

A CRITICAL ANALYSIS OF THE CLAIMS FOR INTER-SET REST INTERVALS, ENDOGENOUS HORMONAL RESPONSES, SEQUENCE OF EXERCISE, AND PRE-EXHAUSTION EXERCISE FOR OPTIMAL STRENGTH GAINS IN RESISTANCE TRAINING

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Abstract

Several recent resistance training reviews and studies have focused on the control of inter-set rest intervals in order to maintain the absolute amount of resistance throughout the performance of multiple sets, generate the highest training volume (repetitions x sets x resistance), and elicit high endogenous anabolic hormone responses. Some reviews and studies also claim that the specific sequence of exercise and pre-exhaustion exercises in a training session are contributing factors to increasing muscular strength. Although some studies reported a significant decrease in the number of completed repetitions for multiple sets of an exercise when shorter rest intervals or different sequences of performing the exercises were employed, there is very little evidence to suggest that these acute differences in performance significantly affect chronic outcomes such as increased muscular strength. This critical analysis challenges the claims and opinions regarding strength gains.

Key words: *order of resistance exercise, muscular strength, scientific integrity*

Introduction

Inter-set rest interval is the time allotted between consecutive sets of a specific exercise. The time usually ranges from 30 seconds to several minutes (e.g., 1, 2, 3, 4, or 5 minutes) in research studies. Several recent reviews on inter-set rest intervals [1-3] claimed that longer rest intervals allow a greater volume of exercise (sets x resistance x repetitions) and that specific resistance training adaptations such as muscular strength, hypertrophy and power are dependent on the ability to maintain a specific number of repetitions for consecutive sets of a given exercise. In addition, other studies claimed that different acute responses of endogenous anabolic hormones, manipulating the sequence of exercises, and pre-exhaustion exercise can have a significant effect on strength gains. However, all these assumptions have very little scientific evidence (resistance training studies) for support. This critical analysis challenges the claims specifically related to strength gains and not other potential resistance training outcomes such as muscular endurance, hypertrophy, power, or health related benefits.

A critical analysis requires citing each specific claim, the studies cited – or the claimant's failure to cite studies – in an attempt to support that claim, and reporting the results of those studies to determine if they actually support the claims. The methodology and results of each study cited in this critical analysis are outlined and in many cases the claims by the au-

thors of these studies are shown to be unsubstantiated or incorrect. In many instances, the conclusions of the study's authors are quoted so that readers will understand that the results reported in this critical analysis for these studies are not my interpretation of the study's results but the actual conclusions of its authors.

Inter-Set Rest Interval Reviews [1-3]

Willardson [1]

In his review of inter-set rest intervals, Willardson [1] claimed that multiple sets are superior to single sets for developing maximal strength gains. He did not cite any resistance training studies to support his claim. His only reference was a meta-analysis by Rhea and colleagues [4]. That meta-analysis has been shown to be highly flawed and failed to meet the burden of proof for the superiority of multiple set training [5]. Consequently, Willardson's claim for the superiority of specific inter-set rest intervals is undermined by his other unsubstantiated assumption that multiple sets of an exercise produce superior strength gains.

Willardson [1] claimed that longer inter-set rest intervals are required for greater increases in muscular strength. He cited two resistance training studies [6-7] in an attempt to support his claim. Pincivero and colleagues [6] randomly assigned either 40-second or 160-second inter-set rest intervals to 15 previously untrained young participants. (Note: throughout this critical analysis, the word *young* designates the subjects'

age ranging from the late teens to early thirties. Most of the subjects were in their mid-twenties). Both groups performed 4-7 sets of 10 maximal, reciprocal, isokinetic, concentric-only knee extension and flexion repetitions at 90°s^{-1} (20 seconds of exercise) three times a week for four weeks. There was no significant difference between groups for 12 out of the 14 measured variables on an isokinetic dynamometer. For one of those two variables, the authors noted that hamstrings average power at 180°s^{-1} significantly increased in the 160-second group but not in the 40-second group. The authors also claimed that quadriceps average power at 60°s^{-1} and quadriceps peak torque at 180°s^{-1} showed a significantly greater improvement in the 160-second rest group. Curiously, that claim in their Results section regarding quadriceps torque conflicts with the claim in their Conclusions section: "*It was also evident that isokinetic quadriceps torque improved after training, as did functional performance. These improvements however, do not appear to be affected by rest interval manipulation*" [p. 234]. Their antithetical statements leave readers to wonder which statement is valid. Both groups showed a significant improvement in functional performance (single leg hop) but there was no significant difference between groups. In addition, the practical application of Pincivero and colleagues' protocol (seven sets of concentric-only muscle actions for each specific exercise with 40-second inter-set rest intervals on an isokinetic dynamometer) to more traditional concentric and eccentric resistance exercise is questionable at best.

Robinson and colleagues [7] compared inter-set rest intervals of 180 seconds, 90 seconds and 30 seconds in 33 moderately-trained young males who were able to squat with a resistance at least 1.3 times their body mass. There was no random assignment of groups and no control group. After completing two warm-up sets, the three groups performed five sets of 10RM parallel squats (10RM designates the completion of 10 repetitions with the inability to complete another repetition) two times per week for five weeks. There was no significant improvement in vertical jump, vertical jump power index, body mass, thigh skinfold or girth measurements in any group. The increase in 1RM squat (1RM designates the maximal resistance for one complete repetition) was significantly greater in the 180-second rest group compared with the 30-second rest group. There was no significant difference in strength gains between the 90-second and 30-second groups. More importantly, in contrast to the claim by Willardson [1] that the subjects in the 180-second group demonstrated greater strength gains than the other two groups, there was no significant difference in strength gains between the 180-second and 90-second rest groups. When commonly recommended inter-set rest intervals (90 seconds versus 180 seconds) were compared, longer in-

ter-set rest intervals did not produce superior strength gains even with the relatively high volume (5 sets) and high intensity (10RM) training protocol. There was no linear continuum of strength gains.

Because most comparisons of traditional inter-set rest intervals in the studies by Pincivero and colleagues [6] and Robinson and colleagues [7] showed no significant difference in strength gains, these studies fail to support Willardson's [1] claim that longer inter-set rest intervals are required for optimal strength gains.

Willardson [1] claimed that when training to *muscular failure* with 50-90% 1RM 3-5 minutes of rest between sets are required to avoid large reductions in training loads in subsequent sets of each exercise. The use of the term *muscular failure* and similar phrases will be explicated shortly in a subsequent paragraph. Willardson inadvertently revealed two unsubstantiated assumptions; that the activation and subsequent stimulation of motor units is dependent on the philosophy that a heavier resistance (greater percent of maximal resistance) will elicit superior strength gains, and that a difference in the actual number of repetitions performed with a maximal effort on the last repetition of a set has any significant influence on increased strength. Both of Willardson's unsupported assumptions have been refuted in great detail. Motor unit activation is dependent on the degree of effort during the final repetitions of a set rather than the absolute amount of resistance or a specific number of repetitions [8-9].

Willardson [2]

In another review, Willardson [2] claimed that the inter-set rest interval is a highly important component of a resistance training protocol and the manipulation of this component determines the degree of specific physiological adaptations such as increased muscular strength. However, most of the references he cited fail to support his opinion. For example, he cited the 2002 American College of Sports Medicine (ACSM) Position Stand on resistance training [10] five times in his brief Introduction (nine times in his review). After a critical analysis of that Position Stand, which showed that it was a highly flawed document bereft of scientific evidence for support [11], the ACSM replaced it with another Position Stand [12]. The new ACSM 2009 Position Stand also failed to support the opinion that different inter-set rest intervals affect outcomes such as muscular strength [13].

Willardson [2] stated that when multiple sets of an exercise are performed to *muscular failure*, the inter-set rest interval has a significant impact on the number of repetitions completed and that the higher volume (resistance x sets x repetitions) provides a greater stimulus for strength gains. He cited four studies [7, 14-16]. The study by Robinson and colleagues [7] was previously discussed.

The study by Willardson & Burkett [14] was not a training study; that is, they simply reported the acute effects of different exercise protocols but did not perform a longitudinal resistance training study and report the chronic effects of the training such as increased strength. Willardson & Burkett compared one, two and three minutes of inter-set rest intervals during five sets of free weight bench press exercise. Sixteen recreationally trained young males performed each of the five sets to *voluntary exhaustion* with 50% 1RM and 80% 1RM. They were instructed to move the resistance as rapidly as possible. In support of their hypothesis, there was a significant decrease in the number of repetitions from the 1st set to the 2nd set and from the 2nd set to the 3rd set for all inter-set rest intervals in both the 50% 1RM and 80% 1RM trials. However, contrary to Willardson and Burkett's hypothesis, there was no significant decrease in repetitions from the 3rd set to the 4th set or from the 4th set to the 5th set for any rest interval or workload. The decrease in the number of repetitions from the 1st set to the 3rd set was significantly greater with the 1-minute rest interval (~77%) compared with the 3-minute rest protocol (~52%) with both the 50% 1RM and 80% 1RM workload.

