Training to failure vs not-to-failure with progressive volume reduction: neuromuscular and metabolic responses in untrained individuals

Entrenamiento hasta el fallo vs. sin llegar al fallo con reducción progresiva del volumen: respuestas neuromusculares y metabólicas en individuos no entrenados

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Abstract

Introduction: Resistance training to failure (RT_{F}) acutely increases neuromuscular and metabolic demands but also induces fatigue that may compromise subsequent training stimuli. Small reductions in volume at the same intensity, while avoiding failure, may attenuate fatigue while preserving training stimuli.
Objective: This study aimed to compare the acute effects of RT_{F} and non-failure resistance training (RT_{NF}) during knee extension exercise.
Methodology: Eleven untrained men completed five RT_{NF} conditions, each involving an individualized reduction ranging from 10–50% relative to number of repetitions performed during RT_{F}. Outcomes included maximum voluntary isometric contraction (MVIC), electromyography (EMG), muscle swelling of the rectus femoris (RF) and vastus lateralis (VL), blood lactate concentration, and perceived exertion (RPE).
Results: RT_{F} elicited greater increases in muscle cross-sectional area of both RF and VL ($p<0.01$) compared with all RT_{NF} conditions. EMG amplitude was higher in RT_{F} than in the 30–50% reduction conditions ($p=0.01$ for VL and RF), while MVIC ($p=0.02$) and EMG frequency differed across protocols ($p=0.02$ for RF; $p=0.03$ for VL). Additionally, lactate and RPE ($p<0.01$) responses were highest following RT_{F}.
Conclusion: In summary, RT_{F} maximizes muscle swelling and metabolic stress, whereas performing repetitions up to 20% short of failure provides a comparable neuromuscular stimulus, while minimizing metabolic stress.

Keywords

Electromyography; muscle fatigue; muscle strength; ultrasonography.

Resumen

Introducción: Entrenamiento de resistencia hasta el fallo (RT_{F}) aumenta agudamente las demandas neuromusculares y metabólicas, pero también induce fatiga que puede comprometer los estímulos de entrenamiento posteriores. Pequeñas reducciones del volumen a la misma intensidad, evitando el fallo, pueden atenuar la fatiga mientras se preservan dichos estímulos.
Objetivo: Este estudio tuvo como objetivo comparar los efectos agudos del RT_{F} y del entrenamiento de resistencia sin llegar al fallo (RT_{NF}) durante el ejercicio de extensión de rodilla.
Metodología: Once varones no entrenados completaron cinco condiciones de RT_{NF}, cada una con una reducción individualizada que osciló entre el 10% y el 50% respecto al número de repeticiones realizadas durante el RT_{F}. Las variables evaluadas incluyeron la contracción isométrica voluntaria máxima (MVIC), la electromiografía (EMG), el aumento del grosor muscular del recto femoral (RF) y del vasto lateral (VL), la concentración de lactato en sangre y la percepción subjetiva del esfuerzo (RPE).
Resultados: El RT_{F} provocó mayores aumentos en el área de sección transversal muscular tanto del RF como del VL ($p<0,01$) en comparación con todas las condiciones de RT_{NF}. La amplitud de la EMG fue mayor en el RT_{F} que en las condiciones con reducciones del 30% al 50% ($p=0,01$ para VL y RF), mientras que la MVIC ($p=0,02$) y la frecuencia de la EMG difirieron entre protocolos ($p=0,02$ para RF; $p=0,03$ para VL). Además, las respuestas de lactato y RPE ($p<0,01$) fueron más elevadas después del RT_{F}.
Conclusiones: En resumen, el RT_{F} maximiza el aumento del grosor muscular y el estrés metabólico, mientras que realizar repeticiones hasta un 20% por debajo del fallo proporciona un estímulo neuromuscular comparable, minimizando el estrés metabólico.

Palabras clave

Electromiografía; fatiga muscular; fuerza muscular; ultrasonografía.

Introduction

Resistance training (RT) is an effective strategy for promoting muscle hypertrophy and strength gains (Armero-Sotillo & Benito Peinado, 2025; Madarsa & Ikhwan Mohamad, 2025), with mechanical tension and metabolic stress serving as the main mediating factors for these adaptations (Ozaki et al., 2015). RT performed to muscle failure (RT_F) has been proposed to maximize these adaptations, potentially due to greater motor unit recruitment and metabolite accumulation compared to RT not performed to failure (RT_{NF}) (Jenkins et al., 2015; Marshall, Robbins, Wrightson, & Siegler, 2012).

Greater acute muscle swelling (commonly referred to as the 'muscle pump') is likely to be induced when RT_F allows a greater number of repetitions to be completed, compared with RT_{NF}. This interpretation aligns with previous finding (Exner et al., 2023), which reinforce the idea that, at a given intensity, performing more repetitions in RT_F leads to elevation of metabolic stress, evidenced by biological markers such as ammonia, creatine kinase (CK), and elevated blood lactate concentrations (Jenkins et al., 2015; Vieira et al., 2022). Hirono et al. (2022) reported that greater acute muscle swelling was associated with greater chronic muscle hypertrophy, suggesting that acute investigations can provide valuable insights into short-term physiological responses that may contribute to long-term adaptations. Moreover, muscle swelling and hypertrophy are not uniform along the muscle length (Kassiano et al., 2023), which could result from mechanical stress that varies across the range of motion (Diniz et al., 2022).

Recent research has shown that hypertrophy gains tend to be similar between RT_F and RT_{NF} when RT volume is equalized or when only small reductions in volume are implemented using repetition in reserve strategy (Lacerda et al., 2020; Refalo, Helms, Robinson, Hamilton, & Fyfe, 2024). However, the similarity in this response may indicate that there is a threshold of metabolic stress and neuromuscular demand beyond which additional stimuli does not lead to significant improvements and may instead increase muscle damage and prolong recovery time. Supporting this hypothesis, a meta-analysis conducted by Vieira et al. (2022) reported greater cellular damage and higher CK levels 48 hours after RT_F, indicating the need for longer recovery periods between RT_F sessions. Thus, determining the appropriate training stimulus becomes essential to maximize neuromuscular adaptation while minimizing unnecessary muscle damage.

