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Combination of Training to Failure and Non-Failure: An Unexplored Approach of Number of Repetitions, Rate of Perceived Exertion, Time Under Tension, Volume-Load, and Muscle Swelling in Trained Individuals

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SUMMARY

Background. Previous studies suggest training to failure may not yield superior muscle responses compared to non-failure training, leaving the combined use unexplored.

Objective. To compare the number of repetitions, volume-load, time under tension (TUT), rate of perceived exertion (RPE), and muscle swelling between two protocols: one involving four sets to failure (TFAS) and the other involving only the final set reaching failure (TFLS).

Methods. Fourteen trained adults completed both conditions in four sessions, with the first two sessions dedicated to determining the one-repetition maximum (1RM) for the barbell preacher curl exercise. In the third session, participants completed TFAS, maxing repetitions across four sets at 70% of 1RM. In the fourth session (TFLS), they fixed repetition in the first three sets (mean achieved during TFAS), with the final set to failure. In both sessions, repetitions, volume-load, RPE, and TUT were recorded post-set. Before and immediately after both TFAS and TFLS, participants' biceps brachii cross-sectional area at 50% of humerus length was measured using ultrasound imaging to assess muscle swelling. Comparisons used ANOVA and paired t-tests.

Results. TFAS had higher RPE across sets (TFLS = 32 ± 4; TFAL = 37 ± 4) and a greater total TUT compared to TFLS (TFLS = 168 ± 44s; TFAL = 178 ± 41s). TFLS achieved more repetitions (TFLS = 38.93 ± 6.51; TFAL = 37.36 ± 5.24) and volume-load (TFLS = 918.55 ± 235.38 kg; TFAL = 888.77 ± 241.46 kg). Both protocols showed similar muscle swelling (TFLS = 23.90 ± 5.27 cm^2; TFAL = 20.73 ± 10.71 m^2).

Conclusions. TFLS allowed for more repetitions with lower RPE, with no difference in swelling.

KEY WORDS

Failure; non-failure; muscle swelling; repetitions; rate of perceived exertion; repetitions.

INTRODUCTION

The prescription of a training program focused on enhancing strength and muscle hypertrophy requires careful consideration of various factors, including biological individuality, contractions mode, specificity, and the physiological effects (1, 2). Recently, there has been extensive debate on whether training to failure is more effective than training without reaching failure in terms of muscle hypertrophy (3-6). The results highlighted that both strategies of training could offer a similar stimulus to induce muscle grown (7). Following the reasoning that muscle hypertrophy is reflected by the difference between protein synthesis and degradation (8), and considering that training to failure can potentially result in a higher anabolic and catabolic milieu compared to non-failure training (9), the idea of finding a balance between the two training strategies for promoting hypertrophy is plausible.

In the study by Lacerda *et al*. (5), it was found that when one leg performed all sets until failure (TFAS: training to failure in all sets), the contralateral leg was able to match the average number of repetitions achieved in the sets to failure. This suggests that if the last set were performed to failure (TFLS: training to failure only at the last set), it could result in a higher number of repetitions than the average value, and, possibly, a greater total number of repetitions than training to failure. In this training perspective, perhaps the advantages of TFAS may complement the benefits of non-failure training in inducing muscle hypertrophy. However, further research is needed to determine the validity of incorporating a combination of training with and without failure across sets.

Exner *et al*. (3) demonstrated that TFAS could result in a higher number of repetitions, muscle swelling, and a higher rate of perceived exertion (RPE) compared to non-failure training. These findings support the notion that training to failure leads to increased physiological stress and physical discomfort compared to non-failure training. However, different results could be observed in a cross-sectional study if TFAS and TFLS protocols were compared using the same variables as Exner *et al*. (3). For instance, TFLS might result in a greater or similar number of repetitions compared to TFAS but with a lower RPE. This hypothesis is supported by Lacerda *et al.* (5) who found that TFAS elicited higher RPE throughout the sets compared to the condition where participants trained with the average number of repetitions performed by TFAS across sets. Therefore, when comparing RPE between TFLS and TFAS across sets, it is possible that during the initial sets, TFLS would exhibit a lower RPE value than TFAS. However, in the final set, the RPE could be similar between the conditions, as both would be training to failure. Comparing the RPE response between TFAS and TFLS could indicate the level of effort and stress in incorporating training to failure in the last set, enabling the analysis a variable relevant for chronic adaptations to exercise (10). Additionally, another variable that could reflect the difference between TFAS and TFLS would be the volume-load (number of repetitions x lifted weight), as this variable appears to influence muscular responses, such as hypertrophy and increased strength, given its association with mechanical stress (11).

When considering muscle swelling, previous studies have suggested that higher training volume could result in greater muscle swelling (12), which supports the findings of Exner *et al.* (3), where TFAS showed a greater number of repetitions and muscle swelling compared to non-failure training. However, a direct comparison of muscle swelling between TFAS and TFLS has not been conducted yet. If training volume indeed has an impact on muscle swelling, it is possible that both types of training could elicit a similar or potentially greater response if the latter condition performs a higher number of repetitions. Furthermore, it is worth noting that muscle swelling observed immediately after the first training session has been suggested as a potential predictor of muscle hypertrophy (13). In this context, comparing muscle swelling between TFAS and TFLS could provide support for the hypothesis of superiority of one condition over another, considering that both conditions would be trained for a period of time.