The primary question is whether the results reported by Willardson & Burkett [14] have any practical application to resistance training. The majority of resistance training studies (see reference 9 for an extensive list of studies) reported no significant difference in strength gains as a result of training with different numbers of repetitions when there is a similar effort on the final repetition of each set. Those results also are strongly supported by the size principle and interpolated twitch studies [8].

A clinically significant application of this study [14] was that the percent decrease in repetitions with 50% 1RM was similar to the decrease with 80% 1RM with all three inter-set rest intervals (76%, 63% and 54%, 1, 2 and 3-minutes intervals, respectively for the 50% 1RM workload; and 78%, 63% and 49%, 1, 2 and 3-minute intervals, respectively for the 80% 1RM workload). Willardson & Burkett [14] corrected their flawed expectation that there would be a greater percent decrease in repetitions with the heavier workload (80% 1RM); that is, they mistakenly believed that the recruitment of fatigue-resistant slow-twitch motor units with the 50% 1RM resistance would cause a significant difference in the percent decrease in repetitions. However, their own results indicated that with the 50% 1RM and 80% 1RM workloads performed to *voluntary exhaustion*, there was a comparable recruitment of slow-twitch and fast-twitch motor units (i.e., smaller and larger motor units). Ironically, their results support the importance of effort (degree of difficulty) on the final repetition of a set rather than any specific

number of repetitions or volume for motor unit activation and subsequent strength gains.

Willardson & Burkett's methodology [14] raises the question of defining the term *voluntary exhaustion*, which was not defined by them. Did the participants *voluntarily* terminate the sets because of some local muscular discomfort or did they attempt to move the resistance despite the discomfort until some physiological *exhaustion* prevented additional repetitions? With the subjects attempting to move the resistance in the free weight bench press as rapidly as possible, should the repetition duration have been monitored and the set terminated at a specific repetition duration; for example, when the repetition duration increased because of fatigue, or decreased because the subjects used greater momentum (mass x velocity)?

If the terms *voluntary exhaustion*, *volitional exhaustion*, *muscular failure* or *muscular fatigue* are included in a study, they should at least be defined by the investigators because these terms are not universally defined and accepted. These terms are italicized throughout this critical analysis to emphasize their importance and lack of actual definitions within each specific study.

The third study cited by Willardson [2] is a training study by Willardson & Burkett [15]. They randomly assigned 15 young males to a 2-minute or 4-minute inter-set rest interval. The participants were consistently performing the free weight squat exercise for a minimum of four years prior to the investigation. The primary purpose was to increase maximal strength and muscle mass. Both groups performed the squat training protocol two times a week (one heavy session and one light session) for 12 weeks. The heavy sessions consisted of two warm-up sets (10 repetitions with 50% and 75% of the resistance for that session) followed by 6-8 sets with 70-90% 1RM. All sets were performed to *volitional exhaustion*. Even though the 4-minute rest group demonstrated significantly higher total volume of work (sets x repetitions x resistance) during the heavy sessions, both groups showed similar significant increases in 1RM squat strength (~18% and 21%, 2-minute and 4-minute groups, respectively), with no significant difference between groups. Willardson & Burkett correctly stated: "*The primary finding of this study was that squat strength gains were not significantly different between groups that rested 2 minutes or 4 minutes between sets*" [p. 149]. Despite the correct claim in their Results section for strength gains in advanced trainees, they erroneously concluded: "*For continued gains in maximal strength, advanced lifters must perform increasingly higher volumes of training*" [p. 151]. Even though their own data did not support that conclusion, they cited three references in an attempt to support that claim [10, 16-17].

The ACSM Position Stand [10] was shown to be a highly flawed document [11]. Reference 16 is

a book, which was cited nine times in the previous review by Willardson [1]. The third reference is another meta-analysis by Rhea and colleagues [17]. A critical analysis [5] of that meta-analysis showed that the conclusions of Rhea and colleagues were illogical, without scientific foundation, and with no practical application to resistance training. The three references [10, 16-17] cited by Willardson [2] failed to support his claim regarding the volume of exercise and strength gains in advanced trainees.

Willardson & Burkett [15] stated: "*Including sufficient rest between sets is essential, particularly when the goal is maximal strength development*" [p. 146]. They cited a review by Weiss [18]. However, Weiss actually concluded that although there is an assumption that a greater volume of exercise – presumably as a result of longer inter-set rest intervals – is a major factor affecting strength gains, "...the magnitude of its importance remains to be demonstrated" [p. 224].

Willardson [2] briefly noted that a training study [19] suggested that as long as a specific threshold volume of exercise is achieved, the inter-set rest interval does not make a systematic contribution to strength gains. However, that threshold was not specified by Ahtiainen and colleagues [19]. Willardson did not discuss the methodology or important results of that study. Ahtiainen and colleagues compared 2-minute and 5-minute inter-set rest intervals (a cross-over design of three months training with each inter-set rest interval) in 13 young males with 6.6 years of continuous resistance training. The participants performed 3-5 sets of Smith machine squats, leg presses and knee extension exercises with a 10RM resistance for the 6-month study. Ahtiainen and colleagues noted that the participants did not have to make drastic changes in their training protocol because the training for this experimental period was similar to what they were previously performing. The main intervention was the change and control of the inter-set rest intervals. There was a significant increase in maximal isometric force and 1RM knee extension for both protocols, with no significant difference between 2-minute and 5-minute inter-set rest intervals. Ahtiainen and colleagues stated: "*When comparing the training protocols independently, the present study showed no differences in the changes in the maximal isometric force, right leg 1RM, or CSA [cross-sectional area] of the quadriceps femoris between the 2 training protocols during the 3-month training periods*" [p. 580].

The review by Willardson [2] presented some evidence for a significant reduction in repetitions when performing multiple sets with the same resistance and shorter inter-set rest intervals. However, he failed to justify his opinion that multiple sets and longer inter-set rest intervals would result in greater strength gains.

de Salles and Colleagues [3]

In a review by de Salles and colleagues [3], they speculated that specific training goals such as muscular strength may depend on the ability to maintain a specific number of repetitions for consecutive sets. They cited the previously discussed review by Willardson [1] and several studies [14, 20-23]. The study by Willardson & Burkett [14] was previously discussed.

There are a series of *experiments* by Kraemer [20] that he retrieved approximately 15 years after he collected the data. In *experiment #1*, Kraemer instructed 20 resistance trained athletes to perform three sets of bench press and leg press exercises with 3-minute inter-set rest intervals. This was followed on another day by a similar protocol using 1-minute intervals. In his Results section Kraemer claimed that the subjects were able to perform three sets of 10RM exercises when they rested three minutes between sets. However, in his Practical Applications section, he claimed that each set was performed to *failure*, but he did not define *failure*. Curiously, 20 strength athletes performed the free-weight bench press and leg press exercises to *failure* with a mean mass of ~141kg and ~225kg, respectively, and they all completed exactly 10 repetitions for each of the three sets for both exercises. Nevertheless, when the rest between sets was reduced to one minute, they performed 10, 8 and 7 repetitions for sets 1, 2 and 3 respectively with the 10RM load. However, neither deSalles and colleagues [3] nor Kraemer [20] noted whether the number of repetitions reported was for the bench press, leg press or a mean of the two exercises.

Although there are those who believe that three sets of 10 repetitions versus three sets of 10, 8 and 7 repetitions, respectively – all performed to muscular *failure* – would have any significant differential effect on strength gains, there is very little evidence to support that belief. In other words, there is no meaningful practical application of Kraemer's formal analysis of his data to resistance training. Kraemer [20] noted also that although there were some important questions in the past years that needed to be addressed, "...for me the answers were initially determined through my role as coach" [p. 131]. His statement is certainly contrary to sound, unbiased, scientific inquiry.

An interesting sidebar concerning *experiment #1* by Kraemer [20] is that he cited one of his earlier studies [24] involving nine young male power lifters and eight young male body builders who were involved in competitive lifting for 4-6 years. He claimed that when the participants used 30-second inter-set rest intervals, the body builders had a much lower percent decrease in the load used for the three sets compared with the power lifters. In fact, Kraemer and colleagues [24] did not report any data for the number of repetitions completed in each set, the inter-set rest interval was

actually only 10 seconds – not 30 seconds, and the load (10RM) remained constant for each of the three sets of 10 upper body and lower body exercises. The power lifters were significantly stronger than the body builders in two of the 10 exercises (bench press and leg press) and their 10RM load was approximately 10% lower than the body builders for those two exercises. There was a significant pre-exercise to post-exercise increase in heart rate, plasma lactic acid, rating of perceived exertion, epinephrine, norepinephrine and dopamine, and a significant decrease in eosinophils and plasma volume in the body builders and power lifters. There was no significant difference between groups for any of these variables. The power lifters reported a significantly higher incidence of dizziness and nausea. However, Kraemer and colleagues concluded: “*There was no significant difference between groups for the total amount of work performed during the entire exercise session*” [p. 249]. Perhaps readers should consider the quality of Kraemer’s accuracy in reporting his own published 10 year-old study to judge his accuracy in reporting his 15 year-old unpublished data.

