



Front-Loading Fatigue: Does the Pre-exhaustion Method influence Resistance Training-induced Muscular Adaptations?

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Abstract

International Journal of Exercise Science 19(1): 1008, 2026. This study aimed to compare the effects of pre-exhaust training and traditional training on muscular hypertrophy, strength, body composition, and muscular endurance in resistance-trained participants over an 8-week study period. We randomly assigned 48 young, resistance trained individuals (male = 32, female = 9; height = 173.0 ± 10.3 cm; weight = 81.7 ± 15.9 kg; age = 22.5 ± 4.1 yrs) to 1 of 2 experimental groups after initial testing: a pre-exhaust resistance training (RT) group (PreEx: n = 24) or a traditional RT group (TRAD: n = 24). The RT protocol consisted of the following lower body exercises: leg extension, Smith squat, seated hamstring curl, barbell Romanian deadlift. Participants in the TRAD group completed all sets for one exercise before performing a different exercise with ~2 minutes of rest between sets. The PreEx group performed a set of a single-joint exercise immediately prior (<10 seconds) to a set of the corresponding multi-joint exercise for that muscle group followed by ~2 minutes of rest. Both groups performed 4 sets of each exercise twice weekly with loads corresponding to 8-12 repetition maximum (RM). Assessments included pre-post measures of muscle thickness of the quadriceps and hamstrings, body composition, 1RM squat strength, local muscle endurance of the quadriceps, and the countermovement jump. Results showed slightly greater improvements in muscle size and body composition favoring TRAD, with statistical uncertainty for a true between-group difference. Changes in strength, local muscular endurance and countermovement jump height were similar between groups. In conclusion, TRAD would seem to be a better option than PreEx for those seeking to optimize muscle hypertrophy. Measures of strength, power and local muscular endurance were relatively similar between conditions, suggesting that PreEx is a viable alternative to TRAD for these outcomes.

Keywords: Time-efficient training, muscle hypertrophy, muscle strength, pre-fatigue, body composition

Introduction

Resistance training (RT) is a known stimulator of skeletal muscle hypertrophy.^{1,2} To optimize hypertrophy results, adjustments to training strategies could be an important consideration for trainees. Traditional training programs involve performing multiple sets of an exercise

sequentially with each subsequent set preceded by a prescribed rest interval (i.e., straight sets). Pre-exhaust training, operationally defined herein as the performance of a single-joint exercise for a muscle group before performing a multi-joint exercise for that same muscle group with minimal rest time between movements, maintains speculative support as an advanced training method within hypertrophy programming.³ Initially proposed by Arthur Jones in the 1970s,⁴ this method conceivably pre-fatigues the target muscle so that it achieves greater stimulation in the ensuing compound exercise rather than the non-pre-fatigued synergists, thereby enhancing hypertrophy of the target muscle.

Current pre-exhaust literature is largely acute, all acute studies on the topic involve the use of surface electromyography (sEMG) to test muscle activation in various pre-exhaust protocols. Results of these studies are somewhat discrepant due to disparities in methodologies. For example, Sparks et al⁵ tested pre-exhaust on the triceps brachii prior to the bench press, the inverse of the Arthur Jones proposed method of fatiguing the main mover of the compound exercise and found greater pec major activity.⁴ Additionally, Brennecke et al⁶ found that the triceps were more active in a bench press after fatiguing the pecs with a pec fly. Similarly, other acute data^{7,8} utilize different methods of investigation, including alternate tested muscle groups, and differing RT protocols - creating uncertainty in what may be extrapolated. Moreover, although sEMG activity can provide insights into muscle activity, the data cannot necessarily be directly extrapolated to longitudinal hypertrophy outcomes.⁹ Thus, the practical implications of such studies must be interpreted cautiously.

To date, only two studies have investigated pre-exhaustion training in a longitudinal fashion, each with different study designs, and both employing untrained participants. Trindade et al¹⁰ assessed the effects of pre-exhaustion of the lower body musculature, wherein 1 group of participants performed the leg extension immediately prior to the leg press, both to momentary failure, followed by 2 additional sets of the leg press without pre-exhaustion, while the other group only performed 3 sets of the leg press to failure. After an 8-week training intervention, both groups achieved comparable increases in muscle thickness (MT) across all sites measured. Alternatively, Fisher et al¹¹ randomized 3 groups to complete a single-set RT protocol with varying exercise orders, with 1 group using the pre-exhaust method and the other 2 performing the same exercises with differing rest times and/or exercise orders. After 12 weeks, no statistically significant between-group differences were observed in measures of whole-body fat-free mass, as estimated by air displacement plethysmography. However, the training volume employed by Fisher et al¹¹ was extremely low, corresponding to roughly 2 fractional weekly sets for some of the muscles trained, which may have been insufficient to induce measurable muscle growth,¹² particularly given the absence of direct measures of hypertrophy.

Long-term, multi-set protocols investigating pre-exhaust RT versus traditional RT (sets for the same muscle group performed consecutively separated by prescribed intraset rest periods) on trained participants is absent in the literature, making it difficult to confidently interpret the efficacy of pre-exhaust RT for hypertrophy outcomes. Thus, the purpose of this study was to compare the effects of pre-exhaust training and traditional training on muscular hypertrophy, strength, body composition, and muscular endurance in resistance-trained participants over an 8-week study period. We hypothesized that a) traditional and pre-exhaust RT would elicit similar effects on lower body muscle size and power, and b) pre-exhaust training would result in greater improvements in lower body muscular endurance while traditional RT would induce superior gains in muscular strength.

