support for the null hypothesis (BF = 0.21 and 0.24, respectively). When the data were combined in a multivariate analysis, the summary Bayes factor decreased to 0.04, providing 'strong' support for the null hypothesis. Within-intervention changes indicated small improvements for the $1RM_{BENCH}$ and small-to-medium improvements for the $1RM_{SQUAT}$ (Figure 1).

Countermovement Jump

The between-group estimate for CMJ height favored FAIL; however, the summary Bayes factor was 0.92, providing no clear support for either the null or alternative hypothesis. Within-intervention changes indicated small-to-medium improvements (Figure 1).

Local Muscle Endurance

The central ATE estimate for the AMRAP outcome was close to zero with a wide credible interval. This resulted in a summary Bayes factor of 0.62, indicating ‘anecdotal support for the null hypothesis. Within-intervention changes suggested potentially large improvements (Figure 1).

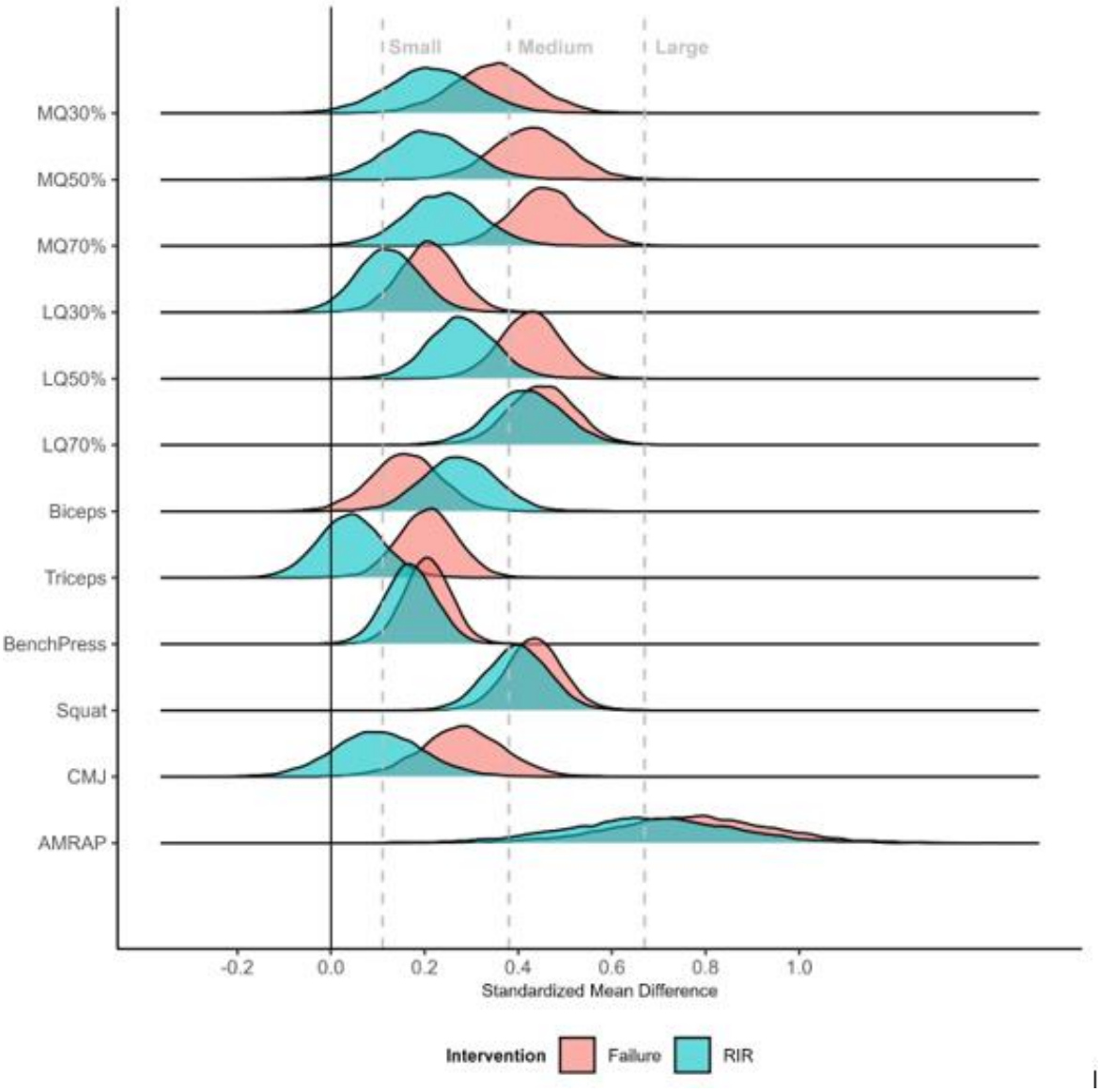

Figure 1: Standardized mean differences illustrating within-intervention changes. MQ = mid quadriceps; LQ = lateral quadriceps; CMJ = countermovement jump; AMRAP = as many repetitions as possible.

RIR Estimation

'Moderate' evidence (BF = 7.5) indicated greater accuracy in the bench press vs the squat, which increased to 'strong' evidence (BF = 12.0) at post-intervention only. 'Moderate' evidence (BF = 3.2) indicated improved RIR accuracy for the bench press, but only 'anecdotal' evidence (BF = 1.1) for improvements in the squat. There was anecdotal support suggesting better accuracy post-intervention in the FAIL group, although the evidence was unclear to draw firm conclusions (see Table S1 in supplementary material).

