

# Effect of resistance training to muscle failure vs non-failure on strength, hypertrophy and muscle architecture in trained individuals

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**ABSTRACT:** The aim of this study was to compare the effects of resistance training to muscle failure (RT-F) and non-failure (RT-NF) on muscle mass, strength and activation of trained individuals. We also compared the effects of these protocols on muscle architecture parameters. A within-subjects design was used in which 14 participants had one leg randomly assigned to RT-F and the other to RT-NF. Each leg was trained 2 days per week for 10 weeks. Vastus lateralis (VL) muscle cross-sectional area (CSA), pennation angle (PA), fascicle length (FL) and 1-repetition maximum (1-RM) were assessed at baseline (Pre) and after 20 sessions (Post). The electromyographic signal (EMG) was assessed after the training period. RT-F and RT-NF protocols showed significant and similar increases in CSA (RT-F: 13.5% and RT-NF: 18.1%;  $P < 0.0001$ ), PA (RT-F: 13.7% and RT-NF: 14.4%;  $P < 0.0001$ ) and FL (RT-F: 11.8% and RT-NF: 8.6%;  $P < 0.0001$ ). All protocols showed significant and similar increases in leg press (RT-F: 22.3% and RT-NF: 26.7%;  $P < 0.0001$ ) and leg extension (RT-F: 33.3%,  $P < 0.0001$  and RT-NF: 33.7%;  $P < 0.0001$ ) 1-RM loads. No significant differences in EMG amplitude were detected between protocols ( $P > 0.05$ ). In conclusion, RT-F and RT-NF are similarly effective in promoting increases in muscle mass, PA, FL, strength and activation.

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## INTRODUCTION

Resistance training (RT) is a potent intervention strategy to increase muscle cross-sectional area (i.e., muscle hypertrophy), muscle strength [1] and muscle architecture parameters (e.g., muscle fibre pennation angle and fascicle length) [2–4]. To maximize these neuromuscular adaptations, it has been recommended to perform RT until muscle failure (RT-F), defined as the point where the activated muscles are incapable of completing another repetition in the appropriate range of motion [5, 6]. It is commonly thought that trained individuals, particularly bodybuilders and strength-trained athletes, benefit most from RT-F [7]. Trained individuals are able to tolerate high training stresses, and it has been suggested that RT-F might provide an extra stimulus to increase muscle mass and strength [8, 9]. Considering that hypertrophic and strength gains tend to slow down or even plateau following long-term training [10], this extra stimulus could be very important to the trained population. However, the effects of RT to muscle failure in trained individuals have been little explored.

It has been suggested that performing RT-F maximizes muscle activation (i.e., electromyographic signal [EMG] amplitude) [7, 11], which is influenced by motor units (MU) recruitment, rate coding

and MU synchronization, among other factors [12]. Particularly, MU recruitment has been considered an essential component for increasing muscle mass and strength [13–15]. However, there is evidence that muscle activation can be maximized without muscle failure (i.e., non-failure [RT-NF]). Sundstrup et al. [16] found that full muscle activation of muscles involved in the lateral raise was achieved 3–5 repetitions prior to muscle failure in untrained women. Assuming that the number of repetitions and fatigue are correlated [4, 17], it is plausible to suggest that RT performed close to muscle failure would be sufficient to promote muscle activation comparable to muscle failure, even in trained individuals. Corroborating this, a recent meta-analysis showed that muscle failure does not result in additional increases in muscle strength compared with non-failure [18]. However, this meta-analysis only focused on muscle strength gains, and included merely four studies with resistance-trained individuals. Thus, the effects of RT-F on the muscle mass of trained individuals are still poorly understood.

Therefore, the aim of this study was to compare the effects of RT-F and RT-NF on muscle mass, strength and activation of trained

individuals. As a secondary aim, we compare the effects of these protocols on muscle architecture parameters (i.e., pennation angle and fascicle length). Our hypothesis was that RT-F and RT-NF would promote similar increases in muscle mass, strength and changes in architecture, with similar muscle activation, in trained individuals.