Overall improvements in physical function after RT intervention have been associated with increases in neuromuscular activation (i.e., motor unit recruitment) and/or muscle strength (Armero-Sotillo & Benito Peinado, 2025). Although RT_F has traditionally been associated with greater motor unit recruitment (Jenkins et al., 2015; Stock, Beck, & Defreitas, 2012), this assumption has been questioned. Muscle motor units vary substantially in fiber size, location, and firing rate, and these properties influence the electromyographic (EMG) signal without necessarily reflecting proportional motor unit recruitment (Bickel, Gregory, & Dean, 2011; Vigotsky, Halperin, Lehman, Trajano, & Vieira, 2017). Furthermore, similar EMG responses have been observed between RT_F and RT_{NF} when volume was equalized, in both trained (Santanielo et al., 2020) and untrained individuals (Lacerda et al., 2020), indicating that there may be no need to train to failure in order to achieve maximal neuromuscular activation. Furthermore, several studies have reported similar adaptations in maximal dynamic strength (1RM) and maximal voluntary isometric contraction (MVIC) between RT_F and RT_{NF} conditions (Lacerda et al., 2020; Santanielo et al., 2020). In contrast, the fatigue induced by RT_F may acutely compromise maximal strength performance (Pareja-Blanco et al., 2017), which is not always desirable. Beyond maximal strength performance after RT, a complementary approach is to examining exercise-induced fatigue by analyzing EMG frequency (Lacerda et al., 2019). Previous studies indicate that the closer an individual is to failure, the greater the reduction in EMG frequency (Pedrosa et al., 2020). This suggests that approaching failure imposes progressively greater neural challenges. Despite the known physiological responses to training to failure, it remains unclear what is the minimal reduction in repetitions, relative to failure, that still elicits meaningful neuromuscular and metabolic responses

While RT_F can enhance metabolic and neuromuscular stimuli, RT_{NF} can produce comparable outcomes when variables such as volume and intensity are equivalent. This is important, given that training status can modulate physiological responses to both RT_F and RT_{NF} (Pedrosa et al., 2024). Therefore, a need exists in examining the magnitude of responses elicited by these training protocols in untrained populations. The choice of untrained populations is crucial because their responses provide a clearer, 'noise-free' signal of the fundamental physiological effect of the training protocol itself, free from the confounding adaptations of prior training.

Therefore, the aim of this study is to examine the acute responses of muscle swelling, EMG in both the frequency and time domains, blood lactate concentrations, MVIC and rate of perceived exertion (RPE) to varying reductions in repetitions (10% to 50%) relative to maximal repetitions to failure. We hypothesize that the percentage reduction in training volume relative to failure is associated with a commensurate reduction in neuromuscular and metabolic responses.

Method

Participants

A priori sample estimation (G*Power 3.1.9.2, Heinrich-Heine Universität Düsseldorf, Düsseldorf, Germany) was performed. This analysis assumed a repeated-measures, within-subjects design with six experimental conditions, effect size ($\eta^2 = 0.81$), $\alpha = 0.05$, power $(1 - \beta) = 0.80$ and a correlation of 0.50. The results indicated a sample size of 12 participants. The effect size was based on a pilot study analyzing muscle swelling of vastus lateralis at 50% of femur. All participants had abstained from RT for at least six months prior to the study. The eligibility criteria included being male, a non-smoker, free from cardiovascular or metabolic disease, with no history of performance-enhancing drug use (e.g., androgenic anabolic steroids; self-reported), no history of muscle-tendon injury, and no engagement in other forms of RT during the study period. Male participants were exclusively recruited to avoid performance variations associated with different phases of the menstrual cycle or oral contraceptive use (Engstad et al., 2025).

Participants were instructed to maintain their regular dietary habits throughout the study and to refrain from using any ergogenic aids. To minimize the influence of circadian rhythm, all testing sessions were conducted at the same time of day (±2h). Additionally, participants were required to abstain from high-intensity exercise for at least 48 hours prior to testing or training sessions, and from any physical activity immediately beforehand. The study was approved by the institutional ethics committee of the corresponding author (CAAE: 76251723.7.0000.5115, approval date: 12/18/2023) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation.

Experimental design

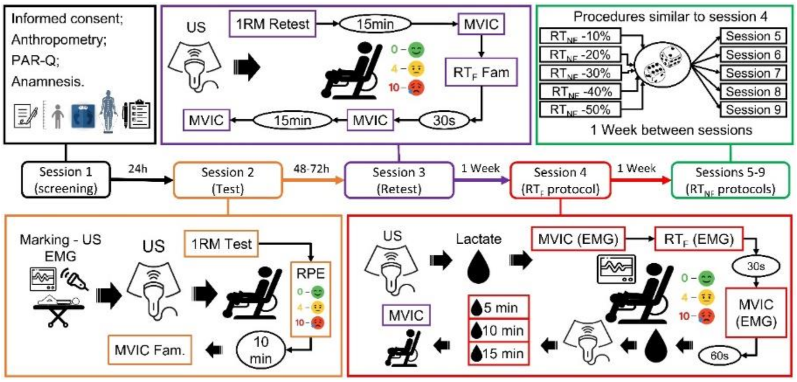
A single-blind, within-subject experimental design was employed, in which the researchers' analyzing data were blinded to the intervention allocation. Each participant completed five experimental conditions, corresponding to individualized reductions of 10%, 20%, 30%, 40%, and 50% in training volume, presented in a randomized order across experimental sessions (Figure 1). The volume reductions were calculated based on the total number of repetitions performed by each participant at 50% of 1RM, ensuring that each reduction represented a specific proportion of the participant's own prior performance. MVIC, EMG, muscle swelling through ultrasonography, and blood lactate concentration were assessed.