Nonetheless, as failure approaches, it is expected that the duration of each repetition will progressively increase, making it challenging to maintain a consistent pre-established duration for each muscular action (14). Consequently, the time under tension (TUT) (15) of a set or of a training session could be longer for TFAS compared to non-failure training, as TFAS would reach failure in all sets and the final repetitions at each set would be performed at a slower speed, resulting in an extended duration. Unfortunately, Lacerda *et al*. (5) did not present information regarding the TUT spent across the training sessions by TFAS and the training protocol that matched the number of repetitions without reaching the failure to elucidate this issue. Nevertheless, in comparing the TUT of a training session between TFAS and TFLS, it is possible to speculate that there would be an equivalence between these protocols. Given that the greater number of repetitions performed by the TFLS protocol could be compensated by the longer TUT of the TFAS protocol during the execution of the final repetitions in each set. Considering the impact of TUT on strength and muscle hypertrophy development (16), analyzing this variable between the TFAS and TFLS protocols would contribute to a better understanding of the effects of these protocols in relation to muscle adaptations in future studies. Furthermore, it could also lead to a deeper understanding of the muscle swelling response between the protocols, taking into consideration the debate regarding a possible association of TUT with muscle swelling (17, 18).

Taking these factors into account, the present study aims to compare the number of repetitions, RPE, TUT, volume-load, and muscle swelling following a training session between the TFAS and TFLS conditions. We hypothesize that TFLS will demonstrate higher NMR, volume-load, and muscle swelling compared to TFAS. Additionally, the latter condition will have a higher RPE, while both conditions will exhibit similar TST.

MATERIALS AND METHODS

Overview

Participants were assigned to two conditions: TFAS and TFLS, in crossover design. The first two experimental sessions aimed to familiarize the participants and perform the one-repetition maximum (1RM) test in the seated bar preacher curl exercise. In the third experimental session, participants performed repetitions to failure at 70% of their 1RM across four sets (TFAS condition). In the fourth experimental session, participants performed the average number of repetitions calculated from the previous session's total repetitions during the first three sets, however, in the fourth set, participants performed repetitions until failure (TFLS condition). The TUT, RPE and volume-load were recorded in both conditions across sets and used for further comparison. Before and after the TFAS and TFLS, images of the cross-sectional area (CSA) of the right biceps brachii were obtained via b-mode ultrasound at 50% of the humerus length for analysis and comparison of muscle swelling. **Figure 1** presents the study design.

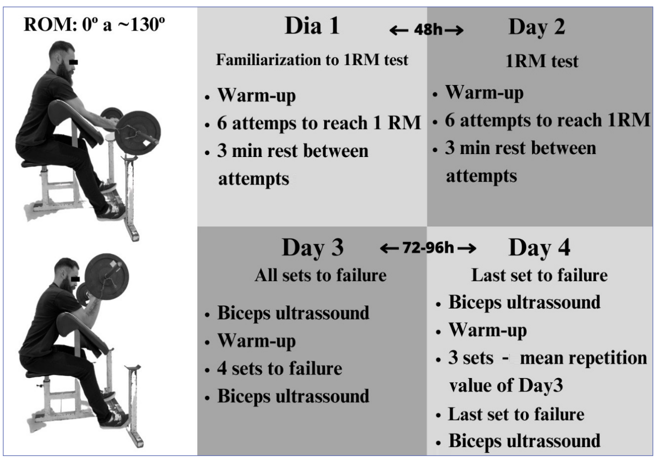

Figure 1. Study design.

ROM: range of motion; 1RM: one repetition maximum test.

Subjects

The sample size was calculated following the procedures suggested by Beck (2013) (19), by using the software G*Power 3.1 (Frauz Faur Universität Kiel, Germany). With reference to paired comparisons (t-test) of means, we calculated the minimum number of individuals needed to achieve a statistical power of at least 80% (p = 0.05). For this calculation, we used data on immediate muscle swelling following a strength training session from the study by Hirono *et al.* (2020) (13) (effect size = 0.967), which indicated a requirement of 14 volunteers. Therefore, the sample was composed of 14 individuals.

Fourteen trained individuals (12 men and two women) with an age range of 18 to 30 years old (mean ± SD: age = 21.5 ± 2.7 years; body mass = 79.9 ± 9.4 kg; height = 1.79 ± 0.08 m; body fat percentage = 13.14 ± 4.08%: calculated with seven skinfold measurements, following established procedures (20); training experience greater than 6 months (30.4 ± 27.1 months) participated in the study). The Ethics committee of the Federal University of Santa Maria approved this study on March 23, 2023 by the number 69325723.2.20000.5346, which complied with international standards. In addition, each subject was instructed not to perform any physical activity on the testing session's days.

Procedures

First experimental session: familiarization of 1RM test

Measurements of height, body mass, and fat percentage (skinfold thickness) were taken. Afterward, participants were positioned for the seated bar preacher curl exercise. The seat height was adjusted to achieve a 45° angle of shoulder flexion (between the humerus and trunk). The elbow was fully extended and reached the bar, which had fixed numbers to enable participants to place their hands at a standardized distance from the center of the bar to the grip location. The positions of the hand and seat were recorded for later replication. Next, the participants performed 10 repetitions using only the weight of the bar as resistance, with a 2s concentric (lifting) phase and a 2s eccentric (lowering) phase. These actions were controlled by a metronome and served as a warm-up. During each repetition, participants performed a 130-degree excursion of elbow flexion, with 0 degrees representing the elbow fully extended. This range of motion was measured and determined using a goniometer.