In another study cited by de Salles and colleagues [3], Richmond & Godard [21] recruited 28 young resistance trained males who could bench press a resistance equal to or greater than their body mass. The participants performed two sets of free weight bench presses for as many repetitions as possible to *volitional exhaustion* with 75% of their predetermined 1RM. They used the same protocol on three separate occasions with 1-minute, 3-minute and 5-minute inter-set rest intervals. There was a significant difference in the number of repetitions between the 1st set (~11.75 repetitions) and 2nd set (~6, 8 and 10 repetitions for the 1-, 3- and 5-minute intervals, respectively), with a significant difference on the 2nd set among the three rest intervals. The authors concluded that if the goal is to maintain a similar number of repetitions on subsequent sets with the same resistance, trainees may require greater than five minutes rest between sets. From an exercise compliance standpoint, their opinion has some limitations regarding session time and its practical application to resistance training. For example, performing a resistance training session consisting of two sets for each of 10 exercises would require a commitment of only about 38 minutes if a 1-minute rest interval were employed. However, it would require a commitment of over two hours a session (~128 minutes) if greater than five minutes rest intervals were used (e.g., ~6 minutes). One would have to present compelling evidence of a significant difference in strength gains to justify such extensive time consuming resistance training sessions and substantially longer sessions if three or more sets were employed. Neither de Salles and colleagues [3] nor Richmond & Godard [21] cited any evidence to justify such a time commitment.

Willardson & Burkett [22] recruited 15 young males who had consistently performed a minimum of three resistance training sessions per week for the previous three years and were classified as experienced lifters. After completing two warm-up sets, the participants performed four sets of free weight squats and bench presses to *voluntary exhaustion* with a predetermined 8RM load. The repetition duration was three seconds eccentric (lowering the resistance) and one second concentric (lifting the resistance). They used 1-minute, 2-minute and 5-minute inter-set rest interval protocols in three separate sessions. The number of repetitions completed for the squat exercise was significantly greater for the 5-minute rest interval compared with the 1-minute and 2-minute rest conditions, with no significant difference between the 1-minute and 2-minute inter-set rest intervals. For the bench press exercise, there were significant differences between all rest intervals, with a greater number of repetitions for the longer inter-set intervals. Willardson & Burkett noted that longer inter-set rest intervals may result in the ability to complete a greater number of repetitions and only a few studies have reported the effect of different inter-set rest intervals on strength gains. They cited only the previously discussed training study by Robinson and colleagues [7] and reported: “*At the conclusion of the study, the 3-minute group demonstrated significantly greater strength gains in the squat (p. < 0.05)*” [p. 25]. As previously discussed however, they failed to report that the only significant difference was between the 3-minute and 30-second rest groups and that there was no significant difference between the 3-minute and 90-second groups.

Miranda and colleagues [23] assigned 14 young males with 6.34 years of resistance training experience to perform six upper body exercises in two sessions that were separated by 48-72 hours. During one session they rested one minute between sets and at another session they rested three minutes between sets. After two warm-up sets, they performed three sets for each of the six free weight and machine exercises in the same sequence (wide grip and close grip lat pull-down, seated row, barbell row, dumbbell and machine biceps curl) with their predetermined 8RM resistance. Subjects were encouraged to perform all sets to *concentric failure*. The researchers did not attempt to control for repetition duration. There was a significant difference in the number of repetitions completed between the 1st and 2nd set for two out of the six exercises, and between the 1st and 3rd set for four of the exercises when they employed the 1-minute inter-set rest interval. There was no significant difference between the 1st and 2nd sets for any of the exercises when they used the 3-minute rest interval, but there was a significant difference between the 1st and 3rd sets in four out of the six exercises. The authors noted that

the majority of exercises showed a significant decrease in the number of repetitions from the 1st to the 3rd sets regardless of the length of the inter-set rest interval.

Miranda and colleagues [23] claimed that they used their specific sequence of exercises because it is very commonly recommended for increasing muscular strength. In fact, a protocol of six exercises in sequence that involves the biceps as the prime mover is not commonly recommended. Exercises that alternate agonist and antagonist muscle groups are more commonly used (e.g., lat pull-down, chest press, seated row, chest flies, etc.). The only reference they cited for their choice of exercise sequence was a study by Pincivero and colleagues [25]. This was not a training study. In fact, Pincivero and colleagues reported on the acute effects of different rest intervals for the thigh muscles, and they did not refer to upper body exercises or any sequence of exercise.

Pincivero and colleagues [25] tested 15 young, previously untrained males and females. They reported a significant reduction in quadriceps and hamstrings peak torque, average power, and total work after performing four sets of 10 maximal concentric reciprocal knee extension and flexion repetitions in a group that employed 40-second inter-set rest intervals. Not surprisingly, there was no significant reduction in any of these variables for another group who used 160-second rest intervals. Pincivero and colleagues concluded that the duration of the inter-set rest interval and its impact on torque production may influence strength gains. They did not cite any references to support their opinion regarding strength gains. It should be recognized that 10 maximal concentric repetitions on an isokinetic dynamometer are quite different from a 10RM performed with free weights or on a weight resistance machine where only the last repetition is a maximal effort, and that very brief 40-second inter-set rest intervals are not usually prescribed in typical resistance training programs. Regarding their opinion on the duration of inter-set rest intervals affecting strength gains, Pincivero and colleagues astutely stated: "*Such a hypothesis, however, warrants continued investigation into the area of training and rehabilitation*" [p. 155].

Similar to the reviews by Willardson [1-2], de Salles and colleagues [3] reported a significant decrease in the number of completed repetitions for some subsequent sets with a few exercises when different inter-set rest intervals were employed [14, 20-23]. However, only one of these studies controlled for repetition duration during the performance of multiple sets [22], none controlled for repetition duration during the initial strength assessment (1RM or 8RM), and none actually defined their terms *failure*, *volitional exhaustion*, *voluntary exhaustion*, or *concentric failure*. Although these resistance training variables may not have a significant effect on chronic adaptations to resistance training, they

are relevant and should be controlled for an accurate assessment and comparison of acute outcomes (e.g., recording the number of repetitions with specific RMs that employ different inter-set rest intervals).

de Salles and colleagues [3] noted that in some studies the resistance was decreased with subsequent sets of exercise in order to maintain a specific number of repetitions (e.g., 10RM) throughout the execution of multiple sets. They claimed that this decrease in resistance may not provide an adequate stimulus for the higher threshold motor units and "*Longer rest intervals may allow for maximal voluntary activation of motor units and maintenance of training intensity*" [p. 773]. They failed to cite any studies to support their claims. In fact, their opinions are typical examples of the misinterpretation of the size principle of motor unit activation.

Motor units are activated through a continuum of lower threshold to higher threshold motor units and activation is dependent on the effort (the degree of difficulty in performing the repetitions) – not the absolute amount of resistance or number of repetitions [8-9]. For example, if an individual executes three sets of 10RM for an exercise with a specific inter-set rest interval (e.g., 1 minute) and the resistance is reduced by approximately 10% for the second and third sets (e.g., 50kg, 45kg and 40.5kg, sets 1, 2 and 3, respectively), the motor unit activation is similar for the three sets because by definition all three sets required a maximal effort (RM). Similarly, if longer inter-set rest intervals were employed (e.g., 5 minutes), a few studies reported that for some exercises the longer rest interval permitted the execution of three sets with the same resistance (e.g., 50kg for the three sets of 10RM), or three sets of RMs with a decreasing number of repetitions (e.g., 10RM, 8RM and 7RM, sets 1, 2 and 3, respectively). If each set was performed with a similar effort in each of these examples, the motor unit activation would be similar for the three sets – and more importantly – similar to the motor unit activation with the shorter inter-set rest intervals.

In an attempt to support their claim that longer inter-set rest intervals result in greater strength gains, de Salles and colleagues [3] cited the previously discussed studies by Pincivero and colleagues [6] and Robinson and colleagues [7], and incorrectly reported the results – as did Willardson [1]. The only other training study cited was by Willardson & Burkett [15], who as previously noted, concluded that the strength gains were not significantly different between 2-minute and 4-minute inter-set rest groups. de Salles and colleagues followed their discussion of these three training studies with an illogical conclusion that these studies suggested that longer rest intervals result in significantly greater strength gains than shorter rest intervals. They failed to support that conclusion.

In addition to the aforementioned studies [6-7, 14-15, 19-25] cited in the previously discussed reviews [1-3], there are a few other noteworthy studies that reported the number of repetitions or volume of exercise as a result of different inter-set rest intervals. Miranda and colleagues [26] recruited 12 young males with at least two years of recreational resistance training experience to perform three sets for each of five upper body exercises with their predetermined 8RM resistance. The subjects completed the exercises with 1-minute inter-set rest intervals in one session and 3-minute intervals at another session. Although there was no attempt to control for repetition duration, subjects were encouraged to perform all sets to *voluntary exhaustion*. Volume of exercise (sets x resistance x repetitions) was recorded for all the exercises in the 1-minute and 3-minute inter-set rest interval sessions. The total volume of exercise was significantly greater for the 3-minute rest interval than the 1-minute rest interval session. With the 1-minute rest intervals there was a significant reduction in the number of completed repetitions between the 1st and 2nd sets for three out of the five exercises, and between the 2nd and 3rd sets for two of the exercises. With the 3-minute rest intervals there was a significant difference in the number of repetitions between the 1st and 3rd sets in four exercises but no significant difference between the 1st and 2nd sets or between the 2nd and 3rd sets for any exercise. The results suggest that the shorter inter-set rest interval in this study showed a significantly greater decrease in repetitions for some of the exercises. The authors concluded: "*The results of this study may have the greatest relevance to programs designed for maximal strength for maintenance of the load and repetitions per set*" [p. 391]. However, they failed to cite any evidence to support their claim that a greater volume of exercise in itself will produce greater strength gains.

