International Journal of EXERCISE SCIENCE

Review Article

Manipulating Resistance Training Variables to Induce Muscle Strength and Hypertrophy: A Brief Narrative Review

JÚLIO BENVENUTTI BUENO DE CAMARGO†1, FELIPE ALVES BRIGATTO‡1, RAFAEL SAKAI ZARONI†1, THIAGO BARBOSA TRINDADE‡2, MOISÉS DIEGO GERMANO‡1, ANTONIO CARLOS TAVARES JUNIOR‡3, THIAGO PIRES DE OLIVEIRA‡4,5,6, PAULO HENRIQUE MARCHETTI‡7, JONATO PRESTES‡2, and CHARLES RICARDO LOPES‡1,8

1Methodist University of Piracicaba, Piracicaba, SP, BRAZIL; 2Catholic University of Brasilia, DF, BRAZIL; 3Sao Paulo State University, School of Science, Bauru, SP, BRAZIL; 4Julio de Mesquita Filho" State University, Rio Claro, SP, BRAZIL; 5Anhanguera University Center, Leme, SP, BRAZIL; 6Claretiano University Center, Rio Claro, SP, BRAZIL; 7Health and Human Performance Department, Montana State University Billings, Billings, MT, USA; 8Faculty Adventist of Hortolândia, Hortolândia, SP, BRAZIL

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 15(4): 910-933, 2022. The regular practice of resistance training (RT) has been shown to induce relevant increases in both muscle strength and size. In order to maximize these adaptations, the proper manipulation of RT variables is warranted. In this sense, the aim of the present study was to review the available literature that has examined the application of the acute training variables and their influence on strength and morphological adaptations of healthy young adults. The information presented in this study may represent a relevant approach to proper training design. Therefore, strength and conditioning coaches may acquire a fundamental understanding of RT-variables and the relevance of their practical application within exercise prescription.

KEYWORDS: Exercise, muscle force, size, thickness

INTRODUCTION

Resistance training (RT) is the main exercise mode to induce muscle strength and mass increases. Such adaptations are able to positively impact one´s capacity to perform daily activities as well as improve overall health and well-being-related parameters, such as physical independence and reduced risk of all cause-mortality (5,80). In addition, RT has also been shown to increment sports performance in athletes of different levels (16).

Since both acute and chronic responses to RT have been shown to be reduced over time (78), the manipulation of RT variables such as volume, intensity, rest intervals, repetition duration, and the type of exercise is warranted to continuously induce both strength and morphological adaptations (52). Given the high inter-individual variability observed in the RT-induced responses (29,48), it seems limited to make very specific recommendations regarding which and how training variables should be emphasized if one´s goal is to maximally stimulate muscle strength and/or size increases. However, the most recent available studies might help to better understand how manipulating the aforementioned variables would enhance these physiological responses. Therefore, the aims of the present study were: (i) to briefly update how the manipulation of RT variables may chronically affect training induced-adaptations; (ii) to provide insight into practical recommendations regarding how to properly implement this information when designing training programs. This study was conducted in accordance with the ethical standards of the International Journal of Exercise (72).

TRAINING VOLUME

The training volume is a relevant variable in programs aiming to increment muscle strength and mass. Generally, volume can be expressed as the product of the number of repetitions performed x sets or the product between the number of repetitions x sets x load lifted (volume load [VL]) (91). Alternatively, the weekly number of sets performed by each muscle group has been shown to be an easier and reliable method to quantify RT-volume in experienced individuals aiming to increase muscle mass (10). In this sense, increases in RT volume may be implemented by increasing: (1) the number of repetitions of a given set/exercise; (2) the number of sets performed in one or more exercises; (3) training frequency; (4) the amount of load lifted, as long as the other variables remain constant.

Under equated VL-conditions, similar hypertrophic adaptations have been described, independently of the manipulation of other variables, as training intensity, rest intervals, order and frequency (14,59,97). Indeed, the use of specialized techniques, as drop-sets and pyramid systems do not provide additional muscle size increases when matched for VL with traditional ones (4,77)

Although an inverted U-shape between RT volume and physiological responses has been proposed, some evidence suggest that morphological muscle adaptations seem to be dose-dependent, with higher volumes inducing larger effects (15,31). However, the exact doses that could maximally stimulate muscle growth still need to be investigated by longitudinal studies. Meta-analytic data from Schoenfeld et al.(94) described 5.4%, 6.6% and 9.8% increases in muscle size following protocols with <5, 5-9 and 10 sets for muscle group/week, respectively. Then, while these data provide relevant information regarding the minimal sets that should be implemented in order to stimulate significant gains in muscle size, the optimal upper limit of sets per muscle group remains to be elucidated. For example, larger increases in vastus lateralis muscle thickness were observed following the adoption of 45 sets/week compared to lower volumes (9 and 27 sets) (92). However, a plateau was observed for the elbow extensor muscles, in which no differences were observed between 30 and 18 sets/week, raising the question of whether the relationship between RT volume and muscle hypertrophy is dependent on the muscle group trained/assessed.

Since the acute post-training elevation in muscle protein synthesis is reduced in trained compared to the untrained lifters (78), it can be suggested that a higher training dose may be required for the first in order to continuously progress strength and morphological adaptations over time. However, the exact influence of the training level in the physiological responses to increased training volumes is still somewhat controversial. In a recent study, Brigatto et al. (15) reported larger increments in muscle thickness when experienced lifters were exposed to a higher volume protocol (32 sets/week/muscle group) when compared to moderate and lower ones (24 and 16, respectively). Conversely, Aube et al. (6) reported no differences in performing 12, 18 or 24 weekly sets in muscle thickness outcomes of highly resistance-trained individuals (back squat relative strength > 2.0). Even though one can suggest that the higher initial strength values of the subjects in Aube et al. (6) compared to those in Brigatto et al. (15) (Back squat 1RM: 165 kg vs 114kg, respectively) may help to explain these different results, comparisons between both studies must be done with some cautions, since muscle thickness assessments were done in different muscles of the quadriceps (vastus lateralis and rectus femoris in Brigatto et al. (15) and Abe et al. (6), respectively). In this sense, these controversial results limit more direct recommendations regarding the proper manipulation of this training variable. Indeed, the high inter-individual variability observed in RT studies might be mainly attributed to intrinsic factors (83). Therefore, the high responsiveness to RT that some subjects present might not be modulated by systematically alternating training variables, such as volume (24).

Also regarding individual responses to different training volumes, the study of Damas et al. (25) observed that participants that accumulated more VL during the experimental period did not necessarily present the largest gains in muscle size. Indeed, some practitioners may beneficiate from low RT-doses when muscle hypertrophy is aimed. Then, the maximum and/or optimal training volume seems to be highly individual.

For muscle strength outcomes, some emerging findings suggest that high-volume does not seem to be strictly necessary to promote greater gains in maximum strength. Aube et al. (6), for example, observed that trained subjects undertaking 18 sets/week experienced larger increases on back squat 1RM compared to those performing 24 sets/week (16.2% vs 5.4%, respectively). Similarly, Schoenfeld et al. (93) observed that performing 6 sets/week was as effective as 30 sets/week for increasing bench press 1RM (9.3% vs 6.8%, respectively). In addition, no difference in squat bench 1RM increases was noted when adopting 9 vs 45 sets/week (18.9% vs 19.6%, respectively). Interestingly, a recent study from our research group reported that the amount of volume required for promoting increases in muscle strength may be lower than the one for inducing muscle hypertrophy (23). Therefore, based on the recent available literature, it can be suggested that muscle strength can be enhanced by prioritizing factors such as improved skill, high intensities, and management of neuromuscular fatigue (49), while concomitantly performing low to moderate training volumes (6 to 18 sets/week).

From a practical standpoint, strength and conditioning coaches should aim to periodically increase VL and assess morphological/strength responses in order to find an optimal training dose for each lifter. This can be achieved by implementing small increases (nearby 20%) (90) in the number of sets performed for each muscle group/week.

TRAINING INTENSITY

Generally, RT intensity can be prescribed as a % of one maximum repetition (% 1RM) or through maximum repetition zones (RM´s). The traditional guidelines dictate that, in order to promote increases in muscle strength and size, intensities above 65% 1RM should be emphasized (1). The repetition continuum states that muscle strength and hypertrophy are enhanced with the adoption of loads corresponding to 1-5RM and 6-12RM, respectively (19). These statements are usually justified by the fact that high loads are required in order to maximize high threshold motor unit recruitment. Despite all muscle fibers present a hypertrophic potential, type 2 muscle fibers seem to present a larger growth potential compared to the type 1 ones (46,65).