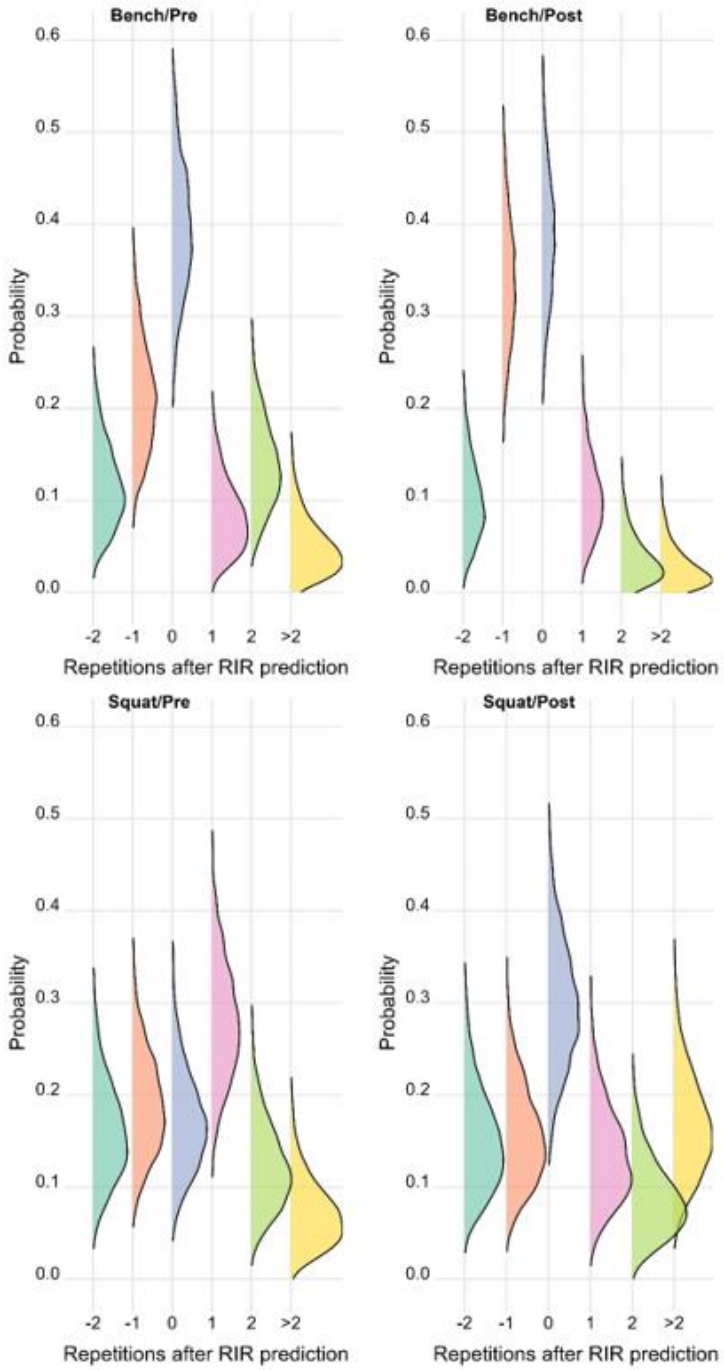

Figure 2: Posterior distributions illustrating RIR accuracy based on probabilities of the difference between predicted and actual repetitions

Recovery Assessment

Subjective assessment measures indicated both groups perceived their recovery to be high. 2-RIR showed slightly greater measures in this assessment compared to FAIL, of questionable practical significance. Objective assessment measures showed no evidence of impairments in recovery across the study period, with similar results between conditions. (See Figure S3 in the supplementary material.)

Nutrition

Consumption of energy and nutrients remained relatively constant over the intervention, with no observable differences between conditions (see Figure S3 in the supplementary material).

Discussion

The present study produced several novel and notable findings that help to fill important gaps in the current literature. First, our results indicate that appreciable muscular gains can be achieved with relatively low set volumes in young, resistance-trained individuals. Second, training to failure during single-set routines may have modestly improved some measures of muscle hypertrophy and power but did not influence markers of strength and muscle endurance. Third, resistance-trained individuals with little to no experience using RIR appear to be able to satisfactorily estimate their 2 RIR in the bench press and back squat after receiving a brief explanation of the concept, and predictive ability is enhanced after an 8-week training program. We discuss the specifics of these findings and their practical implications in the ensuing sections.

Hypertrophy

Both groups elicited what can be considered appreciable increases in MT across most of the assessed sites. Hypertrophy tended to be greater in the lower vs upper body sites, with sample mean MT increases ranging from 2.5% to 9.5% and 1.2% to 4.5% , respectively. The findings add to the emerging body of literature suggesting that time-efficient, single set, RT programs can be a viable option for those seeking to enhance muscle development (2)(5).