Methods

Participants

We recruited 48 male and female volunteers from a university population. Eligible participants were required to: a) be between the ages of 18-40 years, b) answer “no” to all items on the Physical Activity Readiness Questionnaire c) self-report being free from 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 for both the upper and lower body muscles at least 3 times per week (on most weeks) for at least 1 year. Participants were asked to refrain from consuming creatine supplements throughout the course of the study period, as creatine has been shown to positively impact muscular adaptations and body composition when combined with RT.¹³

Participants were randomly assigned to 1 of 2 experimental groups after initial testing: a pre-exhaust RT group (PreEx: n = 24) or a traditional RT group (TRAD: n = 24). Randomization into groups was carried out via online software (www.randomizer.org); group allocation was concealed from the researcher who determined eligibility. Approval for the study was obtained from the college Institutional Review Board this research was carried out in full accordance with the ethical standards of the *International Journal of Exercise Science*.¹⁴ Written informed consent was obtained from all participants prior to starting the study. The methods for this study were preregistered prior to recruitment at: <https://osf.io/uy9a6>. Supplemental Figure S1 provides a CONSORT flowchart of the data collection process.

To determine sample size, we performed simulation-based calibration (SBC) of Bayes factors. We used a modified version of the workflow suggested by Gelfand & Wang¹⁵ and performed SBC of Bayes factors to evaluate whether the correct hypothesis would likely be supported given the sample size and study design.¹⁶ We simulated prior predictive data for a sample size of 22 individuals per group. These priors were derived from recent studies conducted by our group and from meta-analyses examining the distribution of effects in strength and conditioning.^{17,18} The priors, set on a standardized scale, included distributions for typical improvement ($N(0.44, 0.40^2)$), average treatment effect ($N(0.15, 0.05^2)$), heterogeneous response ($N(0, 0.15^2)$), and measurement error ($N(0, 0.03^2)$). The fitting priors used an average treatment effect prior of $N(0, 0.40^2)$.

The SBC started with equal probability (0.5) applied to the two hypotheses. Following the 500 simulations, the posterior model probabilities were calculated, and this quantified the likelihood of each model being chosen a posteriori. These were compared to the prior model probabilities that were used to simulate the data (46.9 [95%CI: 40.79 to 53.1]). We also calculated the average posterior probabilities as a function of the true hypothesis (sensitivity = 78%, specificity = 83%) and identified appropriate distributions of Bayes factors on the log scale. Based on the results of the SBC and given constraints we concluded that our recruitment target of 25 participants per group and potential of 2 to 5 dropouts per group was appropriate to achieve sufficient statistical precision.

Protocol

Resistance Training Procedures.

The RT protocol involved the lower body musculature and consisted of the following exercises: leg extension, Smith squat, seated hamstring curl, barbell Romanian deadlift (RDL). Both groups

performed 4 sets of each exercise, twice weekly within the same session, with loads corresponding to 8-12 repetition maximum (RM). All sessions were performed under the direct supervision of research assistants who verbally encouraged participants to perform each set to the point of momentary muscular failure, herein defined as the inability to perform another concentric repetition with proper technique. Participants in the TRAD group completed all sets for one exercise before performing a different exercise with ~2 minutes of rest between sets. The PreEx group performed a set of a single-joint exercise immediately prior (<10 seconds) to a set of the corresponding multi-joint exercise of that muscle group followed by ~2 minutes of rest for 4 sets (see Figure 1).

Exercises in the PreEx group were ordered as follows: a) seated hamstring curl → barbell RDL, and b) leg extension → smith squat. The order of exercises within each paired set remained constant, but the order in which each pre-exhaust superset (a vs. b) was always “a” then “b”, with the goal to reduce interference of quadriceps fatigue on RDL performance. To reduce interference of hand and forearm fatigue, participants were required to use lifting straps for the RDL. Since the PreEx exercise order remained constant throughout the study, participants in the TRAD group consistently performed the single-joint exercises as the exercise completed before the corresponding multi-joint exercise (i.e. hamstring curl before RDL; leg extension before squat). Table 1 provides an overview of the protocols for both groups.

Table 1. RT protocols for TRAD and PreEx.

Condition	Set 1	Rest	Set 2	Rest	Set 3	Rest	Set 4
TRAD	Hamstrings Curl	2 min	Hamstrings Curl	2 min	Hamstrings Curl	2 min	Hamstrings Curl
	RDL	2 min	RDL	2 min	RDL	2 min	RDL
PreEx	Hamstrings Curl → RDL	2 min	Hamstrings Curl → RDL	2 min	Hamstrings Curl→ RDL	2 min	Hamstrings Curl → RDL

For PreEx, arrow (→) represents taking as little rest as possible between exercises. The remaining exercises were performed in the same manner. Abbreviations: RDL = Romanian deadlift

Repetitions were performed with controlled concentric and eccentric tempos of approximately 1:2. To maintain the target repetition range, loads were adjusted from set to set within each session as well as across the duration of the study period. Participants were given an optional upper body RT program to follow on alternate training days (without supervision) and were instructed to refrain from performing any additional lower body RT for the duration of the study. Both weekly experimental sessions were performed on nonconsecutive days between 9:00am and 4:00pm, and all training was directly supervised by the research team to monitor proper performance and ensure participant safety.

Prior to the 8-week training program, participants underwent 10RM testing to determine initial loads for each exercise. The 10RM testing was consistent with recognized guidelines as established by the National Strength and Conditioning Association.¹⁹ Prior to the first attempt of 10RMs, the assigned research assistant demonstrated proper technique for each exercise. Since the PreEx group performed each multi-joint movement pre-fatigued during the protocol, we used 60% of their determined 10RM as the initial load. Once the initial loads were determined, the participants advanced to the training intervention in the next scheduled session.

Measurements.

The following measurements were conducted pre- and post-study in separate testing sessions. Anthropometric and muscle thickness (MT) assessments were conducted first in the session,

followed by measures of muscle strength and endurance. Each strength assessment was separated by a 10-minute recovery interval to minimize residual fatigue that would impair physical performance.

Anthropometry.

To reduce the potential for confounding from lifestyle factors, participants were told to refrain from eating for 12 hours prior to testing, eliminate alcohol consumption for 24 hours, abstain from strenuous exercise for 48 hours and void their bladder immediately before anthropometric testing.²⁰ Participants' height was measured using a stadiometer and assessments of body mass and changes in percent body fat and segmental lower limb lean mass was obtained by multifrequency bioelectrical impedance analysis (Model 770, InBody Corporation, Seoul, South Korea) as per the instructions of the manufacturer.

