How close to failure? Muscle swelling and EMG responses to resistance training with different proximities to muscle failure

Qué tan cerca del fallo muscular? Inflamación muscular y respuestas EMG al entrenamiento de resistencia con diferentes proximidades al fallo muscular

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Abstract

Introduction: Muscle swelling and electromyography (EMG) are non-invasive markers of peripheral and neuromuscular responses to resistance training. However, no study has examined how graded proximity to muscle failure modulates these responses in trained individuals.

Objective: This study compared the acute responses of EMG and muscle swelling across six protocols differing in proximity to muscle failure in trained men.

Methodology: Fourteen trained men performed the bilateral knee extension exercise with four sets at 60% of one-repetition maximum. Protocols included training to muscle failure (MF) and five non-failure (NMF) conditions with 10%, 20%, 30%, 40%, and 50% fewer repetitions than MF. Cross-sectional area (ultrasound) and normalized EMG (surface electrodes) of the rectus femoris and vastus lateralis were assessed pre- and post-training.

Results: Muscle swelling differed significantly between all protocols for both muscles ($p<0.05$), increasing progressively as repetitions approached failure. For EMG, MF produced the highest activation; however, NMF protocols with small repetition reductions (−10% to −30%) did not differ significantly from each other. Muscle swelling was more sensitive to small changes in repetition volume than EMG amplitude.

Conclusion: These findings indicate that proximity to failure modulates peripheral and neuromuscular responses in a dose-dependent manner, with distinct sensitivity thresholds between variables, providing practical guidance for resistance training prescription.

Keywords

Cross-sectional area; muscle activation; repetition number; resistance training.

Resumen

Introducción: La hinchazón muscular y la electromiografía (EMG) son marcadores no invasivos de respuestas periféricas y neuromusculares al entrenamiento de resistencia. Sin embargo, ningún estudio ha examinado cómo la proximidad al fallo muscular modula estas respuestas en individuos entrenados.

Objetivo: Este estudio comparó las respuestas agudas de EMG e hinchazón muscular en seis protocolos con distintas proximidades al fallo en hombres entrenados.

Metodología: Catorce hombres realizaron la extensión bilateral de rodilla con cuatro series al 60 % de una repetición máxima. Los protocolos incluían el fallo muscular (MF) y cinco condiciones sin fallo (NMF) con 10 %, 20 %, 30 %, 40 % y 50 % menos repeticiones que el MF. Se evaluaron el área transversal (ecografía) y el EMG normalizado (electrodos de superficie) del recto femoral y vasto lateral pre y post entrenamiento.

Resultados: La hinchazón muscular difirió significativamente entre todos los protocolos para ambos músculos ($p < 0,05$), aumentando progresivamente conforme las repeticiones se acercaban al fallo. El MF produjo la mayor activación del EMG; sin embargo, protocolos NMF con pequeñas reducciones de repeticiones (−10 % a −30 %) no difirieron entre sí. La hinchazón fue más sensible a cambios en el volumen de repeticiones que la amplitud EMG.

Conclusiones: Estos hallazgos indican que la proximidad al fallo modula las respuestas periféricas y neuromusculares de forma dependiente de la dosis, con umbrales de sensibilidad distintos entre variables, proporcionando una guía práctica para la prescripción del entrenamiento de resistencia.

Palabras clave

Activación muscular; área de sección transversal; entrenamiento de resistencia; número de repeticiones.

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., 2016). In this context, RT performed to muscular failure (MF) has been proposed to maximize these stimuli, potentially due to greater motor unit recruitment compared to RT not performed to failure (NMF) (Jenkins et al., 2015). However, it remains unclear whether MF has a greater potential to induce long-term adaptations such as increases in muscle strength and hypertrophy when compared to NMF (Grgic et al., 2022; Lacerda et al., 2020). Moreover, MF produces elevated energy demands, leading to greater reductions in performance, higher ratings of perceived exertion, and delayed onset muscle soreness compared with NMF (Refalo et al., 2023; Vieira et al., 2022), raising the question of whether similar physiological stimuli could be achieved with lower training volumes.

A previous study reported that EMG amplitude increases as a set approaches MF, with maximal EMG levels achievable 3–5 repetitions before reaching failure (Sundstrup et al., 2012). In parallel, greater training volumes performed to MF have been shown to promote muscle swelling (Jenkins et al., 2015), and greater acute muscle swelling has been associated with greater chronic muscle hypertrophy (Hirono et al., 2022). EMG amplitude reflects neuromuscular activation and motor unit recruitment (Looney et al., 2016), while muscle swelling represents a peripheral response associated with cellular stress, it may be related in part to hypertrophic signaling (Schoenfeld, 2013). Additionally, approaching failure progressively reduces EMG frequency, suggesting increasing neural fatigue as sets near MF (Pedrosa et al., 2020). Together, EMG amplitude and muscle swelling serve as acute, non-invasive markers of the neural and peripheral mechanisms involved in RT. Although MF consistently promotes acute increases in these variables (Gomes et al., 2021; Jenkins et al., 2015), it remains uncertain whether NMF protocols could produce physiological responses of similar magnitude and whether these markers are sensitive enough to detect graded differences as a function of proximity to MF.