Although the most probable estimates across the sites consistently favored FAIL over 2-RIR (as per our hypothesis), Bayes factors tended to support no differences between FAIL and 2-RIR groups or provide 'anecdotal' support for FAIL being slightly superior to 2-RIR. Further, when combining sites based on muscle region, Bayes factors further supported no probabilistic differences between FAIL and 2-RIR. Between-group estimates favoring FAIL were most prominent in the triceps brachii (CrI = -0.14 to 3.2) and the mid-quadriceps at 50% (CrI = (-0.17 to 3.9) and 70% (Cri = 0.02 to 3.1) femur length, although the magnitudes of effect were relatively modest with anecdotal support for a difference favoring FAIL.

Several meta-analyses have found no statistically significant differences in muscle hypertrophy between failure and non-failure training in multi-set protocols (9, 10), despite the pooled effect sizes slightly favoring failure. Additionally, a recent meta-regression exploring the dose-response relationship between estimated proximity to failure and muscle hypertrophy indicated that changes in muscle size increased as sets were terminated closer to failure (36). These findings seem to be consistent with our results given that most of the central estimates for individual muscle sites favored FAIL over 2-RIR, despite lacking strong probabilistic support. It is possible that a larger sample size and/or a longer intervention duration would increase the support for a difference. It also remains to be determined how training with a further proximity-to-failure (>2 RIR) might influence long-term muscle development. It is recommended that future studies be conducted over longer time periods and incorporate the

posterior distributions presented here into their analyses for more precise estimates, with adjustments as necessary.