Training protocols

Prior to the experimental conditions, participants completed a familiarization session to become accustomed to the exercise protocol and equipment. Before experimental protocols, participants completed a specific warm-up of one set of 10 knee extension exercise repetitions without external load, performed with a muscle action duration of 3s:3s, three seconds for both the concentric and eccentric phases, respectively, using a metronome. For RT_F, participants performed three sets of knee extension exercise at 50% of 1RM. Muscle action was controlled throughout the full range of motion (ROM), resulting in a total of six seconds per repetition. The evaluator provided continuous feedback to participants regarding the muscle actions duration (explain in detail below). In RT_F, all sets were performed until the subjects were unable to execute the concentric action of the pre-established ROM (93°) and duration. A three-minute rest interval was provided between sets, and data on repetition duration and ROM were collected and recorded. Concentric phase was defined as angular displacement from 113° to 20° and the eccentric phase from 20° to 113° (0°=knee fully extended). RT_F was used as a reference to calibrate the

RT_{NF} conditions, in which training volume was systematically reduced relative to the RT_F condition. Consequently, RT_{NF} protocols followed the same procedures; however, the number of repetitions was reduced by a predetermined percentage (10, 20, 30, 40, or 50%) of the total achieved in the RT_F condition. Each experimental session was separated by a one-week interval to minimize residual fatigue and carryover effects.

Figure 1. Experimental design of the study.



RT_F: resistance training to failure; RT_{NF}: resistance training not to failure; MVIC: maximal voluntary isometric contraction test; 1RM: One maximal repetition test; PAR-Q: physical activity readiness questionnaire; RPE: Rating of Perceived Exertion Scale; US: ultrasonography; EMG: electromyography activity; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume related to the total number of repetitions performed by each participant at 50% of 1RM performed in experimental conditions of the study.

ROM and muscle actions duration

ROM and muscle action durations were assessed during both protocols by recording angular displacement with a potentiometer attached to the rotational axis of the knee extension machine's mechanical arm across all training sessions. The raw potentiometer signals were converted into angular displacement values and processed using a fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Muscle action duration was defined as the time interval between the maximum (113° of knee flexion) and minimum (20° of knee flexion) angular positions. Accordingly, concentric duration corresponded to the movement from the maximum to the minimum angle, whereas eccentric duration was defined as the movement from the minimum to the maximum angle. Additionally, concentric, eccentric, and total repetition durations were derived from the angular displacement over time. The potentiometer data were also displayed in real time on a screen, allowing participants to monitor the duration and ROM of each muscle action during all training sessions and tests (Lacerda et al., 2020; Lacerda et al., 2021). Furthermore, a metronome was used to assist participants in maintaining the prescribed repetition durations.

One repetition maximum test (1RM)

The 1RM test was conducted using a knee extension exercise (K&E Fitness, Divinópolis, MG, Brazil). This was preceded by a specific warm-up of one set of 10 knee extension exercise repetitions without weight. Rest intervals of five minutes were provided between each attempt to determine the 1RM, with no more than five attempts required. The 1RM was defined as the maximum load at which the participant could complete a single repetition. The 1RM testing procedure followed the recommendations of the National Strength and Conditioning Association (Harman & Garhammer, 2008). A 1RM retest was conducted at least 48 hours after the initial trial. The intraclass correlation coefficient for the 1RM test–retest reliability was high (ICC: 0.923; 95% CI = 0.709–0.979; $p < 0.001$).

Maximum voluntary isometric contraction test

MVIC was recorded by a type S load cell (AEPH do Brasil, São Paulo, Brazil). Participants were secured in the knee extension exercise with straps positioned across the hip to minimize extraneous body movement. Subsequently, participants were instructed to complete two MVIC of approximately 5 seconds each, with a two-minute rest interval between trials, at a knee joint angle of 60° (Lacerda et al., 2020).

They were instructed to avoid any countermovement prior to initiating the extension and to perform the movement as "hard" as possible (Maffiuletti et al., 2016) during each contraction. Each trial commenced following an auditory cue, and force output was recorded using the load cell. Verbal encouragement was provided throughout each contraction. If peak torque values differed by more than 5% between trials, an additional attempt was performed. The peak value of each trial was subsequently converted offline into Newtons. MVIC tests were performed before experimental intervention and at 30 s and 15 min post-intervention. The intraclass correlation coefficient for the MVIC between experimental condition was high (ICC: 0.984; 95% CI = 0.961–0.995; $p < 0.001$).

Muscle swelling assessment through ultrasonography

For muscle swelling, cross-sectional area (CSA) of the rectus femoris (RF) and vastus lateralis (VL) muscles was assessed using an ultrasound system (VINNO®, V5, Suzhou, China) equipped with a 5 cm linear transducer in "extended-field-of-view" mode. The acquisition procedures were similar to those previously described (Lacerda et al., 2021). Briefly, participants were positioned supine, and measurement sites were marked at 30%, 50%, and 70% of the femur length, measured between the greater trochanter and the lateral epicondyle, and aligned perpendicular to the line connecting the lateral epicondyle and the adductor tubercle.

The ultrasound system was configured with a 10 MHz frequency; image acquisition rate of 21 Hz, gain ranging from 25 dB to 71 dB and depth of image capturing ranging from 2.3 cm to 8 cm. Settings were individually adjusted and maintained throughout the study to ensure optimal image quality of the target muscles. An experienced examiner (L.T.L.) acquired two images at each femur percentage site (30%, 50%, and 70%) before and one after the experimental intervention, resulting in a total of nine images per muscle. During acquisition, the probe was positioned transversely, parallel to the intercondylar line, using a coupled guide on the participant's thigh. The images were analyzed using RadiAnt software (Medixant®, Poznan, Poland). CSA was analyzed based on the absolute changes between pre- and post-measurements. The intraclass correlation coefficient (ICC) were calculated by comparing CSA measurements from images acquired between experimental sessions for both muscles were high (ICC_{VL}: 0.997; 95% CI = 0.994–0.999, $P < 0.001$; ICC_{RF}: 0.997; 95% CI = 0.992–0.999, $p < 0.001$).

