Sports Med (2014) 44:1635–1643
DOI 10.1007/s40279-014-0228-0

REVIEW ARTICLE

The Effect of Inter-Set Rest Intervals on Resistance Exercise-Induced Muscle Hypertrophy

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Published online: 22 July 2014

Abstract Due to a scarcity of longitudinal trials directly measuring changes in muscle girth, previous recommendations for inter-set rest intervals in resistance training programs designed to stimulate muscular hypertrophy were primarily based on the post-exercise endocrinological response and other mechanisms theoretically related to muscle growth. New research regarding the effects of inter-set rest interval manipulation on resistance training-induced muscular hypertrophy is reviewed here to evaluate current practices and provide directions for future research. Of the studies measuring long-term muscle hypertrophy in groups employing different rest intervals, none have found superior muscle growth in the shorter compared with the longer rest interval group and one study has found the opposite. Rest intervals less than 1 minute can result in acute increases in serum growth hormone levels and these rest intervals also decrease the serum testosterone to cortisol ratio. Long-term adaptations may abate the post-exercise endocrinological response and the relationship between the transient change in hormonal production and chronic muscular hypertrophy is highly contentious and appears to be weak. The relationship between the rest interval-mediated effect on immune system response, muscle damage, metabolic stress, or energy production capacity and muscle hypertrophy is still ambiguous and largely theoretical. In conclusion, the literature does not support the hypothesis that training for muscle hypertrophy requires shorter rest intervals than training for strength development or that predetermined rest intervals are preferable to auto-regulated rest periods in this regard.

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1 Introduction

Several review articles have established that multiple sets of resistance exercise result in greater strength development and muscular hypertrophy than a single set [1–4] and that these adaptations are considerably affected by the rest interval between sets, with different rest intervals producing different results for different training goals [4–7]. Correspondingly, rest interval prescriptions commonly vary per training goal [4–6]. To maximize muscle hypertrophy, many authors have proposed that rest intervals of 30–60 s are optimal because they result in the greatest exercise-induced elevations in ostensibly anabolic hormones, notably growth hormone [5, 6]. The American College of Sports Medicine currently recommends 1–2 min rest intervals for training programs designed to stimulate muscular hypertrophy in novice and intermediate trainees with longer rest periods of 2–3 min only being employed for the heavily loaded core exercises of advanced trainees [4]. Since the last in-depth review of the effect of rest intervals on resistance training adaptations [5], much research has been done on the mechanisms underlying these adaptations. This and other new research pertaining to the effect of inter-set rest intervals on resistance training-induced muscular hypertrophy is reviewed here to evaluate current practices and provide directions for future research.

2 Literature Search

PubMed, Google Scholar, and SciELO were employed to search for the phrases ‘rest interval’, ‘rest period’, ‘recovery’ or ‘recovery time’ in combination with ‘strength training’, ‘resistance training’ or ‘resistance exercise’. In addition, manual searches of relevant books, journals, and authors were performed. Studies were included if they examined the relationship between inter-set rest intervals and muscle hypertrophy, or a mechanism underlying or mediating this relationship, and were published in the English language. All cited research and all research citing the material that met the inclusion criteria was also considered for inclusion based on the same criteria. The last search was performed on 30 April 2014.

3 Findings

3.1 Longitudinal Studies Measuring Muscle Hypertrophy

Few studies have directly compared the chronic effects of different rest intervals on muscle hypertrophy. Buresh et al. [8] studied 12 untrained males performing 10-week resistance training programs with a load that resulted in momentary muscle failure on the 8–11th repetition of the last set of every exercise using either 1- or 2.5-min rest intervals between sets. The longer rest interval group experienced significantly greater increases in arm muscular cross-sectional area (MCSA) and a trend for a greater increase in thigh MCSA. The other measurements of body composition and strength did not differ between groups. The authors noted that insufficient statistical power due to the small sample size and high variability in inter-subject responsiveness to training was a limitation of the study, which may explain why the higher increases in strength and muscle cross-sectional area in the longer rest interval group did not reach statistical significance.