When comparing our results with those of Refalo et al. (12), it is conceivable that the influence of proximity-to-failure on muscle hypertrophy may be more potent with single- vs multi-set protocols, whereby differences between proximity-to-failure (e.g., FAIL vs 2-RIR) conditions are likely to be larger with lower set volumes. Although speculative, this may be attributed to the effects of accumulated fatigue from training to failure in these set configurations. In an acute study, Mangine et al. (37) demonstrated that a 3-RIR better maintained the number of repetitions performed and work at greater average velocity compared to failure training across 5 sets at 80% 1RM in the bench press. Moreover, failure training has been shown to negatively impact measures of acute neuromuscular function following performance of 6 sets of the bench press, with impairments sustained at 24 hours post-exercise (8). Conceivably, these deleterious effects would have less relevance in single-set protocols given the lower total training volumes compared to multi-set protocols. It is therefore plausible that performing a greater number of repetitions at high intensities of effort, as was the case in the present study, may enhance hypertrophy when employing single-set routines. Future research should endeavor to better understand mechanisms underlying the phenomenon and their relationship to training volume.

Strength

Both conditions elicited appreciable improvements in dynamic strength, with sample increases ranging from 6.4% to 6.9% and 12.4% to 13.2% in the $1RM_{BENCH}$ and $1RM_{SQUAT}$, respectively. Primary findings also suggest that similar strength development is experienced when comparing single set programs in which individuals train to failure vs employing 2- RIR. This observation aligns with meta-analytic evidence suggesting that training to failure is not obligatory for optimizing maximal strength in multi-set protocols (36, 10). Of note, the results

of Robinson et al. (36) suggest that training with a RIR >2 in multi-set programs do not negatively affect strength adaptations. Future research should investigate whether similar results can be achieved with lower RIR schemes in single-set RT programs.

Overall, the findings suggest that substantial strength development can be achieved with minimalistic RT programs independent of the proximity-to-failure reached. The greater improvements observed in lower- vs upper-body strength may be attributed to the complexity of the squat exercise, which requires greater neuromuscular coordination than the bench press. This discrepancy may have been magnified by the fact that although participants had engaged in RT for at least 1 year prior to the study, inclusion criteria did not specify previous experience performing the squat. Although we employed the use of a Smith machine to reduce the potential for motor learning to influence performance of the assessed exercises, it seems likely that motor learning nevertheless may have persisted in some participants with greater effects observed in the $1RM_{SQUAT}$ than $1RM_{BENCH}$.

Local Muscular Endurance

Both conditions elicited a large improvement in the number of repetitions performed in the knee extension at 60% body weight, with the sample data showing greater relative increases for FAIL vs 2-RIR (31.7% vs 22.5%, respectively). However, the between-group estimate for this outcome was close to zero with a wide CrI (-2.2 to 3.3), thus raising uncertainty as to appreciable differences between conditions. A meta-analysis by Hackett et al. (38) indicated RT to failure was a moderating variable on local muscle endurance (confidence interval = -0.29, 2.54). However, all included studies involved multi-set protocols, limiting generalizability to single-set routines. Future research should further investigate local muscular endurance adaptations in low-volume protocols employing different proximities to failure.

Muscular Power

Our sample results indicated somewhat greater improvements in CMJ height, a proxy for muscular power, for FAIL vs 2-RIR (6.0% vs 1.4%, respectively); however, the Bayes factor did not provide clear support for a difference. Previous meta-analytic evidence indicates similar improvements in measures of muscular power when training to failure or not-to-failure in volume-equated routines (39). However, all included studies in this meta-analysis involved multi-set routines, precluding direct comparison to single-set programs.

It should be noted that our protocol was designed to approximate single-set training programs as customarily described (6), not specifically to optimize muscular power, which requires a high-velocity training component (40). Future research should investigate the effects of proximity to failure in single-set routines using high-velocity concentric actions to better determine its influence on muscular power.

RIR Predictive Ability

The vast majority of RIR predictions were within ±2 repetitions on both the squat and bench press exercises. This level of accuracy was accomplished after a single, brief familiarization session even though the majority of participants never used the method in practice. These results highlight similar RIR prediction accuracy to those of Remmert et al. (41) and Refalo et al. (22), who found that trainees can predict RIR within ~1 repetition when training at 72.5% 1RM in the biceps curl, triceps pushdown and seated row exercise, and at 75% 1RM on the bench press exercise, respectively. Further, results indicated that participants' predictive ability tended to be better for the bench press compared to the squat. This finding suggests that RIR estimation may be influenced by the complexity of the exercise, with accuracy decreasing in movements that involve greater stabilization.