The Henneman´s size principle dictates that full motor unit recruitment, especially from type 2, is only possible within high load/effort tasks (47). Although this principle seems to justify the use of higher loads during RT, some studies have reported similar motor unit recruitment (107) and muscle protein synthesis (17,18) when low loads (nearby 30%) are lifted to the point of concentric failure. Reaching high levels of fiber recruitment seem to be of great relevance in an attempt to promote muscle growth, since it may increase the acute myofibrillar synthetic response, which, in turn, would influence protein balance (2). In this sense, several studies aimed to investigate the chronic effects of different intensities in muscular adaptations. The study of Campos et al. (19) was a pioneer in assessing RT-intensity effects in a controlled manner. Briefly, 32 men with no previous training experience were allocated in one of the following protocols: low repetition group (n=9) that performed 4 sets of 3-5RM; moderate repetition group (n=11) that performed 3 sets of 9-11 RM and a high repetition group (n=7) that performed 2 sets of 20-28 RM. At the end of the experimental period, only the groups performing low and moderate repetitions presented significant increments in cross-sectional area (CSA) of type I, IIa and IIx muscle fibers, highlighting that lower intensities might be sub-optimal in promoting increases in muscle size. Conversely, Schoenfeld et al. (95) observed no differences in the magnitude of muscle thickness increase when comparing low (25-35RM) and moderate (8-12 RM) loads. However, larger increments in maximal strength were observed for the latter condition. These results were also described by Ogasawara et al. (75), in which 9 untrained men presented similar increases in CSA of the pectoralis major and triceps brachialis muscle groups regardless of the intensity adopted (75% 1RM vs 30% 1RM).

More recently, Lasevicius et al. (58), in a within-subject design, aimed to investigate eventual differences in muscular adaptations in a wide range of RT intensities. Similar increments in elbow flexors and vastus lateralis muscles CSA were observed in loads ranging from 40 to 80% 1RM. In addition, lower muscle growth was observed with a 20% 1RM protocol. For muscle strength, larger increments were noted within intensities of 60 and 80% 1RM. It is important to note that, different from some previous investigations, Lasevicius et al. (58) equalized VL between conditions, which strengthens the internal validity of the study. Also under equated VL-conditions, similar results were observed by Kubo et al. (53), in which no differences between the intensities adopted (4 RM, 8 RM and 12 RM) were noted on pectoralis major muscle volume increases (11.3%, 10.1% and 11.3%, respectively). Additionally, the larger increments in muscle strength in the bench press exercise were elicited by the 4RM (28.4%) and 8RM (29.5%) protocols compared to the 12RM (18.7%) one.

Although the majority of the aforementioned studies included only untrained participants, Morton et al. (69) observed similar increases in both type I and type II muscle fiber area when previously recreationally trained men (4.4 years of RT-experience; Bench press relative 1RM: 1.12) performed either high (75-90% 1RM) or low intensity (30-50% 1RM) training protocols. Interestingly, while for the bench press exercise a significantly higher increase in the 1RM test was observed for the high-intensity compared to the low-intensity group (mean difference = 4.9 kg), no between-group differences were noted for the others exercises assessed (knee extension, leg press and shoulder press). Therefore, further studies are warranted in order to better understand if the effects of different training intensities on maximal strength-outcomes are somewhat dependent on the exercise assessed.

The findings of these studies were confirmed by the most recent meta-analysis regarding this topic from Lopez et al. (61), which reported that muscle hypertrophy-outcomes does not seem to differ from the adoption of high (> 80% 1RM) vs low-load (< 60% 1RM) training (Standardized Mean Difference [SMD] = 0.12) or high vs moderate-load (60-79% 1RM) training (SMD = -0.09). In addition, muscle strength increases were higher for high load-training vs both low (SMD = 0.60) and moderate load (SMD = 0.26) training.

It is important to note that the aforementioned studies were performed mostly in untrained or recreationally trained subjects. In this sense, extrapolations for high-level competitive lifters must be done with some caution. Future investigations with individuals presenting large training levels, as relative strength in the squat exercise above 2.0, or large training experience, must be carried out to better understand if muscle hypertrophy can be modulated when adopting distinct training intensities in this population.

Training to muscular failure

As aforementioned, training with light loads and a high level of effort seem to promote the same level of chronic responses compared to those observed in high-intensity protocols. In this sense, taking the sets to the point of muscular failure is usually advocated as mandatory by some RT practitioners and coaches. However, literature regarding this topic is still scarce. Acutely, several studies have reported that training to failure induces more pronounced decrements in neuromuscular performance, higher levels of muscle damage and biochemical fatigue (32,39,40,68), which must be considered when designing RT programs, especially regarding the weekly training frequency that each muscle group is stimulated. In addition, muscle activation, assessed by superficial electromyography, does not seem to differentiate between failure vs non-failure conditions (87,88), with full motor unit activation being reached within 3-5 repetitions next to failure (105).

From a chronic standpoint, the literature has reported that taking sets to the point of concentric failure might not be necessary when aiming to increase muscle strength and size. For example, Sampson and Groeller (87) reported that performing an additional volume induced by performing sets to concentric failure did not enhance maximal strength (1RM) (30.6% vs 28.6% for failure vs non-failure protocols, respectively) and CSA (11.6% vs 10.9% for failure and non-failure protocols, respectively) increases in the elbow flexor muscles of untrained men after 12 weeks. Similarly, Martorelli et al. (64) reported that, within matched VL-condition, avoiding sets to failure promoted similar gains in muscle thickness of the elbow flexor muscles of untrained young women. Interestingly, maximal strength increments were similar even when training sets were performed with a reduced volume (far from failure), highlighting that the concept that increasing training volume does not offer additional gains in muscle strength-related outcomes. Indeed, meta-analytic data from Davis et al. (27) also pointed that non-failure training resulted in a 0.6-1.3% (effect size = 0.32) greater strength increase than failure training, which may eventually represent a clinical advantage for high-level competitive athletes.

The most recent investigations seem to corroborate the aforementioned results. Lasevicius et al. (57) pointed that, within high intensity-protocols (80% 1RM), the adoption of muscular failure does not seem to enhance strength (33.8% and 33.4% for failure vs non-failure conditions, respectively) and hypertrophic (8.1% and 7.7% for failure vs non-failure conditions, respectively) adaptations. However, when adopting lower loads (30% 1RM), a higher magnitude increase in quadriceps CSA was observed in the failure vs non-failure condition (7.8% vs 2.8%, respectively). Then, the intensity adopted during RT programs should be taken into account when manipulating the use of training to concentric failure.

In a within-subject design and under matched-VL conditions, Lacerda et al. (55) also observed similar strength and morphological adaptations between failure vs non-failure protocols. Indeed, the individual responses in the vastus laterallis muscle showed that the non-failure condition promoted an even greater response than the failure one. In addition, neuromuscular activation assessed during the 2nd and 35th sessions did not differ between conditions.

It is important to note that the participants in the study of Lasevicius et al. (57) and Lacerda et al. (2019) were untrained, which limits extrapolation to other populations. Indeed, the effects of RT performed to muscular failure in trained subjects have been little explored. In this sense, Santaniello et al. (88), in a within-subject design, aimed to investigate whether experienced lifters (5.1 years of average RT experience) would beneficiate or not from performing sets to failure. Although higher VL was accumulated during the experimental period in the failure that the non-failure condition (333 vs 295 tons, respectively), similar increases in 1RM leg press (22.2 vs 26.6% for failure and non-failure, respectively) and leg extension (33.3 vs 33.7% for failure and non-failure, respectively) were noted. Additionally, vastus laterallis muscle CSA increases did not differ between both conditions (13.5% vs 18.1% for failure and non-failure, respectively).

More recently, meta-analytic data from Grgic et al. (42) reported that, under non-equated volume conditions, training not to failure induced larger gains in muscle strength compared to failure (Effect size = 0.32). Within matched volume-conditions, however, no additional effects were observed when performing training to failure in both muscle strength and hypertrophy. Interestingly, when analyzing for training level, trained lifters seem to beneficiate from performing repetitions to concentric failure in muscle hypertrophy (Effect size = 0.15, 95% Confidence Interval: 0.03 to 0.26). However, this finding must be interpreted with some caution. Firstly, only 2 studies with trained subjects were included in the meta-analysis. Secondly, the magnitude of the effect and the lower limit of the 95% confidence interval seem to be negligible from a clinical perspective. In this sense, further investigations are required to better understand the responses to training to failure, especially in experienced practitioners.