Ahtiainen et al. [7] studied 13 men with 6.6 ± 2.8 years of continuous strength training experience in a work-equated crossover design of 3 months of higher intensity strength training with a 5-min rest interval compared with a lower intensity program with a 2-min rest interval. They found no significant differences between groups in maximal isometric strength, repetition maximum, or MCSA. However, the 5-min rest interval group significantly increased its maximal isometric force by 5.8 ± 8.0 %, whereas the 2.0 ± 10.9 % increase in the 2-min rest interval group did not reach statistical significance.

Since the programs were matched according to total work, unlike in the study by Buresh et al. [8], the shorter rest interval group had to perform on average one more set than the longer rest interval group for every exercise. Since it is well-established that shortening the rest interval between sets can reduce the number of repetitions that can be performed in subsequent sets [5], in a similarly designed study with a fixed number of sets, the shorter rest interval group may have performed worse than the longer rest interval group due to training with less volume. Buresh et al. [8] found that the 2.5-min rest interval group was capable of using a significantly higher training load than the 1-min rest interval group for the bench press but not for the squat at the end of the training period. This may explain why the 2.5-min rest interval group experienced a significantly greater increase in arm MCSA but the difference between groups in the increase in thigh MCSA did not reach statistical significance. Combined, these studies lend credence to the hypothesis that a longer rest interval length may benefit muscle hypertrophy only if this allows for a higher total amount of work.

A contrary line of reasoning to the argument in favor of longer rest intervals to preserve work capacity over sets is provided by Kraemer et al. [9]. They found that bodybuilders were able to sustain a significantly higher intensity over consecutive sets than power lifters and suggested that this may have been the result of adaptations to training with shorter rest intervals, such as increased capillary and mitochondrial density. However, while increased work capacity may facilitate training with a sufficient training volume, these adaptations correspond to the endurance phenotype that can result in the strength–endurance interference effect and are therefore unlikely to benefit long-term muscle hypertrophy directly [10, 11].

Empirical evidence against the theory that short rest intervals promote muscle hypertrophy, either indirectly via improved work capacity or directly, comes from De Souza et al. [12], who studied two groups totaling 20 recreationally trained young men participating in 8-week resistance training programs. One group trained using a protocol of 4 sets with an 8–10 repetition maximum load with constant rest intervals of 2 min; the other progressively decreased the rest interval to 30 s over the course of the program. There were no significant differences between groups for increases in arm and thigh MCSA, 1 repetition maximum strength, and isokinetic peak torque. The decreasing rest interval group did not develop the work capacity to maintain training intensity over sets and consequently performed less total volume over the course of the program. These findings were replicated by Souza-Junior et al. [13] employing a similar study protocol (in which one group supplemented with creatine, which was incorrectly hypothesized to aid training with decreasing rest intervals).

Recently, Schoenfeld et al. [14] investigated muscular adaptations in a bodybuilding- versus a power lifting-type resistance training program. Inter-set rest intervals in the bodybuilding-type routine were 90 s while the power lifting-type routine rested for 3 min. After 8 weeks, both groups showed significant increases in thickness of the biceps brachii with no differences noted between groups. Although these findings seem to lend credence to a lack of effect from varying rest intervals, it should be noted that the loads and training frequency differed between groups, making it difficult to draw cause–effect conclusions on the topic.

3.1.1 *Effect of Rest Interval Length on Endocrine Response*

The effect on exercise volume is not the only factor to be considered when prescribing rest intervals in training programs. Training programs with different rest intervals induce divergent neuroendocrine adaptations even when equated for volume load [15–17]. As De Salles et al. noted during the last detailed review of the literature on the effects of rest intervals on muscle hypertrophy, "Few studies have compared differences in hypertrophy consequent to workout protocols that involve relatively short versus long rest intervals between sets. The general recommendation for short rest intervals was derived from research that examined acute anabolic hormonal secretions" [5, 6] (p. 981). The argument in favor of 30- to 60-s rest intervals to maximize increases in muscle size is primarily based on acutely elevated growth hormone levels [5, 6].