Rahimi [27] compared the number of completed repetitions during four sets of the free weight squat with 85% 1RM. Twenty resistance trained young males used 1-minute, 2-minute and 3-minute inter-set rest intervals on three occasions that were separated by one week. The repetition duration was a 3-second eccentric phase and 1-second concentric phase. There was no indication of how each set was completed; e.g., a maximal effort of the last repetition or the inability to maintain repetition duration. Rahimi claimed that the 5-minute rest condition allowed a significantly greater volume of exercise for the four sets compared with the 1-minute and 2-minute rest conditions, with no significant difference between 1-minute and 2-minutes rest. He referred to his Table 1 [p. 363]. However, after defining *volume* in his Introduction section as the total number of repetitions multiplied by the resistance, his Table 1 specifically labels each column as the number of repetitions completed. Consequently, his Table 1 does not show the *volume* of exercise as he defined it.

The 6th column in his Table 1 is labeled *Total (reps)*. In fact, the data in that column are not the total number of repetitions; they are the average number of repetitions performed during the four sets (4.55, 5.1 and 6.17 repetitions for the 1-minute, 2-minute and 5-minute conditions, respectively). More importantly, Rahimi did not indicate if the average number of completed repetitions was significantly different for any inter-set rest interval.

Rahimi [27] claimed that a higher volume of training with a specific resistance may stimulate greater strength gains and that resistance trained athletes must perform exercises with maximal or near maximal resistance for repeated efforts (multiple sets) in order to increase muscular strength. His claim is without any scientific foundation.

In another study by Rahimi and colleagues [28] they recruited 11 young male body builders who had trained at least three times a week for the previous two years. The subjects performed four sets of military press, bench press, arm curl, and leg press exercises with 85% of their predetermined 1RM. They performed each set for the maximal number of repetitions using a 1-second concentric and 2-second eccentric repetition duration. One exercise was performed at each of the exercise sessions with 1-minute, 2-minute, and 5-minute inter-set rest intervals. The number of completed repetitions for each of the four exercises was significantly greater for the 5-minute inter-set rest interval compared with the 2-minute and 1-minute protocols. There was no significant difference in the number of completed repetitions between the 1-minute and 2-minute rest interval protocols for any of the exercises.

Rahimi and colleagues [28] claimed that performing a greater volume of exercise (a greater number of repetitions with a given load) stimulates greater strength gains and muscular hypertrophy. They cited two references [7, 27]. The training program by Robinson and colleagues [7] was previously discussed. The aforementioned study by Rahimi [27] reported the acute responses to different inter-set rest intervals but was not a training study. Consequently, these studies do not support the claim by Rahimi and colleagues that a greater number of repetitions with a given load stimulates optimal strength gains and muscular hypertrophy.

Senna and colleagues [29] recruited 14 young males with at least one year of resistance training experience. All the subjects performed three sets for each of three upper body exercises (bench press, pec-deck and triceps push-down) and three lower body exercises (leg press, knee extension and thigh curl) with their predetermined 10RM. The four experimental sessions consisted of 2-minute and 5-minute inter-set and inter-exercise rest intervals for each of the upper body and lower body sessions. They were instructed to perform the maximal

number of repetitions in each set until they could no longer move the resistance in the concentric phase. The researchers did not attempt to control for repetition duration either during the 10RM assessment or the four trial sessions. The total number of repetitions for all the sets and exercises in a session was significantly greater with the 5-minute inter-set rest intervals compared with the 2-minute rest intervals for both the upper body and lower body exercises.

Senna and colleagues [29] claimed that the ability to maintain a constant number of repetitions for subsequent sets of exercise with a specific amount of resistance can result in greater strength gains. They cited two references [1, 15] in an attempt to support their opinion. The reference by Willardson [1] is the previously discussed review, and the training study by Willardson and Burkett [15] reported no significant difference in strength gains between the 2-minute and 4-minute inter-set rest groups – as previously noted in this critical analysis. Therefore, neither reference supported their claim that a greater volume of exercise (more repetitions with a specific resistance) produces greater strength gains. In fact, the results reported by Willardson and Burkett are antithetical to the claim by Senna and colleagues. In their Key Points section, Senna and colleagues stated: “*An important variable when maximal strength is desired is the volume of repetitions or total work*” [p. 201]. They failed to cite any evidence to support that claim.

Bottaro and colleagues [30] recruited 12 young females with seven years of resistance training experience. With their predetermined 10RM load, the participants performed three sets for each of four exercises: knee extension, hack squat, knee flexion, and leg press. They exercised with 30-second, 1-minute and 2-minute inter-set rest intervals on three occasions. Blood samples were taken at rest, immediately, 5, 15 and 30 minutes after the end of each session to assess growth hormone and cortisol responses. The post-exercise elevations in growth hormone were significantly greater following the 30-second rest intervals compared with the 1-minute and 2-minute rest intervals, with no significant difference between the 1- and 2-minute conditions. The cortisol responses were not significantly different among the three protocols. Perhaps the most important point of this study was the concluding statement by Bottaro and colleagues: “*The adaptational importance of an augmented growth hormone response to a resistance exercise protocol remains to be determined*” [p. 76]. Acute elevations in endogenous hormones and their alleged effect on strength gains are discussed in a subsequent section in this critical analysis.

Rodrigues and colleagues [31] recruited 20 previously untrained young males to perform three sets for each of five upper body free weight and machine exercises (barbell bench press, lat pull-down, military

press, triceps machine, and free weight biceps curl). Participants used 1-minute and 3-minute inter-set and inter-exercise rest intervals in two testing sessions separated by 72 hours. They used 80% of their predetermined 1RM and completed each set to *voluntary exhaustion*. No attempt was made to control for repetition duration during the 1RM assessment or the trial sessions. Serum creatine kinase (CK) and lactate dehydrogenase (LDH), which are enzyme markers of muscle damage, were measured before exercise and 24, 48 and 72 hours after exercise. Their hypothesis was that different inter-set rest intervals would elicit significant differences in CK and LDH concentrations. Although the volume of exercise (resistance x repetitions x sets) was significantly greater with the 3-minute rest intervals for four of the exercises, there was no significant difference between the 1-minute and 3-minute rest intervals in either CK or LDH concentrations at any time. The authors concluded that the lack of any significant difference in enzyme responses between exercise protocols was because the higher volume of exercise with the 3-minute rest intervals was balanced by a higher metabolic demand with the 1-minute rest intervals. They rejected their hypothesis that different inter-set rest intervals would invoke different CK and LDH responses.

Rodrigues and colleagues [31] concluded: “*The results of the current study indicate that muscle damage, as indicated by CK and LDH concentrations, was similar when resistance exercises were performed to voluntary exhaustion in untrained subjects, despite significant differences in the volume of exercise completed*” [p. 1661]. They described the alleged muscle damage: “*For SEQ3 [3-minute inter-set rest intervals], the stimulus [for muscle damage] may have been a greater volume load completed. Thus subjects’ muscles were subjected to a greater volume of work during SEQ3, leading to physical disruption of myofibrils and subsequent elevations in markers of muscle damage. Conversely, for SEQ1 [1-minute inter-set rest intervals], the stimulus may have been the accumulation of protons and reactive oxygen species, induced through increased acidosis in the exercising muscles*” [p. 1661]. However, Rodrigues and colleagues did not cite any evidence to suggest that muscle damage – as indicated by the enzymes CK and LDH – is a necessary component or a stimulus for increases in muscular strength or hypertrophy. Therefore, their results have very little practical application to resistance training.

In a study by Simao and colleagues [32], eleven young males with at least two years of resistance training experience performed three sets of chest press and leg press exercises to *fatigue* with their predetermined 10RM. Subjects used 1-minute, 3-minute and 5-minute inter-set rest intervals in three sessions separated by one week. The researchers did not control for repetition

duration during the 10RM assessment or the repetitions performed to *fatigue*. There was a significant decrease in the total number of completed repetitions in the 2nd and 3rd sets for both exercises with all the inter-set rest intervals. The total number of repetitions was significantly greater with the 3-minute and 5-minute intervals compared with the 1-minute interval for both exercises. There was no significant difference in the number of repetitions between the 3-minute and 5-minute protocols for either exercise.