Summing up, from a practical standpoint, RT intensity should be manipulated according to personal preferences and goals. Individuals aiming to increase their strength levels should emphasize the adoption of higher loads, especially above 65%1RM. For those aiming to increase muscle size, the use of a wide range of intensity is feasible (above 40% 1RM). In this sense, strength and conditioning coaches may implement different training intensities along the periodization process in order to avoid physiological and psychological plateaus. Additionally, the use of training to failure is not a critical factor when designing training programs, except when the practitioner personal´s preference is to avoid high loads.

REST INTERVALS

The rest intervals adopted between sets seem to strongly influence RT volume, duration and the predominant metabolic pathway during exercise (112). However, evidence-based recommendations regarding this variable must be done with some caution due to the scarcity of longitudinal studies that directly assessed changes in muscle growth. Briefly, rest intervals might be classified as complete (3-8 minutes) or incomplete (<3 minutes). The main difference between both is the magnitude of phosphocreatine (PC) resynthesis, with higher values being observed during larger intervals. Then, it can be suggested that shorter rest intervals would impair one´s ability to accumulate higher amounts of training volume during a session/period of RT. In this sense, several studies have reported that short intervals induce significant reductions in training volume (total number of repetitions) compared to larger ones. Ratamess et al. (81), for example, reported that, during 5 sets of the bench press exercise, significant reductions in the number of repetitions performed were already observed in the 2nd set of each of these protocols (30 and 60 seconds). For the longer rest conditions (3 and 5 minutes), however, significant reductions in total volume were only observed after the 4th and 5th sets, respectively, confirming findings from other investigations (66,79,113).

Traditionally, long rest intervals (> 3 minutes), in order to maintain a high intensity, are prescribed for enhancing muscle strength outcomes (84,86). For muscle hypertrophy, however, intervals ranging from 30 seconds to 1 minute are usually preferred due to higher metabolic and hormonal responses noted during this condition. Bottaro et al. (11), for example, observed that rest intervals of 30 seconds, despite a higher reduction in VL, induced a more pronounced post-exercise elevation in growth hormone levels compared to 60 and 120 seconds, corroborating previous results reported by Kraemer et al.(50,51). However, there seems to exist compelling evidence that these acute increases in hormones concentration that occur after an RT session do not further stimulate muscle protein synthesis (111) or skeletal muscle hypertrophy (110). In this sense, some studies aimed to longitudinally investigate the effects of different rest intervals on muscle morphological adaptations. Schoenfeld et al.(96) assigned resistance-trained men to two different experimental groups: 1 (SHORT) and 3 minutes (LONG) of rest intervals between sets. Both groups performed 3 sets of 7 exercises in full-body sessions. Although both groups presented significant increases in maximal strength values from the pre to post-intervention moments, larger increments were observed for the LONG group compared to the SHORT in both squat (15.2% vs 7.6%, respectively) and bench press (12.7% vs 4.1%, respectively) exercises. Regarding hypertrophy, only the LONG group presented significant increases in elbow flexor (5.4%) and triceps (7.0%) muscle thickness. For the anterior quadriceps muscle, both groups presented significant increases. However, larger increases were observed for the LONG compared to the SHORT group (13.3% vs 6.9%, respectively). These results might be, in part, justified by the higher VL accumulated by the LONG group during the intervention period, since RT programs with higher VL may enhance muscle adaptations (15,93). Then, based on these findings, within a matched number of sets-condition, RT-adaptations seem to be enhanced when performing sessions with longer rest intervals between the sets.

Divergent results from Schoenfeld et al. (96) were reported in the study of Ahtiainen et al. (3), in which similar morphological adaptations were observed between long and short rest intervals. Some methodological differences can justify these distinct results. Firstly, a 2-minute interval was adopted for the short interval protocol during Ahtiainen et al. (3). Secondly, both groups were submitted to a matched VL condition. Then, subjects in the short interval group performed a larger number of sets in order to equate the VL performed by those allocated in the longer interval group, which can mainly explain the similar results between both groups. Therefore, it can be suggested that minimal rest intervals of 2 minutes with an additional number of sets may be adopted when aiming to increase muscle size.

More recently, Longo et al. (60) also provided relevant insight into the effects of the rest interval duration between sets on strength and morphological outcomes. In a within-subject design, each participant´s lower limb was allocated in a long (LI [3 minutes]), short (SI [1 minute]) or short interval performing the same VL that LI (VLI-SI) condition. During all conditions, participants performed a unilateral 10-week program (leg press exercise) with an 80% 1RM load. Interestingly, all protocols, regardless of the VL accumulated and the rest interval adopted during the experimental period were able to significantly increase muscle strength. For muscle hypertrophy, similar increases were noted in quadriceps CSA in LI and VLI-SI conditions (13.1%

and 12.9%, respectively), showing that both long and short rest intervals may be adopted for enhancing muscle mass increments as long as the VL between conditions is equated.

Another possible use of this variable during RT programs is the self-selected rest interval (SSRI), which basically consists of allowing each participant to perform another set whenever he/she feels entirely recovered from the previous one, without effectively monitoring time (85). To the authors of the present review's knowledge, the study of Simao et al. (102) was the only one to assess the chronic effects of this approach. Briefly, resistance-trained participants were allocated in an SSRI or a fixed rest interval (FRI [75 seconds]) group, performing exercises for upper limbs for 8 weeks, with 3 sets of 75% 1RM. During the bench press and shoulder press exercises, a large number of repetitions were performed for the SSRI group. In addition, both groups presented similar increases in muscle strength in all the exercises assessed. Therefore, although FRI was 37% more time-efficient, SSRI may be a viable option when designing RT programs that aim to increase muscle strength. Additional studies assessing muscle hypertrophy-outcomes induced by SSRI must be carried out to better understand its morphological effects.

From a practical standpoint, RT practitioners can achieve significant increments in muscle strength and size with both short and long rest intervals. Individual goals and time availability should be considered when manipulating this training variable. In order to enhance maximal strength, longer intervals (minimum of 3 minutes) must be prioritized. For muscle hypertrophy, the use of longer intervals may afford lifters to accumulate more VL, which might represent a chronic advantage in inducing increases in muscle size. However, under reduced time availability conditions, short rest intervals (1-2 minutes) may also be adopted, but, implementing additional sets might help practitioners to accumulate similar VL compared to those observed with longer rest intervals.

REPETITION DURATION

The repetition duration refers to how long (in seconds) each repetition of a given set takes to be completed. Usually, this variable is expressed in three sequential digits: the first one refers to the duration of the concentric phase, the second to an eventual isometric phase during the transition of concentric to eccentric phase, and the third to the eccentric phase of the lift.

The intensity adopted may be a relevant factor regarding the repetition duration. Loads above 85% 1RM may induce higher durations in the concentric phase, even under maximal intended explosive effort of the lifter. In this sense, the control of each repetition duration may be more feasible with loads lower than 85% 1RM (95). Additionally, with increasing fatigue levels towards the end of the sets, the repetitions velocity tends to decrease due to a reduced force output from the active muscle fibers (67). However, the responses to different repetition durations in both concentric and eccentric phases are still not completely elucidated.

Acute studies regarding responses to protocols with distinct durations in concentric and eccentric phases have described conflicting results. Goto et al. (41) reported greater blood lactate concentration following a 5:1 duration for concentric and eccentric actions, respectively. Lacerda et al. (56) observed that a short repetition duration (3 seconds/repetition) induced higher EMG and blood lactate levels than a longer repetition duration (6 seconds/repetition). It is important to describe that, although not completely elucidated, some evidence report that increased blood lactate levels may stimulate skeletal muscle hypertrophy through a reduced expression of myostatin and increased proliferation of satellite cells (37,76), which suggests that increasing concentric phase duration could offer some advantage in promoting muscle size increases. However, this hypothesis warrants further investigation to be confirmed.

For both the studies of Goto et al. (41) and Lacerda et al. (56), the number of repetitions performed was not matched between the experimental protocols, which limits inferences about the real effects of the repetition duration on these acute physiological responses. Within equated-volume conditions (number of repetitions), longer concentric muscle actions seem to induce higher EMG amplitude values as also greater neuromuscular fatigue compared to the shorter ones (54). However, recent evidence suggests that the duration of each repetition may not be a critical factor for enhancing acute responses to an RT session. Morton et al. (70), for example, reported similar phosphorylation of anabolic signaling proteins when repetitions are performed to task failure, independently of the repetition duration. Indeed, strictly controlling the duration of each repetition may reduce the amount of volume performed during a training session and also elicit lower EMG responses compared to self-selected durations (73).