We also demonstrated that participants' predictive ability improved over the 8-week study period, with greater improvements observed in the bench press compared to the squat. The FAIL group tended to improve their predictive ability to a greater extent than the 2-RIR

group. This would suggest that consistently training to failure enhances the ability to gauge RIR. However, the evidence on this outcome can be considered anecdotal, with limited ability to draw strong inferences on the topic. Overall, the results provide additional support for the validity of the RIR method when training with moderate loads in resistance trained individuals.

Limitations

Our study had several limitations that should be considered when drawing practical inferences. First, the sample consisted of healthy young men and women with at least one year of RT experience. The generalizability of findings to other populations therefore should be inferred cautiously. Moreover, although the participants in our study had previous RT experience, the majority would not be considered elite lifters. The findings therefore cannot necessarily be generalized to highly trained individuals. Second, we opted to employ an ecologically valid training program and thus employed submaximal loads equating to a medium repetition range (8-12RM). Given evidence that RIR accuracy diminishes with the use of lighter loads (42), the overall findings therefore cannot necessarily be extrapolated to higher repetition routines. Moreover, considering that the magnitude of load correlates with a greater ability to produce force (43), the strength results cannot necessarily be extrapolated to protocols specifically designed to maximize force production, such as those employed by powerlifters. Third, we did not record participants' previous training volume, which could have influenced our findings as some participants potentially decreased their previous training volume to different extents than others. Finally, we only assessed MT changes for the upper arms and legs, and thus inferences cannot necessarily be made for hypertrophy of the other muscles. Future research should address these limitations to fully elucidate the practical implications of the topic.

Conclusion

Appreciable muscular adaptations were observed when performing just two, 30-minute total body RT sessions per week over an 8-week study period. This reinforces the veracity of the claim that a lack of time should not be a barrier to regular participation in RT programs, even for resistance trained individuals. Moreover, results were achieved even though all participants had been previously training with multi-set programs and thus experienced a reduction in volume across the intervention. Our findings therefore indicate that resistance trained individuals not only can maintain muscular gains employing low set volumes, but potentially enhance adaptations at least over relatively short training periods.

While the overall trends for muscle hypertrophy tended to favor FAIL over 2-RIR, Bayes factors generally supported no probabilistic differences between the two groups or provided only weak support for training to failure being more effective. As such, although training to failure may be necessary to maximize development in certain muscles during single-set programs, significant hypertrophy nevertheless can be achieved employing 2- RIR. Moreover, improvements in measures of strength and local muscular endurance appear to be independent of proximity- to- failure. Thus, trainees can realize beneficial effects from time-efficient routines with less discomfort than previously believed, which may help to remove potential perceived barriers to RT and facilitate long-term exercise adherence (44).

Finally, we show that resistance trained individuals can predict RIR within ±2 repetitions after a brief familiarization session. Moreover, participants' predictive ability improved over the 8-week study period, providing support for the use of the method in estimating proximity to failure when training in a moderate repetition range. Predictive ability tended to be superior in the bench press vs the squat, suggesting that exercise selection may influence the accuracy of estimation.

Contributions

BJS conceived of the idea for the study. BJS, PAK, MW, MR, MC, AM, TH and AP designed the methodology for the study. TH, AP, AM, AE, MS, AZ and MR assisted with acquisition of data. PAS conducted the statistical analysis. All authors critically interpreted the data, drafted and/or revised the article, and approved the final version of the manuscript draft.

Conflict of interest

BJS formerly served on the scientific advisory board for Tonal Corporation, a manufacturer of fitness equipment. All other authors report no competing interests with the content of this manuscript.

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Data and Supplementary Material Accessibility

Data can be requested from the corresponding author upon reasonable request. Supplementary material are available on the Open Science Framework project page: https://osf.io/fkts9/files/osfstorage

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