Two minutes after the last repetition of the warm-up, participants initiated the familiarization of 1RM test in the same exercise and position of warm-up. The 1RM test familiarization was performed throughout a full ROM, with a 3 min recovery interval between attempts. A final value was obtained within 6 attempts. Each attempt started with the elbow fully extended. The bar was handed to the participant in this initial position, who then performed a concentric muscle action until 130° of elbow flexion (forearm perpendicular to the ground). The bar load was progressively increased (minimum of 0.5 kg, where all the weights were previously measured using a three-digit scale) until the participant was unable to perform the concentric action with proper form. Hence, the 1RM value corresponded to the weight lifted in the previous successful attempt. Similar procedures for 1RM achievement have been previously described for the preacher curl exercise (21)

Second experimental session: 1RM test

This session occurred 48-72h after the last session. In this, a sole 1RM test was conducted, following the procedures previously established during the 1RM test familiarization. The data obtained from the 1RM test in this session was collected for subsequent statistical analysis. The Intra-class Correlation Coefficient ($ICC_{3,1}$) value between the 1RM results of the familiarization session and the test session was calculated and were (r = 0.99). The average weight lifted during the familiarization phase was 33.42 ± 11.49 kg, while during the test session was 34.99 ± 11.44 kg.

Third experimental session: TFAS

This session took place 48-72 hours after the second session. Participants underwent ultrasound examination, during which two measurements of biceps brachii CSA were obtained at 50% of the distance from the acromion to the lateral epicondyle of each humerus using B-mode ultrasound (Siemens Healthcare, ACUSON S2000, Germany). Ultrasound images were captured at a frequency of 21 frames per second using a 10 MHz linear transducer with a depth of 6-8 cm and a gain of 13dB. The settings were adjusted individually to ensure a clear image of the entire muscle for an extended field of view and replication in subsequent moments. Two trained technicians performed the ultrasound scans, moving the transducer in a line perpendicular to the humeral at a relatively constant speed. The images were saved to a hard drive and coded for blinded CSA calculation using Horos® software (Annapolis, Maryland, USA). The mean CSA value from the two images was used for statistical analysis. Images of the CSA of the biceps brachii before and after the performance of the protocols are shown in **figure 2**.

After the ultrasound image collection, participants proceeded with a warm-up in the seated bar preacher curl exercise, following a similar protocol as the warm-up for the 1RM test. After a two-minute rest, participants performed repetitions (0°-130° of elbow flexion) to failure across four sets, with an intensity of 70% of their 1RM and 2 minutes interval between sets. The repetitions were performed with a controlled tempo of 2s for the concentric action and 2s for the eccentric action, guided by a metronome and the range of motion checked by one of the evaluators. A chronometer was started as each participant began lifting the weight and was stopped at the point of failure. The time spent from the timer's initiation to its interruption is considered as the set's TST. It was observed that as participants approached failure (~ last two repetitions), the duration of each repetition increased. Therefore, the last repetitions were performed with a longer duration than 4s. After each set, the participants indicated their RPE by selecting a number on a scale ranging from 0 to 10. The scale corresponds to the effort level to perform the whole set, with 0 representing minimal effort and 10 indicating maximum effort. The number of repetitions, TUT, and RPE were recorded for each set and were utilized for statistical analysis. In addition, immediately after the last set, participants underwent another round of ultrasound imaging following the same procedures as before. The purpose was to acquire two new images and measure the CSA value once again. The relative difference

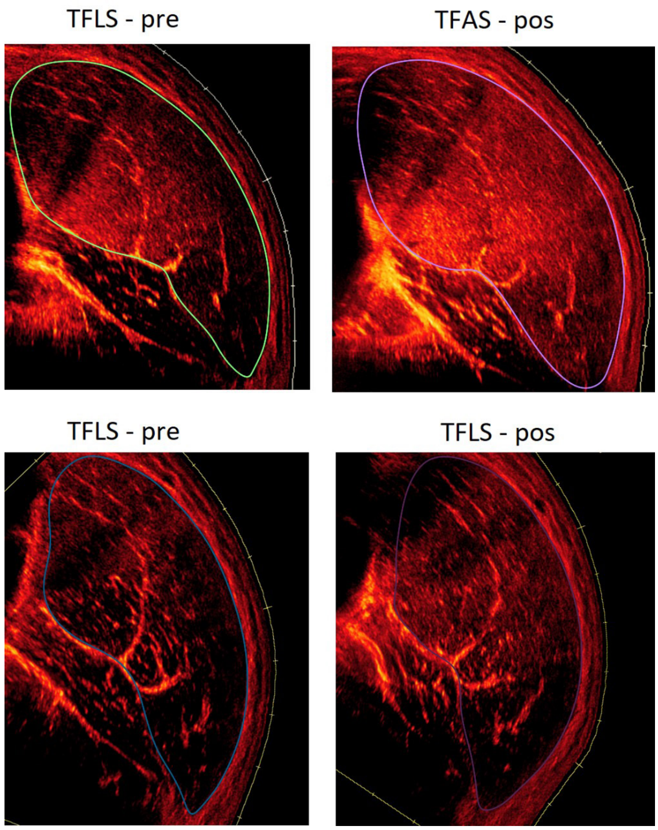

Figure 2. Images of the CSA of the biceps brachii.

TFAS: training to failure in all sets; TFLS: training to failure only at the last set; CSA: cross-section area.

in CSA between the pre- and post-TFAS measurements was used for statistical analysis.

Fourth experimental session: TFLS

Between 72-96 hours after the last session, participants returned to the laboratory and repeated all ultrasound and procedures in the seated bar preacher curl exercise. Conversely, during the first three sets, participants performed a fixed number of repetitions, corresponding to the average number of the four sets carried out in TFAS. At the fourth set, participants performed the repetitions until failure.