A recent study by Souza et al. (2026) examined the acute responses of EMG, muscle swelling, blood lactate, and perceived exertion to varying reductions in volume (10–50% relative to MF) in untrained individuals. Their findings indicated that MF maximized muscle swelling and metabolic stress, whereas performing repetitions up to 20% short of failure provided a comparable neuromuscular stimulus while minimizing metabolic stress. However, training status is known to modulate physiological responses to both MF and NMF (Pedrosa et al., 2024), and it remains unclear whether these findings extend to trained individuals, whose chronic neuromuscular adaptations may alter the acute responses to proximity to failure. Understanding this distinction is relevant for practical training prescription, as trained individuals represent the population most commonly applying strategies based on proximity to failure in real-world strength training contexts.

Despite the relevance of these markers, no studies conducted specifically in trained individuals have examined EMG and muscle swelling across NMF protocols with graded percentages of repetition reduction relative to MF (i.e., 10%, 20%, 30%, 40%, and 50% fewer repetitions). It remains unknown whether there is a minimum proximity to MF necessary to elicit meaningful changes in these variables in this population, and whether the dose-response relationship between repetition volume and neural and peripheral responses follows a linear pattern or presents a threshold effect. Furthermore, although NMF performed close to MF may be effective for stimulating adaptations without the acute fatigue and discomfort associated with MF (Vieira et al., 2022), the specific threshold at which proximity to failure becomes sufficient to match MF-level responses has not been established in trained individuals. Clarifying this relationship could have direct implications for training prescription, including optimizing repetition volume to reduce fatigue accumulation, improve session-to-session recovery, and tailor loading strategies for specific populations.

Therefore, this study aimed to compare the acute responses of EMG and muscle swelling between MF and NMF protocols performed with 10%, 20%, 30%, 40%, and 50% fewer repetitions than MF in trained individuals. We hypothesized that MF would result in greater EMG and muscle swelling responses, and that as a set approached MF, progressive increases in both variables would occur.

Method

Participants

Sample size calculation was performed using GPower software (version 3.1.7), following the guidelines provided by Beck (2013). This analysis assumed a repeated-measures within-subjects design, a significance level of 5%, and a statistical power of 80%. The effect size used was $\eta^2 = 0.81$, derived from a pilot study conducted previously in the same laboratory analyzing muscle swelling of the vastus lateralis under the same exercise protocol. Although this effect size is large by conventional standards (Cohen, 1988), it reflects the magnitude observed under highly controlled laboratory conditions with a homogeneous population. Similarly, this effect size was adopted by a study with a similar experimental design (Souza et al., 2026). To mitigate the potential risk of sample size overestimation associated with a large effect size, the minimum required sample (n = 7) was doubled to 14 volunteers, also accounting for potential dropouts. Additionally, the high posterior effect size values observed in the results of the present study ($\eta^2 = 0.72–0.90$) reinforce that the determined sample size was adequate.

A total of 14 male volunteers participated in this study, aged between 18 and 35 years (mean ± SD: age = 23.71 ± 4.56 years; body mass = 83.56 ± 11.08 kg; height = 1.78 ± 0.09 m; body fat percentage = 15.21 ± 3.07%; experience in strength training = 3.79 ± 3.37 years). Participants were selected based on having at least one year of experience in strength training, no musculoskeletal injuries in the lower limbs, spine, or pelvis within the last six months, no use of any ergogenic aids, and no cardiovascular issues. The exclusion criteria were: 1) voluntary withdrawal; 2) failure to attend data collection sessions on the scheduled days and times consecutively; 3) presence of any disease or pathology that would interfere with data collection; 4) use of medication that could affect data collection during the study period; 5) participation in additional strength or aerobic training for the lower limbs during the data collection period.

To minimize the influence of potential confounding variables, participants received standardized instructions before each session: (a) to maintain their regular dietary habits and avoid heavy meals within two hours before testing; (b) to abstain from caffeine and other ergogenic substances for at least 24 hours before each session; (c) to refrain from high-intensity physical activity for at least 48 hours before each session; and (d) to maintain adequate hydration throughout the study period. All sessions were conducted at the same time of day for each participant (within a ±2-hour window) to control for circadian rhythm effects.

The study was approved by the institutional ethics committee of the corresponding author (CAAE: 72597123.7.0000.5149), following the Declaration of Helsinki and National Health Council guidelines (Resolution 466/2012). Volunteers received detailed information about the study's objectives, procedures, risks, and benefits, signed informed consent, and were informed they could withdraw at any time.

Experimental design

In this study, a repeated measures experimental design was used, in which all volunteers performed all training sessions on the knee extension exercise. Knee extension exercise was performed bilaterally. A total of 8 data collection sessions were performed, with a minimum interval of 48 hours and a maximum interval of 72 hours between sessions.

In session 1, volunteers signed the informed consent form, completed a medical history screening to confirm eligibility, underwent anthropometric assessments, and were familiarized with the one-repetition maximum (1RM) test. In session 2, the volunteers performed the 1RM test and were familiarized with the maximal voluntary isometric contraction (MVIC) test and the MF protocol. In session 3, ultrasound scans were initially performed to determine the values of the cross-sectional area (CSA) of the vastus lateralis and rectus femoris muscles. After collecting the CSA images, the MVIC test was conducted. Ten minutes after the MVIC test, all volunteers performed the MF protocol with 60% of 1RM. EMG was recorded from the vastus lateralis and rectus femoris muscles during all sets of the training protocol. After completing the protocol, ultrasound scans were again conducted to determine the CSA values of the aforementioned muscles. In data collection sessions 4 through 8, all volunteers performed the NMF protocols. The NMF protocols were executed with 10%, 20%, 30%, 40%, and 50% fewer repetitions than the MF protocol, with each NMF protocol being distributed in a balanced and random manner among the volunteers through a draw. The NMF protocols (-10% to -50%) were executed by each volunteer based on the total number of repetitions performed during each set of the MF session, which was conducted in data collection session 3. The MVIC, EMG, and CSA procedures were again used during the NMF protocols, and the MVIC values were used for EMG normalization.