Lactate

Lactate concentrations were determined from capillary whole-blood samples obtained from the hyperemic earlobe using sterile disposable lancets (YSI 2500, YSI Incorporated, Yellow Springs, Ohio, USA). The earlobe was first cleaned with neutral soap and water, followed by sterilization with 70% alcohol prior to puncture. A 30 µL blood sample was collected into heparinized capillary tubes, which were then transferred into tubes containing 60 µL of 1% sodium fluoride and stored in a refrigerator at −20 ºC. Blood samples were collected immediately before, and at 1, 5, 10, and 15 minutes after the experimental intervention. Samples were subsequently thawed and analyzed in duplicate. The ICC for the lactate between experimental condition was high (ICC: 0.919; 95% CI = 0.806–0.977, $p < 0.001$).

Electromyography activity

The electromyographic and potentiometer signals were synchronized using an 8-channel system (SAS1000V8-WF, EMG System do Brasil®, São José dos Campos, Brazil) connected to a A/D Converter (NI USB-6009, National Instruments, Austin, TX, USA) at a sampling rate of 4 kHz. Signals were recorded and processed using specialized software (DasyLab 11.0; Measurement Computing Corporation, Norton, MA, USA) using a bipolar montage (gain: 2000×; CMRR: ≥100 dB; impedance: 10^9 Ohms; signal-to-noise ratio: ≤3 µV RMS; range: ±5000 µV). Following skin preparation (trichotomy and cleaning with 70% alcohol), disposable Ag/AgCl surface electrodes (Qingdao Bright Medical Manufacturing Co. Ltd., Qingdao, China) were placed over the RF and VL with a 2 cm interelectrode distance. A reference electrode was positioned over the patella of the respective limb. These methods were consistent with the recommendations of surface EMG for noninvasive assessment of muscles (SENIAM) (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). To ensure reproducibility, the electrode placement sites for EMG recordings were marked with a permanent marker and maintained consistently across all experimental sessions.

For the time domain, the EMG data was filtered (4th-order Butterworth band-pass filter of 20–500 Hz) before calculating the EMG amplitude as the root mean square (EMG_{RMS}). Before commencing each training session, participants were asked to perform an MVIC test for 5 seconds on the knee extension machine exercise at 60° knee flexion (controlled by the potentiometer). The EMG_{RMS} value found during the MVIC test was then used as a reference for the normalization of the subsequent protocol measurements (normalization test). The mean EMG of concentric muscle actions for each protocol was then calculated. These values were divided by the respective reference values previously described, generating the normalized EMG_{RMS} per protocol. The mean for each of the 6 protocols of EMG_{RMS} was used in the statistical analysis as the mean neuromuscular activation for each training session. The ICC for the $EMG_{RMS(VL)}$ and $EMG_{RMS(RF)}$ between experimental condition were high (ICC_{VL}: 0.980; 95% CI = 0.995–0.994; $p < 0.001$; ICC_{RF}: 0.968; 95% CI = 0.927–0.990; $p < 0.001$).

For the frequency domain (FREQ), median frequency values obtained during the MVIC were derived from the power spectral density estimated using Welch’s method, a procedure that averages partially overlapping windowed segments to provide a smoother and more reliable spectral estimate. The segment length was limited to a maximum of 2048 samples (corresponding to 512 ms at a 4000-Hz sampling rate). The mean frequency was defined as the frequency that divides the spectral power into two equal halves. FREQ measurements were performed before experimental intervention and at 30 s and 15 min post-intervention. The ICC for the $FREQ_{VL}$ and $FREQ_{RF}$ between experimental condition were high (ICC_{VL}: 0.935; 95% CI = 0.852–0.980; $p < 0.001$; ICC_{RF}: 0.934; 95% CI = 0.848–0.979; $p < 0.001$).

Rate of perceived exertion

To assess participant’s RPE, we used the Omnibus-Resistance (Robertson et al., 2003). After each set during protocols, participants were asked to indicate how hard the exercise felt on an 11-point Likert-type scale, anchored from 0 (extremely easy) to 10 (extremely hard). The median of all three sets was calculated for analysis. The procedure for the establishment of the low (“1” score) and high (“10” score) anchors for each individual’s perceived exertion was read to volunteers during performing one repetition in knee extension exercise without adding weight to the equipment and in 1RM test, respectively.

Statistical Analysis

Data was entered into SPSS (Statistics for Windows, version 22) and screened for missing values and outliers. The ICC was calculated to assess the reliability of 1RM, MVIC, ultrasonography, lactate and EMG measurements. The Shapiro–Wilk test was performed to evaluate the normality of the data. If no deviations from normality were observed, two-way analysis of variance (ANOVA) was conducted to examine the effects of training protocol and time on MVIC, EMG frequency, and lactate. MVIC and EMG frequency were analyzed as the changes of pre-experimental interventions. When a significant main effect was detected, post hoc pairwise comparisons were performed using the least significant difference (LSD) test. The assumption of sphericity was evaluated using Mauchly’s test prior to conducting repeated-measures analyses and Huynh-Feldt correction was considered when necessary. Additionally, a one-way ANOVA was conducted to assess differences in muscle swelling (CSA), EMG time domain, and FREQ. For RPE, a non-parametric Friedman test was performed. Partial eta square effect size (ηp^2) was calculated and interpreted as small (<0.01), medium (0.02–0.13), or large (>0.14) (Cohen, 1988). In addition, statistical power (1−β) was calculated for all analyses. A threshold of 0.80 was considered acceptable. Data are presented as mean and standard deviation (SD) unless stated otherwise, and statistical significance was set at $p < 0.05$.