For the reliability measurement of CSA, we computed the $ICC_{3,1}$ for the two CSA measurements taken during the third and fourth experimental sessions (n = 148 images with $ICC_{3,1} = 0.99$) (21, 22). In these sessions, another researcher assessed 35% of all the images, resulting in an also high measurement reliability $ICC_{3,1}$ (r = 0.98) between them, procedure performed previously in our laboratory (23).

Statistical analysis

Initially a descriptive analysis of the data was performed. The normality and homogeneity of variances were verified using Shapiro-Wilk and Mauchly's tests, respectively. The biceps brachii CSAs at pre- and post-performance of TFAS and TFLS were transformed into relative values (%) as indicator of muscle swelling (*((post - pre) / pre) × 100*). To compare the number of repetitions, TUT, volume-load and RPE across sets (repeated measures) and conditions (TFAS and TFLS), the ANOVA two-way tests were used. To compare the overall (sum of values across sets) number of repetitions, TUT, volume-load and RPE, and muscle swelling, the paired t tests were used. When necessary, the Bonferroni *post-hoc* test was used to identify the differences found by ANOVA. The level of significance was $\alpha = 0.05$. In addition, eta squared (η^2) values are reported to reflect the magnitude of the differences in each treatment by ANOVA (small = 0.01, medium = 0.06, and large = 0.14 (24). All statistical procedures were performed in the Social Package Software Statistic (SPSS 22.0 for Windows, Chicago, IL, USA).

RESULTS

The normality of the distribution was confirmed by the Shapiro-Wilk test, and all volunteers who started the collection data were able to finish within the specified time. For most volunteers, a recovery period until 96 hours was needed after the TFAS condition execution. However, some volunteers needed longer time and two extra days were given. For note, volunteers reported greater pain in the biceps after TFAS compared to TFLS. The inferential comparisons of the investigated variables are presented in the following sequence.

Repetitions and volume load

The ANOVA found an interaction effect between factors ($p < 0.001$; $n^2 = 0.33$). TFAS performed greater number of repetitions in the first set compared to TFLS, and this last condition performed greater number of repetitions at the other sets. Intra-condition analysis showed TFAS performed more repetitions at the first set compared to other sets, while TFLS did not show differences across sets. Additionally, paired t-test showed the TFLS performed more repetitions summed across sets than TFAS ($p = 0.011$).

Considering the volume-load, ANOVA found an interaction effect between factors ($p < 0.001$; ES = 0.33). TFAS showed greater volume-load in the first set compared to TFLS, and this last condition exhibited greater volume-load in the other sets. Intra-condition analysis showed TFAS lifted more volume-load at the first set compared to other sets, while TFLS did not show differences across sets. Additionally, paired t-test showed the TFLS lifted more volume-load summed across sets than TFAS ($p = 0.010$). **Figure 3** illustrates the comparison of number of repetitions and volume-load between conditions.

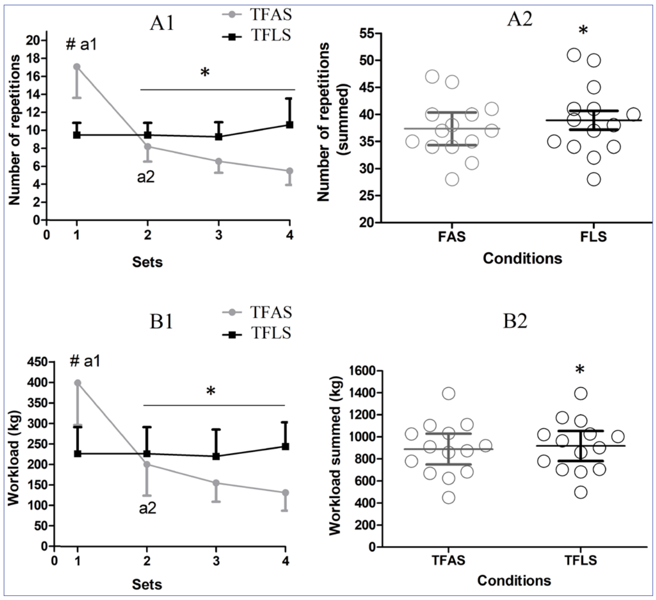

Figure 3. Comparison of repetitions (**A1, A2**) and volume-load (**B1, B2**) between conditions.
*Greater than TFAS. #greater than TFLS; a1: greater than other sets within TFAS; a2: greater than 3rd and 4th set within TFAS; $p < 0.05$; TFAS: training to failure in all sets; TFLS: training to failure only at the last set.

Time under tension (TUT) and Rate perceived exertion (RPE)

According to ANOVA there was an interaction effect between factors ($p < 0.001$; $n^2 = 0.33$). Compared to TFLS, TFAS presented greater TUT at the 1st set, similar at the 2nd set, and lower at the 3rd and 4th sets. Intra-condition analysis showed TFAS spent greater TUT at the 1st set than other sets, 2nd set was greater than the 4th set, and this last set presented similar TUT than 3rd set. TFLS presented greater TUT at the last set compared to other sets, in which presented similar values between them. Additionally, paired t-test showed the TFAS spend more TUT summed across sets than TFLS ($p = 0.005$).

Considering the RPE, ANOVA found an interaction effect between factors ($p = 0.001$; ES = 0.33). TFAS showed greater RPE in the first three sets compared to TFLS and a similar value at the last set. Intra-condition analysis showed the TFAS exhibited lower RPE at the first set compared to other sets, while in TFLS the RPE was increasing across sets. Additionally, paired t-test showed the TFAS exhibited greater RPE summed across sets than TFLS ($p < 0.001$). **Figure 4** illustrates the comparison of TUT and RPE between conditions.