Chronically, there is a paucity of data regarding the effects of manipulating the duration of the repetition in strength and morphological outcomes. The data to the present moment suggests that performing the repetitions with a fixed duration does not enhance muscular adaptations. Claflin et al. (21), for example, did not observe differences in single fiber CSA between faster and slower velocities. Indeed, intentionally performing repetitions with very long duration (10 seconds for concentric and 4 seconds for eccentric phases) impairs the increases in fiber CSA compared to the traditional ones (1-2 seconds for each phase) (98). More recently, in a within-subject design and under equated-volume conditions, similar increases in maximal strength (1RM leg extension) (9.7 kg and 10.6 kg) and CSA (0.94 cm^2 and 1.3 cm^2) were observed for self-selected and fixed (2 seconds for each phase) repetition duration, respectively, in untrained men (20).

It should be noted that the training level of the participants included in those studies limits inferences about the effects of manipulating repetition duration on muscle strength and hypertrophy. Therefore, it remains to be investigated if highly trained subjects would eventually present different results when comparing short to long repetition duration protocols.

Together, the current evidence suggests that repetition duration does not seem to be a critical variable to be controlled when implementing RT programs. Strength and conditioning coaches may adopt a wide range of repetition duration and take into account the practitioner´s personal preference. Additionally, avoiding extreme high repetition duration (super-slow movements) may allow lifters to reach high levels of muscle activation and to accumulate more training volume during a given period, which in turn may induce relevant muscle strength and size increments.

EXERCISE SELECTION AND ORDER

Resistance exercises, according to the number of joints evocated during a given movement, are commonly classified as multi-joint (MJ) or single-joint (SJ) exercises. A large number of muscle groups are recruited during MJ exercises, while specific muscle groups are requested during the SJ ones. The general guidelines state that both MJ and SJ exercises should be included in RT programs. However, some studies have reported that the addition of SJ exercises to an exclusively MJ program does not enhance RT-induced adaptations. Gentil et al. (36), for example, observed no differences in muscle strength and thickness of untrained men when adding elbow flexion and extension movements to the bench press and lat pulldown exercises. Similar results were reported by Barbalho et al.(9) and De França et al.(33). It is important to note, though, that these studies have methodological limitations that must be considered before excluding SJ exercises from training programs. First, not all trained muscles were included in the morphological assessments, as is the case of the elbow extensors in Gentil et al. (36). Second, the instrumentation (arm circumference and skinfold thickness) adopted in order to assess morphological outcomes in Barbalho et al. (9) and De França et al. (33) do not separately discriminate the actual increases in muscle size. Additionally, there seems to be compelling evidence that distinct muscle groups present different magnitude of size increases when exposes to MJ or SJ exercises. For example, training programs containing exclusively MJ exercises for the lower limbs (back squat, leg press) seem to result in higher magnitude increases in vastus laterallis muscle size than rectus femoris in both untrained (45) and trained (62) subjects. Conversely, performing RT programs based solely on SJ exercises (leg extension) induces larger increase in rectus femoris size compared to vastus lateralis (28).

It is also interesting to note that MJ and SJ exercises seem to be able to promote distinct increases in different regions of given muscle groups. For example, performing exclusively the knee extension exercise induced a larger relative increase in the CSA of the distal than the proximal portion of the rectus femoris muscle (109), as so performing an SJ exercise (lying barbell triceps) for 12 weeks resulted in a higher CSA increase in the medial and proximal portions of the triceps brachialis compared to the distal one (109). Contrastingly, performing an MJ exercise (closed grip dumbbell press) induced a higher CSA increase in the medial compared to the proximal and distal portions of the triceps muscle (108).

More recently, some investigations have pointed out that performing exclusive MJ exercises programs may be sub-optimal for enhancing arm muscle hypertrophy. In a within-subject study, Manarinno et al. (63) observed that performing SJ (biceps curl exercise) induced a significantly higher increase in elbow flexor muscle thickness compared to an MJ exercise (dumbbell row) (11.0% vs 5.1%, respectively). Similarly, the CSA from the three heads of the triceps muscle only increased when both SJ (lying barbell triceps) and MJ (barbell bench press) exercises were performed by untrained men after 10 weeks (12).

Together, these findings suggest that individuals aiming to maximally and/or symmetrically increase muscle size may beneficiate from a wide range of exercises, especially when combining MJ and SJ movements. Notwithstanding, extrapolations must be done with some caution since most of these studies included only untrained participants (12,63,109). Therefore, additional studies with advanced lifters must be addressed to better understand the effects of combining MJ and SJ exercises on morphological outcomes.

Regarding the order of the exercises, the American College of Sports Medicine recommends that MJ exercises that allow a higher load-mobilization should be performed earlier during RT sessions than the SJ ones (1). However, this guideline has been questioned by some acute investigations. Sforzo and Touey (100), for example, reported that, regardless of the type of the exercise (MJ or SJ), a significantly reduced number of repetitions were performed in the exercises allocated at the end of each experimental session. Similar results were noted in other investigations for both untrained (8) and recreationally trained (99,101) lifters. In addition, different exercises orders do not seem to induce distinct responses in the rate of perceived exertion (PSE) and blood lactate concentrations (101).

It is important to highlight that there is still a paucity of longitudinal studies that investigated the effects of different orders of exercise in muscular adaptations, and the results are somewhat conflicting. Overall, muscle strength increments in MJ and SJ exercises seem to be strongly influenced by MJ-SJ and SJ-MJ orders, respectively. Manipulating the order may negatively influence training intensity due to increased fatigue levels, which can explain the lower strength increments in the exercises performed later during the sessions (74). The exact influence of exercise order on muscle hypertrophy outcomes, however, is far from being completely elucidated. Avelar et al. (7) noted similar increases in muscle thickness of the biceps brachialis following both MJ-SJ (+ 14.2%) and SJ-MJ (+13.8%) protocols. Interestingly, only the MJ-SJ group showed an increase in mid-thigh thickness from pre- to post-training (MJ-SJ = +7.2%, SJ-MJ = +3.9%). Similar morphological adaptations between different exercise orders were also reported by Simao et al. (103) and Spineti et al.(104), in which biceps and triceps muscle thickness/volume (respectively) presented similar responses from pre to post-intervention moments for both orders (MJ-SJ or SJ-MJ). However, it is important to note that, although no significant statistical difference was noted, the effect sizes analysis showed that triceps muscle volume increased in a higher magnitude in SJ-MJ compared to the MJ-SJ protocol (1.08 vs 0.40, respectively) in Spineti et al. (104). More recently, although not statistically significant, performing an SJ exercise (lying barbell triceps) before an MJ one (barbell bench press) impaired the increase in the pectoralis muscle CSA when compared to the opposite order (+5.6% vs %10.6%, respectively), probably due to a lower VL performed in the bench press during SJ-MJ protocol. The same interference of different orders was not observed for the triceps brachialis muscle, with similar increases in CSA between MJ-SJ (+11.5%) and SJ-MJ (+10.4%)(12).

It is important to note that the majority of the studies assessing the effects of exercise order on muscular adaptations recruited untrained (7–9,36) or only recreationally trained (33,99,101) subjects. Then, extrapolations to high-level lifters should not be done, and future investigations must help to clarify muscle strength and hypertrophic adaptations in this population.

Some practical recommendations may be done regarding this topic. Firstly, the type of exercise performed (MJ vs SJ) should not guide coaches' decisions when manipulating the order of the exercises. Secondly, if one´s goal is to maximize strength levels, priority exercises should be performed earlier during a training session. In addition, although not completely clear, individuals aiming to increase the size of a specific muscle group may beneficiate when performing exercises where this muscle acts as an agonist, independently of the type of the movement.

TRAINING FREQUENCY

Generally, RT-frequency refers to how many times a given muscle is stimulated on a weekly basis (52). Increasing training frequency is usually adopted to accumulate a large VL for a specific muscle group, which, in turn, would induce higher magnitudes of strength and hypertrophy adaptations (26). Although a meaningful number of studies has investigated the effects of manipulating RT-frequency, specific recommendations regarding this variable must be done with some caution, especially because of methodological differences between them. While some studies compared the effects of distinct frequencies under matched-training volume (number of sets) between groups (13,34,82,115), others aimed to verify if the increments in training volume induced by higher training frequencies would enhance RT-adaptations (25,30,71). In addition, a wide range of participants' characteristics is usually observed, such as age, gender and previous training experience.