Procedures

Experimental session 1 (anthropometric measurements)

Body mass was obtained using a digital scale (FILIZOLA, Brazil) with an accuracy of 0.1 kg, while height was recorded using a stadiometer attached to the scale, with an accuracy of 0.5 cm (FILIZOLA, Brazil). Body fat percentage was calculated according to the 7-site skinfold protocol used by Jackson and Pollock (Jackson & Pollock, 1978), with two measurements taken for each skinfold using a caliper (INNOVARE 4, Cescorf Equipamentos LTDA®). Subsequently, volunteers were individually positioned on a seated knee extension machine (Master; Minas Gerais, Brazil) with standardized joint alignment (hip at 110°, lateral femoral epicondyle aligned with the rotation axis, distal pad ~3 cm above the medial malleolus). These positions were recorded for replication across sessions. Volunteers were then familiarized with the 1RM test.

Experimental session 2 (1RM test)

The 1RM test was performed following previous guidelines as follows (Diniz et al., 2014): a maximum of six attempts; a five-minute rest period; gradual weight progression based on the perception of the volunteers and evaluators. The weight on the equipment was progressively increased until it was no longer possible to reach 10° of knee flexion (0° = fully extended knee) during the concentric action. The 1RM value corresponded to the weight lifted in the previous attempt. Each attempt in the 1RM test followed the same sequence: after positioning the volunteer on the equipment according to the individual standardization, the volunteer was required to perform a concentric action to reach at least 10° of knee flexion (0° = fully extended knee) and then perform an eccentric action back to the initial range of motion (ROM). A reliability analysis was conducted comparing the familiarization session values with those from the 1RM test session, resulting in an intraclass correlation coefficient (ICC) of 0.945, a standard error of measurement (SEM) of 2.40 kg, and a relative standard error of measurement of 2.9%. Ten minutes later, the volunteers were familiarized with the MVIC test and the MF protocol. These respective procedures will be further described later.

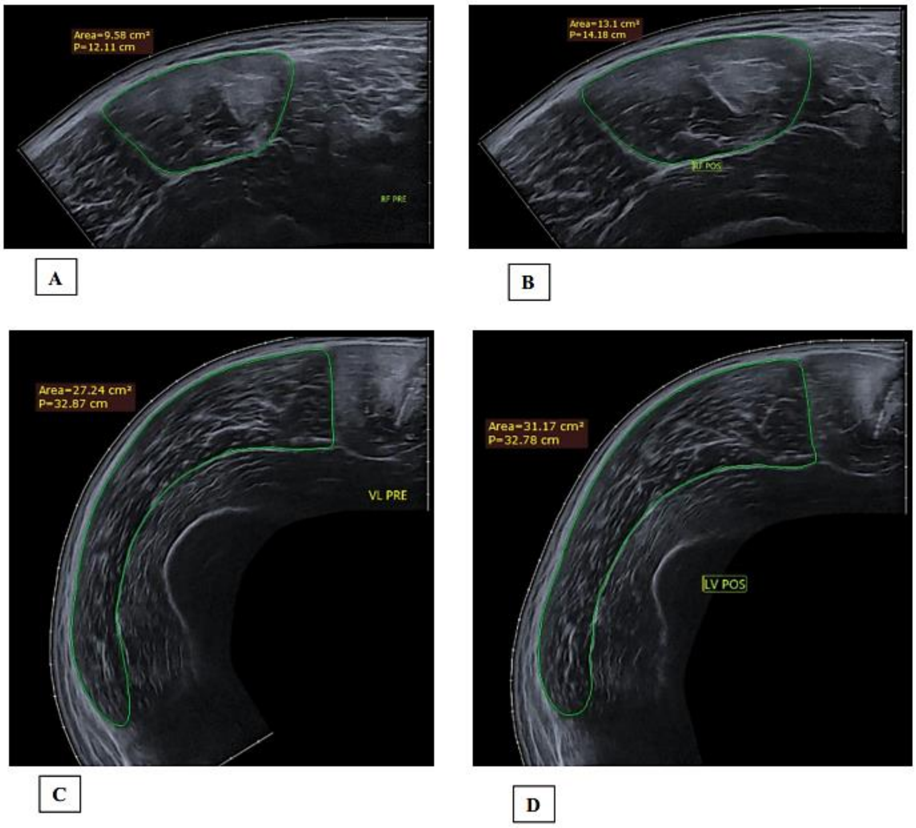
Experimental session 3 (ultrasound measurements pre-and post; MVIC test with EMG recording; MF protocol)