Research indicates that the post-exercise elevations in hormones associated with short rest intervals are related to increased metabolic stress, which manifests in the accumulation of metabolites, particularly lactate, inorganic phosphate, and hydrogen ion [18]. The use of limited rest intervals does not allow the body sufficient time to re-establish homeostasis, resulting in a heightened build-up of these metabolites in muscle. Although the exact mechanisms have yet to be fully elucidated, it is believed that high levels of acidosis associated with metabolite accumulation may potentiate growth hormone release via chemoreflex stimulation mediated by intramuscular metaboreceptors and group III and IV afferents [19]. There also is evidence that lactate may directly mediate acute testosterone production, possibly by stimulating testicular cyclic adenosine 3′:5′ monophosphate [20].

Several studies have investigated the effect of the inter-set rest interval on endocrine response. Kraemer et al. [21] studied the intra-individual effects of six resistance training sessions systematically varying in intensity (5 repetition maximum vs. 10 repetition maximum), total work load (high vs. low) and rest interval (1 vs. 3 min) on acute endocrine response in nine young, recreationally trained men. They found that training sessions employing 1-min rest intervals resulted in higher serum growth hormone area under the concentration–time curve (AUC) response in the 2 h post-exercise than training sessions employing 3-min rest intervals. No relationship between growth hormone secretion and total work output was observed, but there was a negative interaction effect for training intensity, i.e., the 1-min rest interval protocols resulted in more growth hormone production with 10 than with 5 repetition maximum loads. Serum testosterone and insulin-like growth factor 1 (IGF-1) AUC responses did not differ significantly between training sessions. Similar results were found by Kraemer et al. [22] in women with the addition that the same training parameters mediating growth hormone secretion also mediated increases in cortisol.

More recent research supports the findings that short rest intervals acutely increase serum cortisol and growth hormone levels without affecting IGF-1 serum levels. Rahimi et al. [23] studied serum cortisol and IGF-1 response in ten recreationally trained men. Each performed three strength training sessions consisting of 4 sets of squats and bench presses, utilizing a rest interval each session of either 1, 1.5, or 2 min in a counterbalanced order. The length of the rest period had no significant effect on serum IGF-1 increases in the 30 min post-exercise, but serum cortisol was higher in the 1 and 1.5 min groups than in the 2 min group.

Rahimi et al. [24] studied ten resistance-trained men performing three separate exercise sessions of 4 sets of bench presses and squats to repetition failure at 85 % of their 1 repetition maximum with either 1-, 1.5-, or 2-min rest intervals. Serum cortisol levels in the 30 min post-exercise were significantly higher in the 1- and 1.5-min rest interval groups than in the 2-min rest interval group.

Boroujerdi and Rahimi [25] studied ten recreationally trained men performing five sets of bench presses and squats at an intensity corresponding to their 10 repetition maximum during two separate sessions, once with a 1-min rest and once with a 3-min rest interval. In the first hour post-exercise, serum growth hormone but not IGF-1 levels were higher in the 1-min group than in the 3-min group.

Bottaro et al. [26] compared the effects on acute growth hormone response of three resistance exercise programs, using either a 0.5-, 1-, or 2-min rest interval, consisting of four lower-body exercises with 3 sets performed to repetition failure at a load corresponding to the 12 recreationally trained women's 10 repetition maximum. The AUC relationship for growth hormone was greatest in the 0.5-min rest interval group, with no significant difference between the 1- and 2-min groups. Interestingly, and contrary to the other studies mentioned above [14, 23, 24], cortisol response did not significantly differ between groups.

The effect of rest interval length on testosterone serum levels is more equivocal. Rahimi et al. [27] found that rest intervals under 1.5 min blunted the acute testosterone response. They studied ten resistance-trained men performing three separate exercise sessions of 4 sets of bench presses and squats to repetition failure at 85 % of their 1 repetition maximum with either 1-, 1.5-, or 2-min rest intervals. Immediately post-exercise, serum cortisol levels were higher and serum testosterone levels were lower in the 1- and 1.5-min rest interval groups than in the 2-min rest interval group. At 30 min post-exercise, the testosterone to cortisol ratio was no longer significantly higher. Kraemer et al. [14] also found differences in the temporal serum testosterone curve but no significant AUC differences and Kraemer et al. [21] found no differences in women at any timepoint. Conversely, the discussed study by Buresh et al. [8] found higher serum testosterone levels in the 1-min rest interval group than in the 2.5-min rest interval group.