The traditional recommendations of the ACSM state that, in order to increase muscle strength, trained individuals should stimulate each muscle group twice weekly (1). However, the most recent studies have reported that increased RT-frequencies do not seem to promote additional increments in this variable. Colquhoun et al. (22), for example, submitted 28 trained men to 3x/week vs 6x/week training programs for each muscle group. Similar increases in 1RM tests were observed in the exercises assessed (Bench press, Squat and Deadlift) in the pre to post-intervention moments, with no between-group differences. When comparing training frequencies of 1 vs 5x sessions/week, even with a larger VL accumulated in the higher frequency conditions, Gomes et al. (38) and Zaroni et al. (115) could not observe any difference in strength increases between experimental groups. Then, it can be suggested that, with an equal number of sets performed/week, lower and higher RT-frequencies promote similar strength gains. However, a recent study by our research group (23) observed that increasing training frequency in 2 daily sessions (4 weekly sessions per muscle group) induced a significantly higher increase in maximal strength of the lower limbs (back squat exercise) compared to performing 1 daily session (2 weekly sessions per muscle group) in resistance-trained men (16.1% and 7.8% for 2 and 1 daily sessions, respectively). In addition, all subjects performing twice-daily sessions and 77% of the subjects performing once daily session increased their back squat 1RM from pre to post-intervention. This finding corroborates previous studies in which splitting training volume into twice-daily sessions also induced larger gains in muscle strength (43,44). However, these studies were conducted in high-level competitive weightlifters. In this sense, additional investigations conducted in recreational-level lifters must help to better understand the findings regarding muscle strength that were observed in Correa et al. (23).

The adoption of higher training frequencies as a means for increasing muscle size has been justified by a theoretical model proposed by Dankel et al. (26). Briefly, a reduced number of sets/session for each muscle group would allow sustained levels of muscle protein synthesis as long as a high training frequency (up to 6 weekly sessions for each muscle group) is performed. Such hypothesis is mainly based on the fact that trained individuals present an attenuated response in the acute elevations of myofibrillar protein synthesis. Although somewhat rational, this hypothesis does not seem to be corroborated by longitudinal studies. Several longitudinal investigations that assessed the effects of different RT-frequencies did not observe differences in morphological adaptations between the experimental conditions, independently of the frequencies adopted. When comparing 1 vs 2 weekly sessions per muscle group, for example, similar hypertrophy was observed by Brigatto et al. (13), Gentil et al. (35) and Tavares et al. (106) for both upper and lower limbs muscles. Similarly, even higher training frequencies (4x/week in Yue et al. (114) and Correa et al. (23); 5x/week in Gomes et al. (38); 6x/week in Saric et al. (89) were not able to induce larger increases in muscle size compared to the lower ones (1-2x/week). Then, it can be suggested that increasing training frequency does not provide additional increments in muscle morphological outcomes, as long as the same number of weekly sets/muscle is performed. Interestingly, Zaroni et al. (115) was the only study to the present date that favored higher RT-frequencies. After an 8-week training program, although both frequencies (1 [split routine] and 5 [full body routine] sessions/muscle/week) resulted in significant increases in muscle thickness from pre to post-intervention moments, higher-magnitude increases in elbow flexors (8.5% and 3.8% for 5 and 1x/week, respectively) and vastus lateralis (9.7% and 5.4% for 5 and 1x/week, respectively) muscles were noted for the group that stimulated each muscle group 5x/week. According to the authors of the study (115), the higher VL accumulated in the 5 compared to the 1x/week group (22.3%) can justify these findings. However, it is important to stress that, higher VL observed with increased training frequencies does not always induce larger responses regarding muscle strength and size. Indeed, it seems that such response is strongly individual, with some subjects responding better to higher and others to lower RT-frequencies (25).

Then, from a practical standpoint, RT-practitioners can present significant muscle strength and mass increases adopting both low and high training frequencies. Personal preferences and the available time to perform each training session must be considered when manipulating this variable. Moreover, strength coaches should aim to individually prescribe RT-frequency in order to improve the intra-subject responsiveness to training.

CONCLUSIONS AND PRACTICAL RECOMMENDATIONS

The present study aimed to provide insight into how the manipulation of RT-variables may enhance muscle strength and mass responses. Additionally, practical recommendations are also provided for strength and conditioning coaches to understand how to better implement these data when designing exercise programs (see Table 1). For training volume, progressively implementing higher training volumes (through increases in the number of sets or volume load) and assessing its effects on an individual basis seems to be relevant to reach optimal physiological adaptations. A wide range of RT-intensities, according to personal goals and preferences, might be adopted to enhance muscle hypertrophy. In addition, taking training sets to the point of muscle concentric failure does not seem to provide additional gains, except when light loads are mobilized. Regarding the rest intervals between sets, short rest intervals between sets (1-2 minutes) may be adopted when practitioners dispose of a short time available to perform training sessions, as long as an increased number of sets is implemented in order to guarantee a higher VL. The duration of each repetition should not be strictly controlled, since this could impair muscle activation and the volume performed. Moreover, extremely slow movements (over 10 seconds/repetition) should be avoided, since it may impair RT-adaptive responses. Independently of the type of exercise performed (MJ or SJ), priority exercises/muscles should be allocated earlier within a session, especially if increased muscle strength is the main goal. Additionally, adding SJ exercises to an MJ program may enhance hypertrophic adaptations, especially for the muscles that act as synergists during MJ movements. Lastly, regarding RT-frequency, each muscle group can be stimulated in both low (1-2) and high (>3) frequencies on a weekly basis. Personal preferences and availability to perform the training sessions should be taken into account, as also individual responses, when manipulating this variable in exercise programs.

Table 1. Training variables and practical recommendations to maximize muscle strength and hypertrophy.

Training variable	Main findings and practical recommendations
Volume	Minimum of 10 weekly sets/muscle group for muscle hypertrophy To implement small-magnitude increases on the number of sets (20%) To periodically monitor individual physiological responses for each volume performed
Intensity	Adopt a wide range of intensities for muscle hypertrophy (minimum of 40% 1RM) Prioritize higher intensities (above 60% 1RM) for muscle strength
Training to failure	No additional effects of training to failure for both muscle strength and hypertrophy Periodically use training to failure especially for trained lifters may provide some benefits
Rest intervals	Both long and short rest intervals may induce significant strenght and morphological adaptations Increase the number of sets performed may be useful when short intervals are adopted Personal preferences and time availability must be considered
Repetition duration	Both long and short repetition duration may be adopted Self-selected repetition duration should be prefered to avoid impairments on training volume Avoid excessive slow movements
Exercise selection	Both multi and single-joint exercises should be included in training programs Including single-joint exercises may offer additional muscle hypertrophy for bi-articular muscles Take into account modality specificites and indiviual goals
Order of exercises	Priority exercises/muscles must be performed earlier within the training sessions
Frequency	No additional effects of increasing training frequency under equated volume (weekly number of sets) Adopting full-body routines may offer some advantage for experient lifters Personal preferences and availability to perform the sessions over the week must be considered

REFERENCES

1. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Med Sci Sports Exerc 41(3): 687–708, 2009.

2. Adams GR, Bamman MM. Characterization and regulation of mechanical loading-induced compensatory muscle hypertrophy. Compr Physiol 2(4): 2829–70, 2012.

3. Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ, Häkkinen K. Short vs. long rest period between the sets in hypertrophic resistance training: Influence on muscle strength, size, and hormonal adaptations in trained men. J Strength Cond Res 19(3): 572–82, 2005.

4. 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 117(2): 359–69, 2017.

5. Artero EG, Lee DC, Ruiz JR, Sui X, Ortega FB, Church TS, et al. A prospective study of muscular strength and all-cause mortality in men with hypertension. J Am Coll Cardiol 57(18): 1831–7, 2011.

6. Aube D, Wadhi T, Rauch J, Anand A, Barakat C, Pearson J, et al. Progressive Resistance Training Volume: Effects on Muscle Thickness, Mass, and Strength Adaptations in Resistance-Trained Individuals.. J Strength Cond Res 36(3): 600-607, 2022.

7. Avelar A, Ribeiro AS, Nunes JP, Schoenfeld BJ, Papst RR, Trindade MC de C, et al. Effects of order of resistance training exercises on muscle hypertrophy in young adult men. Appl Physiol Nutr Metab 44(4): 420–4, 2019.

8. Balsamo S, Tibana RA, Nascimento DDC, Franz CB, Lyons S, Faigenbaum A, et al. Exercise order influences number of repetitions and lactate levels but not perceived exertion during resistance exercise in adolescents. Res Sport Med 21(4): 293–304, 2013.

9. Barbalho M, Gentil P, Raiol R, Fisher J, Steele J, Coswig V. Influence of Adding Single-Joint Exercise to a Multijoint Resistance Training Program in Untrained Young Women. J strength Cond Res 34(8): 2214–9, 2020.