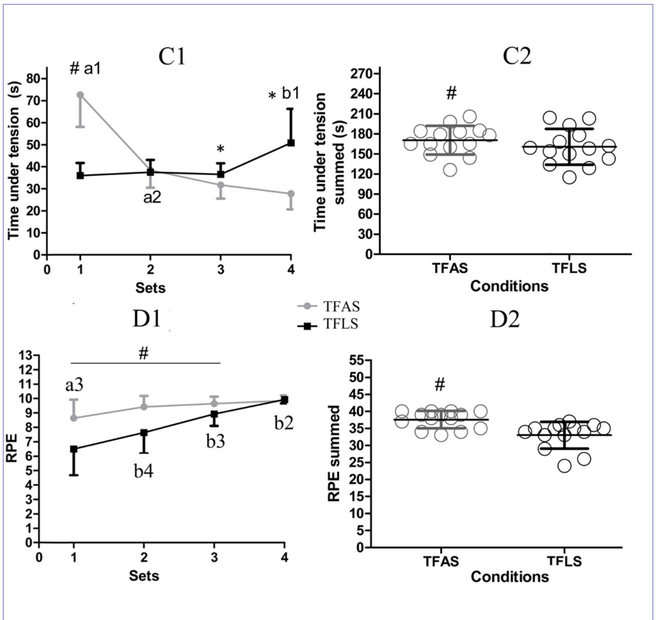

Figure 4. Comparison of time under tension (C1, C2) and rate of perceived exertion (D1, D2) between TFAS and TFLS.

*Greater than TFAS. #greater than TFLS; a1: greater than other sets for the TFAS; a2: greater than 4th set for TFAS; a3: lower than the other sets for TFAS; b1: greater than other sets for TFLS; b2: greater than all sets for TFLS; b3: greater than the first two sets for TFLS; b4: greater than 1st set for TFLSM; $p < 0.05$; TFAS: training to failure in all sets; TFLS; training to failure only at the last set.

Muscle swelling

Considering the muscle swelling results, there was no difference in the mean pre-CSA values between conditions (11.67 ± 3.30 cm^2 × 11.46 ± 3.50 cm^2) before TFAS and TFLS, respectively. This suggests that the recovery time was sufficient to reduce the swelling in the brachial biceps muscle in such a way that the CSA values were in similar conditions before the execution of each condition. Considering muscle swelling comparison results, the paired t-test did not find any differences between the conditions ($p = 0.229$). **Figure 5** illustrates the muscle swelling comparison.

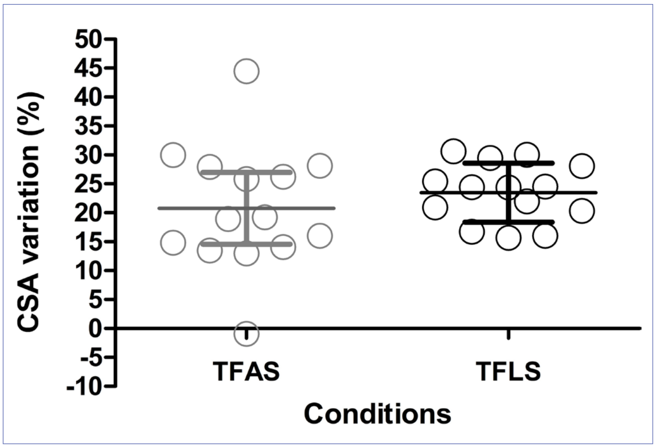

Figure 5. Comparison of muscle swelling after TFAS and TFLS.

CSA: cross-sectional area; TFAS; training to failure in all sets; TFLS; training to failure only at the last set; no difference was detected; $p > 0.05$.

DISCUSSION

The present studied aimed to compare the number of repetitions, TUT, RPE, volume-load and muscle swelling between TFAS and TFLS across four sets. Compared to TFLS, TFAS showed greater TUT, RPE number of repetitions and volume-load only at the initial sets. At the final sets, TFLS showed greater number of repetitions, volume-load, TUT and similar RPE. Considering the amount of all TUT, RPE, volume-load and number of repetitions across sets, TFLS showed greater number of repetitions and volume-load, while TFAS showed greater values for TUT and RPE. In the intra-condition analysis, it was observed that TFAS exhibited a greater number of repetitions, volume-load, and TUT in the first set compared to the subsequent sets. Additionally, TFAS showed lower RPE values in the first set compared to the other sets. On the other hand, TFLS demonstrated similar values across sets concerning the number of repetitions, TUT, and volume-load. However, RPE increased as the sets progressed. Furthermore, there was no significant difference in biceps swelling between the TFLS and TFAS conditions.

The muscle swelling after a resistance training session has been recognized as a potent hypertrophy inducer (13). While the complete mechanism is still to be determined, it is believed that during exercises heavily reliant on anaerobic metabolism, muscle swelling occurs due to changes in intracellular and extracellular water balance caused by heightened vascular permeability (25). Prior studies utilizing bioimpedance spectroscopy have indicated associations between changes in intracellular and extracellular water balance and variations in ion concentration, with metabolic changes observed in skeletal muscle cells post-exercise (26). As a consequence, muscle swelling can be considered an indirect indicator of the accumulation of metabolic stress (27), and consequently, it may play an important role for the hypertrophy process (28). Corroborating with this argumentation, previous studies have found a positive association between acute muscle swelling in the middle of a training period and hypertrophy (29, 30). Furthermore, this association exists even when muscle swelling is measured on the first day training and linked to hypertrophy (13).