Results

A total of 12 participants were randomized and began the study. One participant did not complete all tests due to illness unrelated to the study and was excluded. This resulted in a final sample of 11 participants (age: 23.27 ± 4.92 years; height: 180.00 ± 7.00 cm; body mass: 74.19 ± 15.91 kg; body fat: 18.3 ± 8.32%; fat-free mass: 59.85 ± 10.53 kg). Considering this missing data, post hoc power analysis was calculated for each outcome. Additionally, table 1 presents parameters controlled to ensure standardized training-load prescription.

Table 1. Parameters controlled to ensure standardized training-load prescription

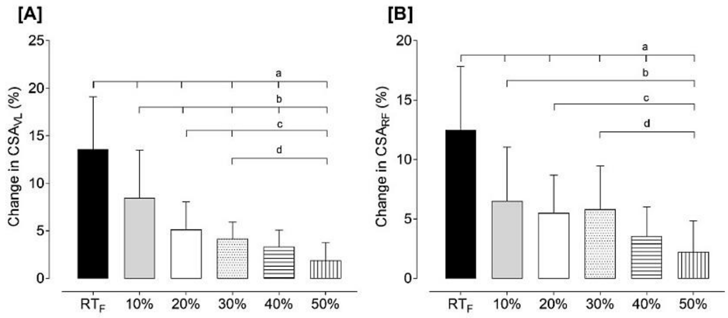
	Experimental condition					
Variable	RT_F	10%	20%	30%	40%	50%
Rep. Duration	6.08±0.3	5.97±0.42	5.99±0.35	6.05±0.31	6.00±0.31	5.95±0.33
Number of Reps.	21.55±5.41	19.45±5.05	17.18±3.95	15.27±3.82	13.00±3.19	11.00±2.90
Range of Motion (ROM)	81.44±1.09	81.32±1.03	81.90±0.88	81.76±1.04	81.39±0.85	81.38±0.66

RT_F: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. Data are present as mean and SD. Rep. Duration: Repetition duration; Number of Reps.: number of repetitions.

Muscle swelling (changes in CSA)

For CSA_{VL}, a significant effect was found for protocol ($F_{2.53,22.85} = 23.67$, $p < 0.01$, $\eta p^2 = 0.72$; power = 0.99). For CSA_{RF}, a significant effect was found for protocol ($F_{5,45} = 15.43$, $p < 0.01$, partial $\eta^2 = 0.63$; power = 0.99). Detailed information for least significance difference post hoc comparisons for both muscles is presented in Figure 2A–B.

Figure 2. Muscle swelling across experimental conditions

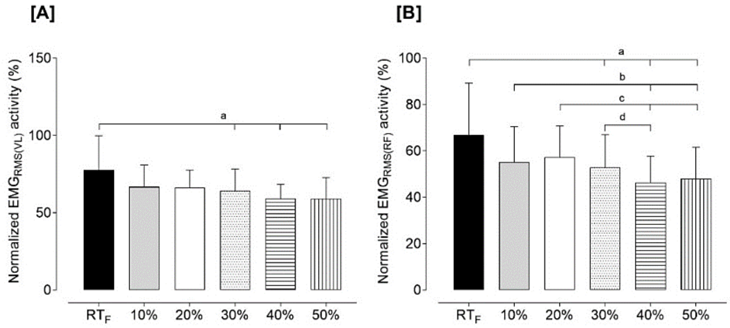


A) Changes in vastus lateralis; B) Changes in rectus femoris muscles; RT_F: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. CSA_{VL}: cross sectional area of vastus lateralis; CSA_{RF}: cross sectional area of rectus femoralis. ^{a}denotes differences from RT_F. ^{b}denotes differences from 10%. ^{c}denotes difference from 20%. ^{d}denotes differences from 30%. Data are presented as mean and SD.

Amplitude EMG (RMS)

For the time domain, EMG_{VL}, a significant effect was found for protocol ($F_{2.75,27.49} = 4.88$, $p = 0.01$, $\eta p^2 = 0.32$; power = 0.84). Least significance difference post hoc comparisons indicated that RT_F were significantly higher compared to the protocols with 30%, 40%, and 50% reductions in volume, whereas no significant differences were observed between RT_F and the 10% and 20% reduction protocols (Figure 3A). No other differences were found among protocols. For EMG_{RF}, a significant effect was found for protocol ($F_{2.40,24.08} = 5.16$, $p = 0.01$, $\eta p^2 = 0.34$; power = 0.82) (Figure 3B). Similarly, EMG_{RF} was significantly higher in RT_F than in the 30%, 40%, and 50% protocols, with no differences compared to the 10% and 20% protocols.