Muscle Thickness.

Ultrasound imaging was used to obtain measurements of MT. As previously described,²¹ 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 technician saved the image to a hard drive and obtained MT dimensions by measuring the distance from the subcutaneous adipose tissue-muscle interface to either the aponeurosis or the muscle-bone interface.

Measurements were taken on the right side of the body for the following muscle groups: (1) anterior mid-thigh (a composite of the rectus femoris and vastus intermedius), (2) anterior lateral thigh (a composite of the vastus lateralis and vastus intermedius), (3) posterior medial thigh (semitendinosus and semimembranosus). Mid and lateral anterior thigh measurements were obtained at 30%, 50%, and 70% between the lateral condyle of the femur and greater trochanter. Medial hamstrings measures were obtained at 40% and 60% between the popliteal fossa and gluteal fold.

To help ensure that training-induced swelling in the muscles did not obscure MT results, images were obtained at least 48 hours after the training sessions both in the pre- and post-study assessment. This is consistent with research showing that acute increases in MT return to baseline within 48 hours following a RT session²² and that muscle damage is minimal after repeated exposure to repeated long-term exercise stimulus.²³ 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 coefficient (ICC) from our lab for MT measurements are >0.94 with coefficients of variation (CV) of $\leq 3.3\%$.

Lower Body Muscle Power.

As previously described,²¹ participants performed a countermovement jump as a means to assess lower body muscular power. Participants were instructed on proper performance of the countermovement jump. Performance 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, they 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), which was attached to a hand-held computer that records airtime and thereby identifies jump height. The participant stood on the mat and performed 3 maximal-effort countermovement jumps with a 1-minute rest period between each trial. The highest jump was recorded as the final value. The test-retest ICC from our lab for CMJ measurement is 0.93 with a CV of 3.1%.

Dynamic Muscle Strength.

As previously described,²¹ dynamic lower body strength was assessed by 1RM testing in the squat exercise performed on a Smith machine (Hammer Strength Equipment, Life Fitness, Rosemont, IL, USA). Participants reported to the lab having refrained from any exercise other than activities of daily living for at least 48 hours prior to baseline testing and at least 48 hours prior to testing at the conclusion of the study. Repetition maximum testing was consistent with recognized guidelines as established by the National Strength and Conditioning Association.¹⁹ Participants performed a specific warm-up set of 5 Smith squats repetitions at ~50% 1RM followed by 1 to 2 sets of 2-3 repetitions at a load corresponding to ~60-80% 1RM with 1 minute of rest between sets. Participants then performed sets of 1 repetition of increasing weight for 1RM determination. Three to 5 minutes rest was provided between each successive attempt. To successfully perform the 1RM, participants were required to descend to a parallel position (i.e., upper thigh in line with the floor) and rise until the hip and knees were fully extended; confirmation of squat depth was obtained by a research assistant positioned laterally to the participant. The test-retest ICC from our lab for 1RM squat measurement is (0.95) with a CV of 3.8%.

Muscle Strength-Endurance.

As previously described,²¹ lower-body muscular strength-endurance was assessed by performing the leg extension exercise (Life Fitness, Westport, CT) using 60% of the participant's initial body mass. 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 using a full range of motion (90 degrees of leg flexion to 0 degrees) while maintaining a constant cadence of 1-0-1-0 as monitored by a metronome. The test was terminated when the participant could not perform a complete repetition with proper form and tempo. Muscular endurance testing was carried out after assessment of muscular strength to minimize effects of metabolic stress potentially interfering with performance of the latter. The test-retest ICC from our lab for lower-body muscular strength-endurance measurement is 0.93 with a CV of 6.1%.

Session Rating of Perceived Exertion.

To assess differences in session rating of perceived exertion (SRPE), scores were obtained for all training sessions across the intervention. Session RPE has been considered a reliable assessment of overall fatigue of a training session in varying RT protocols.²⁴ As previously described,²⁵ following the conclusion of each training session, participants passively rested for ~10 minutes before being asked to provide a RPE for the entire training session. Participants received instruction on how to use the RPE scale during the 10RM testing session. A member of the research team asked participants to choose a number on a 10-point scale with 0 classifying as sitting still during the entire session and 10 classifying maximal effort during the session.

Recovery Assessment.

As previously described,²¹ to assess recovery timelines across the study period, we conducted both subjective and objective assessments. Firstly, participants were asked to rate their subjective recovery status immediately prior to the first, second, eighth, and final training sessions using the Perceived Recovery Scale (PRS) proposed by Laurent et al.²⁶ The scale gauges recovery in a range of 0 to 10, 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 improvement in performance.

Immediately after completing the subjective recovery assessment, participants performed the CMJ test as previously described on the previously described Just Jump mat. This assesses the extent of accumulated fatigue using a performance-based measure. The highest jump was used as the final score for that session.

Dietary Adherence.

To avoid potential dietary confounding of results, participants were advised to continue their usual nutritional regimen. Dietary adherence was assessed by self-reported 5-day food records (including at least 1 weekend day) using MacroFactor (<https://macrofactorapp.com/>). Nutritional data was collected twice during the study: 1 week before the first training session and during the final week of the training protocol. Participants were instructed 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 app, and the program provided relevant information as to total energy consumption and macronutrient distribution.

Blinding.

To minimize the potential for bias, the ultrasound technician who obtained the MT measurements was blinded to group allocation and the statistician performed blinded analyses for all primary outcomes.

Statistical Analysis

All analyses were conducted in R (version 4.4.2) within a Bayesian framework. Bayesian statistics provide an alternative to frequentist approaches by incorporating prior information (e.g., from previous studies) and by expressing inferences as probabilities. The effect of condition (PreEx vs TRAD) on outcome variables was estimated using complete case analysis of covariance models, with participants with missing baseline values omitted. Overall data completeness was high (98.3%). For individual outcomes, the number of participants omitted due to missing baseline values ranged from $n = 1$ (2.4%) to $n = 5$ (12.2%).