Simao and colleagues [32] noted that the total volume of exercise, which they defined as the number of completed repetitions for multiple sets with a specific resistance, is affected by the inter-set rest interval and then claimed that the greater volume affects the degree of strength gains and muscle hypertrophy. They cited two studies [19, 33] in an attempt to support that claim. The previously discussed study by Ahtiainen and colleagues [19] reported no significant difference in strength gains or muscle cross sectional area as a result of training with 2-minute and 5-minute inter-set rest intervals. The study by Weir and colleagues [33] reported no significant difference in repeated 1RM bench press after resting for 1, 3, 5 or 10 minutes between attempts in 16 young males with at least two years of resistance training experience. This was not a training study and therefore does not support the claim by Simao and colleagues. The training study by Ahtiainen and colleagues showed that a greater volume of exercise with the longer inter-set rest intervals did not elicit greater strength gains or muscle hypertrophy.

Mirzaei and colleagues [34] recruited 17 young males with at least three years of resistance training experience. The subjects performed four consecutive sets of the barbell bench press with 60% and 90% of their predetermined 1RM. During six sessions, which were separated by 48 hours, they used 1.5-minute, 2.5-minute and 4-minute inter-set rest intervals with each load. They were instructed to move the resistance as rapidly as possible until the point of *voluntary exhaustion*. There was a significant decrease in the number of completed repetitions from the 1st set to the 4th set for all inter-set rest intervals with both the lighter (60% 1RM) and heavier (90% 1RM) loads. The sustainability of performing repetitions was significantly greater with the longer inter-set rest intervals with both loads. The authors concluded: "*The ability to sustain repetitions while keeping the intensity [load] constant may result in a higher training volume and, consequently, greater gains in muscular strength...*" [p. 15]. Although the results support their claim for higher training volume with longer rest intervals, they did not cite any evidence to suggest that the higher volume would produce greater strength gains.

In another study by Mirzaei and colleagues [35], they recruited 18 young males with at least three years of resistance training experience. The participants per-

formed four sets of barbell squats with 60% and 90% of their predetermined 1RM. They used 1.5-minute, 2.5-minute and 4-minute inter-set rest intervals. The load and rest intervals were randomized for the six sessions. Repetition duration was a 3-second eccentric phase and 1-second concentric phase. However, the authors noted that because of fatigue, the duration of the concentric phase increased toward the end of each set and ranged from one to three seconds until the subjects reached *voluntary exhaustion*. There was a significant difference between the 1.5-minute and 4-minute rest protocols and between the 2.5-minute and 4-minute protocols in the ability to maintain the number of completed repetitions in subsequent sets with both the 60% 1RM and 90% 1RM loads. There was no significant difference between the 1.5-minute and 2.5-minute inter-set rest intervals. For example, the average number of repetitions was approximately six for the 1st set and decreased during the 4th set to an average of two, two and four repetitions, 1.5-minute, 2.5-minute and 4-minute rest intervals, respectively.

Mirzaei and colleagues [35] claimed that studies reported that strength gains with different inter-set rest intervals have shown greater strength gains with longer inter-set rest intervals. They cited only two studies [6-7], which were previously discussed in this critical analysis. Mirzaei and colleagues noted that in the study by Pincivero and colleagues [6], they reported that longer inter-set rest intervals produced greater strength gains. However, there was no significant difference between the 40-second and 160-second rest interval groups for 12 out of the 14 measured outcomes. Mirzaei and colleagues also claimed that Robinson and colleagues [7] demonstrated that 3-minute rest intervals were superior to 90-second and 30-second rest intervals for producing strength gains in the free weight squat. In fact, the strength gains in the squat were significantly greater in the 3-minute group compared with the 30-second group. However, there was no significant difference in strength gains between the 3-minute and 90-second rest groups or between the 90-second and 30-second rest groups. Neither of these training studies cited by Mirzaei and colleagues supports the concept that there is a linear continuum of longer inter-set rest intervals and greater strength gains. Another question, which is beyond the scope of this critical analysis, is whether four consecutive sets of any exercise are necessary to stimulate optimal strength gains.

Larson and Potteiger [36] recruited 15 young males with at least one year of resistance training experience and who could perform 10 repetitions in the squat exercise with 1.25 times their body mass. The participants performed four consecutive sets of barbell squats with 85% of their predetermined 10RM to *voluntary exhaustion*, which was described as the point where a repetition could not be completed with proper technique. The

repetition duration for the 10RM assessment and the three trial sessions was two seconds eccentric and three seconds concentric. Three inter-set rest intervals were counterbalanced: three minutes, time to achieve post-exercise recovery heart rate equal to 60% age-predicted maximal heart rate, and a work (exercise) to rest ratio of 1:3. They calculated the recovery time (inter-set rest interval) by multiplying the exercise time by three for each set. The rest time for the work to rest ratio was 234, 163, 125, and 102 seconds for sets 1-4, respectively. Although the authors did not report the exercise time for each set, the percent decrease in the number of repetitions between subsequent sets is identical to the percent decrease in recovery time between sets. For each inter-set rest interval condition the number of complete repetitions significantly decreased for each subsequent set. There was no significant difference among the three rest intervals for the decrease in repetitions and no significant difference in total repetitions for the four sets (~41, ~43 and ~42 repetitions, 3-minute, post-exercise HR recovery, and 1:3 work:rest ratio, respectively). The authors concluded: "*The repetitions performed for each condition were similar despite differences in recovery time*" [p. 117].

There also are several resistance training textbooks [37-41] written by well-known physiologists who also claimed that different inter-set rest intervals significantly affect strength gains. For example, to optimize muscular strength these experts recommended minimal inter-set rest intervals of 2-3 minutes [37], 3-5 minutes [38-39], 4-5 minutes [40], and 3-7 minutes [41]. However, none of these authors cited any resistance training studies to support their opinion regarding inter-set rest intervals and strength gains.

In the first issue of the *Journal of Applied Sport Science Research* [42] in 1987, which in 1993 became the *Journal of Strength and Conditioning Research*, Knuttgen and Kraemer (Kraemer was and still is the Editor-in-Chief of that journal) stated: "*It will be the objectives of the authors of this technical report to consider and discuss terminology related to both muscle contraction and resistance exercise and present a set of definitions for suitable and accurate terminology*" [p. 1]. They stated: "*The resistance (mass of the free weight) at which the subject could perform only one lift and not be able to repeat it is termed the one repetition maximum or 1RM*" [p. 7]. They specifically noted: "*Because of the problems involved with the term strength meaning different things to different people, it is proposed by the authors that the term strength be employed to refer to the maximal force a muscle or muscle group can generate at a specified velocity*" [p. 6]. The key phrase is *specified velocity* (repetition duration). Knuttgen and Kraemer also stated that in order to accurately assess the relationship between the number of repetitions and the 1RM for a specific exercise, a metronome should be used to maintain a constant

cadence (repetition duration). They concluded: "*The terminology described and the definitions proposed are presented for the purpose of bringing a combination of clarity and precision to the description of various forms of resistance exercise*" [p. 10].

With the exception of the aforementioned study by Larson and Potteiger [36], readers would be challenged to locate studies published in the *Journal of Strength and Conditioning Research* or any other journal over the last 23 years where the researchers controlled for velocity of movement or repetition duration while testing the 1RM with free weights or traditional resistance exercise machines. Because the 1RM is very often reported as the measure of muscular strength from pre-training to post-training (as will be discussed in the next section of this critical analysis), failure to control this variable (repetition duration) may significantly compromise the accuracy of the 1RM assessments or other RMs such as a 3RM, 5RM, 10RM, etc.

Any increase or decrease in repetition duration, especially at the beginning of the concentric phase, which may be a weaker position in the range of motion for some exercises, affects the amount of momentum (mass x velocity) used to perform the lift. Differences in momentum can affect the ability to lift a specific amount of maximal resistance (1RM) or influence the number of repetitions performed with a specific resistance. Sakamoto and Sinclair [43] recruited 13 young males with 3.9 years of resistance training experience. During five randomly assigned sessions, all the subjects completed as many repetitions as possible on a Smith machine bench press. There were five resistance loads (40, 50, 60, 70 and 80% of the predetermined 1RM) executed at four different repetition durations, concentric and eccentric phases, respectively: slow (2.8 and 2.8 seconds), medium (1.4 and 1.4 seconds), fast (1.0 and 1.0 seconds), and ballistic (as fast as possible). They did not allow the subjects to pause during the transitions from the concentric to eccentric or eccentric to concentric phases. Subjects were instructed to continue lifting until *failure*, which was defined as the inability to attain full elbow extension. As the subjects fatigued during the sets, they were unable to maintain the assigned repetition duration but were further encouraged to complete as many repetitions as possible.

There was a significantly greater number of completed repetitions with the shorter repetition durations with the five different amounts of resistance (40-80% 1RM). There was no significant difference between the fast and ballistic conditions. Sakamoto and Sinclair [43] concluded: "*This study clearly showed that the relationship between intensity [% 1RM] and the number of repetitions was affected by movement velocity [repetition duration] and that a faster velocity [shorter repetition duration] resulted in more repetitions being performed*" [p. 526].