## MATERIALS AND METHODS

### Participants

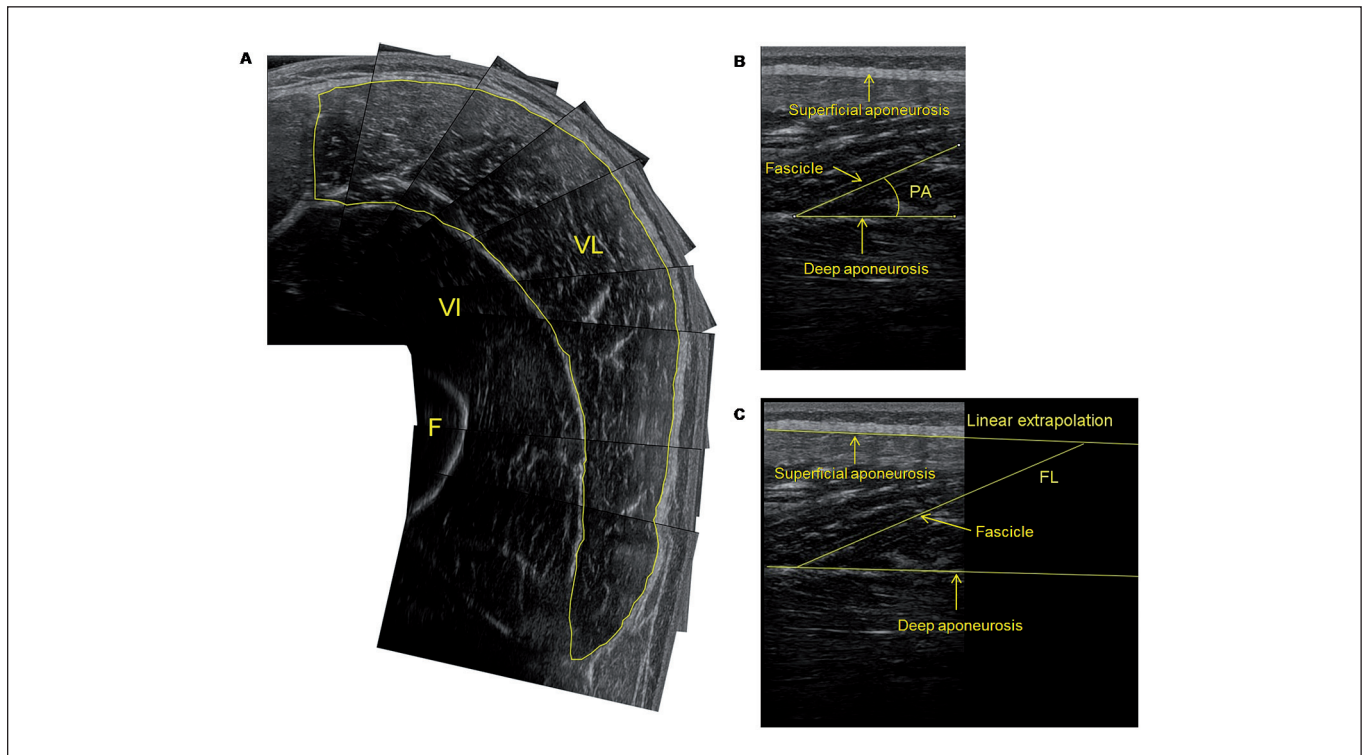
Out of eighteen RT experienced men who volunteered to participate in this study, fourteen participants (age:  $23.1 \pm 2.2$  years; height:  $172.1 \pm 5.1$  cm; body mass:  $74.4 \pm 5.9$  kg; RT experience:  $5.1 \pm 2.6$  years) completed 100% of training sessions. Four participants did not complete all sessions or dropped out for personal reasons, and thus were not included in the analyses.

In order to be considered as resistance-trained, participants were required to have been training their lower limbs with a frequency of twice per week for at least the past 2 years prior to recruitment and performing  $45^\circ$  leg press and leg extension exercises in their RT routines. In addition, participants were free from any existing musculoskeletal disorders or risk factors as assessed by the PAR-Q and stated they had not taken anabolic steroids for the previous year. Participants were also advised to maintain their dietary habits and not to consume any other nutritional supplement besides the one provided by the principal investigator after each RT session (i.e., 30 g of Iso Whey Protein, strawberry flavour – Max Titanium – Brazil).

The study was conducted in accordance with the revised version of the Helsinki Declaration [19] and ethical approval was granted by the university's ethics committee. Participants signed a consent form before participation.

### Experimental design

Initially, participants visited the laboratory to perform assessments of vastus lateralis muscle cross-sectional area (CSA) and architecture variables (i.e., pennation angle [PA] and fascicle length [FL]). Next, familiarization with the 1-RM test and training protocols was performed. Seventy-two hours later, a new 1-RM test was performed. If 1-RM values differed more than 5% from the previous test, a subsequent test was performed after another 72 h interval [20]. On average, each participant performed three 1-RM tests. To reduce between-subject variance, a within-subject design was applied so that each participant's leg was randomly allocated to one of two training protocols: RT-F or RT-NF. Additionally, leg dominance was counterbalanced between protocols. At the midpoint of the training period (5 weeks), 1-RM was reassessed to adjust training load. Muscle CSA, muscle architecture and 1-RM tests were re-assessed 72 h following the last training session. Additionally, 72 hours after the final 1-RM test, muscle activation was assessed through EMG, with each leg performing its respective training protocol in the leg extension machine only. All assessments were carried out at the same time of day.



**FIG. 1.** Representative images from the vastus lateralis (VL) muscle used for (A) cross-sectional area, (B) pennation angle (PA) and (C) fascicle length (FL) measurements. VI, vastus intermedius; F, femur.

### *Muscle cross-sectional area (CSA)*

Vastus lateralis CSA was assessed through ultrasound imaging (US) following the procedures described in our previously published validation study (Fig. 1A) [21]. Participants were instructed to abstain from vigorous physical activities for at least 72 h prior to each CSA assessment [22, 23]. A B-mode US, with a linear probe set at 7.5 MHz (Samsung, MySono U6, São Paulo, Brazil), was used to acquire the images. The point corresponding to 50% of femur length, measured as the distance between the greater trochanter and the lateral epicondyle of the femur, was marked as the reference for the acquisition of images. Sequential images of the vastus lateralis muscle were acquired every 2 cm in the sagittal plane. Then, the sequence of images was opened in Power Point (Microsoft, USA), manually rotated to reconstruct the entire fascia of the vastus lateralis muscle and saved as a new image file. These reconstructed images were opened in the ImageJ software and the “polygonal” function was used to determine vastus lateralis CSA by a blinded and trained technician. The coefficient of variation (CV) and the typical error (TE) of CSA measures were 0.84% and 0.28 cm<sup>2</sup>, respectively.

### *Pennation angle (PA) and fascicle length (FL)*

Muscle architecture (Fig. 1B and 1C) measures of the VL muscle were assessed at the same time and site of the CSA acquisition, with the probe oriented longitudinally to the muscle belly. The PA was defined as the angle formed by the intersection of a fascicle and the deep aponeurosis. FL was defined as the distance from the fascicle origin in the deep aponeurosis to insertion in the superficial aponeurosis [24, 25]. Whenever a whole fascicle was not visible in a single image, linear extrapolation was used to estimate FL. The mean value of three images was used to determine PA and FL using the “Angle” tool and “Straight” tool, respectively, of the ImageJ software. All assessments were carried out by a blinded and trained technician. The CV and TE were respectively 0.79% and 0.18° for PA assessments and 0.81% and 0.05 cm for FL measurements.