Other findings by Buresh et al. [8] further complicate the literature. They found higher serum cortisol levels in the 1-min rest interval group than in the 2.5-min rest interval group as expected, but the difference in growth hormone levels did not reach statistical significance. The authors attributed this to low statistical power. Moreover, the higher cortisol and testosterone serum levels in the 1-min rest interval group were only found in week 1, not in weeks 5 or 10, suggesting the body's endocrine response may adapt to the training stress of shorter rest intervals.

In the aforementioned study by Ahtiainen et al. [7], no differences in acute or chronic endocrine response were observed, measured by levels of total testosterone, free testosterone, cortisol, and growth hormone in response to training with 2- or 5-min rest intervals. The authors also noted a trend for attenuated acute hormonal responses throughout the course of the 6-month training period. The finding of a reduced exercise-induced increase in cortisol after prolonged resistance training is in agreement with earlier research in young, untrained men [28, 29] and a trend for the same attenuation was found for growth hormone, possibly due to a reduced accumulation of blood lactate during exercise [28]. The acute growth hormone response to high-intensity endurance exercise also diminishes in untrained men after 3 weeks of training [30].

In summary, shorter rest intervals can be used to alter the hormonal milieu in the first hours post-exercise, specifically elevating serum growth hormone and cortisol levels. Rest intervals of 0.5–1 min appear to be required to significantly increase acute serum growth hormone levels compared with other rest intervals. Rest intervals under 2 min also elevate serum cortisol levels in the majority of studies, leading to a decrease in the testosterone to cortisol ratio. Endocrinological adaptations may cancel out these changes over time.

3.1.2 The Relationship Between Post-Exercise Endocrine Response and Muscle Hypertrophy

The relationship between the changes in hormonal milieu and actual muscle hypertrophy was not investigated in most of the studies discussed above. A study by Goto et al. [31] that directly measured increases in muscle cross-sectional area in untrained males has been repeatedly cited as providing the link between exercise-induced growth hormone release and muscle hypertrophy [5, 6]. In this study it was shown that a resistance training program consisting of 5 sets of 3–5 repetitions with 3-min rest periods acutely elevated serum growth hormone levels less than a program consisting of 6 sets of 10–15 repetitions. Moreover, over a 4-week period, a group employing the higher-intensity program with an extra set of 25–35 repetitions added to it experienced greater post-exercise serum growth hormone elevations and a trend towards greater increases in MCSA than the group without this extra set. The trend towards greater muscle hypertrophy in the group performing the extra set may simply have been the result of the increased training volume, regardless of intensity or rest interval. Therefore, this study does not provide support for the argument that shorter rest intervals maximize muscle hypertrophy mediated by transiently increased post-exercise growth hormone secretion.

Since Ahtiainen et al. [7] found no differences in endocrine response or muscle hypertrophy in groups training with different rest intervals, studies employing training programs known to elicit a high endocrine response fail to observe changes in muscle hypertrophy between different rest intervals [13, 21], and Buresh et al. [8] found superior muscle hypertrophy and less endocrine response in the 2.5-min rest interval group compared with the 1-min rest interval group, the available empirical evidence does not support the theory that elevations in ostensibly anabolic hormones as a result of rest intervals less than 1 min cause or mediate chronic muscle hypertrophy. The finding by Buresh et al. [8] that arm MCSA but not upper body strength was greater in the long rest interval group is also in disagreement with the hypothesis that longer rest intervals benefit strength at the expense of muscle hypertrophy.