10. Baz-Valle E, Fontes-Villalba M, Santos-Concejero J. Total Number of Sets as a Training Volume Quantification Method for Muscle Hypertrophy: A Systematic Review. J strength Cond Res 35(3): 870–8, 2021.

11. Bottaro M, Martins B, Gentil P, Wagner D. Effects of rest duration between sets of resistance training on acute hormonal responses in trained women. J Sci Med Sport 12(1): 73–8, 2009.

12. Brandão L, de Salles Painelli V, Lasevicius T, Silva-Batista C, Brendon H, Schoenfeld BJ, et al. Varying the Order of Combinations of Single- and Multi-Joint Exercises Differentially Affects Resistance Training Adaptations. J strength Cond Res 34(5): 1254–63, 2020.

13. Brigatto FA, Braz T V., Zanini TC da C, Germano MD, Aoki MS, Schoenfeld BJ, et al. Effect of Resistance Training Frequency on Neuromuscular Performance and Muscle Morphology After 8 Weeks in Trained Men. J strength Cond Res 33(8): 2104–16, 2019.

14. Brigatto FA, Braz T V., Zanini TCC, Germano MD, Aoki MS, Schoenfeld BJ, et al. Effect of Resistance Training Frequency on Neuromuscular Performance and Muscle Morphology After 8 Weeks in Trained Men. J Strength Cond Res 33(8): 2104–16, 2019.

15. Brigatto FA, Lima LE de M, Germano MD, Aoki MS, Braz T V., Lopes CR. High Resistance-Training Volume Enhances Muscle Thickness in Resistance-Trained Men. J Strength Cond Res 36(1):22-30, 2022.

16. Buckner SL, Jessee MB, Dankel SJ, Mattocks KT, Abe T, Loenneke JP. Resistance exercise and sports performance: The minority report. Med Hypotheses 113: 1–5, 2018.

17. Burd NA, Holwerda AM, Selby KC, West DWD, Staples AW, Cain NE, et al. Resistance exercise volume affects myofibrillar protein synthesis and anabolic signalling molecule phosphorylation in young men. J Physiol 588(16): 3119–30, 2010.

18. Burd NA, West DWD, Staples AW, Atherton PJ, Baker JM, Moore DR, et al. Low-load high volume resistance exercise stimulates muscle protein synthesis more than high-load low volume resistance exercise in young men. PLoS One 5(8), 2010.

19. Campos GER, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al. Muscular adaptations in response to three different resistance-training regimens: Specificity of repetition maximum training zones. Eur J

Appl Physiol 88(1–2): 50–60, 2002.

20. Chaves TS, De Campos Biazon TMP, Dos Santos LME, Libardi CA. Effects of resistance training with controlled versus self-selected repetition duration on muscle mass and strength in untrained men. PeerJ 2020(3), 2020.

21. Claflin DR, Larkin LM, Cederna PS, Horowitz JF, Alexander NB, Cole NM, et al. Effects of high- and low-velocity resistance training on the contractile properties of skeletal muscle fibers from young and older humans. J Appl Physiol 111(4): 1021–30, 2011.

22. Colquhoun RJ, Gai CM, Aguilar D, Bove D, Dolan J, Vargas A, et al. Training volume, not frequency, indicative of maximal strength adaptations to resistance training. J Strength Cond Res 32(5): 1207–13, 2018.

23. Correa DA, Brigatto FA, Braz TV, de Camargo JBB, Aoki MS, Marchetti PH LC. Twice-daily sessions result in a greater muscle strength and a similar muscle hypertrophy compared to once-daily session in resistance-trained men. J Sport Med Phys Fit 62(3):324-336, 2022.

24. Damas F, Angleri V, Phillips SM, Witard OC, Ugrinowitsch C, Santanielo N, et al. Myofibrillar protein synthesis and muscle hypertrophy individualized responses to systematically changing resistance training variables in trained young men. J Appl Physiol 127(3): 806–15, 2019.

25. Damas F, Barcelos C, Nóbrega SR, Ugrinowitsch C, Lixandrão ME, Santos LMED, et al. Individual Muscle Hypertrophy and Strength Responses to High vs. Low Resistance Training Frequencies. J Strength Cond Res 33(4): 897–901, 2019.

26. Dankel SJ, Mattocks KT, Jessee MB, Buckner SL, Mouser JG, Counts BR, et al. Frequency: The Overlooked Resistance Training Variable for Inducing Muscle Hypertrophy? Sport Med 47(5): 799–805, 2017.

27. Davies T, Orr R, Halaki M, Hackett D. Effect of Training Leading to Repetition Failure on Muscular Strength: A Systematic Review and Meta-Analysis. Sport Med 46(4): 487–502, 2016.

28. Ema R, Wakahara T, Miyamoto N, Kanehisa H, Kawakami Y. Inhomogeneous architectural changes of the quadriceps femoris induced by resistance training. Eur J Appl Physiol 113(11): 2691–703, 2013.

29. Erskine RM, Jones DA, Williams AG, Stewart CE, Degens H. Inter-individual variability in the adaptation of human muscle specific tension to progressive resistance training. Eur J Appl Physiol 110(6): 1117–25, 2010.

30. Farinatti PTV, Geraldes AAR, Bottaro MF, Lima MVIC, Albuquerque RB, Fleck SJ. Effects of different resistance training frequencies on the muscle strength and functional performance of active women older than 60 years. J Strength Cond Res 27(8): 2225–34, 2013.

31. Figueiredo VC, de Salles BF, Trajano GS. Author's Reply to Souza et al: Comment on: "Volume for Muscle Hypertrophy and Health Outcomes: The Most Effective Variable in Resistance Training." Sport Med 48(5): 1285–7, 2018.

32. Fonseca FS, Costa BD de V., Ferreira MEC, Paes S, de Lima-Junior D, Kassiano W, et al. Acute effects of equated volume-load resistance training leading to muscular failure versus non-failure on neuromuscular performance. J Exerc Sci Fit 18(2): 94–100, 2020.

33. de França HS, Branco PAN, Guedes Junior DP, Gentil P, Steele J, Teixeira CVLS. The effects of adding single-joint exercises to a multi-joint exercise resistance training program on upper body muscle strength and size in trained men. Appl Physiol Nutr Metab 40(8): 822–6, 2015.

34. Gentil P, Fischer B, Martorelli AS, Lima RM, Bottaro M. Effects of equal-volume resistance training performed one or two times a week in upper body muscle size and strength of untrained young men. J Sports Med Phys Fitness 55(3): 144–9, 2015.

35. Gentil P, Fisher J, Steele J, Campos MH, Silva MH, Paoli A, et al. Effects of equal-volume resistance training with different training frequencies in muscle size and strength in trained men. PeerJ 2018(6), 2018.

36. Gentil P, Soares SRS, Pereira MC, da Cunha RR, Martorelli SS, Martorelli AS, et al. Effect of adding single-joint exercises to a multi-joint exercise resistance-training program on strength and hypertrophy in untrained subjects. Appl Physiol Nutr Metab 38(3): 341–4, 2013.

37. Gilson H, Schakman O, Kalista S, Lause P, Tsuchida K, Thissen JP. Follistatin induces muscle hypertrophy through satellite cell proliferation and inhibition of both myostatin and activin. Am J Physiol - Endocrinol Metab 297(1), 2009.

38. Gomes GK, Franco CM, Nunes PRP, Orsatti FL. High-Frequency Resistance Training Is Not More Effective Than Low-Frequency Resistance Training in Increasing Muscle Mass and Strength in Well-Trained Men. J Strength Cond Res 33: S130–9, 2019.

39. González-Badillo JJ, Rodríguez-Rosell D, Sánchez-Medina L, Ribas J, López-López C, Mora-Custodio R, et al. Short-term Recovery Following Resistance Exercise Leading or not to Failure. Int J Sports Med 37(4): 295–304, 2016.

40. González-Hernández JM, García-Ramos A, Colomer-Poveda D, Tvarijonaviciute A, Cerón J, Jiménez-Reyes P, et al. Resistance Training to Failure vs. Not to Failure: Acute and Delayed Markers of Mechanical, Neuromuscular, and Biochemical Fatigue. J strength Cond Res 35(4): 886–93, 2021.

41. Goto K, Ishii N, Kizuka T, Kraemer RR, Honda Y, Takamatsu K. Hormonal and metabolic responses to slow movement resistance exercise with different durations of concentric and eccentric actions. Eur J Appl Physiol 106(5): 731–9, 2009.

42. Grgic J, Schoenfeld BJ, Orazem J, Sabol F. Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: A systematic review and meta-analysis. J Sport Heal Sci S2095-2546(21)00007-7 Online ahead of print. 2021.