Ultrasound measurements

CSAs were measured to determine muscle swelling. For this, marks were made on the anterior thigh region to identify reference points for acquiring the ultrasound images. For both the rectus femoris and vastus lateralis muscles, 50% of the distance between the anterior superior iliac spine and the superior border of the patella was used as the landmark for ultrasound recording (Noorkoiv et al., 2010). After marking, volunteers were asked to lie supine with their knees extended for 15 minutes before imaging acquisition. Then, while remaining in this position, rectus femoris imaging recording was performed. In next step, the volunteer was instructed to lie in a lateral decubitus position, with the lower limb resting on a "step", with the knee extended and keeping the lower limb fully relaxed while the vastus lateralis image was recorded. For both muscles, the ultrasound probe was placed transversely on the volunteer's thigh, guided by a micropore tape as a reference for landmarks, and a panoramic ultrasound image was taken. The ultrasound settings were adjusted to a frequency of 10 MHz, with image capture depth ranging from 7.7 to 9.7 cm and gain between 50 and 64 dB (Lacerda et al., 2020). These settings could be modified based on each volunteer to achieve the best image quality for subsequent analysis. For CSA measurement, images were recorded using a portable ultrasound (Vinno® Q5-7L, China) with a linear matrix transducer with a frequency range of 6-16 MHz. The portable ultrasound was connected to a computer, and the Vinno software allowed real-time image visualization.

These images were saved, and later, a previously trained evaluator outlined the muscle CSAs. The CSA determination was done using the RADIANT software. A reliability analysis intra-evaluator of CSA was performed following the guidelines of the study by Weir et al. (2005). Pre-session values from each experimental session were used. For the CSA of the rectus femoris muscle, an intraclass correlation coefficient (ICC3k) of 0.997, a standard error of measurement (SEM) of 0.1 cm^2, a coefficient of variation (CV) of 0.89%, and a relative SEM of 1.69% were obtained. For the CSA of the vastus lateralis muscle, an ICC3k of 0.998, an SEM of 0.37 cm^2, a CV of 1.22%, and a relative SEM of 1.72% were obtained. These reliability measures corroborate findings in the literature, where ICC values of 0.99 were reported (Lacerda et al., 2020). Muscle swelling was assessed pre- and immediately post-training protocol (Figure 1).

Figure 1. Panoramic ultrasound scans of muscle swelling



Example of panoramic ultrasound scans (A) pré and (B) post-exercise of the rectus femoris and (C) pré and (D) post-exercise of the vastus lateralis. Both images are from the same volunteer referring to the MF protocol.

Electromyography measurements

After the ultrasound measurements, the MVIC test with EMG recording was performed. Bipolar surface electrodes were placed at standardized anatomical landmarks: at 50% of the distance between the anterior superior iliac spine and the superior border of the patella for the rectus femoris, and at 2/3 (66%) of the same distance to the lateral femoral epicondyle for the vastus lateralis (Hermens et al., 2000). Electrode pairs were spaced 2 cm apart, with the ground electrode on the patella. Skin was prepared by shaving and alcohol cleaning, and electrode positions were marked with a semi-permanent pen for session-to-session reproducibility. An electromyograph with a synchronization conversion plate (XControl®) was used for signal acquisition.

EMG was recorded during the MVIC test and throughout all the training protocols. All EMG data were recorded and analyzed using appropriate software (DasyLab 11.0; Measurement Computing Corporation, MA). The EMG data acquisition was amplified by 500 times, filtered (4th-order bandpass filter of 20-500 Hz, Butterworth type), and the EMG amplitude was calculated using the root mean square (RMS) method, considering the average signal across the entire duration of each training series. Normalization of the signal was performed by dividing the value obtained during the training series by the RMS peak during the MVIC test and multiplied by 100 (Lacerda et al., 2020; Besomi et al., 2020). A reliability analysis was conducted between sessions for the RMS data of the rectus femoris and vastus lateralis from the MVIC test. For the rectus femoris, ICC_{3k} of 0.95, SEM of 0.12 V, and relative SEM of 13.38% were obtained. For the vastus lateralis, an ICC_{3k} of 0.961, SEM of 0.08 V, and relative SEM of 12.17% were obtained. Literature reports ICC values of 0.97 (Lacerda et al., 2020).

MVIC Test

The MVIC test was performed after the ultrasound measurements. The MVIC test was conducted on the same equipment used for the training protocols, which allows the measurement of angle and force values, by a potentiometer installed on the machine's rotation axis and a load cell fixed to the cable at the back of the machine, respectively (Diniz et al., 2022). The MVIC test consisted of two attempts at a 60° knee flexion angle (0° = fully extended knee), each lasting 5 seconds, with a 3-minute rest between each attempt (Lacerda et al., 2020). During the MVIC test, verbal encouragement was provided to the volunteer to apply maximum force against the fixed lever of the knee extension equipment. The highest peak force value recorded at this angle was used as the representative value for the MVIC performance at this angle (Correa et al., 2011). The MVIC test was performed before each session of the training protocols with EMG recording. Subsequently, the electromyographic signal was filtered, rectified, and analyzed with a 1-second interval around the force peak using RMS (Diniz et al., 2022).

MF training

After a 10-minute rest period following the MVIC test, the volunteers performed the training protocols on the seated bilateral knee extension exercise using the knee extension equipment. This consisted of 4 sets at 60% of 1RM with a 2-minute rest between sets. Each repetition lasted 4 seconds: 2 seconds concentric and 2 seconds eccentric with a ROM of 100° to 10° of knee flexion (0° = fully extended knee). The repetition duration was controlled using a metronome.