Additionally, the contention that acute exercise-induced elevations in ostensibly anabolic hormones, irrespective of whether they are the result of rest interval manipulation, correspond with chronic muscle hypertrophy has become a controversial topic in recent years. Support for the hormone hypothesis originated from observational data showing that post-exercise hormonal elevations positively correlated with the magnitude of muscle hypertrophy. McCall et al. [32] found a strong association between acute growth hormone response and the degree of muscle fiber hypertrophy in type I and type II fibers after 12 weeks of high-volume resistance training. Similarly, Ahtiainen et al. [33] demonstrated that acute testosterone elevations were strongly correlated with increases in quadriceps femoris MCSA following 21 weeks of resistance training. Both the McCall et al. [32] and Ahtianen et al. [33] studies had small sample sizes (11 and 16 subjects, respectively), thereby limiting the ability to draw conclusions. More recently, West and Phillips [34] conducted a larger trial of 56 subjects and found that acute growth hormone elevations had only a weak association with increases in type II fiber area ($r = 0.28$) and no correlation between hypertrophy and transient post-exercise increases in testosterone. Follow-up work by the same lab found no relationship between exercise-induced changes in free testosterone, growth hormone, or IGF-1 levels and muscle fiber hypertrophy [35]. Results from the limited number of longitudinal studies on the topic are conflicting, with some showing a positive relationship [36] while others failed to demonstrate any effect [37]. A comprehensive review of the subject by Schoenfeld stated, "Research is contradictory as to whether or not the post-exercise anabolic hormonal response associated with metabolic stress plays a role in skeletal muscle hypertrophy. Given the inconsistencies between studies, any attempts to draw definitive conclusions on the subject would be premature at this time" [37] (p. 1,726). The review concluded that if acute systemic factors are in fact involved in the post-exercise hypertrophic response, the overall magnitude of the effect would be of small consequence.

Moreover, growth hormone has never been found to have direct anabolic properties in skeletal muscle at physiological levels, only in connective tissue [18, 38–43]. While it is possible that this is a unique feature of the specific isoforms in exogenous growth hormone [18], there is no empirical in vivo support for the hypothesis that growth hormone in general is in any way causally related to muscle hypertrophy. Growth hormone's anabolic properties also appear to be primarily or even solely mediated by IGF-1 and testosterone [18, 38], neither of which has been shown to be concurrently elevated post-exercise as a result of employing rest intervals of less than 1 min. Conversely, the anabolic properties of testosterone have been well-established [18] and the testosterone to cortisol ratio is employed as a measure of overtraining in athletes [44]. It is thus dubious whether the increase in serum growth hormone and cortisol as a result of rest intervals under 2 min is beneficial for increasing muscle hypertrophy.

3.2 Effect of Rest Interval Length on Metabolic Stress

It is possible that other aspects related to metabolic stress may play a role in the hypertrophic response to manipulating rest periods. Specifically, the exercise-induced build-up of metabolic byproducts has been theorized to drive anabolism through various factors besides acute hormonal elevations, including increased fiber recruitment, alterations in local myokines, heightened production of reactive oxygen species, and cell swelling [45]. Cell swelling provides a potential mechanism by which short rest periods may mediate hypertrophic gains. There is a body of in vitro research showing that alterations in cellular hydration status impact net protein balance. Specifically, swelling of a cell mediates an increase in protein synthesis and a decrease in protein breakdown while cellular dehydration has the opposite effect [46]. These findings have been seen across a variety of different cell types including muscle fibers. As discussed, short rest intervals have been shown to increase metabolite accumulation, particularly lactic acid. Research shows that intramuscular lactate triggers volume regulatory mechanisms that enhance cell swelling, and these effects may be magnified by the exercise-induced acidosis [46]. It remains to be determined whether cell swelling pursuant to resistance exercise promotes anabolism in vivo and, if so, whether limiting rest interval length is a viable strategy to meaningfully influence the hypertrophic response.

3.3 Effect of Rest Interval Length on Muscle Damage

Aside from endocrinological response, metabolic stress, and work capacity, the effects of rest periods in resistance training may be mediated by muscle damage. Muscle damage may in turn mediate muscle hypertrophy by the release of inflammatory agents, satellite cell activation, and upregulation of the IGF-1 system, although direct empirical evidence establishing a causal relation is lacking and high muscle damage has been shown to negatively impact muscle hypertrophy [47].

Findings from blood flow restricted (BFR) exercise cast doubt on the importance of muscle damage in promoting muscle growth. The use of BFR, which typically involves very short rest periods, has repeatedly been shown to produce robust muscle hypertrophy yet the evidence suggests that these adaptations occur in the relative absence of muscle damage [48]. However, it is not clear whether muscle hypertrophy would be even greater after BFR exercise in the presence of damage to muscle, so this association must be interpreted with caution.