### *Maximal dynamic strength*

Maximal dynamic strength was assessed through unilateral 1-RM tests in the 45° leg press (NK-5070; NakaGym, Diadema, SP, Brazil) and leg extension (NK-5060; NakaGym, Diadema, SP, Brazil) machines. The 1-RM test was performed following the recommendations described by Brown and Weir [26]. The CV and TE were respectively 1.45% and 3.12 kg for the 45° leg press 1-RM tests and 2.01% and 1.13 kg for leg extension.

### *Resistance training protocols*

RT protocols were performed unilaterally using conventional 45° leg press and leg extension machines, in this order, twice a week for 10 weeks (20 training sessions). Before the start of the RT period, participants reported the weekly number of sets typically performed for the quadriceps in their previous RT routine (sets: 19.1 ± 8.5,

range 7–42). Based on individual training logs, each participant had their weekly number of sets increased by 20% to better explore individual adaptive responses and increase the precision of RT effects on muscle hypertrophy [27]. After the 20% increase, sets were equally distributed between the 45° leg press (sets: 11.5 ± 5.1, range 4–25) and leg extension (sets: 11.6 ± 5.2, range 4–25) machines. Prior to each RT session, participants performed a general warm-up on a cycle ergometer pedalling at 20 km·h<sup>-1</sup> for 5 minutes. For the RT-F protocol, repetitions were performed at 75% 1-RM to the point of inability to complete a repetition with the full range of motion (i.e., 90 degrees) [5, 6], as evaluated by researchers familiar with the protocol. For the RT-NF protocol, participants were previously instructed on and familiarized with the criteria for muscular failure. Thus they were instructed to interrupt repetitions voluntarily, according to each's own perception of fatigue, before reaching that known point of muscular failure, independently of how many repetitions short of failure they stopped at [4, 28]. Repetitions were performed at 75% 1-RM. A 2-minute rest interval was allowed between sets in both protocols. All participants were previously instructed on the criteria for RT-F and RT-NF protocols.

### *Number of repetitions (Nrep)*

The number of repetitions performed by each participant at every set and training session was charted and annotated by researchers. From these records, the average number of repetitions performed per set (Nrep) was calculated for each participant and the group average Nrep was obtained and reported in the results for each protocol.

### *Volume load (VL)*

Loads (kg) were recorded for each training session. From the charted values, accumulated volume load (VL) was calculated for each participant as sets × repetitions × load (kg) considering the entire training period (20 RT sessions), and the group average VL was obtained and reported in the results for each protocol.

### *Muscle activation*

Activation of the vastus lateralis muscle was assessed by the amplitude of the EMG signal according to recommendations [29]. Following skin preparation, self-adhesive disposable electrodes were placed over the vastus lateralis muscle with an inter-electrode distance of 2 cm. A reference electrode was fixed on the opposite ankle. For better stability, micropore tape was applied over the electrodes. Then, participants performed a maximal voluntary isometric contraction (MVIC) test. Following a 5-minute warm-up on a cycle ergometer at 20 km·h<sup>-1</sup>, participants were positioned in a leg extension machine with knees fixed at 90° of knee flexion. The leg extension machine arm was locked at 90°. Participants were asked to gradually build force and hold it for three seconds at maximal force. Three trials were performed, with 1-minute rest between trials, and the highest root mean square (RMS) value attained was used for normalizing EMG signals. To differentiate concentric and eccentric EMG signals, an

electrogoniometer (*EMG System*, São José dos Campos, SP, Brazil) was placed at the estimated centre of rotation of the knee joint (i.e., intercondylar line). EMG and electrogoniometer signals were acquired using the EMG832C electromyographic device (*EMG System*, São José dos Campos, SP, Brazil) and active bipolar surface electrodes with pre-amplifier gains of 20-fold and a common-mode rejection rate > 100 db. After performing the MVIC, a 5-minute interval was allowed. Next, for EMG acquisition, participants were instructed to exercise each leg following the resistance training protocols to which they were allocated. Both protocols were performed with 75% 1-RM, adjusted according to the participants' most recent 1-RM value. Training protocols are described in detail in the "resistance training protocols" section. A 2-minute rest interval was allowed between sets. Signals were collected at 1000 Hz and filtered with an eighth order Butterworth bandpass filter set at 20–500 Hz. Data processing was performed off-line using a custom MATLAB routine (MathWorks, Natick, MA). Initially, EMG data were normalized using MVIC data. Following data normalization, the beginning and ending of each repetition was manually identified on the MATLAB routine for each set. Minimal and maximal angle values were used to define the end of the eccentric and concentric phases, respectively. Muscle activation was calculated using the mean RMS of the EMG signal of the concentric phase of the last three repetitions.

#### Statistical analysis

Following visual inspection of the data, the Shapiro-Wilk test was performed to verify data normality. Paired *t*-tests were implemented to compare baseline values of the dependent variables (CSA, 1-RM, PA and FL) as well as values of EMG, Nrep and 10-week accumulated VL between protocols (RT-F or RT-NF). Intra-protocol (post- vs. pre-values) effect sizes (ES) for small sample sizes were calculated according to Hedges and Olkin [30]. ES values were classified as

small ( $ES \leq 0.49$ ), medium ( $0.5 \leq ES \leq 0.79$ ), and large ( $ES \geq 0.80$ ). Subsequently, a mixed model having protocols (RT-F and RT-NF) and time (Pre and Post) as fixed factors and subjects as a random factor was implemented for each dependent variable (CSA, FL, PA and 1-RM). Data are presented as means and standard deviations and significance was set at  $P < 0.05$ . Statistical analyses were performed on SAS 9.3 software (SAS institute Inc., Cary, NC, USA).