Figure 3. Neuromuscular activity across experimental conditions

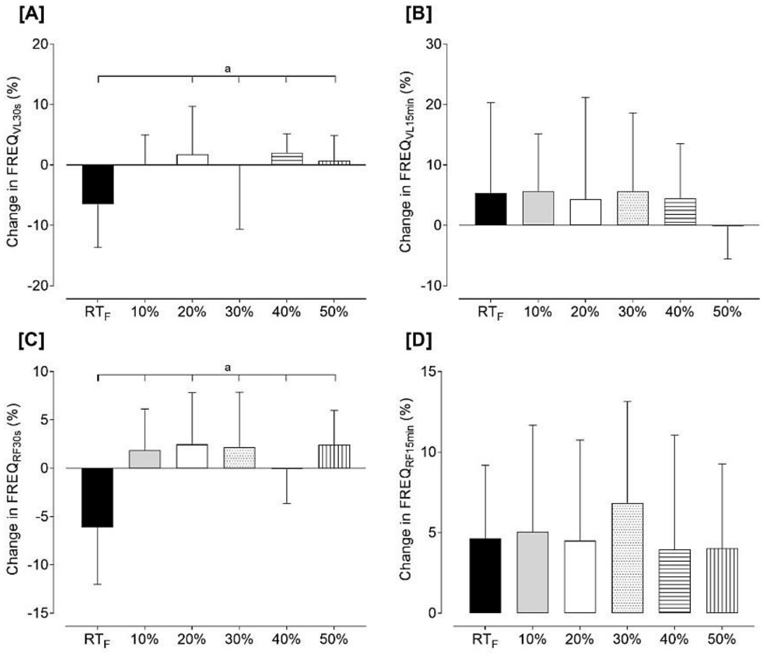


A) Normalized EMG_{RMS} of the vastus lateralis; B) Normalized EMG_{RMS} of the rectus femoris. 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. $EMG_{RMS(VL)}$: electromyography root mean square of vastus lateralis; $EMG_{RMS(RF)}$: electromyography root mean square of rectus femoralis. ^{a}denotes differences from RT_F. ^{b}denotes differences from 10%. ^{c}denotes difference from 20%. ^{d}denotes differences from 30%. Data are presented as mean and SD.

Frequency EMG (median data)

Related to $FREQ_{VL}$, no significant effect was found for protocol ($F_{5,45}$ = 8.44, p = 0.65, ηp^2 = 0.06; power = 0.21) and time ($F_{1,9}$ = 1.77, p = 0.21, ηp^2 = 0.16; power = 0.22). However, a significant effect was found for interaction ($F_{4.62,41.61}$ = 2.72, p = 0.035, ηp^2 = 0.23; power = 0.74). Related to $FREQ_{RF}$, a significant effect was found for time ($F_{1,10}$ = 14.82, p = 0.01, ηp^2 = 0.59; power = 0.93) and interaction ($F_{5,50}$ = 2.94, p = 0.02, ηp^2 = 0.22; power = 0.81). However, no significant effect was found for protocol ($F_{5,50}$ = 2.10, p = 0.08, partial η^2 = 0.17; power = 0.64). Results of each analysis and least significance difference post hoc comparisons are reported in Figure 4.

Figure 4. Neuromuscular fatigue parameters across experimental conditions.

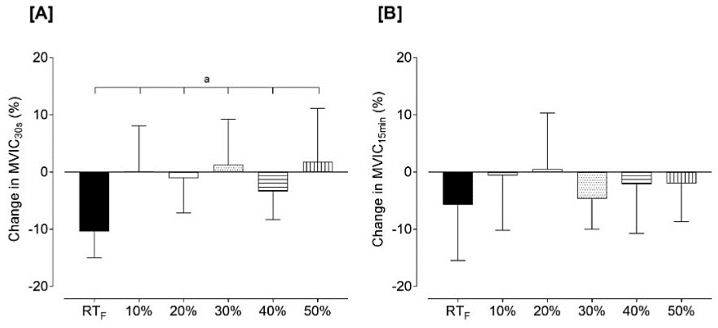


A) Changes in frequency domain EMG activity for vastus lateralis muscle at 30 s after experimental conditions; B) Changes in frequency domain EMG activity for vastus lateralis muscle at 15 min after experimental conditions. C) Changes in frequency domain EMG activity for rectus femoris muscle at 30 s after experimental conditions; D) Changes in frequency domain EMG activity for rectus femoris muscle at 15 min after experimental conditions. RT_F: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. ^{a}denotes differences from RT_F. Data are presented as mean and SD.

Maximal strength performance (change in MVIC)

For MVIC, a significant effect was found for protocol ($F_{4.56,45.65}$ = 3.04, p = 0.02, ηp^2 = 0.23; power = 0.79) and interaction ($F_{5,50}$ = 2.77, p = 0.02, ηp^2 = 0.21; power = 0.78). However, no significant effect was found for time ($F_{1,10}$ = 0.13, p = 0.72, ηp^2 = 0.01; power = 0.06) (Figure 5).

Figure 5. Strength performance across experimental conditions.



A) Changes in maximal voluntary isometric contraction (MVIC) at 30s after experimental conditions; B) Changes in maximal voluntary isometric contraction (MVIC) at 15 min after experimental conditions; RT$_F$: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. ^{a}denotes differences from RT$_F$. Data are presented as mean and SD.

Blood lactate concentration

For lactate, a significant effect were found for protocol ($F_{3.58,35.82} = 37.57$, $p < 0.01$, $\eta p^2 = 0.79$; power = 0.99), time ($F_{1.33,13.32} = 70.49$, $p < 0.01$, $\eta p^2 = 0.87$; power = 0.99) and interactions ($F_{8.70,87.04} = 19.31$, $p < 0.01$, $\eta p^2 = 0.65$; power = 0.99). Detailed information for least significance difference post hoc comparisons is presented in Table 2.

Table 2. Lactate response at different time points across the experimental conditions.

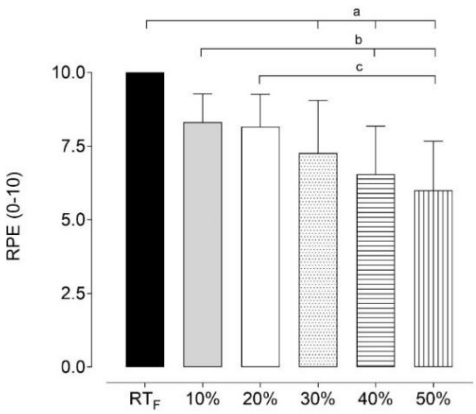
	Experimental condition					
Variable	RTF	10%	20%	30%	40%	50%
LacPRE (mmol/L)	1.26±0.37	1.28±0.37	1.22±0.54	1.27±0.42	1.24±0.48	1.35±0.51
Lac1MIN (mmol/L)	4.63±0.87*	4.29±0.78*	3.42±1.32^{ab*}	2.84±0.72ab*	2.52±0.96abc*	2.36±0.75^{abcd*}
Lac5MIN (mmol/L)	5.07±1.24$^{*\$}$	3.66±0.83a$^{*\$}$	3.04±1.19^{ab*}	2.53±0.88ab$^{*\$}$	1.94±0.59abcd$^{*\$}$	1.89±0.70$^{abcd*\$}$
Lac10MIN (mmol/L)	4.24±1.22$^{*\#}$	2.95±0.84$^{a*\$\#}$	2.47±1.20$^{a*\$\#}$	1.95±0.63ab$^{*\$\#}$	1.53±0.50$^{abcd\$\#}$	1.36±0.66$^{abcd\$\#}$
Lac15MIN (mmol/L)	3.43±1.23$^{*\$\#\&}$	2.18±0.58$^{a*\$\#\&}$	1.80±0.92$^{a*\$\#\&}$	1.38±0.41$^{ab\$\#\&}$	1.10±0.28$^{abcd\$\#\&}$	1.19±0.43$^{abc\$\#}$