Several studies have investigated the effect of rest interval length on muscle damage. Mayhew et al. [49] studied nine men performing 10 sets with 65 % of 1 repetition maximum loads on separate occasions with either 1- or 3-min rest periods, keeping total work load volume constant between sessions. The shorter rest interval group experienced greater serum creatine kinase (CK) activity 24 h post-exercise and greater post-training monocytosis and lymphocytosis, suggesting that the short rest intervals augmented muscle damage and inflammation. This is remarkable in that the immune system response to resistance exercise is only minimally affected by other training parameters [50]. A limitation of the study by Mayhew et al. [49] is that the exercise sessions were not randomly allocated: the 1-min rest protocol was always performed before the 3-min protocol. Since it is well-established that the adaptations collectively known as the repeated bout effect reduce serum C activity following subsequent similar exercise [51], the findings by Mayhew et al. [49] are methodologically biased in this regard.

Other studies employing both similar and different resistance training protocols with rest intervals that span from 0.5 to 3 min in populations ranging from sedentary to professional bodybuilders have failed to replicate the finding that shorter rest intervals increase serum CK activity in muscle in the 96 h post-exercise [52–57].

However, rest intervals influence muscle damage in certain individuals. There is marked inter-individual variation in serum CK response to resistance training [54, 58, 59]. Machado and Willardson [58] separated high and normal responding participants based on peak serum CK activity being in the 90th percentile or not, respectively. Both groups performed two full body training sessions using 3 sets with 10 repetition maximum loads for each exercise. They used 1-min rest intervals on one occasion and 3-min rest intervals during the other. Only in the high responder group was serum CK activity significantly greater by approximately 70 %, suggesting that these individuals had poorer tolerance to short rest intervals. Machado et al. [59] replicated the above finding in a similar experimental design using 4 sets of biceps curls at 85 % of 1 repetition maximum loads. The high and medium responder groups experienced significantly greater CK activity after the 1-min protocol than after the 3-min protocol.

It should be noted that excessive muscle damage can impair exercise performance and recovery. Severe damage has been shown to reduce the force-producing capacity of muscle by 50 % or more [60] and an inability to train at full capacity will necessarily have a negative impact on the hypertrophic response [61]. In addition, there is evidence that severe muscle damage impedes recovery, with full regeneration of strength and function sometimes taking weeks depending on severity [62, 63].

4 Conclusion

Previous recommendations to employ 0.5- to 1-min rest intervals in resistance training programs designed to maximally stimulate muscle hypertrophy mediated by an elevation in post-exercise serum growth hormone levels have become scientifically untenable. To date, no study has demonstrated greater muscle hypertrophy using shorter compared with longer rest intervals. Longitudinal studies that directly measured hypertrophy in groups with various rest intervals found either no differences between groups or, in the study by Buresh et al. [8], a higher increase in muscle girth in the group using 2.5-min rest intervals than in the group using 1-min rest intervals. However, there is a dearth of controlled research on the topic and the studies that have been conducted have methodological limitations, obscuring the ability to draw definitive conclusions.

The effects of serum hormone levels in the acute post-exercise period on muscle hypertrophy are highly contentious, especially in the case of growth hormone, the primary hormone purported to mediate the relationship between rest intervals shorter than 1 min and muscle hypertrophy. The decrease in testosterone to cortisol ratio associated with rest intervals shorter than 2 min may be detrimental to muscle growth, but this remains a theoretical concern in the absence of empirical support. Other hormone levels seem to generally be unaffected by the manipulation of inter-set rest periods.

While metabolic stress and cell swelling as a result of insufficient rest between sets to clear metabolic byproducts may theoretically mediate muscle hypertrophy, the current research is largely limited to in vitro studies and extrapolations from BFR exercise. There is currently no direct empirical evidence to support the hypothesis that shortening inter-set rest periods will benefit chronic muscle hypertrophy as a result of increased metabolic stress.

Rest interval length does not seem to be associated with markers of muscle damage, with the exception of an increase in individuals with a high serum CK response to resistance training. In these individuals, the extraordinary increase in muscle damage may impair muscle hypertrophy [47, 58, 59].