## RESULTS

### Baseline measurements

There were no significant differences in baseline values ( $P > 0.05$ ) between protocols for CSA, PA, FL and 1-RM in the 45° leg press and leg extension exercises.

### Number of repetitions (Nrep)

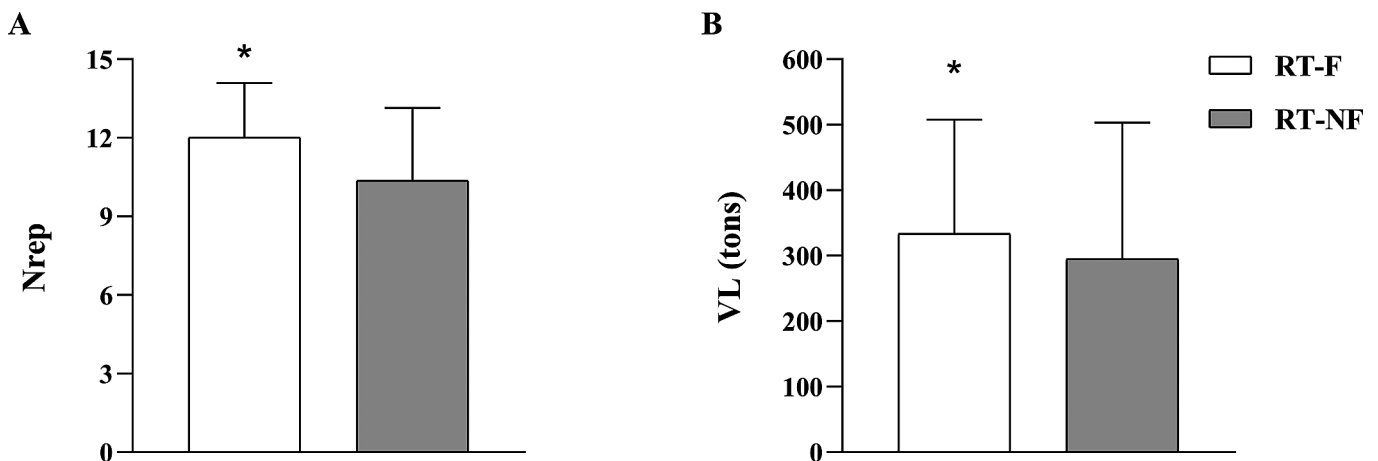
Significant differences in Nrep were found between protocols (RT-F:  $12.0 \pm 2.1$ ; RT-NF:  $10.4 \pm 2.8$ ;  $P = 0.004$ ; Fig. 2A). On average, participants in RT-NF interrupted sets, voluntarily, at  $1.6 \pm 1.8$  repetitions short of failure, which represents 13.6% less repetitions performed in RT-NF when compared to the number executed in RT-F.

### Volume load (VL)

Significant differences in VL were detected between protocols (RT-F:  $333.9 \pm 174.1$  tons; RT-NF:  $295.4 \pm 207.9$  tons;  $P = 0.01$ ; Fig. 2B). The mean difference between protocols was  $38.4 \pm 53.5$  tons, which represents a VL 11.5% smaller in RT-NF when compared to that accumulated in RT-F.

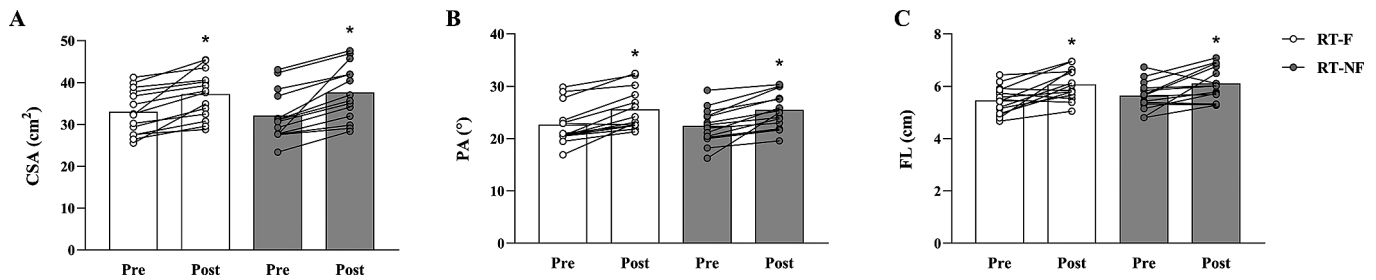
### Muscle cross-sectional area (CSA) and muscle architecture

Results of the mixed model showed no protocol vs time interaction (CSA:  $F[1, 26] = 0.88$ ,  $P = 0.35$ ; PA:  $F[1, 26] = 0.01$ ,  $P = 0.93$ ; FL:  $F[1, 26] = 0.44$ ,  $P < 0.51$ ) or protocol effect (CSA:

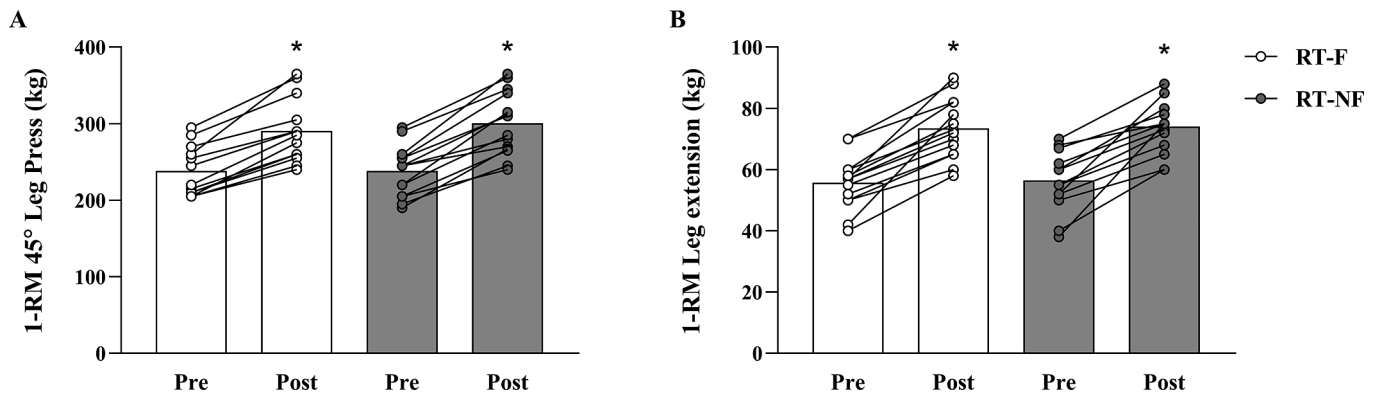


**FIG. 2.** (A) Number of repetitions performed per set for the quadriceps and (B) accumulated volume load after 10 weeks of resistance training. Values presented as mean  $\pm$  SD. \*Significantly different from RT-NF ( $P < 0.05$ ).

## Resistance training to muscle failure in trained individuals



**FIG. 3.** (A) Muscle cross-sectional area (CSA), (B) pennation angle (PA) and (C) fascicle length (FL) measured at baseline (Pre) and after 10 weeks (Post) of resistance training to muscle failure (RT-F) and resistance training to non-failure (RT-NF) protocols. Circles represent individual values. \*Significantly different from Pre (main time effect,  $P < 0.05$ ).

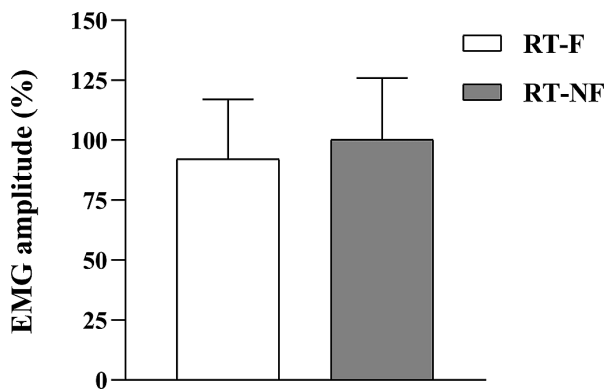


**FIG. 4.** (A) Maximum dynamic strength (1-RM) in 45° leg press and (B) leg extension machines, measured at baseline (Pre) and after 10 weeks (Post) of resistance training to muscle failure (RT-F) and resistance training to non-failure (RT-NF) protocols. Circles represent individual values. \*Significantly different from Pre (main time effect,  $P < 0.05$ ).

**TABLE 1.** Muscle cross-sectional area (CSA), pennation angle (PA), fascicle length (FL) and maximal dynamic strength (1-RM) at baseline (Pre) and after training (Post) for resistance training (RT) to muscle failure (RT-F) and non-failure (RT-NF).

Variable	Protocol	Pre	Post	ES	$\Delta\%$ (95% CI)
CSA (cm <sup>2</sup> )	RT-F	32.9 ± 5.3	37.2 ± 5.6	0.7	13.5% (7.0 to 20.0)
	RT-NF	32.0 ± 5.9	37.5 ± 6.6	0.8	18.1% (9.4 to 26.8)
PA (°)	RT-F	22.6 ± 3.8	25.5 ± 3.9	0.7	13.7% (8.1 to 19.4)
	RT-NF	23.7 ± 3.4	28.5 ± 3.4	1.4	14.4% (7.0 to 21.8)
FL (cm)	RT-F	5.4 ± 0.5	6.1 ± 0.6	1.0	11.8% (5.0 to 18.6)
	RT-NF	5.1 ± 0.6	5.7 ± 0.6	1.0	8.6% (2.2 to 15.1)
1-RM (kg) LP	RT-F	237.5 ± 31.7	290.0 ± 40.2	1.4	22.2% (17.8 to 26.6)
	RT-NF	237.5 ± 33.0	299.9 ± 41.5	1.6	26.6% (20.8 to 32.5)
1-RM (kg) LE	RT-F	55.6 ± 8.6	73.3 ± 9.8	1.8	33.3% (22.6 to 44.0)
	RT-NF	56.4 ± 9.6	73.9 ± 8.4	1.9	33.7% (20.5 to 46.9)

\*Significantly different from Pre (main time effect,  $P < 0.05$ ). Values presented as mean ± SD, mean percentage changes ( $\Delta\%$ ), confidence interval (95% CI), effect size (ES), leg press (LP) and leg extension (LE).



**FIG. 5.** Electromyographic (EMG) amplitude normalized by maximal voluntary isometric contraction from the resistance training to muscle failure (RT-F) and resistance training to non-failure (RT-NF) protocols. Values presented as mean  $\pm$  SD.

$F[1, 26] = 0.02, P = 0.89$ ; PA:  $F[1, 26] = 0.01, P = 0.90$ ; FL:  $F[1, 26] = 0.36, P = 0.55$ ) for either variable. However, a main time effect was observed for CSA ( $F[1, 26] = 49.67, P < 0.0001$ ; Fig. 3A), PA ( $F[1, 26] = 61.31, P < 0.0001$ ; Fig. 3B) and FL ( $F[1, 26] = 22.67, P < 0.0001$ ; Fig. 3C). Both training protocols significantly increased CSA, PA and FL from Pre to Post (Table 1).