All inferences were made from posterior distributions of model parameters describing estimates of the effect of intervention allocation and strength of evidence for the existence of a difference through Bayes factors. As a final set of analyses, we conducted hierarchical models using standardized mean difference values to account for the multiple tests conducted within each outcome domain (MT, performance, and body composition). These models shared information across outcomes, shrinking individual estimates toward a pooled mean and thereby reducing the potential for overestimating effects due to random variation. Interpretation focused on the

distribution of the hyperparameters and specifically, the pooled mean to provide an overall assessment of the effect size across outcomes within each domain.

Informative prior distributions were used based on meta-analysis data on the specific research question and general strength and conditioning literature.^{17,18} All analyses were performed using the R wrapper package brms interfaced with Stan to perform sampling. A complete Bayesian workflow was adopted, which include prior predictive checks, posterior predictive checks, and simulation-based calibration of Bayes factors. To improve accuracy, transparency and replication of the analyses, the WAMBS-checklist (When to worry and how to Avoid Misuse of Bayesian Statistics) was used and reported (see supplemental file).²⁷

Results

Of the 48 participants that initially volunteered to participate, 41 completed the study (male = 32, female = 9; height = 173.0 ± 10.3 cm; weight = 81.7 ± 15.9 kg; age = 22.5 ± 4.1 yrs). All participants in the PreEx group who dropped out of the study ($n = 3$) did so due to time constraints, while the participants in TRAD ($n = 4$) dropped the study due to a) time constraints ($n = 1$), b) injuries unrelated to the study protocol ($n = 2$), and c) injury incurred from the study protocol ($n = 1$). Other adverse events included several incidents of lightheadedness (PreEx: $n = 7$, TRAD: $n = 4$) and intermittent reports of lower back pain primarily attributed to performance of the RDL. The final group sizes included for analyses were PreEx = 21 and TRAD = 20. Of those completing the protocol, average attendance was 91.6% and 92.9% of sessions for TRAD and PreEx, respectively. Descriptive summaries of nutritional data are presented in the WAMBS checklist (see supplementary files), with results showing no evidence of differences between groups. Raw data for all outcomes are presented in the supplementary material (Table S1).

Muscle thickness

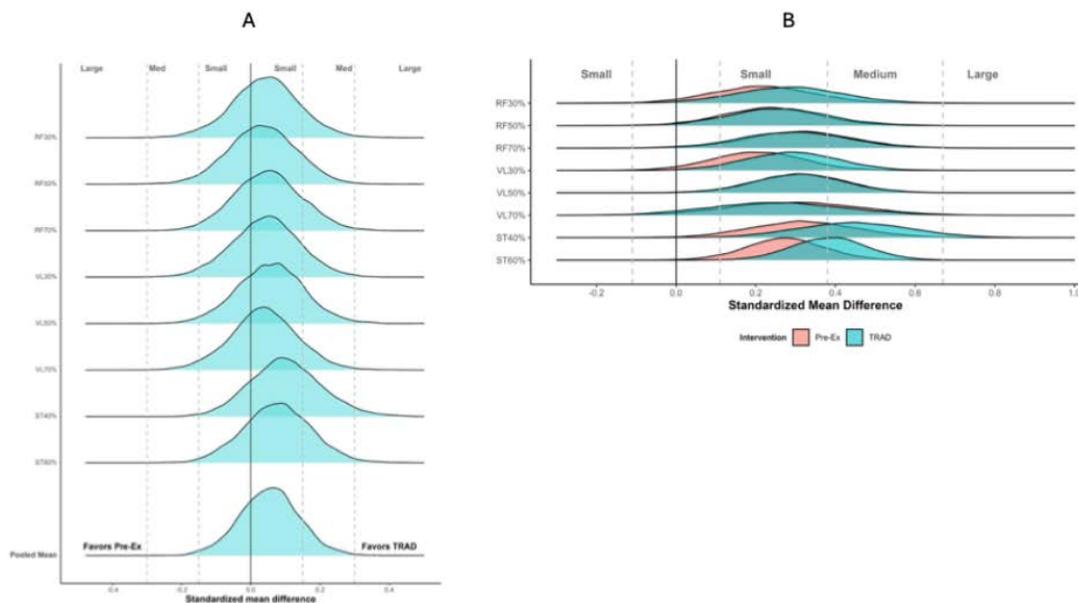


Figure 1. Standardized mean differences in muscle thickness between groups (A) and standardized mean changes within groups (B). The distributions and their relative areas reflect the probabilities of the most likely standardized values. Thresholds for small, medium, and large differences/changes are shown to help interpret the practical meaningfulness of the predominant portions of each distribution. Abbreviations: RF = Rectus femoris, VL = Vastus lateralis, ST = Semitendinosus, Pre-Ex = pre-exhaust group. TRAD = Traditional group.

Findings were consistent across all muscle sites, with point estimates uniformly favoring the TRAD intervention (Figure 1A; Table 2). However, the associated posterior probabilities of superiority were relatively low, and Bayes factors generally offered “anecdotal” to “moderate” probabilistic support for the null hypothesis over a true effect. When data from the 8 muscle sites were pooled using a hierarchical model, the standardized mean difference favored TRAD (0.06; 95% CrI: -0.12 to 0.23), with a posterior probability of superiority of 0.740. Within-group analyses based on standardized change scores suggested that both interventions likely elicited small to moderate hypertrophic responses (Figure 1B).

Table 2. Summary Table of Effect Size Estimates for All Outcomes.