Studies that used the free weight bench press exercise reported a significant difference in repetition duration for each subsequent repetition when performing a 5RM [44] and when performing repetitions to *fatigue* with 60%, 65%, 70% and 75% 1RM – even when the subjects were instructed to move the bar as fast as possible for each repetition [45].

These results are relevant for acute studies that have reported the number of completed repetitions at a specific percent of the 1RM (as discussed in this section of the critical analysis) when the repetition duration or velocity for a specific range of motion is not controlled.

Section Summary

Several studies have reported a significant reduction in the number of completed repetitions during the execution of multiple sets with some exercises when shorter versus longer inter-set rest intervals were employed and a greater acute increase in endogenous hormones with shorter inter-set rest intervals. However, these investigators failed to support their claims that a decrease in the number of repetitions or the absolute amount of resistance for subsequent sets significantly affects strength gains. These unsupported claims are based perhaps on a misinterpretation of the size principle of motor unit activation and an unsubstantiated belief that a high volume of exercise (resistance x repetitions x sets) will produce superior strength gains.

Adaptations to Resistance Training with Different Inter-Set Rest Intervals

Several studies have actually investigated the effect of different inter-set rest intervals on strength gains. The training studies by Pincivero and colleagues [6], Robinson and colleagues [7], Willardson & Burkett [15], and Ahtiainen and colleagues [19] were previously discussed.

Gentil and colleagues [46] recruited 40 previously untrained but physically active young males who were randomly assigned to one of two training groups. Half the subjects rested two minutes between sets and the others rested four minutes between sets. All the participants performed two sets of 8-12 repetitions for each of five upper body and lower body free weight and machine exercises two times a week for 12 weeks. The repetition duration was two seconds concentric and two seconds eccentric. All the sets were performed to *volitional fatigue*. Upper body and lower body strength was assessed with 1RM bench press and leg press exercises, respectively, pre-training and post-training. Both groups significantly increased 1RM bench press and leg press. There was no significant difference in strength gains between groups for either exercise. Gentil and colleagues concluded that the 2-minute rest

group attained significant strength gains similar to the 4-minute rest group and they spent half the time in the gym (~18 minutes compared with ~ 36 minutes, 2-minute and 4-minute groups, respectively).

de Salles and colleagues [47] recruited 36 young males with a minimum of four years of continuous resistance training and randomly assigned them to 1-minute, 3-minute or 5-minute inter-set rest interval resistance training protocols. The 1RM bench press and leg press were assessed pre-training and post-training. Participants performed three sets for each of eight upper body free weight and machine exercises in one session and five lower body machine exercises in another session. Both sessions were completed two times a week for 16 weeks. They alternated the resistance between 4-6RM and 8-10RM with each session and all sets were continued to *volitional exhaustion*. The 5-minute inter-set rest group showed a significantly greater increase in bench press 1RM than the 1-minute group, with no significant difference between the 1-minute and 3-minute groups or between the 3-minute and 5-minute groups. The increase in 1RM leg press was significantly greater for the 3-minute and 5-minute groups compared with the 1-minute group, with no significant difference between the 3-minute and 5-minute groups. Although there were some significant differences in strength gains among the groups, the statement in their Practical Applications section claiming that the 3-minute and 5-minute inter-set rest intervals resulted in greater upper-body and lower-body strength gains is not supported by their own results; that is, there was no significant difference between the 3-minute and 1-minute groups in upper body strength gains. As they did in their previously discussed review [3], de Salles and colleagues again incorrectly reported the results of studies by Pincivero and colleagues [6] and Robinson and colleagues [7].

Simao and colleagues [48] assigned 12 young males with at least four years of resistance training experience to either a 1-minute or 3-minute inter-set rest interval resistance training protocol. All the participants performed three sets of 10RM for each of seven upper body and lower body exercises (bench press, leg press, biceps curl, hack squat, lat pull-down, triceps push-down, and abdominal) three times a week for eight weeks. There was a significant increase in bench press, leg press and biceps curl strength (10RM) for both groups. However, there was no significant difference between groups for any of the strength gains. Simao and colleagues stated: “*We conclude that independent of rest interval, no significant differences were observed in 10RM loads in RE [resistance exercise] during eight weeks*” [p. 353].

Buresh and colleagues [49] randomly assigned 12 previously untrained young males to either a 1-minute inter-set rest interval or a 2.5-minute inter-set rest

interval resistance training program. Participants performed 2-3 sets of 8-11 repetitions for nine upper body and lower body exercises in one session and seven other upper body exercises in another session. Both sessions were completed two times a week for 10 weeks. Smith machine squat and bench press 5RM were assessed pre-training and post-training. There was no significant difference in the pre-exercise to post-exercise change in testosterone, cortisol or growth hormone at the end of the 10-week study. Although the 2.5-minute rest group had a significantly greater increase in arm muscle cross-sectional area compared with the 1-minute rest group, there was no significant difference between groups for the increase in thigh muscle cross-sectional area, 5RM bench press or 5RM squat. The authors noted that the 2.5-minute rest group had lower arm cross-sectional area at the beginning of the study and that because of this difference they may have had a greater potential for muscular hypertrophy. The only other significant difference between groups was that the 2.5-minute rest group's weekly training time (~258 minutes) was significantly greater (~100 minutes longer) than the 1-minute rest group (~158 minutes). Buresh and colleagues concluded: *"These findings suggest that, at least in the early stages of a resistance training program, changes in lean tissue and strength may be mediated more strongly by factors other than the magnitude of hormonal response induced by the training"* [p. 70].

de Souza and colleagues [50] randomly assigned 20 young males with at least one year of resistance training experience to either a constant rest interval (2 minutes) between sets and exercises (group CI) or a decreasing rest interval group (group DI) whose rest intervals between sets and exercises gradually

decreased (120, 105, 90, 75, 60, 45 and 30 seconds) as training progressed over the eight weeks. All the subjects performed three sets of 10-12RM for each exercise during the first two weeks and four sets of 8-10RM during the next six weeks. Each of the 10 free weight and machine upper body exercises (including the free weight bench press) and four lower body exercises (including the free weight squat) were performed two times a week using a six-day a week split routine. Total training volume for all the sessions over the eight weeks for the bench press and the squat was significantly greater for the CI group. Both groups showed a significant increase in 1RM bench press and 1RM squat, knee extensor and flexor isokinetic peak torque, and arm and thigh cross-sectional area (CSA) assessed with MRI. de Souza and colleagues concluded: *"The results showed no significant differences in strength or muscle CSA gains because of the different training protocols"* [p. 6].

Section Summary

Nine studies [6-7, 15, 19, 46-50] reported the strength gains as a result of training with different inter-set rest intervals. Only three studies [6-7, 47] reported significantly greater strength gains for some exercises in the groups that used longer inter-set rest intervals compared with very brief inter-set rest intervals (Table 1).

Hormonal Responses and Strength Gains

Several studies by the same lead author have reported the acute endogenous hormonal responses to 1-minute and 3-minute inter-set rest intervals with loads of 5RM and 10RM [51-53]. All the young participants,

Table 1. Results of resistance training with different inter-set rest intervals

Reference	Status	Inter-set rest intervals	Strength gains
Pincivero et al. [6]	Untrained	40 or 160 seconds	*160 > 40 in 2 out of 14 measured variables LB
Robinson et al. [7]	Trained	30, 90 or 180 seconds	*180 > 30 LB NSD 180 vs 90, 90 vs 30 LB
Willardson & Burkett [15]	Trained	2 or 4 minutes	NSD LB
Ahtiainen et al. [19]	Trained	2 or 5 minutes	NSD LB
Gentil et al. [46]	Untrained	2 or 4 minutes	NSD UB or LB
de Salles et al. [47]	Trained	1, 3 or 5 minutes	*5 > 1 UB NSD 1 vs 3 UB NSD 3 vs 5 UB *5 > 1, *3 > 1 LB NSD 3 vs 5 LB
Simao et al. [48]	Trained	1 or 3 minutes	NSD UB or LB
Buresh et al. [49]	Untrained	1 or 2 minutes	NSD UB or LB
de Souza et al. [50]	Trained	2 minutes or 120-30 seconds	NSD UB or LB

*Significantly greater strength gains between groups

NSD = no significant difference in strength gains between groups

UB = upper body exercises, LB = lower body exercises

who were resistance trained but not competitive lifters, performed multiple sets of eight upper and lower body resistance exercises. The hormonal responses for the males [51], females [52], and males and females [53] were similar in the three studies. The 1-minute inter-set rest intervals with the 10RM load produced significantly greater acute growth hormone responses compared with the 3-minute rest intervals and the heavier 5RM load. There was no significant difference among the resistance training protocols for changes in testosterone. In these three studies the authors noted that although growth hormone responses appear to be the most sensitive to different resistance training protocols, they each concluded: *"Still whether subsequent adaptations are related to the acute temporal increases or the more prolonged time integrated increases during a recovery time period remains unknown"* [51, p. 1447]; *"Furthermore, the role of anabolic hormones in mediating the chronic adaptations of protein accretion and muscle hypertrophy resulting from heavy-resistance training requires further study"* [52, p. 602]; and *"The adaptational effects of such differential hormonal responses to heavy resistance exercise on cellular adaptations in muscle, connective tissue, and bone remain to be determined"* [53, p. 234].