In this sense, our results allow us to speculate that TFAS and TFLS could promote a similar hypertrophic response, as there were no differences in the muscle swelling response between conditions. However, it should be noted that the TFLS group showed higher volume-load and number of repetitions and, furthermore, lower RPE compared to TFAS, suggesting a lower effort throughout the repetitions to achieve a higher total mechanical demand. This response advocates that there was a lower level of physiological stress (a lower catabolic environment) to achieve a higher mechanical effort. Considering the inhibitory effect of elevated catabolic markers (such as cortisol), on muscle hypertrophy (31, 32), as well as the importance of mechanical stress for this response (33), it is conceivable that TFLS could offer advantages in promoting hypertrophy over TFAS after a period of training. However, protein catabolism markers were not assessed in the current study, thus limiting our conclusions to speculative inferences. Future research endeavors are warranted to explore this aspect further and provide a more comprehensive understanding of the topic.

Furthermore, Exner *et al.* (2023) (3) demonstrated that training without reaching muscle failure at both 30% and 60% of 1RM, with a controlled tempo of 1s for concentric and 1s for eccentric phases, using the dumbbell elbow flexion exercise across three sets, resulted in less swelling in the elbow flexor muscles compared to TFAS, regardless of the intensity. However, in this study, TFAS performed greater number of repetitions and longer TUT; factors relevant for muscle swelling increase (CSA acute increase) (27, 34). Due to having completed a higher number of repetitions, it is reasonable to expect that TFAS would have shown a higher volume-load and anaerobic energy supply than training with no failure. This increased metabolite production may have contributed to a greater muscle swelling compared to the other condition. Additionally, the longer TUT of TFAS may have led to a greater reduction in blood flow than the other type of training, contributing to greater fluid retention by the muscle fibers. In the present study, despite TFAS having a longer TUT, TFLS showed a higher number of repetitions, potentially balancing the mechanisms that promote muscle swelling.

Considering the number of repetitions, and volume-load it becomes apparent that the time to recover from fatigue caused by the first set to failure was inadequate within the 2-minute rest period. Consequently, fatigue accumulates across the sets, resulting in a decline in the number of repetitions and volume-load in each subsequent set. This significant reduction in repetitions performed until failure aligns with findings from other studies employing a two or even tree minutes rest period (35, 36). Notably, fatigue accumulation triggers various physiological changes, including reductions in pH and energetic substrate availability (37). On the other hand, incorporating sets with repetitions distant from failure in the initial sets and reserving failure only for the last set could facilitate consistent repetitions and volume-load across all sets. This strategic approach of avoiding failure until the final set may enable individuals to achieve higher total repetitions and volume-loads, potentially fostering advantageous effects on muscle hypertrophy and performance improvements. However, further chronic research is imperative to ascertain the most effective training approach between conditions.

Considering the TUT, TFAS exhibited greater values in the first set compared to TFLS, which is expected since the latter condition performed fewer repetitions. However, in the last two sets, TFLS showed greater TUT than TFAS due to a higher number of repetitions performed. Nonetheless, it is noteworthy that despite the higher overall number of repetitions in TFLS, it did not result in a greater overall TUT. This discrepancy suggests that factors other than the number of repetitions may influence the TUT in these training protocols. According to Vieira *et al.* (38), when repetitions are performed to failure, the muscle action speed is decreased due to fatigue, what leading to an increase in TUT. In support of this rationale, the present study found that despite there being no difference in the number of repetitions across sets for TFLS, the TUT to perform the last set was greater than in the previous sets. This finding supports the rationale that fatigue may slow down the repetitions performed near failure. Indeed, the slower duration of the repetitions near failure across the sets, likely influenced the overall greater TUT for TFAS compared to TFLS.

The present study has several limitations that should be taken into consideration. The sample consisted of young adults trained in strength, which means the results cannot be extrapolated to other populations and conditions. Additionally, only two women participated in the study, and it would have been more appropriate to have a more balanced gender representation to avoid gender bias. Blood collection and analysis were not conducted, which could have provided valuable insights into metabolic or hormonal responses. Additionally, the experimental design did not allow for randomization between conditions, which may have led to a potential learning effect or increased discomfort tolerance in the TFLS situation. Moreover, the study only analyzed one muscle and one muscular region, and other muscles and regions could potentially respond differently.

In summary, the results of TFAS corroborate with previous findings concerning a reduction in the number of repetitions and volume-load and an increasing of RPE and TUT across sets when compared to sets not performed to failure (38). The results of the present study open up an avenue for investigation and training focusing on muscle responses, such as muscle hypertrophy, through the utilization of TFLS. This condition demonstrated the ability to lift a higher amount of weight, perform a greater number of repetitions, and elicit a similar muscle swelling response as TFAS while being associated with lower perceived stress. Although a chronic study is essential for a better understanding of the responses using the TFLS protocol, the results of this study allow for the hypothesis of a superior or similar hypertrophic response to TFAS, with potentially less effort required, which could be applicable to other exercises or reduce the need for recovery between training sessions.

CONCLUSIONS

TFAS and TFLS induced a similar muscle swelling response, with greater number of repetitions and volume-load values for TFLS, while TFAS exhibited higher TUT and RPE. Our results indicate that TFLS in the barbell preacher curl exercise leads to significant muscle swelling and allows for achieving a higher number of repetitions and volume-load with lower discomfort compared to TFAS. This suggests that TFLS may promote an anabolic stimulus similar to TFAS but in a less catabolic environment, which could enhance the hypertrophy response. This is particularly interesting for individuals seeking this adaptation.

FUNDINGS

None.