In MF protocol, all sets were performed until the volunteer could no longer execute the concentric muscular action at the pre-established ROM, which was 10° of knee flexion (0° = fully extended knee). The ROM was 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 (Lacerda et al., 2020).

Experimental sessions 4 to 8 (non-muscle failure training, NMF -10% to -50% randomized)

In these sessions, the same procedures conducted in session 3 were repeated: ultrasound measurements pre- and post-training and the MVIC test with EMG recording. The only procedure that differed from the previous session was that the volunteers performed the NMF protocol.

The order of the NMF sessions was randomly assigned to each volunteer using a complete randomization procedure, in which all five NMF conditions (-10%, -20%, -30%, -40%, -50%) were randomly ordered through a simple draw conducted by a researcher not involved in data collection. Each volunteer received a unique randomized sequence, ensuring that all conditions were performed by all participants (complete within-subject counterbalancing). No two consecutive sessions were allocated to the same condition. The NMF sessions were conducted with the same configuration as the MF session and with the same ROM, except for the number of repetitions. The number of repetitions for the NMF protocols was based on the total number of repetitions performed during each set of the MF session. The number of repetitions was reduced by 10%, 20%, 30%, 40%, and 50% from the total repetitions completed during each set of the MF session. These specific percentages were selected to provide a systematic, evenly spaced dose-response gradient from near-failure (90% of MF repetitions) to a substantially reduced volume (50% of MF repetitions), covering the full spectrum of proximity to failure commonly encountered in practical training settings (Refalo et al., 2023; Vieira et al., 2022). This approach allows for the identification of potential thresholds in neuromuscular and peripheral responses, including whether a minimum proximity to failure is required to elicit meaningful changes in EMG and muscle swelling. These reductions were also sufficient to ensure that no participant reached muscle failure in any set of the NMF protocols. Since it is not possible to perform decimal numbers of repetitions (i.e., 14.7 repetitions), the decimal value was rounded to a whole number to perform the NMF. Values above 0.5 were rounded up, and values below 0.5 were rounded down (i.e., 14.7 = 15 repetitions; 14.4 = 14 repetitions)

(Table 1). The number of repetitions per set per individual is available in the Supplemental File (Table 1). This objective, percentage-based approach was preferred over subjective scales such as repetitions-in-reserve (RIR) or rating of perceived exertion (RPE), given the well-documented limitations of these tools at the individual level, with reported standard errors of measurement of 2.64–3.38 repetitions even among experienced lifters (Steele et al., 2017; Hackett et al., 2012; Zourdos et al., 2016).

Table 1. Total number of repetitions verified in MF and total number of repetitions calculated for each NMF protocol

Subject	MF	NMF -10%	NMF -20%	NMF -30%	NMF -40%	NMF -50%
1	31	27.9	24.8	21.7	18.6	15.5
2	32	28.8	25.6	22.4	19.2	16
3	24	21.6	19.2	16.8	14.4	12
4	35	31.5	28	24.5	21	17.5
5	29	26.1	23.2	20.3	17.4	14.5
6	34	30.6	27.2	23.8	20.4	17
7	29	26.1	23.2	20.3	17.4	14.5
8	28	25.2	22.4	19.6	16.8	14
9	35	31.5	28	24.5	21	17.5
10	30	27	24	21	18	15
11	28	25.2	22.4	19.6	16.8	14
12	31	27.9	24.8	21.7	18.6	15.5
13	27	24.3	21.6	18.9	16.2	13.5
14	26	23.4	20.8	18.2	15.6	13
Mean	29.93	26.94	23.94	20.95	17.96	14.96
SD	3.32	2.98	2.65	2.32	1.99	1.66

Training to muscle failure (MF); training not to muscle failure (NMF); standard deviation (SD).
Since it is not possible to perform decimal numbers of repetitions (i.e., 14.7 repetitions), the decimal value was rounded to a whole number to perform the NMF. Values above 0.5 were rounded up, and values below 0.5 were rounded down (i.e., 14.7 = 15 repetitions; 14.4 = 14 repetitions).

Statistical analysis

For the EMG analysis, the average RMS of the 4 sets performed in each session of the experimental protocols was used. That is, the RMS of each set was normalized by the RMS of the MVIC test, resulting in a relative value for each set. Since 4 sets were performed, the average of these relative values from the four sets was calculated to assess the EMG activity for each experimental protocol. Two one-way repeated measures ANOVAs were conducted to compare the EMG data between training sessions, one for each muscle. For muscle swelling analysis, the relative variation of CSA from pre- to post-protocol was calculated (post - pre / pre * 100). Thus, two one-way repeated measures ANOVAs were also performed, one for each muscle. For all ANOVAs, the Bonferroni post hoc test was applied when necessary. To report effect size, eta squared (η^2) was used, classified as small ($\eta^2 < 0.01$), medium (η^2 between 0.02 and 0.06), and large ($\eta^2 > 0.14$) (Cohen, 1988). The normality and sphericity of all data were assessed using the Shapiro-Wilk and Mauchly tests, respectively. When sphericity was violated, the Greenhouse-Geisser correction was applied. Data are presented as mean ± standard deviation and individual values. All statistical procedures were conducted using SPSS version 21, and the graphs were created using GraphPad Prism version 8. The significance level was set at 0.05 ($p \leq 0.05$).

Results

Muscle swelling

Table 2 presents descriptive statistics (mean, standard deviation, and 95% confidence interval) for the percentage changes in the CSA of the rectus femoris and vastus lateralis muscles across experimental protocols.