More than two decades ago Kraemer [54] proclaimed that assessing hormonal responses to different exercise protocols is necessary to identify specific exercise variables that alter circulating hormonal concentrations. He cited the previously discussed article by Knuttgen and Kraemer [42]. However, Knuttgen and Kraemer did not even mention the word hormone or the phrase hormonal responses in their article. Consequently, Kraemer's reference to the Knuttgen and Kraemer article failed to support his claim regarding hormonal responses.

Kraemer [54] stated: *"The exact contribution of exercise-induced alterations of GH to muscle tissue growth and the importance of heavy resistance exercise as an exercise modality used to elicit these changes remain to be determined"* [p. S154]. The influence of exercise induced endogenous hormone responses on strength gains still remains to be determined.

Despite the lack of evidence to support any cause and effect relationship between acute hormonal responses and strength gains, some resistance training experts have expressed their opinion that it is important to create a high endogenous hormonal environment to optimally enhance strength gains. For example, in a lengthy review of hormonal responses and adaptations to resistance training, Kraemer and Ratamess [55] claimed that larger muscle group exercises should be performed prior to smaller muscle group exercises early in the training session to elicit greater hormonal responses, which in turn, would expose smaller muscles to a greater hormonal envi-

ronment and result in optimal strength gains. They cited three studies [56-58] in an attempt to support their claims. The study by Ahtiainen and colleagues [56] reported acute hormonal and neuromuscular responses to two resistance exercise protocols in 16 recreationally trained young males. Four sets of leg presses, two sets of squats, and two sets of knee extension exercises with the 12RM were compared to the same protocol but with the 12RM plus ~15% additional resistance. The heavier load required assistance from spotters for 3-5 repetitions in order to complete the 12 repetitions. Both protocols resulted in significant increases in growth hormone, testosterone and cortisol, with a significantly greater increase in growth hormone and cortisol following the heavier resistance protocol. However, this was not a training study and therefore is not relevant to the purported cause and effect relationship between acute hormonal responses and chronic adaptations such as strength gains.

Another study by Ahtiainen and colleagues [19], which was previously discussed in this critical analysis, reported the acute and chronic hormonal responses to different inter-set rest intervals and their effect on strength gains and muscular hypertrophy. Recall that they compared 2-minute and 5-minute inter-set rest intervals in young males with 6.6 years of continuous resistance training. Ahtiainen and colleagues stated: *"The present study shows that the present hypertrophic SR [short rest] and LR [long rest] protocols induced similar acute hormonal and neuromuscular responses and the length of the recovery times (i.e., 2 and 5 minutes) between the sets did not influence the magnitude of these responses. The present study also shows that long-term training adaptations in muscle strength and mass did not differ between the 2 hypertrophic strength-training protocols examined in the group of young men with a background in strength training"* [p. 581].

In the second study cited by Kraemer and Ratamess [55], Guezennec and colleagues [57] recruited 11 young male weight-trained athletes with at least one year of regular resistance training experience. The participants performed 3-4 sets of 10 repetitions with 70% 1RM for 3-4 exercises per session 3-4 times a week for one month. During the next 3-4 months, the resistance was increased to 95% 1RM and the number of repetitions was reduced to three. Hormone levels were assessed every month after performing six sets of eight repetitions in the bench press exercise with 70% 1RM (designated as the *submaximal test*) and was followed by one set for the maximal number of repetitions possible with 70% 1RM (designated as the *maximal test*). Kraemer and Ratamess incorrectly described the exercise protocol as *conventional strength training* (3-4 sets of 3-10 repetitions with 70-90% 1RM) followed by an increased load for three repetitions. They also claimed that there were minor

elevations in testosterone during the *conventional* training, and a limited testosterone response with the heavier training. In fact, there was no significant difference in testosterone after the submaximal or maximal tests at any time during the study [57]. The 1RM free weight bench press significantly increased approximately 17% from pre-training to post-training but the authors did not report any 1RM comparisons between the so-called *conventional* training and the heavier (~95% 1RM) resistance training. This was not a comparative training study. Guezennec and colleagues concluded: "*From these data, there is no reason to suspect a role of androgens in the improvement of performance*" [p. 104].

There was only one resistance training study cited by Kraemer and Ratamess [55] that compared different training groups. Hansen and colleagues [58] trained the elbow flexors in 16 young, previously untrained males. The participants were divided into two groups (random assignment not noted) who performed four sets of unilateral seated biceps curls and four sets of standing biceps curls for 8-12 repetitions (~10RM) with a decrease in resistance every two sets. In addition to the biceps curls, one group then performed eight sets of 10RM leg presses (8-12 repetitions) with one minute inter-set rest intervals and decreasing resistance every two sets. The authors noted that the purpose of the lower body protocol (decreasing the resistance) was to maintain the range of repetitions using the 1-minute inter-set rest interval and stimulate a high hormonal response. All the participants trained two times a week for nine weeks. Their protocol is contrary to what was described by Kraemer and Ratamess; that is, they incorrectly claimed that the group "*...performed lower-body exercises prior to the elbow flexion exercises*" [p. 342]. The participants who performed lower body exercise in addition to the arm exercises actually performed the lower body exercises after the arm exercises.

Kraemer and Ratamess [55] also reported: "*...testosterone was significantly elevated when lower-body exercises were performed first, and muscle strength increased to a greater extent...*" [p. 342]. As noted, the lower body exercises were performed after the elbow flexion exercises. The arm plus lower body exercise group showed a significant increase in testosterone, growth hormone and cortisone pre-exercise to post-exercise and a significant increase in isometric elbow flexion strength pre-training to post-training. There was no significant increase in testosterone in the arm-only exercise group and no significant increase in isometric strength for the arm-only exercise group. Hansen and colleagues [58] did not question why their previously untrained young male participants in the arm-only training group did not show any significant increase in isometric strength after performing

eight sets of biceps curls two times per week for nine weeks.

Kraemer and Ratamess [55] neglected to note that initial isometric arm strength in the arm plus lower body exercise group was significantly lower (20-25%) than the arm-only exercise group. Hansen and colleagues [58] cautioned that "*...one should be careful when interpreting the results because the two groups did not have the same initial starting strength...*" [p. 352]. More importantly, Kraemer and Ratamess also failed to mention that what Hansen and colleagues defined as *functional strength* (standing 1RM biceps curl) significantly increased in both groups, with no significant difference between groups. Kraemer and Ratamess incorrectly concluded: "*These data provide support for performing large muscle mass, multiple joint exercises early in the workout and smaller muscle mass exercises later in the workout when training to enhance muscle strength*" [p. 342]. In fact, the methodology and results reported by Hansen and colleagues do not support that conclusion.

In a presentation entitled *The Role of Endogenous Hormones: Human Muscular Hypertrophy* at the 2009 National meeting of the American College of Sports Medicine, Kraemer noted the significantly greater isometric strength gains in the arm plus lower body group in the aforementioned study by Hansen and colleagues [58] but again failed to mention the difference in initial strength levels between groups and – perhaps more importantly – the similar strength gains in 1RM biceps curl. In a review of muscle hypertrophy, Kraemer and Spiering [59] also reported the results of Hansen and colleagues with an apparently similar bias, which was a misrepresentation of that study.

Kraemer and Ratamess [55] concluded: "*Resistance exercise elicits a milieu of hormonal responses critical to acute muscular force and power production as well as subsequent tissue growth and remodeling. In general, the acute response is dependent upon the stimulus (e.g., intensity, volume, muscle mass involvement, rest intervals, frequency) and may be the most critical element to tissue remodeling*" [p. 356]. Although the acute hormonal responses may be dependent on the aforementioned variables in some studies, there is very little evidence to suggest that the acute hormonal response has any significant effect on chronic adaptations such as strength gains. The three studies [56-58] cited by Kraemer and Ratamess [55] failed to support their claim that greater endogenous hormonal responses produce optimal strength gains.

Rahimi and colleagues [60] recruited 10 young males with at least one year of resistance training experience. All the participants used 60-second, 90-second, and 120-second inter-set rest intervals with four minutes rest between exercises. They performed four sets of bench press and squat exercises to *failure*

with 85% of their predetermined 1RM. The weight bar was secured on both ends with linear bearings to allow only vertical movement. The sessions were randomly counterbalanced on three different occasions, which were separated by 48-72 hours. Each repetition consisted of a 1-second concentric and 3-second eccentric phase. Blood samples were analyzed for growth hormone and testosterone concentrations pre-exercise, immediately and 30 minutes post-exercise.