DATA AVAILABILITY

Data are available as online supplement (**appendix 1-7**).

CONTRIBUTIONS

GFP, FLL: conceptualization, writing – original draft, data collection. ABGB: data collection and image analysis; AKL: conceptualization, data collection. MECR, DGDS, LRM, TDLN: data collection. LIL: study conception. All authors: writing - review & editing.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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Appnedix 1. Individual cross sectional area values at at 50% of biceps brachii.

Volunteers	Cross Sectional Area (CSA)											
	TFAS PRE			TFAS POST			TFLS PRE			TFLS POST		
	CSA cm^2			CSA cm^2			CSA cm^2			CSA cm^2		
	1	2	Mean	1	2	Mean	1	2	Mean	1	2	Mean
Qa	4.93	4.97	4.95	6.98	7.33	7.15	4.64	4.54	4.59	6.03	5.92	5.97
De	12.94	12.50	12.72	14.90	14.31	14.61	14.67	14.34	14.51	16.88	16.69	16.78
Ug	16.25	15.11	15.68	17.56	18.21	17.89	16.16	16.49	16.33	18.65	19.24	18.95
Th	13.69	13.59	13.64	15.97	15.68	15.83	13.65	13.93	13.79	16.21	15.98	16.10
Fj	11.72	11.92	11.82	14.96	14.88	14.92	11.59	11.68	11.64	14.35	14.59	14.47
Sl	9.60	9.60	9.60	11.35	11.48	11.42	8.64	8.69	8.66	10.41	10.54	10.48
Vl	7.72	7.72	7.72	9.87	10.19	10.03	7.43	7.45	7.44	9.49	9.94	9.72
Fm	13.71	13.99	13.85	17.37	17.48	17.43	14.34	14.13	14.23	17.58	17.88	17.73
Bm	12.73	13.00	12.86	14.34	14.72	14.53	12.01	12.03	12.02	14.98	14.93	14.95
Hp	14.99	13.57	14.28	18.25	18.33	18.29	13.53	13.26	13.39	17.21	17.46	17.34
Rs	9.82	9.88	9.85	9.54	9.96	9.75	8.52	8.76	8.64	10.67	10.11	10.39
Mv	7.66	7.43	7.54	9.57	9.72	9.65	7.76	8.05	7.91	10.22	10.04	10.13
Jv	16.71	15.85	16.28	19.82	19.00	19.41	15.45	15.80	15.62	19.96	19.22	19.59
Mw	12.13	13.33	12.73	14.47	14.42	14.45	11.40	12.06	11.73	14.50	14.11	14.31
MEAN	11.86	11.80	11.83	14.14	14.17	14.15	11.30	11.44	11.37	14.14	14.07	14.11
±	2.92	2.75	2.81	3.63	3.40	3.51	2.83	2.81	2.81	3.51	3.44	3.47

Two images were taken, and the mean value was used for statistical analysis. TFAS: Training to Failure at all Sets; TFLS: Training to Failure only at the Last Set; SD: standard deviation.

Appnedix 2. Maximum number of repetitions performed across 4 sets using TFAS and TFLS in the preacher curl exercise.

Volunteer	Number of Repetitions									
	TFAS					TFLS				
	1 SET	2 SET	3 SET	4 SET	Summed	1 SET	2 SET	3 SET	4 SET	Sum
Qa	24	9	9	4	46	12	12	12	15	51
De	17	13	8	9	47	12	12	12	14	50
Ug	12	7	5	4	28	7	7	7	7	28
Th	16	8	6	5	35	9	9	6	10	34
FJ	15	8	5	6	34	9	9	9	7	34
Sl	22	6	5	4	37	9	9	9	12	39
Vl	18	8	7	7	40	10	10	10	10	40
Fm	13	8	5	5	31	8	8	8	8	32
Bm	15	7	7	6	35	9	9	9	10	37
Hp	15	9	6	4	34	9	9	9	8	35
Rs	16	9	8	7	40	10	10	10	15	45
Mv	22	7	7	5	41	10	10	10	11	41
Jv	18	9	7	4	38	10	10	10	8	38
Mw	16	7	7	7	37	9	9	9	14	41
MEAN	17.07	8.21	6.57	5.50	37.36	9.50	9.50	9.29	10.64	38.93
±	3.47	1.67	1.28	1.56	5.24	1.34	1.34	1.64	2.92	6.51

TFAS: Training to Failure at All Sets; TFLS: Training to Failure only at the Last Set. SD: standard deviation.

Appnedix 3. Rate of perceived exertion across 4 sets using TFAS and TFLS in the preacher curl exercise.

Volunteer	Rate Perceived Exertion									
	TFAS					TFLS				
	1 SET	2 SET	3 SET	4 SET	Summed	1 SET	2 SET	3 SET	4 SET	Sum
Qa	8	9	9	9	35	8	8	9	10	35
De	7	9	9	9	34	7	8	9	10	34
Ug	10	10	10	10	40	8	9	9	10	36
Th	9	9	10	10	38	8	9	10	10	37
FJ	9	10	10	10	39	5	8	10	10	33
Sl	7	8	9	10	34	5	7	8	9	29
Vl	9	9	9	10	37	8	9	9	10	36
Fm	6	8	9	10	33	3	5	8	10	26
Bm	9	10	10	10	39	7	8	9	10	34
Hp	8	10	10	10	38	7	8	10	10	35
Rs	10	10	10	10	40	8	8	9	10	35
Mv	9	10	10	10	39	3	4	7	10	24
Jv	10	10	10	10	40	8	8	9	10	35
Mw	10	10	10	10	40	6	8	9	10	33
MEAN	8.64	9.43	9.64	9.86	37.57	6.50	7.64	8.93	9.93	33.00
±	1.28	0.76	0.50	0.36	2.53	1.83	1.45	0.83	0.27	3.90

TFAS: Training to Failure at All Sets; TFLS: Training to Failure only at the Last Set. SD: standard deviation.