Lac$_{PRE}$: blood lactate concentration at baseline; Lac$_{1MIN}$: blood lactate concentration at 1 min post training protocol; Lac$_{5MIN}$: blood lactate concentration at 5 min post training protocol; Lac$_{10MIN}$: blood lactate concentration at 10 min post training protocol; Lac$_{15MIN}$: blood lactate concentration at 15 min post training protocol; RT$_F$: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. ^{a}denotes differences from RT$_F$. ^{b}denotes differences from 10%. ^{c}denotes difference from 20%. ^{d}denotes differences from 30%. *denotes difference from Lac$_{Pre}$; $^\$$denotes difference from Lac$_{1MIN}$; $^\#$denotes difference from Lac$_{5MIN}$; $^\&$denotes difference from Lac$_{10MIN}$. Data are presented as mean and SD.

Perceptual exertion

For RPE median scores, a significant effect for protocol was found (X^2 (5) = 44.47; $p < 0.01$; Kendall's W effect size = 0.81) (Figure 6).

Figure 6. Perceived effort across experimental conditions.



RT_F: resistance training to failure; 10 to 50% denotes individualized reductions of 10%, 20%, 30%, 40%, or 50% in training volume. [a]denotes differences from RT_F. [b]denotes differences from 10%. [c]denotes difference from 20%. Data are presented as median and interquartile range.

Discussion

We examined the acute effects of varying reductions in repetitions (10% to 50%) relative to RT_F performed at 50% of 1RM on neuromuscular, metabolic and perceptual parameters of untrained men. Specifically, we analyzed muscle swelling, EMG (amplitude and frequency), MVIC, blood lactate concentrations, and RPE. Overall, the findings support the hypothesis that greater reductions in training volume are associated with proportionally lower neuromuscular and metabolic responses.

Our primary findings showed that RT_F elicited greater muscle swelling, neuromuscular, metabolic and perceptual demands compared to all other protocols in untrained individuals. As exercise approaches muscle failure, metabolic stress increases, leading to an elevated level of osmotic metabolites such as inorganic phosphate and free creatine (de Freitas, Gerosa-Neto, Zanchi, Lira, & Rossi, 2017; Schoenfeld, 2010). These metabolites enhance intracellular osmotic pressure, promoting fluid influx into the muscle fiber and contributing to transient muscle swelling (Schoenfeld, 2013). Previous evidence has also shown a linear relationship between the number of repetitions performed and muscle swelling assessed through the transverse relaxation time (T_2) measured via MRI, a technique that indirectly captures shifts in intracellular and interstitial fluid and changes in osmotic balance (Yue et al., 1994). Ultimately, muscle swelling reflects increased intracellular hydration, which has been theorized to activate anabolic signaling pathways and potentially contribute to hypertrophic adaptations (Schoenfeld, 2010, 2013). This mechanism may help explain our findings, as we observed more pronounced muscle swelling in the RT_F condition, with proportional reductions as repetitions decreased across the other protocols (10–50%). Although we did not directly analyze hypertrophy, our results may align with previous evidence demonstrating associations between acute muscle swelling and chronic hypertrophy after six weeks of RT (Hirono et al., 2022). Conversely, it is noteworthy that RT_F can also induce substantial more physiological stresses (Davies, Orr, Halaki, & Hackett, 2016) and muscle damage (Damas et al., 2016), which can require a prolonged recovery period between training sessions, consequently affecting intensity and volume of subsequent sessions (Davies, Orr, Halaki, & Hackett, 2016).

With respect to EMG activity, RT_F elicited higher EMG amplitude compared with the 30–50% reduction conditions. Several variables influence neuromuscular activation, including volume, intensity, and time under tension (Corradi et al., 2021; Lacerda et al., 2016). With respect to volume, previous evidence has shown that RT_F induces greater EMG amplitude compared with RT_{NF} (Gomes et al., 2021; Sundstrup et al., 2012). These findings may be partially explained by the premise that additional motor units must be recruited to maintain force output as fatigue develops (Rooney, Herbert, & Balnave, 1994). When RT_F protocols are performed with light loads (50% 1RM), this effect appear to be even more pronounced (Looney et al., 2016). Conversely, when total volume is equalized within a session, similar EMG amplitude has been reported for both RT_F and RT_{NF} protocol, contradicting this initial assumption (Lacerda et al., 2020). In this context, our results showed that reductions of up to 20% in the RT_{NF} produced EMG activity comparable to RT_F, suggesting that the neuromuscular system was stimulated in a similar manner. This is consistent with findings in untrained women showing that full motor-unit recruitment occurs within 3–5 repetitions of failure, indicating that RT_F is not required (Sundstrup et al., 2012). Together, these results suggest a volume threshold beyond which additional repetitions offer no further neuromuscular benefit. Although EMG amplitude does not fully capture motor-unit recruitment (Vigotsky, Halperin, Lehman, Trajano, & Vieira, 2017), factors such as firing frequency and motor-unit synchronization also contribute. Notably, studies using EMG decomposition report recruitment of higher-threshold motor units when the vastus lateralis is fatigued (Stock, Beck, & Defreitas, 2012).