OUTCOMES	Effect Size Estimate (95%CrI)	Posterior Probability Favoring TRAD	Strength of evidence
Muscle thickness			
Rectus femoris 30% (mm)	0.5 (-1.7 to 2.7)	0.687	0.35: “Anecdotal” support H_0
Rectus femoris 50% (mm)	0.3 (-1.7 to 2.5)	0.615	0.31: “Moderate” support H_0
Rectus femoris 70% (mm)	0.0 (-1.9 to 2.0)	0.511	0.31: “Moderate” support H_0
Vastus lateralis 30% (mm)	0.9 (-0.3 to 2.1)	0.943	1.2: “Anecdotal” support H_1
Vastus lateralis 50% (mm)	0.2 (-1.1 to 1.6)	0.637	0.31: “Moderate” support H_0
Vastus lateralis 70% (mm)	0.4 (-1.4 to 2.2)	0.666	0.45: “Anecdotal” support H_0
Semitendinosus 40% (mm)	0.7 (-0.7 to 2.1)	0.836	0.54: “Anecdotal” support H_0
Semitendinosus 60% (mm)	0.5 (-0.8 to 1.9)	0.782	0.32: “Moderate” support H_0
Hierarchical Pooled Mean – Muscle thickness (SMD)	0.06 (-0.12 to 0.23)	0.740	
Performance			
Vertical jump (cm)	1.3 (-1.0 to 3.3)	0.876	0.55: “Anecdotal” support H_0
Squat (kg)	1.8 (-5.4 to 9.0)	0.692	0.30: “Moderate” support H_0
Endurance (reps)	-0.3 (-2.7 to 2.2)	0.405	0.56: “Moderate” support H_0
Hierarchical Pooled Mean – Performance (SMD)	0.08 (-0.54 to 0.65)	0.610	
Body Composition			
Body fat (%)	-1.2 (-2.3 to -0.1)	0.986	2.1: “Anecdotal” support H_1
Fat Free Mass (kg)	0.7 (-0.2 to 1.7)	0.941	0.34: “Anecdotal” support H_0
Hierarchical Pooled Mean – Body Composition (SMD)	1.0 (-0.3 to 0.5)	0.768	

Performance

Findings were generally consistent across all performance outcomes, with point estimates either very close to 0 or slightly favoring the TRAD intervention (Figure 2A; Table 2). Similar to MT outcomes, the posterior probabilities of TRAD superiority were relatively low, and Bayes factors typically provided “moderate” support for the null hypothesis over a meaningful effect. When data from the 3 performance tests were pooled using a hierarchical model, central estimates were close to zero (0.08; 95% CrI: -0.54 to 0.65) and the distribution demonstrated considerable uncertainty. Within-group analyses of standardized change scores indicated that both interventions likely led to negligible to small improvements in countermovement jump, small to moderate gains in squat performance, and moderate to large increases in muscular endurance (Figure 2B).

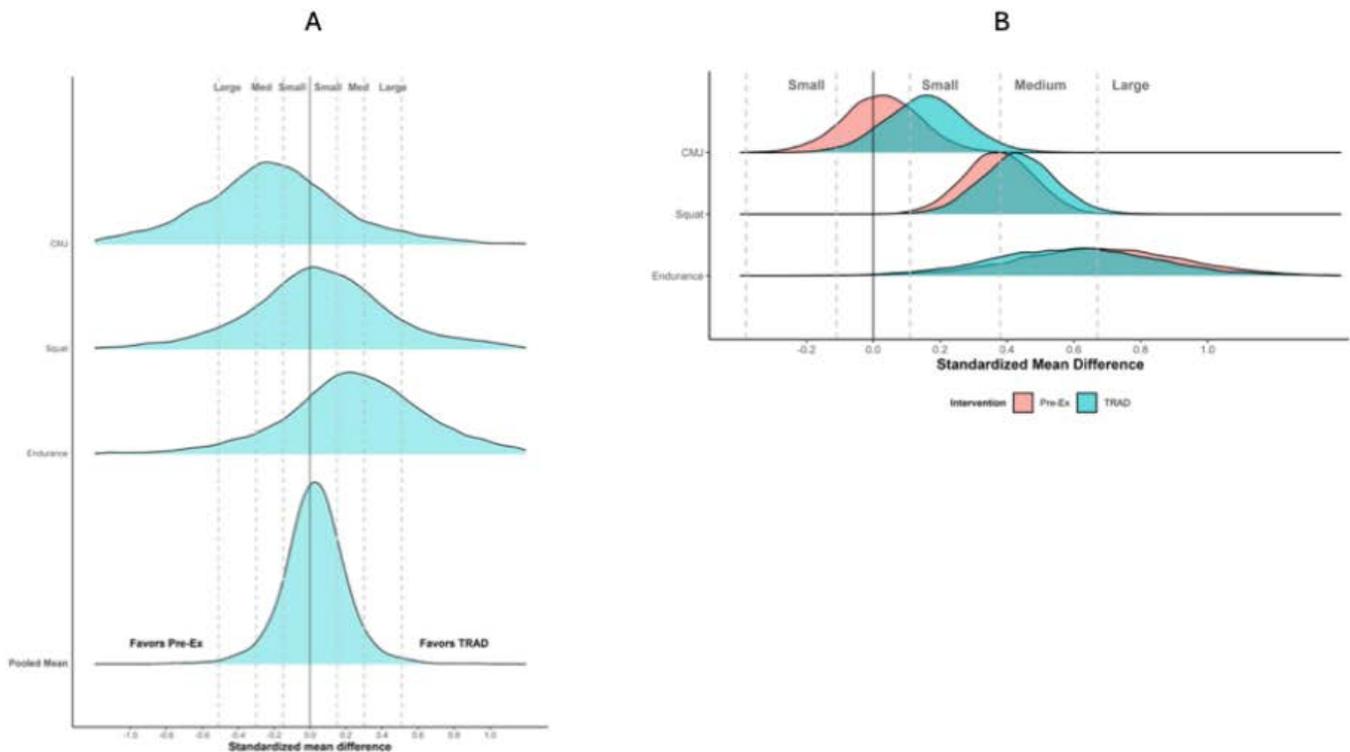


Figure 2. Standardized mean differences in performance metrics between groups (A) and standardized mean changes within groups (B). The distributions and their relative areas reflect the probabilities of the most likely standardized values. Thresholds for small, medium, and large differences/changes are shown to help interpret the practical meaningfulness of the predominant portions of each distribution. Abbreviations: CMJ = Counter movement jump. Pre-Ex = pre-exhaust group. TRAD = Traditional group.