43. Hakkinen K, Kallinen M. Distribution of strength training volume into one or two daily sessions and neuromuscular adaptations in female athletes. Electromyogr Clin Neurophysiol 34(2): 117–24, 1994.

44. Häkkinen K, Pakarinen A. Serum hormones in male strength athletes during intensive short term strength training. Eur J Appl Physiol Occup Physiol 63(3–4): 194–9, 1991.

45. Häkkinen K, Pakarinen A, Kraemer WJ, Häkkinen A, Valkeinen H, Alen M. Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. J Appl Physiol 91(2): 569–80, 2001.

46. Haun CT, Vann CG, Mobley CB, Osburn SC, Mumford PW, Roberson PA, et al. Pre-training skeletal muscle fiber size and predominant fiber type best predict hypertrophic responses to 6 weeks of resistance training in to previously trained young men. Front Physiol 10(3): 297, 2019.

47. Henneman E. Relation between size of neurons and their susceptibility to discharge. Science 126(3287): 1345–7, 1957.

48. Hubal MJ, Gordish-Dressman H, Thompson PD, Price TB, Hoffman EP, Angelopoulos TJ, et al. Variability in

muscle size and strength gain after unilateral resistance training. Med Sci Sports Exerc 37(6): 964–72, 2005.

49. Kassiano W, Costa B, de Lima-Júnior D, Gantois P, de Souza Fonseca F, de Sousa Fortes L. Revisiting the relationship between resistance training dose and strength gains: what is the real role of volume? J Trainology 10(2): 10–5, 2021.

50. Kraemer WJ, Fleck SJ, Dziados JE et al. Changes in hormonal concentrations after different heavy resistance exercise protocols in women. J Appl Physiol 75(2): 594—604., 1993.

51. Kraemer WJ, Marchitelli L, Gordon SE, Harman E, Dziados JE, Mello R, et al. Hormonal and growth factor responses to heavy resistance exercise protocols. J Appl Physiol 69(4): 1442–50, 1990.

52. Kraemer WJ, Ratamess NA. Fundamentals of Resistance Training: Progression and Exercise Prescription. Med Sci Sports Exerc 36(4): 674–88, 2004.

53. Kubo K, Ikebukuro T, Yata H. Effects of 4, 8, and 12 Repetition Maximum Resistance Training Protocols on Muscle Volume and Strength. J strength Cond Res 35(4): 879–85, 2021.

54. Lacerda LT, Costa CG, Lima F V., Martins-Costa HC, Diniz RCR, Andrade AGP, et al. Longer concentric action increases muscle activation and neuromuscular fatigue responses in protocols equalized by repetition duration. J Strength Cond Res 33(6): 1629–39, 2019.

55. Lacerda LT, Marra-Lopes RO, Diniz RCR, Lima F V., Rodrigues SA, Martins-Costa HC, et al. Is Performing Repetitions to Failure Less Important Than Volume for Muscle Hypertrophy and Strength? J strength Cond Res 34(5): 1237–48, 2020.

56. Lacerda LT, Martins-Costa HC, Diniz RCR, Lima F V., Andrade AGP, Tourino FD, et al. Variations in Repetition Duration and Repetition Numbers Influence Muscular Activation and Blood Lactate Response in Protocols Equalized by Time Under Tension. J Strength Cond Res 30(1): 251–8, 2016.

57. Lasevicius T, Schoenfeld BJ, Silva-Batista C, Barros T de S, Aihara AY, Brendon H, et al. Muscle Failure Promotes Greater Muscle Hypertrophy in Low-Load but Not in High-Load Resistance Training. J Strength Cond Res Publish 36(2):346-351, 2022.

58. Lasevicius T, Ugrinowitsch C, Schoenfeld BJ, Roschel H, Tavares LD, De Souza EO, et al. Effects of different intensities of resistance training with equated volume load on muscle strength and hypertrophy. Eur J Sport Sci 18(6): 772–80, 2018.

59. Lasevicius T, Ugrinowitsch C, Schoenfeld BJ, Roschel H, Tavares LD, De Souza EO, et al. Effects of different intensities of resistance training with equated volume load on muscle strength and hypertrophy. Eur J Sport Sci 18(6): 772–80, 2018.

60. Longo AR, Silva-Batista C, Pedroso K, de Salles Painelli V, Lasevicius T, Schoenfeld BJ, et al. Volume Load Rather Than Resting Interval Influences Muscle Hypertrophy During High-Intensity Resistance Training. J Strength Cond Res Publish 19(7): 246-254, 2020.

61. Lopez P, Radaelli R, Taaffe DR, Newton RU, Galvão DA, Trajano GS, et al. Resistance Training Load Effects on Muscle Hypertrophy and Strength Gain: Systematic Review and Network Meta-analysis. Med Sci Sports Exerc 53(6): 1206–16, 2021.

62. Mangine GT, Redd MJ, Gonzalez AM, Townsend JR, Wells AJ, Jajtner AR, et al. Resistance training does not induce uniform adaptations to quadriceps. PLoS One 13(8), 2018.

63. Mannarino P, Matta T, Lima J, Simão R, Freitas de Salles B. Single-Joint Exercise Results in Higher Hypertrophy of Elbow Flexors Than Multijoint Exercise. J Strength Cond Res Publish 35(10):2677-2681, 2022.

64. Martorelli S, Cadore EL, Izquierdo M, Celes R, Martorelli A, Cleto VA, et al. Strength training with repetitions to failure does not provide additional strength and muscle hypertrophy gains in young women. Eur J Transl Myol 27(2): 6339, 2017.

65. McCall GE, Byrnes WC, Dickinson A, Pattany PM, Fleck SJ. Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. J Appl Physiol 81(5): 2004–12, 1996.

66. Miranda H, Fleck SJ, Simão R, Barreto AC, Dantas EHM, Novaes J. Effect of two different rest period lengths on the number of repetitions performed during resistance training. J Strength Cond Res 21(4): 1032–6, 2007.

67. Mookerjee S, Ratamess N. Comparison of Strength Differences and Joint Action Durations between Full and Partial Range-of-Motion Bench Press Exercise. J Strength Cond Res 13(1): 76–81, 1999.

68. Morán-Navarro R, Pérez CE, Mora-Rodríguez R, de la Cruz-Sánchez E, González-Badillo JJ, Sánchez-Medina L, et al. Time course of recovery following resistance training leading or not to failure. Eur J Appl Physiol 117(12): 2387–99, 2017.

69. Morton RW, Oikawa SY, Wavell CG, Mazara N, McGlory C, Quadrilatero J, et al. Neither load nor systemic hormones determine resistance training-mediated hypertrophy or strength gains in resistance-trained young men. J Appl Physiol 121(1): 129–38, 2016.

70. Morton RW, Sonne MW, Farias Zuniga A, Mohammad IYZ, Jones A, McGlory C, et al. Muscle fibre activation is unaffected by load and repetition duration when resistance exercise is performed to task failure. J Physiol 597(17): 4601–13, 2019.

71. Nakamura Y, Tanaka K, Yabushita N, Sakai T, Shigematsu R. Effects of exercise frequency on functional fitness in older adult women. Arch Gerontol Geriatr 44(2): 163–73, 2007.

72. Navalta JW, Stone WJ, Lyons TS. Ethical Issues Relating to Scientific Discovery in Exercise Science. Int J Exerc Sci 12(1): 1–8, 2019.

73. Nóbrega SR, Barroso R, Ugrinowitsch C, Da Costa JLF, Alvarez IF, Barcelos C, et al. Self-selected vs. fixed repetition duration: Effects on number of repetitions and muscle activation in resistance-trained men. J Strength Cond Res 32(9): 2419–24, 2018.

74. Nunes JP, Grgic J, Cunha PM, Ribeiro AS, Schoenfeld BJ, de Salles BF, et al. What influence does resistance exercise order have on muscular strength gains and muscle hypertrophy? A systematic review and meta-analysis. Eur J Sport Sci 21(2): 149–57, 2021.

75. Ogasawara R, Loenneke JP, Thiebaud RS, Abe T. Low-Load Bench Press Training to Fatigue Results in Muscle Hypertrophy Similar to High-Load Bench Press Training. Int J Clin Med 04(02): 114–21, 2013.

76. Ohno Y, Ando K, Ito T, Suda Y, Matsui Y, Oyama A, et al. Lactate stimulates a potential for hypertrophy and regeneration of mouse skeletal muscle. Nutrients 11(4), 2019.

77. Ozaki H, Kubota A, Natsume T, Loenneke JP, Abe T, Machida S, et al. Effects of drop sets with resistance training on increases in muscle CSA, strength, and endurance: a pilot study. J Sports Sci 36(6): 691–6, 2018.