Appendix 4. Time under tension across 4 sets using TFAS and TFLS in the preacher curl exercise.

Volunteer	Time Under Tension (s)									
	TFAS					TFLS				
	1 SET	2 SET	3 SET	4 SET	Summed	1 SET	2 SET	3 SET	4 SET	Sum
Qa	99	43	44	20	206	45	47	47	65	204
De	61	59	36	42	198	47	48	43	65	203
Ug	51	30	24	21	126	26	26	29	34	115
Th	73	46	33	27	179	35	41	28	58	162
FJ	64	33	22	25	144	33	35	35	31	134
Sl	94	27	25	19	165	35	36	35	52	158
Vl	78	38	36	31	183	40	39	38	51	168
Fm	57	39	26	27	149	31	35	34	43	143
Bm	63	36	32	34	165	38	38	35	43	154
Hp	63	41	32	24	160	29	32	34	34	129
Rs	69	43	40	32	184	38	38	40	77	193
Mv	94	33	32	26	185	36	36	40	47	159
Jv	76	38	30	21	165	38	39	38	35	150
Mw	75	32	32	39	178	32	35	35	76	178
MEAN	72.64	38.43	31.71	27.71	170.50	35.93	37.50	36.50	50.79	160.71
±	14.61	8.03	6.16	7.08	21.55	5.76	5.57	5.05	15.49	26.82

TFAS: Training to Failure at All Sets; TFLS: Training to Failure only at the Last Set. SD: standard deviation.

Appendix 5. Volume load across 4 sets using TFAS and TFLS in the preacher curl exercise.

Volunteer	Volume load (Kg)									
	TFAS					TFLS				
	1 SET	2 SET	3 SET	4 SET	Summed	1 SET	2 SET	3 SET	4 SET	Sum
Qa	234.7	88.01	88.01	39.12	449.84	117.35	117.35	117.35	146.69	498.74
De	399.01	305.12	187.77	211.24	1103.14	281.65	281.65	281.65	328.59	1173.54
Ug	440.33	256.86	183.47	146.78	1027.44	256.86	256.86	256.86	256.86	1027.44
Th	472.08	236.04	177.03	147.53	1032.68	265.55	265.55	177.03	295.05	1003.18
FJ	378.84	202.05	126.28	151.54	858.71	227.3	227.3	227.3	176.79	858.69
Sl	398.4	108.65	90.55	72.44	670.04	162.98	162.98	162.98	217.31	706.25
Vl	350.66	155.85	136.37	136.37	779.25	194.81	194.81	194.81	194.81	779.24
Fm	366.28	225.4	140.88	140.88	873.44	225.4	225.4	225.4	225.4	901.60
Bm	390.81	182.38	182.38	156.32	911.89	234.49	234.49	234.49	260.54	964.01
Hp	490.77	294.46	196.31	130.87	1112.41	294.46	294.46	294.46	261.74	1145.12
Rs	250.24	140.76	125.12	109.48	625.6	156.4	156.4	156.4	234.6	703.80
Mv	366.37	116.57	116.57	83.27	682.78	166.53	166.53	166.53	183.18	682.77
Jv	660.24	330.12	256.76	146.72	1393.84	366.8	366.8	366.8	293.44	1393.84
Mw	398.61	174.39	174.39	174.39	921.78	224.22	224.22	224.22	348.78	1021.44
MEAN	399.81	201.19	155.85	131.93	888.77	226.77	226.77	220.45	244.56	918.55
±	102.95	76.63	46.35	43.75	241.46	65.24	65.24	65.48	58.96	235.38

TFAS: Training to Failure at All Sets; TFLS: Training to Failure only at the Last Set. SD: standard deviation.

Appendix 6. Maximum repetition test result in the preacher curl exercise.

One Repetition Maximum Test (kg)		
Volunteer	**1RM/familiarization**	**1RM test**
Qa	11.69	13.97
De	31.32	33.53
Ug	50.71	52.42
Th	40.59	42.15
FJ	34.67	36.08
Sl	25.87	25.87
Vl	24.53	27.83
Fm	35.88	40.25
Bm	35.76	37.22
Hp	46.57	46.74
Rs	21.25	22.35
Mv	23.39	23.49
Jv	51.26	52.4
Mw	34.45	35.59
MEAN	33.42	34.99
±	11.49	11.44

SD: Standard deviation.

Appendix 7. Participants' profile.

Volunteer	Age (yrs)	Heigth (cm)	Mass (kg)	Time of experience (months)	Body fat (%)
Qa	18	170	62.9	24	15.49
De	22	188	89.6	36	16.42
Ug	25	190	95.6	96	17.88
Th	22	183	89	36	9.56
FJ	25	168	77.3	6	12.84
Sl	18	185	71.4	6	8.05
Vl	21	172	66.8	7	10.67
Fm	25	176	85.6	30	16.97
Bm	18	179	82	36	8.71
Hp	21	179	84.4	8	12.16
Rs	22	173	72.8	15	14.38
Mv	18	169	68.5	6	14.33
Jv	22	194	88	72	6.61
Mw	24	173	84.2	48	20.33
MEAN	21.50	178.50	79.86	30.43	13.17
±	2.68	8.36	9.94	27.11	4.08

SD: Standard deviation.