Table 2. Descriptive statistics for the percentage changes in the CSA

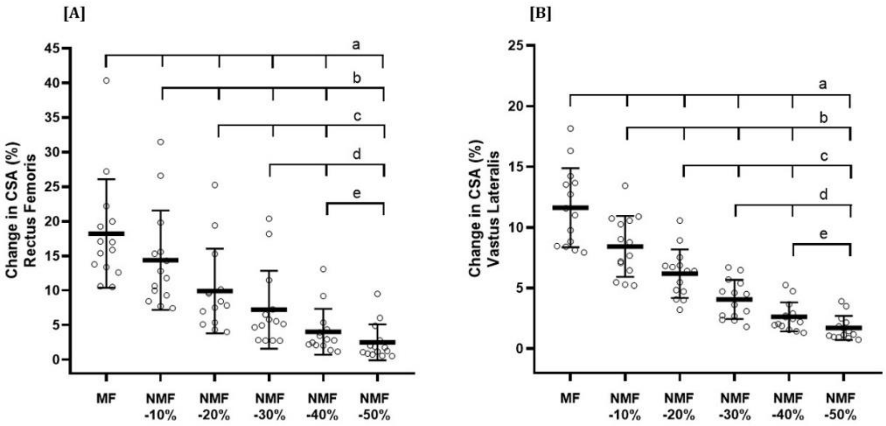
	Rectus Femoris (%)			Vastus Lateralis (%)		
Protocol	Mean	SD	CI 95%	Mean	SD	CI 95%
MF	18.22	7.84	13.69 – 22.75	11.63	3.26	9.75 – 13.51
NMF -10%	14.37	7.18	10.22 – 18.51	8.43	2.51	6.98 – 9.88
NMF -20%	9.92	6.11	6.39 – 13.45	6.19	2.01	5.03 – 7.34
NMF -30%	7.21	5.63	3.96 – 10.46	4.06	1.62	3.12 – 4.99

NMF -40%	4.02	3.31	2.11 – 5.93	2.63	1.19	1.94 – 3.31
NMF -50%	2.49	2.60	0.99 – 3.99	1.71	0.99	1.14 – 2.28

Training to muscle failure (MF); training not to muscle failure (NMF); standard deviation (SD); confidence interval (CI 95%).

Significant differences in muscle swelling were observed between all protocols for the rectus femoris (F1.44, 18.83 = 74.873; $\eta^2 = 0.85$; $p < 0.001$) and the vastus lateralis (F1.53, 19.98 = 111.403; $\eta^2 = 0.90$; $p < 0.001$). Post hoc comparisons revealed that all protocols differed significantly from each other ($p < 0.05$), with MF producing the greatest muscle swelling for both muscles. Each successive reduction in repetitions relative to failure (from NMF -10% to NMF -50%) resulted in progressively smaller muscle CSA changes (Figure 2).

Figure 2. Changes in muscle swelling according to proximity to muscular failure



Relative change in muscle swelling of the rectus femoris (A) and vastus lateralis (B). Symbols indicate: mean (horizontal lines), standard deviation (vertical lines), individual values for each training protocol (hollow circles). [a] denotes differences from MF; [b] denotes differences from NMF -10%; [c] denotes differences from NMF -20%; [d] denotes differences from NMF -30%; [e] denotes differences from NMF -40%. Data are presented as the mean, standard deviation, and individual values. Cross-sectional area (CSA).

Electromyography

Table 3 presents descriptive statistics (mean, standard deviation, and 95% confidence interval) for EMG of the rectus femoris and vastus lateralis muscles across the different experimental protocols.

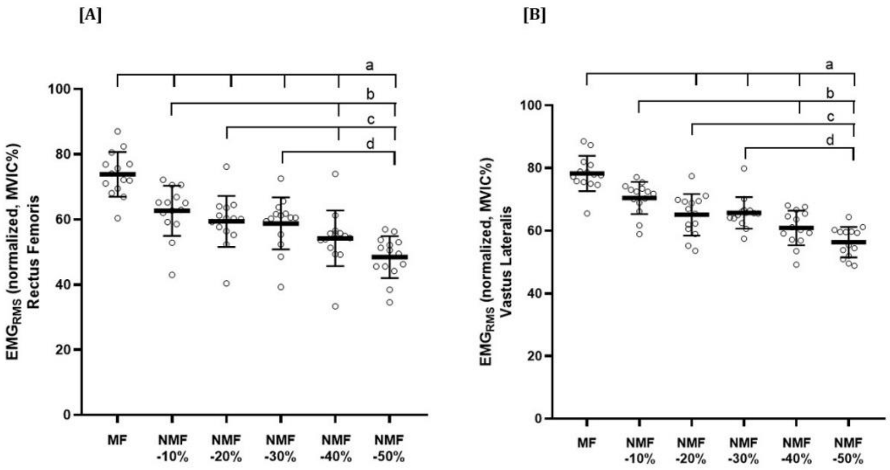
Table 3. Descriptive statistics for the EMG

	Rectus Femoris (% MVIC)			Vastus Lateralis (% MVIC)		
Protocol	Mean	SD	CI 95%	Mean	SD	CI 95%
MF	73.84	6.86	69.88 – 77.80	78.26	5.63	75.01 – 81.51
NMF -10%	62.65	7.68	58.22 – 67.08	70.42	5.11	67.47 – 73.37
NMF -20%	59.40	7.82	54.88 – 63.91	65.07	6.63	61.24 – 68.90
NMF -30%	58.79	8.00	54.17 – 63.41	65.68	5.06	62.75 – 68.60
NMF -40%	54.22	8.53	49.29 – 59.14	60.82	5.56	57.61 – 64.03
NMF -50%	48.43	6.46	44.70 – 52.16	56.33	4.85	53.53 – 59.13

Training to muscle failure (MF); training not to muscle failure (NMF); standard deviation (SD); confidence interval (CI 95%); maximum voluntary isometric contraction (%MVIC).