#### Maximum dynamic strength (1-RM)

The mixed model analyses indicated that there was no protocol vs time interaction (45° leg press:  $F[1, 26] = 1.56, P = 0.22$ ; leg extension:  $F[1, 26] = 0.00, P = 0.94$ ) or protocol effect (45° leg press:  $F[1, 26] = 0.14, P = 0.71$ ; leg extension:  $F[1, 26] = 0.05, P = 0.82$ ). However, a main time effect was detected in both 1-RM tests: 45° leg press ( $F[1, 26] = 209.17, P < 0.0001$ ; Fig. 4A) and leg extension ( $F[1, 26] = 131.80, P < 0.0001$ ; Fig. 4B). In both training protocols, 1-RM values in the 45° leg press and leg extension exercise increased significantly from Pre to Post (Table 1).

#### Muscle activation

No significant differences ( $P > 0.05$ ) in muscle activation values were detected between protocols (RT-F:  $92.2 \pm 24.9\%$ ; RT-NF:  $100.3 \pm 25.6\%$ ; Fig. 5).

## DISCUSSION

Our main findings show that both muscle failure (RT-F) and non-failure (RT-NF) protocols were similarly effective at inducing muscle hypertrophy, muscle strength gains and changes in muscle architecture in trained individuals. Additionally, both protocols produced similar EMG amplitude, confirming our initial hypothesis.

An important limitation of the current literature is that, to date, most studies investigating RT-F have been conducted in untrained

individuals. It has been suggested that as an individual becomes more experienced, there is an increasing need to challenge the neuromuscular system with higher levels of effort [8, 9]. However, this hypothesis is not supported by the findings of the present study. For muscle strength, our results are in line with those of a meta-analysis composed of studies with untrained and trained subjects [18], which found no advantage for RT-F compared with RT-NF. Regarding muscle hypertrophy, we also observed similar increases in CSA between RT-F and RT-NF. Our results are in contrast to those of Karsten et al. [31] and Pareja-Blanco et al. [32] (RT-F group reached muscle failure during only 56.3% of total training sets), who reported a greater increase in muscle thickness (elbow flexors and vastus medialis) and CSA (vastus lateralis and intermedius) for RT-F, respectively, regardless of the number of repetitions and volume load equalization. Discrepancies between the studies may be attributable to several factors. First, in the studies by Karsten et al. [31] and Pareja-Blanco et al. [32] the difference between the number of repetitions per set performed in the RT-F and RT-NF sessions was  $\sim 50\text{--}60\%$ . It should be noted that differences in the number of repetitions per set between RT-F and RT-NF were rather small in the present study ( $-13.6\%$ ;  $-1.64$  reps), indicating that the non-failure protocol performed sets close to full fatigue. In view of the relationship between fatigue and muscle activation [33], when the exercise is performed close to muscle failure, the level of fatigue seems sufficient for complete muscle activation, as shown in the present study and in others with untrained individuals or who have undergone other training modes [4, 16]. Thus, it seems that as long as RT is carried to a point of significant fatigue (likely only 1 to 2 repetitions shy of failure), increases in muscle activation and mass will be similar to those of RT performed to failure. Second, neither of those studies [31, 32] consider the number of sets previously performed by participants in their RT routines. Individuals were randomly assigned to the RT-F and RT-NF protocols, which consisted of an equal number of sets for all. In this case, a given subject can increase, maintain or decrease the number of sets compared with his RT routine before the commencement of the experimental protocol. In fact, neglecting the subjects' training history may have influenced the adaptations resulting from the RT-F and RT-NF protocols, since large increases or decreases in the number of weekly sets have the potential to modulate the adaptive response [27]. Alternatively, our study employed an individualized number of sets, increasing by 20% the number of weekly sets subjects previously performed in their training. Finally, another potential explanation as to the inconsistent findings between studies may be related to the experimental design. In our study we used a within-subject design, which allows greater control of biological variability compared to a between-subject design [34]. Comparing the RT-F and RT-NF protocols in the same subject decreases genetic influences [35] and minimizes the effects of factors such as nutrition, training level and sleep [36, 37], which can affect RT-induced adaptations. Therefore, we believe that the use of a within-subject design and considering the training history of participants

(i.e., the volume of sets previously performed) may have minimized confounding factors in adaptations to RT-F and RT-NF in our study.

Another possible explanation for the similar hypertrophic and muscle strength gains are the changes in muscle architecture (i.e., muscle PA and FL). In the present study, RT-F and RT-NF produced comparable increases in PA (13.7% and 12.4%, respectively) and FL (12.7% and 10.4%, respectively) after 10 weeks of training. Similar to muscle hypertrophy, there is a lack of studies investigating RT-F and RT-NF effects on muscle architecture parameters. However, it is possible to compare our results with those of a study that investigated the adaptations in muscle architecture following a training intervention in trained individuals. Our results are in line with the study of Angleri et al. [2], who showed that drop-set, crescent pyramid and traditional RT protocols promote similar increases in PA (10.3%, 11% and 10.6%, respectively) and FL (9.1%, 8.9% and 8.9%, respectively), which were accompanied by similar increases in muscle hypertrophy and strength. Current evidence indicates that increases in muscle PA and FL allow for an increase in contractile material, with a possible increase in cross bridge formation [38]. In turn, these increases would result in a greater number of cross bridges simultaneously activated during a muscle contraction, increasing maximum force capacity [38]. If true, the similar increases in PA and FL found for RT-F and RT-NF would indicate that muscle growth resulted from addition of sarcomeres in parallel, consequentially increasing maximum force capacity to a similar extent for both RT-F and RT-NF.