78. Phillips SM, Tipton KD, Ferrando AA, Wolfe RR. Resistance training reduces the acute exercise-induced increase in muscle protein turnover. Am J Physiol - Endocrinol Metab 276(1 39-1): 118–24, 1999.

79. Rahimi R. Effect of different rest intervals on the exercise volume completed during squat bouts. J Sport Sci Med 4(4): 361–6, 2005.

80. Rantanen T, Avlund K, Suominen H, Schroll M, Frändin K, Pertti E. Muscle strength as a predictor of onset of ADL dependence in people aged 75 years. Aging Clin Exp Res 14(3 Suppl): 10–5, 2002.

81. Ratamess NA, Falvo MJ, Mangine GT, Hoffman JR, Faigenbaum AD, Kang J. The effect of rest interval length on metabolic responses to the bench press exercise. Eur J Appl Physiol 100(1): 1–17, 2007.

82. Ribeiro AS, Schoenfeld BJ, Silva DRP, Pina FLC, Guariglia DA, Porto M, et al. Effect of two- Versus three-Way split resistance training routines on body composition and muscular strength in bodybuilders: A pilot study. Int J Sport Nutr Exerc Metab 25(6): 559–65, 2015.

83. Roberts MD, Haun CT, Mobley CB, Mumford PW, Romero MA, Roberson PA, et al. Physiological differences between low versus high skeletal muscle hypertrophic responders to resistance exercise training: Current perspectives and future research directions. Front Physiol 9(JUL), 2018.

84. de salles BF, Simão R, Miranda F, Novaes JS WJ. Rest Interval between Sets in Strength Training. Sport Med 39(9): 765–77, 2009.

85. de Salles BF, Polito MD, Goessler KF, Mannarino P, Matta TT, Simão R. Effects of fixed vs. self-suggested rest between sets in upper and lower body exercises performance. Eur J Sport Sci 16(8): 927–31, 2016.

86. de Salles BF, Simão R, Miranda H, Bottaro M, Fontana F, Willardson JM. Strength increases in upper and lower body are larger with longer inter-set rest intervals in trained men. J Sci Med Sport 13(4): 429–33, 2010.

87. Sampson JA, Groeller H. Is repetition failure critical for the development of muscle hypertrophy and strength? Scand J Med Sci Sport 26(4): 375–83, 2016.

88. Santanielo N, Nóbrega SR, Scarpelli MC, Alvarez IF, Otoboni GB, Pintanel L, et al. Effect of resistance training to muscle failure vs non-failure on strength, hypertrophy and muscle architecture in trained individuals. Biol Sport 37(4): 333–41, 2020.

89. Saric J, Lisica D, Orlic I, Grgic J, Krieger JW, Vuk S, et al. Resistance training frequencies of 3 and 6 times per week produce similar muscular adaptations in resistance-trained men. J Strength Cond Res 33: S122–9, 2019.

90. Scarpelli MC, Nóbrega SR, Santanielo N, Alvarez IF, Otoboni GB, Ugrinowitsch C, et al. Muscle Hypertrophy Response Is Affected by Previous Resistance Training Volume in Trained Individuals. J Strength Cond Res Publish pub ahead of print. 2020.

91. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. J Strength Cond Res 24(10): 2857–72, 2010.

92. Schoenfeld BJ, Contreras B, Krieger J, Grgic J, Delcastillo K, Belliard R, et al. Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men. Med Sci Sports Exerc 51(1): 94–103, 2019.

93. Schoenfeld BJ, Contreras B, Krieger J, Grgic J, Delcastillo K, Belliard R, et al. Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men. Med Sci Sports Exerc 51(1): 94–103, 2019.

94. Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. J Sports Sci 35(11): 1073–82, 2017.

95. 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 29(10): 2954–63, 2015.

96. Schoenfeld BJ, Pope ZK, Benik FM, Hester GM, Sellers J, Nooner JL, et al. Longer interset rest periods enhance muscle strength and hypertrophy in resistance-trained men. J Strength Cond Res 30(7): 1805–12, 2016.

97. Schoenfeld BJ, Ratamess NA, Petersen MD, Contreras B, Sonmez GT, Alvar BA. Effects of Different Volume-Equated Resistance Training Loading Strategies on Muscular Adaptations in Well-Trained Men. J Strength Cond Res 28(10): 2909–18, 2014.

98. Schuenke MD, Herman JR, Gliders RM, Hagerman FC, Hikida RS, Rana SR, et al. Early-phase muscular adaptations in response to slow-speed versus traditional resistance-training regimens. Eur J Appl Physiol 112(10): 3585–95, 2012.

99. Senna GW, Willardson JM, Scudese E, Simão R, De Oliveira CQ, De Oliveira Lima J, et al. Multi- to Single-Joint or the Reverse Exercise Order does not Affect Pectoralis Major Workout Performance. J Hum Kinet 66(1): 223–31, 2019.

100. Sforzo GA, Touey PR. Manipulating Exercise Order Affects Muscular Performance during a Resistance Exercise Training Session. J Strength Cond Res 10(1): 20–4, 1996.

101. Simão R, Farinatti PDTV, Polito MD, Maior AS, Fleck SJ. Influence of exercise order on the number of repetitions performed and perceived exertion during resistance exercises. J Strength Cond Res 19(1): 152–6, 2005.

102. Simão R, Polito M, Freitas de Salles B, Marinho DA, Garrido ND, Junior ERTS, et al. Acute and Long-Term Comparison of Fixed vs. Self-Selected Rest Interval Between Sets on Upper-Body Strength. J Strength Cond Res Publish 36(2):540-544, 2022.

103. Simão R, Spineti J, de Salles BF, Oliveira LF, Matta T, Miranda F, et al. Influence of exercise order on maximum strength and muscle thickness in untrained men. J Sport Sci Med 9(1): 1–7, 2010.

104. Spineti J, De Salles BF, Rhea MR, Lavigne D, Matta T, Miranda F, et al. Influence of exercise order on maximum strength and muscle volume in nonlinear periodized resistance training. J Strength Cond Res 24(11): 2962–9, 2010.

105. Sundstrup E, Mortensen OS, Jakobsen MD, Andersen LL, Andersen CH, Zebis MK. Muscle activation strategies during strength training with heavy loading vs. repetitions to failure. J Strength Cond Res 26(7): 1897–903, 2012.

106. Tavares LD, de Souza EO, Ugrinowitsch C, Laurentino GC, Roschel H, Aihara AY, et al. Effects of different strength training frequencies during reduced training period on strength and muscle cross-sectional area. Eur J Sport Sci 17(6): 665–72, 2017.

107. van den Tillaar R, Andersen V, Saeterbakken AH. Comparison of muscle activation and kinematics during free-weight back squats with different loads. PLoS One 14(5), 2019.

108. Wakahara T, Fukutani A, Kawakami Y, Yanai T. Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. Med Sci Sports Exerc 45(11): 2158–65, 2013.

109. Wakahara T, Miyamoto N, Sugisaki N, Murata K, Kanehisa H, Kawakami Y, et al. Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance

training. Eur J Appl Physiol 112(4): 1569–76, 2012.

110. West DWD, Burd NA, Tang JE, Moore DR, Staples AW, Holwerda AM, et al. Elevations in ostensibly anabolic hormones with resistance exercise enhance neither training-induced muscle hypertrophy nor strength of the elbow flexors. J Appl Physiol 108(1): 60–7, 2010.

111. West DWD, Kujbida GW, Moore DR, Atherton P, Burd NA, Padzik JP, et al. Resistance exercise-induced increases in putative anabolic hormones do not enhance muscle protein synthesis or intracellular signalling in young men. J Physiol 587(21): 5239–47, 2009.

112. Willardson JM. A brief review: Factors affecting the length of the rest interval between resistance exercise sets. J Strength Cond Res 20(4): 978–84, 2006.

113. Willardson JM, Burkett LN. A comparison of 3 different rest intervals on the exercise volume completed during a workout. J Strength Cond Res 19(1): 23–6, 2005.

114. Yue FL, Karsten B, Larumbe-Zabala E, Seijo M, Naclerio F. Comparison of 2 weekly-equalized volume resistance-training routines using different frequencies on body composition and performance in trained males. Appl Physiol Nutr Metab 43(5): 475–81, 2018.

115. Zaroni RS, Brigatto FA, Schoenfeld BJ, Braz T V., Benvenutti JC, Germano MD, et al. High Resistance-Training Frequency Enhances Muscle Thickness in Resistance-Trained Men. J strength Cond Res 33: S140–51, 2019.