Significant differences in EMG activity were observed for the rectus femoris (F2.96, 38.51 = 33.783; $\eta^2 = 0.72$; $p < 0.001$) and vastus lateralis (F5, 65 = 43.973; $\eta^2 = 0.77$; $p < 0.001$). For the rectus femoris, post hoc comparisons showed that MF produced significantly greater EMG than all NMF protocols ($p < 0.05$). For the vastus lateralis, MF did not differ statistically from NMF -10% ($p > 0.05$), but was significantly greater than NMF -20%, -30%, -40%, and -50% ($p < 0.05$). Additionally, NMF -10%, -20%, and -30% did not differ from each other for either muscle ($p > 0.05$) (Figure 3).

Figure 3. Changes in EMG according to proximity to muscular failure



Normalized EMG_{RMS} of the rectus femoris (A) and vastus lateralis (B). Symbols indicate: mean (horizontal lines), standard deviation (vertical lines), individual values for each training protocol (hollow circles). ^{a} denotes differences from MF; ^{b} denotes differences from NMF -10%; ^{c} denotes differences from NMF -20%; ^{d} denotes differences from NMF -30%. Data are presented as the mean, standard deviation, and individual values.

Discussion

This study aimed to compare the response of EMG and muscle swelling between MF and NMF executed with a number of repetitions 10%, 20%, 30%, 40%, and 50% lower than MF. The results of rectus femoris and vastus lateralis muscle swelling, differed between MF and NMF ($p < 0.05$). MF showed the greatest muscle swelling response compared to the other protocols, and regarding the NMF protocols, there was a gradual increase in muscle swelling with the increase in the number of repetitions. Of note, our protocols presented small differences (~1 repetition per set) between conditions. A key observation was that muscle swelling appeared sensitive even under very low-volume conditions (e.g., NMF -50%), and differences as small as three repetitions across protocols may have been sufficient to elicit distinct swelling responses, suggesting that ultrasound may be a sensitive tool to detect acute muscle responses even at low volumes. These differences could be explained by different mechanisms.

The progressive increase in muscle swelling with greater proximity to failure can be explained by complementary mechanisms. First, since muscle swelling results from fluid shifting into the intracellular space, this response can be indirectly estimated by changes in CSA assessed through transverse relaxation time (T2) in MRI scans (Adams et al., 1992). Yue et al. (1994) reported that T2 increased linearly with the number of repetitions for each of the elbow flexor muscles at any intensity ($r^2 \geq 0.97$; $p < 0.001$), suggesting that the more repetitions performed, the greater the fluid entry into the intracellular space, leading to an increase in cell volume and culminating in muscle swelling — a pattern consistent with the dose-dependent swelling response observed across our NMF protocols. Second, fast-twitch fibers are particularly sensitive to osmotic changes, likely due to their high concentration of water transport channels known as aquaporin-4 (Frigeri et al., 1998). Considering that exercise closer to failure is associated with progressive recruitment of fast-twitch fibers as fatigue accumulates (Enoka et al., 2008), this mechanism could further amplify the swelling response as proximity to failure increases, helping to explain the tendency toward greater muscle swelling observed in MF compared to NMF conditions. Together, these two mechanisms — a linear osmotic response to repetition volume and a fatigue-driven recruitment of fast-twitch fibers — operate concurrently and may act synergistically as the number of repetitions approaches failure. Although the present findings are acute, Hirono et al. (2022) found positive correlations between muscle swelling after the first training session and muscle hypertrophy over 6 weeks ($\rho = 0.44–0.59$), suggesting that the dose-dependent swelling pattern observed here may have relevance for chronic adaptations, though any such extrapolation remains hypothetical and requires confirmation through longitudinal research. Therefore, although a difference in muscle swelling was observed between the protocols in the present study, it remains unclear whether these acute differences would translate into differences in chronic adaptations (i.e., muscle hypertrophy).