This study is not without limitations. 1) Only moderate to high loads were used, and the results could be different when training to failure with low loads, as recently demonstrated in untrained subjects [39]. The same does not seem to happen when exercise is carried out to a point close to failure [4]. 2) We only investigated the hypertrophic responses of the VL muscle. Thus, we cannot confirm that the results will be similar when investigating different muscle groups, as different muscles might show different responses to muscle failure. Additionally, only a single point was assessed. Considering that non-uniform hypertrophy can occur within a single muscle, assessing multiple points would allow us to investigate how the different portions of the VL respond to the failure stimulus. However, non-uniform responses appear to be more common when different exercises are used throughout the RT programme [40], which did not happen in the present study. 3) Muscle strength assessments and RT were limited to the lower limbs, more specifically to the 45° leg press and leg extension exercises, and should not be extrapolated

to different exercises and muscle groups. In this sense, similar muscle strength gains have already been demonstrated in the upper limbs for failure vs non-failure protocols in a trained population [41], which might indicate that both lower and upper limbs respond to muscle failure in a similar way. 4) We did not consider how hormonal responses to one-leg exercise could affect responses in the opposite leg. However, a study investigated hormonal responses and its effect on muscle CSA and strength using a unilateral design in which subjects trained both knee extension and leg press exercises [42], similar to the design we adopted. The studies' results showed no acute increase in ostensibly anabolic systemic hormones, but hypertrophy occurred nonetheless. Also, isotonic 1-RM increased only for the trained leg. This way, we do not believe hormonal responses could have negatively impacted our findings. On the other hand, a within-subject design (i.e., unilateral) allows greater control of biological variability compared to a between-subject design [34].

As a practical application we suggest that despite only receiving the instruction to voluntarily interrupt the exercise close to failure, the RT-NF protocol produced important neuromuscular adaptations. This indicates that it is a simple and easy way to maximize gains without the need to reach muscle failure.

## CONCLUSIONS

This study shows that resistance training to muscle failure or non-failure is similarly effective in promoting increases in muscle hypertrophy, strength, pennation angle and fascicle length, while also resulting in similar muscle activation in trained individuals.

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## Conflict of interest

The authors declare that they have no conflict of interest.

## REFERENCES

- ACSM. Progression models in resistance training for healthy adults. *Medicine and science in sports and exercise*. 2009; 41(3):687–708.
- Angleri V, Ugrinowitsch C, Libardi CA. Crescent pyramid and drop-set systems do not promote greater strength gains, muscle hypertrophy, and changes on muscle architecture compared with traditional resistance training in well-trained men. *Eur J Appl Physiol*. 2017;117(2):359–69.
- Voet NB, van der Kooij EL, Riphagen, II, Lindeman E, van Engelen BG, Geurts AC. Strength training and aerobic exercise training for muscle disease. *The Cochrane database of systematic reviews*. 2013(7):CD003907.
- Nóbrega SR, Ugrinowitsch C, Pintanel L, Barcelos C, Libardi CA. Effect Of Resistance Training To Muscle Failure Versus Volitional Interruption At High- And Low-Intensities On Muscle Mass And Strength. *The Journal of Strength & Conditioning Research*. 2018; 32(1):162–9.
- Schoenfeld BJ, Peterson MD, Ogborn D, Contreras B, Sonmez GT. Effects of Low- vs. High-Load Resistance Training on Muscle Strength and Hypertrophy in Well-Trained Men. *J Strength Cond Res*. 2015;29(10):2954–63.
- Jenkins ND, Housh TJ, Bergstrom HC, Cochrane KC, Hill EC, Smith CM, Johnson GO, Schmidt RJ, Cramer JT. Muscle activation during three sets to failure at 80 vs. 30% 1RM resistance exercise. *Eur J Appl Physiol*. 2015; 115(11):2335–47.
- Willardson JM. The application of training to failure in periodized multiple-set resistance exercise programs. *J Strength Cond Res*. 2007;21(2):628–31.
- Zatsiorsky VM, Kraemer WJ. *Science and Practice of Strength Training*. 2nd ed. Champaign, IL: Human Kinetics; 2006.
- Cressey EM, West CA, Tiberio DP, Kraemer WJ, Maresh CM. The effects of ten weeks of lower-body unstable surface training on markers of athletic performance. *J Strength Cond Res*. 2007;21(2):561–7.
- Zatsiorsky V. *Science and practice of strength training*. Champaign: Human Kinetics; 1995. 242 p.
- Schoenfeld B, Grgic J. Does Training to Failure Maximize Muscle Hypertrophy? *Strength and conditioning journal*. 2019; 41(5):108–13.
- Vigotsky AD, Beardsley C, Contreras B, Steele J, Ogborn D, Phillips SM. Greater electromyographic responses do not imply greater motor unit recruitment and 'hypertrophic potential' cannot be inferred. *J Strength Cond Res*. 2015.
- Morton RW, Sonne MW, Farias Zuniga A, Mohammad IYZ, Jones A, McGlory C, Keir PJ, Potvin JR, Phillips SM. Muscle fibre activation is unaffected by load and repetition duration when resistance exercise is performed to task failure. *The Journal of physiology*. 2019;597(17):4601–13.
- Burd NA, Holwerda AM, Selby KC, West DWD, Staples AW, Cain NE, Cashaback JGA, Potvin JR, Baker SK, Phillips SM. Resistance exercise volume affects myofibrillar protein synthesis and anabolic signalling molecule phosphorylation in young men. *J Physiol*. 2010;588(Pt 16):3119–30.
- ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc*. 2009; 41(3):687–708.
- Sundstrup E, Jakobsen MD, Andersen CH, Zebis MK, Mortensen OS, Andersen LL. Muscle activation strategies during strength training with heavy loading vs. repetitions to failure. *J Strength Cond Res*. 2012; 26(7):1897–903.
- Buckner SL, Jessee MB, Mattocks KT, Mouser JG, Counts BR, Dankel SJ, Loenneke JP. Determining Strength: A Case for Multiple Methods of Measurement. *Sports Med*. 2016.
- Davies T, Orr R, Halaki M, Hackett D. Effect of Training Leading to Repetition Failure on Muscular Strength: A Systematic Review and Meta-Analysis. *Sports Med*. 2016;46(4):487–502.
- Association WM. World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects. *JAMA*. 2013;310(20):2191–4.
- Levinger I, Goodman C, Hare DL, Jerums G, Toia D, Selig S. The reliability of the 1RM strength test for untrained middle-aged individuals. *J Sci Med Sport*. 2009;12(2):310–6.
- Lixandrão ME, Ugrinowitsch C, Bottaro M, Chacon-Mikahil MP, Cavaglieri CR, Min LL, Oliveira de Souza E, Laurentino GC, Libardi CA. Vastus lateralis muscle cross sectional area ultrasonography validity for image-fitting in humans. *Journal of strength and conditioning research*. 2014.
- Damas F, Phillips SM, Lixandrão ME, Vechin FC, Libardi CA, Roschel H, Tricoli V, Ugrinowitsch C. Early resistance training-induced increases in muscle cross-sectional area are concomitant with edema-induced muscle swelling. *European journal of applied physiology*. 2016;116(1):49–56.
- Newton MJ, Morgan GT, Sacco P, Chapman DW, Nosaka K. Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *Journal of strength and conditioning research*. 2008;22(2):597–607.
- Scanlon TC, Fragala MS, Stout JR, Emerson NS, Beyer KS, Oliveira LP, Hoffman JR. Muscle architecture and strength: adaptations to short-term resistance training in older adults. *Muscle Nerve*. 2013;49(4):584–92.
- Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol* (1985). 2007;103(5):1565–75.
- Brown LE, Weir JP. ASEP procedures recommendation I: accurate assessment of muscular strength and power. *J Exerc Physiol Online*. 2001; 4(3):1–21.
- Scarpelli MC, Nóbrega SR, Santanielo N, Alvarez IF, Otoboni GB, Ugrinowitsch C, Libardi CA. Muscle Hypertrophy Response Is Affected by Previous Resistance Training Volume in Trained Individuals. *J Strength Cond Res*. 2020(27).
- Pitcher JB, Miles TS. Influence of muscle blood flow on fatigue during intermittent human hand-grip exercise and recovery. *Clin Exp Pharmacol Physiol*. 1997; 24(7):471–6.
- SENIAM P. Recommendations for sensor locations on individual muscles 2005 [cited 2016 12 Jan]. Available from: [http://seniam.org/sensor\\_location.htm](http://seniam.org/sensor_location.htm).
- Hedges L, Olkin I. *Statistical Methods for Meta-Analysis*. New York, NY: Academic Press; 1985.
- Karsten B, Fu YL, Larumbe-Zabala E, Seijo M, Naclerio F. Impact of Two High-Volume Set Configuration Workouts on Resistance Training Outcomes in Recreationally Trained Men. *J Strength Cond Res*. 2019.
- Pareja-Blanco F, Rodríguez-Rosell D, Sánchez-Medina L, Sanchis-Moysi J, Dorado C, Mora-Custodio R, Yáñez-García JM, Morales-Alamo D, Pérez-Suárez I, Calbet JAL, González-Badillo JJ. Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scand J Med Sci Sports*. 2017;27(7):724–35.
- Adam A, De Luca CJ. Recruitment order of motor units in human vastus lateralis muscle is maintained during fatiguing contractions. *J Neurophysiol*. 2003;90(5):2919–27.
- MacInnis MJ, McGlory C, Gibala MJ, Phillips SM. Investigating human skeletal muscle physiology with unilateral exercise models: when one limb is more powerful than two. *Appl Physiol Nutr Metab*. 2017;42(6):563–70.