Considering muscle strength, RT_F caused a significant reduction in MVIC values immediately after session cessation compared to all other protocols. The reduction in MVIC may be partially explained by metabolite accumulation activating group III and IV afferents, which exert an inhibitory effect on the central nervous system (Carroll, Taylor, & Gandevia, 2017; Enoka et al., 2011). This afferent feedback decreases spinal excitability and, combined with the fatigue-induced reduction in muscle fiber conduction velocity (Place, Bruton, & Westerblad, 2009), results in a lower neural drive to the muscle (Tornero-Aguilera, Jimenez-Morcillo, Rubio-Zarapuz, & Clemente-Suarez, 2022). Consequently, motoneuron firing rates decline, reducing the muscle's capacity to generate maximal force. Additionally, in agreement with the MVIC response, $FREQ_{VL}$ and $FREQ_{RF}$ followed a similar pattern. EMG frequency-domain measures have frequently been proposed as indicators of muscle fatigue (Masuda, Masuda, Sadoyama, Inaki, & Katsuta, 1999; Mullany, O'Malley, St Clair Gibson, & Vaughan, 2002). This may reflect physiological processes occurring within the muscle, such as metabolic stress, ionic disturbances, or reduced membrane excitability (Brody, Pollock, Roy, De Luca, & Celli, 1991; Jenkins et al., 2015; Place, Bruton, & Westerblad, 2009). Furthermore, the observed reduction in the EMG frequency domain after RT_F is consistent with previous findings from fatiguing protocols (Lacerda et al., 2019; Masuda, Masuda, Sadoyama, Inaki, & Katsuta, 1999; Mullany, O'Malley, St Clair Gibson, & Vaughan, 2002). This response may be related to slow action potential propagation (Masuda, Masuda, Sadoyama, Inaki, & Katsuta, 1999), induced by greater metabolic stress (Jenkins et al., 2015), which directly affects conductivity velocity. It has also been proposed that shifts in the EMG power spectrum toward lower frequencies, partly driven by decreases in intramuscular pH, contribute to reductions frequency-domain variables during protocols performed to failure (Brody, Pollock, Roy, De Luca, & Celli, 1991).

The inverse relationship between blood lactate concentrations and training volume observed in the present study suggests that progressive reductions in volume imposed lower metabolic stress, potentially resulting in faster recovery across the post-exercise time points, as values returned toward baseline more rapidly. This finding aligns with the premise that lactate is a byproduct of the glycolytic system whose concentration is modulated according to training load arrangement (i.e., volume, intensity, time under tension) and acts as a potential signaling molecule capable of modulating beneficial adaptations in several tissues (Brooks, 2018; Ferguson et al., 2018). Nevertheless, performing RT_F is thought to impose greater demands on energy systems and elicit higher anabolic signaling than RT_{NF} (Grgic & Schoenfeld, 2019; Nishimura et al., 2010; Schoenfeld, 2010), thereby inducing higher metabolic stress and delaying recovery. In contrast, similar hypertrophic responses between RT_F and RT_{NF} protocols early reported (Lacerda et al., 2020) reinforce the reasoning that there is a threshold for metabolic stress beyond which no further beneficial effects are realized (Schoenfeld & Grgic, 2019). Our result appears to support this notion, suggesting that a 10–20% reduction in volume may induce considerable metabolic demand without exceeding this threshold, which could still support hypertrophy adaptations. This reasoning warrants further investigations into chronic responses provided by RT_F and RT_{NF} at varying proximities to failure.

Lastly, the maximal RPE scores observed after RT_F align with the notion that greater perceptual effort is required to maintain performance as fatigue accumulates (Emanuel, Rozen, & Halperin, 2020). Higher RPE values during RT_F compared with RT_{NF} have also been reported previously (Vieira et al., 2022). Additionally, correlations between exercise tolerance and mental fatigue have been described (Marcora, Staiano, & Manning, 2009). Ultimately, the greater accumulation of metabolic by-products, such as lactate, observed in the presented study corroborates supports earlier associations between metabolic stress and increased RPE.

This study presents several limitations. First, the relatively small sample size may have reduced the statistical power to detect subtle differences across conditions. Indeed, observed power values were high

(≥ 0.93) across most outcome measures. Second, the randomization across five experimental conditions, while using one condition as a reference to determine volume reductions, may have introduced bias, as individual fatigue responses and volume-response relationships are not necessarily linear, even when counterbalanced. However, the experimental sessions were interspersed by one week, and the counterbalancing strategy likely minimized systematic order effects. Finally, the findings are limited to untrained young adults and may not generalize to other populations or to different exercise modalities. Nevertheless, this sample allows for a clearer observation of the acute physiological responses without the confounding influence of chronic adaptations. Lastly, there are strengths to be highlighted. For instance, the experimental protocols conducted in untrained individuals using an objective reduction in training volume referenced to RT_F, along with the inclusion of both neuromuscular and metabolic assessments, address an important gap in literature. Furthermore, from a practical standpoint, these findings provide trainees and practitioners with evidence that choosing between RT_F and RT_{NF} imposes distinct demands that should be considered when prescribing RT.

Conclusions

In summary, choosing between RT_F or varying proximities to failure in untrained individuals should be guided by the specific adaptations one aims to elicit. RT_F appears to be preferable when the goal is to induce greater muscle swelling. However, when the priority is elevating the neuromuscular demand, reducing repetitions by up to 20% can provide a comparable stimulus, as demonstrated by the similar EMG amplitude observed. Therefore, performing a protocol in closer proximity to, but not reaching, failure may offer an alternative for achieving similar neuromuscular activation while minimizing metabolic stress.

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