Body composition

Point estimates favored TRAD for both body composition outcomes (Figure 3A; Table 2). In univariate analyses TRAD showed a greater reduction in body fat percentage compared to PreEx (-1.2; 95% CrI: -2.3 to -0.1%), with a high posterior probability of superiority ($P(<0) = 0.986$). The Bayes factor provided “anecdotal” evidence supporting the alternative hypothesis. For fat-free mass, point estimates also favored TRAD (0.7; 95% CrI: -0.2 to 1.7 kg), although the posterior probability was lower ($P(>0) = 0.941$) and the Bayes factor supported the null hypothesis, reflecting greater uncertainty. Within-group analyses of standardized change scores indicated that both interventions likely produced negligible to small changes in body composition. However, a modest increase in body fat percentage was observed in PreEx compared to a modest body fat loss in TRAD (Figure 3B).

Volume Load

The median net volume loads for TRAD and PreEx were 188,500 kg (IQR: [141,700 to 225,200]) and 145,800 kg (IQR: [109,600 to 182,100]), respectively. As a percentage difference, it was estimated that volume load was 29.8% greater for TRAD (95% bootstrap interval: -4.9 to +73.0%).

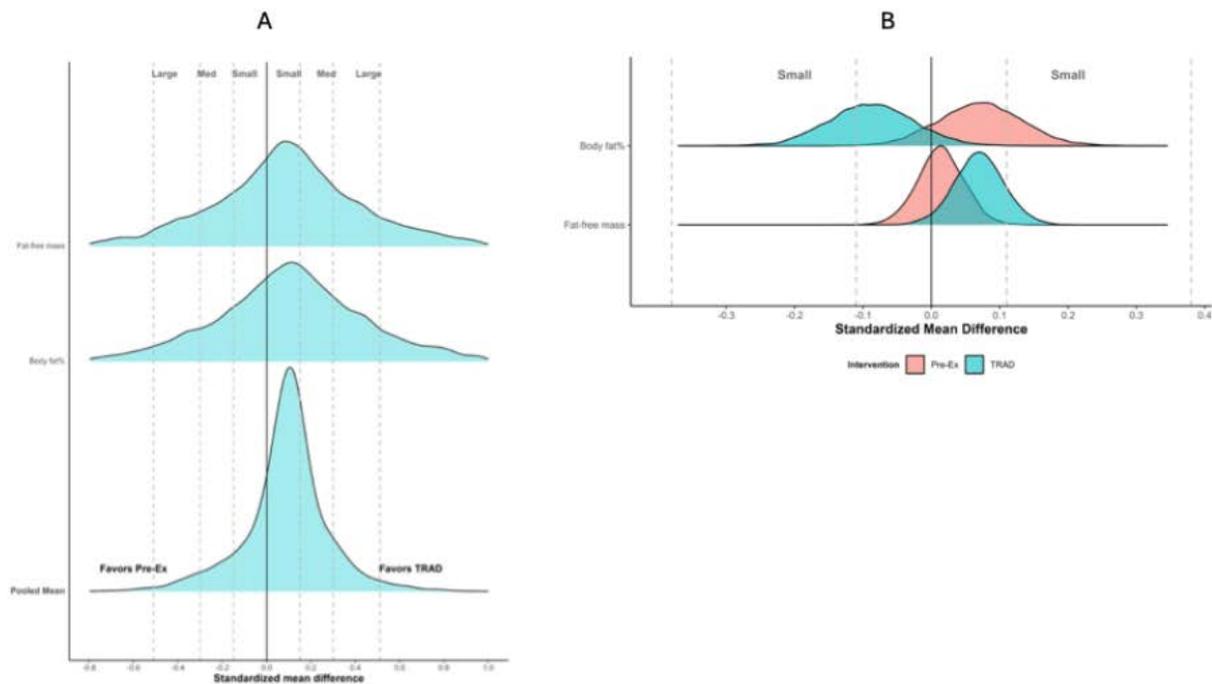


Figure 3. Standardized mean differences in body composition between groups (A) and standardized mean changes within groups (B). The distributions and their relative areas reflect the probabilities of the most likely standardized values. Thresholds for small, medium, and large differences/changes are shown to help interpret the practical meaningfulness of the predominant portions of each distribution. Abbreviations: Pre-Ex = pre-exhaust group. TRAD = Traditional group.

Discussion

This is the first longitudinal study to investigate the effects of the pre-exhaust protocol, as originally intended,⁴ on muscular adaptations in resistance-trained individuals. Although the TRAD group accumulated a substantially greater volume load across the intervention, changes in MT and body composition were only slightly greater in TRAD and accompanied by uncertain statistical evidence for a true between-group difference. Moreover, changes in power, strength, and muscular endurance were similar between groups. Additionally, SRPE values were greater in PreEx compared to TRAD when averaged across the 8-week study protocol, and pre-session recovery status was similar. Training session duration was substantially lower for PreEx compared to TRAD. The following discussion aims to interpret these findings in the context of the current state of the literature and to provide insights into potential practical implications.

Time and SRPE

Consistent with other findings reported in the superset literature,²⁵ the PreEx protocol was completed in 35.9% less time compared to the TRAD group (PreEx = 26:22, TRAD = 41:09). In addition, SRPE values were nearly a full point greater over the duration of the intervention within the PreEx group (PreEx = 7.94, TRAD = 7.08). These findings support evidence showing that a greater training density (i.e., more work in less time) training correlates to higher ratings of perceived exertion.²⁸ Additionally, although the training protocol (failure proximity, exercises, total sets, rep range) remained constant throughout the 8 weeks – theoretically allowing

participants to become accustomed to the protocol stimulus – SRPE scores remained relatively similar across the intervention with RPE scores tending to be lower for TRAD.