More generally, the literature as a whole suggests that rest interval manipulation has minor effects on muscle hypertrophy compared with other training parameters such as work volume, which suffers when inter-set rest is insufficient even in trainees accustomed to this type of training [6, 12, 13]. Given that the positive effects of full recovery between sets on strength and power are well-documented and that Buresh et al. [8] found increased muscular hypertrophy but not strength in the higher rest interval group compared with the shorter rest interval group, the literature does not support the theory that training for maximum muscle hypertrophy requires shorter rest intervals than training for strength.

Another consideration with regard to prescribing short rest intervals is safety. Fatigue can negatively impact neuromuscular postural control and proprioception throughout the body (e.g. [6, 64–69]. Concerns have been raised with regard to the ability to adhere to correct exercise technique when very short rest periods are employed, especially during performance of complex multi-joint exercises with heavy loads [70]. A recent study investigated an extreme conditioning protocol where resistance-trained participants performed the back squat, deadlift, and bench press exercises with as little rest between sets as they could manage [71]. Exercise technique as measured by hip and knee joint angles deteriorated throughout the exercise session, although the changes did not correlate with ratings of perceived exertion, blood lactate levels, or heart rate. Future research is required to establish the safety of using very short rest periods, especially during technically challenging multi-joint exercises performed close to momentary muscle failure.

Furthermore, the required rest period for full recovery varies per training intensity, magnitude of load lifted, sex, age, type of muscle contraction, exercise order, and the individual's muscle strength [6, 64–66], not to mention practically unfeasibly measurable genetic factors such as serum CK responsiveness [58, 59]. As such, it may not be worthwhile to prescribe fixed rest intervals in the first place and instead let psychological readiness to perform auto-regulate inter-set recovery periods. It is possible that trainees intuitively learn to account for the factors that influence the relationship between the inter-set rest interval and subsequent performance. This form of rest interval auto-regulation has been employed successfully in one study of resistance-trained men [72] in which the self-suggested rest interval length averaged 157 ± 37 s and was relatively stable across multi-joint and joint isolation exercises for the upper and lower body. There was no statistically significant between-group difference in rest interval length between the group employing self-suggested rest intervals and the group employing fixed 2-min rest intervals. Both groups rested significantly longer than a group employing a fixed 1-min rest interval. In the experience of the authors, most trainees in commercial gyms do not strictly monitor their rest intervals. Future research may investigate how stable auto-regulated rest intervals are and how they change as a result of factors that are known to change rest interval requirements to determine the need to monitor rest intervals strictly.

There is much to be elucidated on the effects of inter-set rest intervals in resistance training on muscle hypertrophy. A replication of the study by Buresh et al. [8] employing a study design that incorporates power analysis to determine the required amount of statistical power would help determine if the higher testosterone but not growth hormone response as a result of shortened rest periods was a statistical anomaly, if muscle hypertrophy is indeed greater with 2.5- than with 1-min rest intervals, and if the endocrine response to shortened rest intervals decreases over time.

Additionally, future research should take into account and control for the fact that the endocrine response, particularly that of cortisol and testosterone, to strength training depends on the exercise time relative to the circadian rhythm of the participants [73, 74].

Also, since recovery capacities differ across individuals, large sample sizes or stratification of the participant pool may be required to find significant differences in muscle hypertrophy attributable to the length of the rest intervals across groups. This will allow us to infer if reduced work capacity tolerance for shortened rest intervals, whether due to strength level or CK activity, influences optimal rest interval length.

The literature would likewise benefit from studies employing a wider range of rest intervals, comparing groups utilizing 0.5-, 2-, and 5-min rest periods, for example, to potentially differentiate between improvements in muscle strength and hypertrophy.

A final recommendation to researchers is to compare controlling for total work load volume and not doing so. This will distinguish between the effects of rest intervals per se and the effects of altered training volume in studies such as that by Ahtiainen et al. [7]. If this is not done, it is arguably preferable not to equate the work load volume across groups, since this mimics the practices outside the laboratory and consequently improves the applicability of the findings in common training settings.

Acknowledgments The authors have no conflict of interest to declare. No sources of funding were used to assist in the preparation of this review.

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