Based on the EMG response, not all protocols showed significant differences from each other, regardless of the muscle evaluated. For the rectus femoris, MF showed the highest EMG response when compared to all NMF protocols. For the vastus lateralis, MF was higher than all NMF protocols, except NMF -10%. Nonetheless, the NMF protocols, for both muscles, small reductions in the number of repetitions did not differ from each other, seemingly not influencing EMG. Fatigue might help to explain the increase in EMG showed here. As muscle fatigue increases, the need to recruit additional motor units arises to maintain the strength required to perform a task (Conwit et al., 2000). Hence, it could be expected that MF would result in higher EMG responses, as shown in other studies (Sundstrup et al., 2012; Gomes et al., 2021). The study by Sundstrup et al. (2012) showed that during the execution of 15 RM, there was a gradual increase in EMG activity. The authors found that, when the exercise was performed with lower intensity until muscle failure (~15 RM), EMG was higher during the last repetitions for all muscles analyzed. The authors highlighted that an EMG plateau was reached after approximately 10-12 repetitions of the 15 RM performed, indicating that a maximum level of EMG could be reached 3-5 repetitions before muscle failure and that training to muscle failure is not necessary to fully recruit all motor units in untrained women (Sundstrup et al., 2012). Several factors may help explain the discrepancies between studies. First, training status likely plays an important role: while Sundstrup et al. (2012) recruited untrained women, the present study included trained men with an average of 3.8 years of resistance training experience. Trained individuals typically present greater motor unit synchronization and more efficient neuromuscular strategies (Del Vecchio et al., 2019), which may attenuate the EMG plateau effect observed in untrained populations. Second, the number of sets differed substantially: Sundstrup et al. (2012) used a single-set protocol, whereas the present study employed four sets, likely promoting progressive fatigue accumulation across sets and thereby increasing the relative demand placed on the neuromuscular system during MF. Third, the load used in the present study (60% 1RM) may interact differently with trained participants in terms of motor unit recruitment thresholds compared with the intensity employed by Sundstrup et al. (2012). These methodological and population differences should be considered when interpreting the divergent EMG findings between studies.

Unlike the study by Sundstrup et al. (2012), the present study did not find similar EMG activity between MF and NMF protocol. However, the NMF protocols (10%, 20%, and 30%) did not differ between each other for both muscles. It is important to notice that unlike from Sundstrup et al. (2012), our protocols had only ~1 repetition per set difference between protocols. Highlighting the how small the difference can be to show differences in EMG activity between protocols. Yet, for vastus lateralis EMG activity, the comparison between MF and NMF -10% showed a borderline result ($p = 0.07$) with a large effect size ($d = 1.46$). One perspective that could help explain this pattern is that the average difference between these NMF protocols was approximately 3 total repetitions (Table 1), corresponding to less than one repetition per set. Such small differences may not have been sufficient to generate the additional neuromuscular demand required to recruit extra motor units, increase discharge rates, or otherwise influence RMS amplitude (Del Vecchio et al., 2019) to a statistically detectable degree — particularly since participants did not approach muscle failure in these conditions (Conwit et al., 2000). Furthermore, since the average EMG across all 4 sets was analyzed, any progressive increase in neuromuscular activation from the 1st to the 4th set may have been attenuated by the averaging procedure, potentially limiting the detection of subtle between-protocol differences. These analytical and methodological constraints should be considered when interpreting the null findings.

Taken together, the present findings suggest a conceptual model in which proximity to muscle failure modulates both peripheral and neuromuscular responses in a dose-dependent manner. From a peripheral standpoint, muscle swelling appears to increase progressively as the number of repetitions approaches failure, likely reflecting cumulative fluid shifts associated with osmotic and metabolic stress — a pattern consistent with the linear relationship between repetitions and T2 relaxation time reported by Yue et al. (1994). From a neuromuscular standpoint, EMG amplitude appears to require a minimum proximity to failure to be significantly elevated above lower-volume conditions, as evidenced by the absence of significant differences among the NMF -10%, -20%, and -30% protocols. Importantly, these two response profiles are not independent: as fatigue accumulates and metabolic by-products rise closer to failure, both the osmotic stimulus for swelling and the recruitment demand for additional motor units increase concurrently. This integrated perspective suggests that training proximity to failure may act as a shared regulatory stimulus for peripheral and neuromuscular adaptations, and that the threshold for meaningful changes in each variable may differ — with muscle swelling being more sensitive to small changes in volume than EMG amplitude. These observations, however, should be interpreted cautiously given the cross-sectional, acute nature of the study, and their relevance for long-term adaptations remains to be established.

The present study has limitations and strengths that should be acknowledged. Averaging EMG across sets may have obscured intra-set dynamics, preventing detection of subtle differences in neuromuscular activity. Additionally, our findings are restricted to trained men, which limits generalizability to women, older adults, and untrained populations, all of whom may exhibit substantially different neuromuscular and swelling responses to proximity-to-failure manipulations. Future studies should extend this line of research to broader populations and investigate whether the acute differences observed here predict meaningful long-term hypertrophic adaptations. Although perceptual scales such as repetitions-in-reserve (RIR) or rating of perceived exertion (RPE) were deliberately not employed, given the well-documented limitations of these tools at the individual level (Hackett et al., 2012; Steele et al., 2017; Zourdos et al., 2016), future research could combine objective and perceptual indicators of proximity to failure to investigate convergences and divergences between these approaches. On the other hand, the methodological approach used in this study allowed precise control over proximity to failure, eliminating subjective bias and enabling a systematic investigation of the dose-response relationship between repetitions and acute physiological responses. While we deliberately avoided perceptual scales for the reasons described in the Methods, future studies could combine objective and perceptual indicators of proximity to failure to explore convergences and divergences between these approaches.

Conclusions

In conclusion, among trained men, MF produced the greatest acute muscle swelling, with swelling increasing progressively in NMF protocols as the number of repetitions approached failure. EMG activity was highest during MF, while small reductions in repetitions (-10% to -30%) did not result in statistically significant differences in EMG between those NMF conditions. These findings suggest that proximity to muscle failure modulates both peripheral (muscle swelling) and neuromuscular (EMG) responses, with muscle swelling appearing more sensitive to small changes in repetition volume than EMG amplitude.

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