Hypertrophy

Both groups experienced appreciable increases in MT throughout the study. Mean differences slightly favored TRAD overall (Figure 1), with some sites favoring TRAD more than others. For example, a lateral anterior thigh measurement favored TRAD, with a posterior probability of 0.943 (95% CrI: -0.3 to 2.1). However, credible intervals for other sites and pooling of data had substantial overlap with a null effect, limiting confidence in a true between-group difference. Notably, all measured sites numerically favored TRAD, and this occurred despite a modest reduction in body fat in TRAD versus a modest increase in PreEx – an effect that might otherwise be expected to confer a slight anabolic advantage to the latter.²⁹ Although speculative, the slightly blunted hypertrophic response observed in PreEx might be explained by a markedly reduced volume load (~30%) due to a fatigue-induced decrease in the magnitude of loading over the course of the study compared to TRAD. Given that mechanical tension is the primary driver of muscle hypertrophy,³⁰ consistently training with lighter loads at a given repetition range may attenuate anabolic signaling and thus lead to suboptimal muscle development. This hypothesis warrants further investigation.

Given the paucity of research on the topic, it remains difficult to compare and contrast our results to other longitudinal protocols. Fisher et al¹¹ and Trindade et al¹⁰ both investigated the effects of variations of a pre-exhaust protocol, but did not pre-exhaust before every set, and used a single-set protocol, respectively. Our study is the first to longitudinally examine the pre-exhaust of performing the single-joint exercise immediately prior to every multi-joint set in a multi-set protocol. Thus, our novel findings address an important gap in the literature, as this style of pre-exhaust has not been directly tested but is the most frequently employed pre-exhaust method in ecologically valid settings and is consistent with how the method was originally proposed.⁴

From a practical standpoint, our results suggest that a) PreEx can be a time-efficient method to augment muscle hypertrophy, b) PreEx can elicit appreciable gains in muscle size while requiring lower loads on multi-joint exercises compared to TRAD, and c) for those aiming to optimize hypertrophy, TRAD is likely the more effective choice, although differences were small and not strongly supported by inferential evidence.

Strength Outcomes

Both PreEx and TRAD experienced similar increases in 1RM squat performance over the study period. Although the effect estimate slightly favored TRAD (mean difference: 1.8 [95% CrI: -5.4 to 9.0 kg]), the wide credible interval and associated uncertainty leave little confidence in a true difference between conditions. Since strength gains tend to be optimized at higher loads,³¹ and the TRAD group performed sets at higher percentages of their pre-determined 1RM, it is curious as to why squat 1RM gains were not greater for TRAD compared to PreEx. This result could potentially be due to both groups training within the same repetition range throughout the 8-weeks, keeping specificity in lower repetition ranges equal between groups.

Our findings are generally consistent with those of Trindade et al¹⁰ and Fisher et al,¹¹ who both reported no statistically significant differences in strength changes between pre-exhaustion

and traditional set training. However, Trindade et al¹⁰ reported discrepant results between 1RM increases in the leg press and leg extension, with the latter showing a large within-group standardized mean difference effect size difference favoring the pre-exhaust compared to traditional condition (2.24 vs 0.85, respectively) despite the lack of a statistical interaction. Alternatively, the results of Fisher et al¹¹ displayed greater absolute pre-post study increases in leg press and chest press strength favoring traditional training compared to pre-exhaustion. Given the disparate methods between studies, it is difficult to compare and contrast findings. Of note, Trindade et al¹⁰ employed untrained participants while we employed participants with previous resistance training experience. Moreover, Fisher et al¹¹ assessed strength as a function of changes in volume load using a repetition range of 8 to 12 repetitions at tempo of 2-s concentric and 4-s eccentric (which is more of a strength-endurance metric) while we assessed the outcome using 1RM testing. Although speculative, these factors, and perhaps other methodological differences, may have influenced the somewhat conflicting results between studies.

Muscle Endurance

Both groups achieved similar increases in repetitions performed during the lower body strength-endurance assessment (mean difference: -0.3 [95% CrI: -2.7 to 2.2 repetitions]). This result contradicts our initial hypothesis that long-term adherence to PreEx RT would enhance local muscular endurance more than TRAD, conceivably due to the constant exposure to greater magnitudes of fatigue and metabolic stress. The mechanisms underlying comparable endurance-strength outcomes between groups are uncertain but can plausibly be a result of TRAD averaging greater volume loads lifted on the leg extension machine over the course of the study protocol. Though pre- to post-study squat 1RM changes were likely practically insignificant between groups, total strength gains specifically on the leg extension exercise may have been greater in TRAD compared to PreEx by the end of the intervention, allowing TRAD to match endurance performance. Additionally, some evidence suggests that local muscular endurance improvements are heightened when training with more than 15 repetitions.³² The fact that neither group trained in this repetition range may help to explain the lack of pre- to post-study differences between-groups in this outcome.

Muscular Power

PreEx and TRAD both experienced similar but minimal pre- to post-study increases in CMJ. Although strength improvements have the potential to increase power output,³³ a common prescription to directly enhance muscular power is to include plyometric exercises and RT that emphasizes quick changes of direction, augmenting the stretch shortening cycle.¹⁹ Thus, the negligible changes observed in CMJ may be attributed to the fact that our protocol included only exercises with controlled repetition tempos (~1:2).