35. Bouchard C, An P, Rice T, Skinner JS, Wilmore JH, Gagnon J, Pérusse L, Leon AS, Rao DC. Familial aggregation of VO<sub>2</sub>(max) response to exercise training: results from the HERITAGE Family Study. *J Appl Physiol* (1985). 1999; 87(3):1003–8.
36. Hawley JA, Burke LM, Phillips SM, Spriet LL. Nutritional modulation of training-induced skeletal muscle adaptations. *J Appl Physiol* (1985). 2011; 110(3):834–45.
37. Halson SL. Sleep in elite athletes and nutritional interventions to enhance sleep. *Sports Med*. 2014; 44 Suppl 1(Suppl 1):S13–23.
38. Aagaard P, Andersen JL, Dyhre-Poulsen P, Leffers AM, Wagner A, Magnusson SP, Halkjaer-Kristensen J, Simonsen EB. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol*. 2001; 534(Pt. 2):613–23.
39. Lasevicius T, Schoenfeld BJ, Silva-Batista C, Barros TS, Aihara AY, Brendon H, Longo AR, Tricoli V, Peres BA, Teixeira EL. Muscle Failure Promotes Greater Muscle Hypertrophy in Low-Load but Not in High-Load Resistance Training. *J Strength Cond Res*. 2019.
40. Fonseca RM, Roschel H, Tricoli V, de Souza EO, Wilson JM, Laurentino GC, Aihara AY, de Souza Leão AR, Ugrinowitsch C. Changes in exercises are more effective than in loading schemes to improve muscle strength. *J Strength Cond Res*. 2014;28(11):3085–92.
41. Drinkwater EJ, Lawton TW, Lindsell RP, Pyne DB, Hunt PH, McKenna MJ. Training leading to repetition failure enhances bench press strength gains in elite junior athletes. *J Strength Cond Res*. 2005;19(2):382–8.
42. Wilkinson SB, Tarnopolsky MA, Grant EJ, Correia CE, Phillips SM. Hypertrophy with unilateral resistance exercise occurs without increases in endogenous anabolic hormone concentration. *Eur J Appl Physiol*. 2006;98(6):546–55.