Our study has several limitations that should be considered when interpreting the findings in a practical context. First, the sample consisted of healthy males and females between the ages of 18-40 years old with at least 1 year of consistent RT experience. As such, the results may not be generalizable to individuals of different ages, training experiences, and health conditions. Additionally, although participants in this study had prior RT experience, the majority were not high-level lifters, necessitating caution when making inferences to advanced trainees. Second, this study exclusively investigated the effects of the pre-exhaust method on lower body RT. Thus, findings can only be generalized to the lower body, and the specific exercises, exercise order, and techniques employed within the protocol. For example, both groups performed their hamstring

exercises first to prevent fatigue in the quadriceps from limiting RDL performance, which may not be how a practitioner may choose to employ the strategy outside of a lab setting. Moreover, practitioners may perform some combination of exercises as paired sets, and some as traditional sets in their individual programming, and there are numerous versions of pre-exhaust paired sets that can be used for both the upper and lower body. Thus, those in the field should use caution when attempting to generalize these findings to those with differing training protocols. Third, only 22% (TRAD = 5, PreEx = 4) of the participants that completed the protocol were actively employing RDLs in their programming immediately prior to participation, while 73% (TRAD = 16, PreEx = 14) had previous experience with RDLs in general. The lack of consistent RDL performance also may have been the cause for reports of back pain, defined herein as general lower back pain prevalent enough to cause a missed session or an intra-session reduction in load (TRAD = 5, PreEx = 3). Only 1 of these participants had been consistently performing the exercise prior to the study. Moreover, the TRAD group had 1 dropout due to back pain. Although speculative, it seems likely that if each participant were performing RDLs consistently prior to involvement, there would be fewer reports of back pain due to habituation with exercise technique. Fourth, we did not assess participants' previous lower body training volumes, which could have influenced findings as some participants pre- to intra-study volume may have been altered more than others.³⁴ Fifth, we did not account for participants' previous training volume. Some studies suggest this variable may be a factor in muscular adaptations^{34,35} while others show no effect.^{36,37} The random allocation of participants conceivably should have accounted for potential confounding effects from any discrepancies in this regard. Sixth, other than creatine, we did not exclude the use of supplements that may have affected performance (e.g., caffeine, β -alanine, nitrate-based pre-workouts, etc.), nor did we monitor whether subjects took these supplements during the study. Although we cannot rule out that the supplements may have impacted performance, the random allocation of subjects and relatively large sample makes it unlikely that any such use, if it did occur, meaningfully influenced between-group differences in outcomes. Finally, MT measures were only obtained at sites in the anterior and posterior thigh. Thus, inferences cannot be made for hypertrophy of the other muscles involved in the prescribed exercises such as the glutei and adductors. Future research should address these limitations to fully elucidate practical use of this style of RT.

In conclusion, TRAD showed slightly more favorable changes in MT across all measured sites compared to PreEx, although the differences were accompanied by statistical uncertainty. This trend may, in part, be explained by the greater volume load accumulated in TRAD, which likely increased mechanical tension exposure over the training period. The magnitude of hypertrophic differences between conditions would seem to have limited practical relevance to recreational trainees. Alternatively, TRAD would seem to be a better option than PreEx for those seeking to optimize muscle hypertrophy. Measures of strength, power and local muscular endurance were relatively similar between conditions, suggesting that PreEx is a viable alternative to TRAD for these outcomes.

The results from this study have particular relevance to individuals with time constraints, as pre-exhaust RT reduces training time by 36% while promoting appreciable muscular adaptations. This is important as time constraints represent one of the largest barriers to RT adherence.³⁸ However, sRPE values were consistently higher for PreEx compared to TRAD, indicating that the protocol is more difficult to perform than typical straight-set programs. This outcome should be considered when weighing the costs vs benefits of employing PreEx in ecologically valid settings.

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Competing Interests

BJS formerly served on the scientific advisory board for Tonal Corporation, a manufacturer of fitness equipment. JE is the owner of Built With Science. All other authors report no conflicts of interest.

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Supplementary material can be viewed at: <https://osf.io/ua9hg/>

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Supplementary Table

Table S1. Descriptive summary of raw pre- and post-intervention values for all outcomes.

Variable	PreEx (n=21)			Traditional (n=20)		
	Pre	Post	Δ%	Pre	Post	Δ%
1RM squat (kg)*	105.1 ± 36.5	118.1 ± 36.6	12.4	111.5 ± 33.2	126.5 ± 38.5	13.5
Countermovement jump (cm)	47.2 ± 9.1	47.2 ± 9.4	0	47.0 ± 9.1	48.5 ± 8.1	3.2
Leg extension endurance (reps)	17.1 ± 5.7	21.1 ± 7.3	23.4	18.4 ± 5.7	21.9 ± 6.4	19.0
Anterior mid-thigh 30% (mm)	55.7 ± 10.3	57.5 ± 10.8	3.2	54.5 ± 7.4	57.0 ± 7.3	4.6
Anterior mid-thigh 50% (mm)	46.6 ± 10.0	48.7 ± 9.6	4.5	47.6 ± 8.4	49.9 ± 7.9	4.8
Anterior mid-thigh 70% (mm)	35.3 ± 8.1	37.7 ± 8.2	6.8	37.1 ± 7.7	39.4 ± 7.3	6.2
Anterior lateral thigh 30% (mm)	30.2 ± 4.6	31.1 ± 3.4	3.0	34.2 ± 4.3	35.6 ± 4.9	4.1
Anterior lateral thigh 50% (mm)	36.6 ± 5.1	38.3 ± 4.6	4.6	40.5 ± 5.6	42.3 ± 6.1	4.4
Anterior lateral thigh 70% (mm)	36.3 ± 5.1	37.8 ± 4.3	4.1	39.5 ± 5.6	40.9 ± 6.1	3.5
Posterior medial thigh 40% (mm)	27.7 ± 6.0	29.4 ± 6.3	6.1	27.1 ± 4.5	29.5 ± 5.4	8.9
Posterior medial thigh 60% (mm)	25.8 ± 7.0	27.8 ± 7.8	7.8	28.7 ± 7.3	31.5 ± 8.3	9.8
Fat-free mass (kg)	62.7 ± 14.1	62.9 ± 14.0	0.0	65.3 ± 12.2	66.9 ± 12.5	2.5
Body fat %	19.7 ± 8.5	20.3 ± 8.2	0.6	22.6 ± 8.7	21.8 ± 8.5	-0.8

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