Total training volume (resistance x repetitions x sets) significantly decreased during the four sets of the squat and the bench press during the three inter-set rest interval protocols [60]. There was no significant difference in the decrease in training volume as a result of the three different inter-set rest interval protocols for either the bench press or squat exercises. The pre-exercise to post-exercise changes in hormonal concentrations represent both the leg press and squat exercises. The pre-exercise to immediate post-exercise increase in growth hormone was significantly greater following the 60-second inter-set rest intervals compared with the 120-second intervals. There was no significant difference in growth hormone responses between the 60-second and 90-second intervals or between the 90-second and 120-second rest intervals. At 30 minutes post-exercise there was no significant difference in these responses for the bench press or squat exercises among the three inter-set rest intervals. The increase in testosterone after the 90-second and 120-second inter-set rest intervals was significantly greater than the 60-second rest intervals immediately post-exercise. There was no significant difference in testosterone concentrations between the 90-second and 120-second inter-set rest intervals. At 30 minutes post-exercise there was no significant difference in the testosterone responses for either the bench press or squat exercises. This study demonstrated that when more commonly used inter-set rest intervals are employed (90 seconds and 120 seconds) there was no significant difference between protocols for growth hormone or testosterone concentrations immediately post-exercise and no significant difference among any of the three inter-set rest intervals at 30 minutes post-exercise for the bench press or squat exercise.

Rahimi and colleagues [60] claimed that resistance exercise is the most effective way to increase the concentrations of endogenous anabolic hormones, which subsequently stimulate strength gains and muscle hypertrophy. They cited two references in an attempt to support that claim [61-62]. Boroujerdi and Rahimi [61] reported the acute effects of five sets of 10RM bench press and squat exercises on growth hormone and IGF-1 responses immediately after and one hour post-exercise for the 1-minute and 3-minute inter-set rest intervals. The 10 recreationally trained young males used a resistance that was ~15% greater than their predetermined 10RM so that assistance (*forced*

repetitions) would be required for each set. Growth hormone concentrations significantly increased from pre-exercise to post-exercise (immediately and 1-hour post-exercise) following both the 1-minute and 3-minute rest interval protocols, with a significantly greater increase for the 1-minute rest protocol immediately post-exercise. There was no significant difference in growth hormone concentrations between the 1-minute and 3-minute inter-set rest interval protocols one hour post-exercise. There was no significant change in IGF-1 concentrations from pre-exercise to immediately post-exercise following either rest interval protocol but there was a significant increase at one hour post-exercise. However, there was no significant difference in the IGF-1 increases between the 1-minute and 3-minute protocols.

The second reference cited by Rahimi and colleagues [60] is a *Current Opinion* by Spiering and colleagues [62] that contains a plethora of unsupported claims for their so-called *upstream signal* of resistance exercise that determines specific so-called *downstream events*. Regarding the claim by Spiering and colleagues that resistance exercise induced endogenous hormonal responses potentiate strength gains, the only reference cited was the training study by Hansen and colleagues [58]. This study, which was previously discussed in this critical analysis, showed that although there was a significantly greater increase in isometric elbow flexor strength in a group that trained in a higher internal hormonal environment (arm plus lower body exercise), the increase in what Hansen and colleagues defined as functional strength (1RM biceps curl) showed no significant difference in strength gains between the low hormonal environment (arm-only exercise) and high hormonal environment (functional strength gains of ~19.0% and 19.7%, respectively). Spiering and colleagues neglected to report this important outcome.

These two references [61-62] do not support the claim by Rahimi and colleagues [60] that the concentrations of endogenous anabolic hormones stimulate strength gains. Nevertheless, Rahimi and colleagues [60] concluded: "*Of particular importance to the RE [resistance exercise] practitioner is that specific combinations of RE variables must be used to optimize the desired functional outcome (muscle strength, muscle power, muscle size, or muscle endurance). Therefore, it is recommended that short rest periods can be used to stimulate hypertrophy and that long rest periods are used to maximize strength gains*" [p. 8]. They failed to cite any resistance training studies to support their claims regarding the effect of different resistance training protocols on functional outcomes or their recommendations for specific inter-set rest intervals for optimal strength gains or muscle hypertrophy.

In a study specifically designed to assess the acute hormonal responses to unilateral and bilateral resistance

exercise, Migiano and colleagues [63] assigned 10 recreationally resistance trained young males to perform five upper body dumbbell exercises (bench press, row, military press, biceps curl, and triceps kickback) either unilaterally or bilaterally in a random assignment separated by one week. Participants performed three sets of 10 repetitions for each exercise with 80% 1RM. The inter-set rest interval was two minutes. Blood samples were collected pre-exercise, immediately after exercise, and 5, 15 and 30 minutes post-exercise. The volume of bilateral exercise (resistance x sets x repetitions) was approximately twice as great as the unilateral exercise. Although there was no significant difference between protocols for the elevations in testosterone or cortisol, the bilateral protocol produced a significantly higher immunoreactive growth hormone response for all post-exercise times.

Migiano and colleagues [63] claimed: “*An acute resistance exercise-induced increase in anabolic hormones appears to be important for priming the signaling systems, which helps in adaptations from resistance training*” [p. 129]. They cited one reference in an attempt to support that opinion. However, that reference was not a resistance training study; it was a review by Michels and Hoppe [64] of the rapid actions of androgens, which did not even mention adaptations to resistance training. The only resistance training study cited by Migiano and colleagues was the previously discussed study by Hansen and colleagues [58] where only one of the measured variables (isometric strength) in the initially weaker group showed a significantly greater outcome in the higher hormonal environment.

In their Practical Applications section, Migiano and colleagues [63] also claimed that their study supports their recommendation to begin the exercise session with large muscle group exercises such as the leg press, squat and power clean to purportedly optimize the workouts by increasing the hormonal concentrations prior to exercising the smaller muscle groups. Similar to their previous claims, their recommendation is without any scientific foundation. The concept of the *sequence of exercise* is discussed in a subsequent section in this critical analysis.

In a recent resistance training study by West and colleagues [65], 12 young previously untrained but recreationally active males volunteered to train the elbow flexor muscles and lower body muscles for 15 weeks. They used a within-subject design so that all the participants trained contralateral arms on separate days under very different hormonal environments: LH = low hormone (arm-only exercise) and HH = high hormone (arm plus lower body exercises). In the LH condition, one arm performed 3-4 sets of 8-12 repetitions on a preacher bench pulley system with ~95% 10RM. The exercise continued until the participants could no longer maintain good form or

complete the range of motion. In the HH condition (72 hours later during weeks 1-6 and 48 hours later during weeks 7-15), the participants performed the identical arm workout for the contralateral arm but it was followed by five sets of 10 repetition leg presses and three sets of 12 repetitions for knee extension and knee flexion exercise with ~90% 10RM. Inter-set rest intervals were two minutes for the arm exercise and one minute for the lower body exercises. During weeks 1-6 they trained each arm three times every two weeks and the frequency was increased to twice a week during weeks 7-15. The participants consumed 18g of whey protein immediately before and 90 minutes after the arm exercise to support maximal rate of muscle protein synthesis in both the LH and HH conditions. Magnetic resonance imaging and muscle biopsies were performed on both arms pre-training and post-training to assess arm cross-sectional area and muscle fiber cross-sectional area, respectively.

West and colleagues [65] reported no significant increase in growth hormone, IGF-1 (insulin-like growth factor 1) or testosterone from pre-exercise to post-exercise in the LH condition, but highly significant elevations in all the anabolic hormones after the HH condition (arm plus lower body exercises). Cortisol and DHEA-S (dehydroepiandrosterone sulfate) were also significantly elevated post-exercise after the HH condition. There was a significant increase in both arms for isometric strength (LH = 20%, HH = 19%), 1RM (LH = 23%, HH = 25%), 10RM (LH = 46%, HH = 47%), type I muscle fiber cross-sectional area (LH = 9%, HH = 11%), type II muscle fiber cross sectional area (LH = 21%, HH = 24%), and elbow flexor cross-sectional area (LH = 12%, HH = 10%). There was no significant difference between contralateral arms for any of these adaptations. West and colleagues concluded: “*Despite vast differences in hormone availability in the immediate postexercise period, we found no differences in the increases in strength or hypertrophy in muscle exercised under low or high hormone conditions after 15 weeks of resistance training*” [p. 64].

In a recent review, West and colleagues [66] stated: “*There has been confusion surrounding the influence of exercise-induced changes in systemic ostensibly ‘anabolic’ hormones such as growth hormone (GH), insulin-like growth factor-1 (IGF-1), and testosterone on muscle hypertrophy. Despite little empirical evidence, it has been hypothesized that the post-exercise rise in concentration of these hormones is important for inducing hypertrophy and thus has been used as a surrogate measure of hypertrophy potential. We contend that there is a complete lack of merit for purportedly anabolic exercise-induced elevations in systemic hormones to be used as proxy markers of hypertrophy*” [p. 1372].

In a resistance training study by Wilkinson and colleagues [67], they trained 10 previously untrained

young males three times a week for eight weeks. Participant performed three sets of 6-10 unilateral repetitions with 80-90% 1RM until they reached *voluntary fatigue* for knee extension and leg press exercises. Although their comparison was between a resistance-trained limb and the contralateral control limb – and not between two trained limbs or between two different protocols – the authors reported significant increases in unilateral quadriceps strength (1RM), muscle cross-sectional area (computerized tomography), and vastus lateralis (percutaneous muscle biopsies). There were no significant changes in the contralateral untrained limb. Most importantly, there were no significant changes in total or free testosterone, testosterone to cortisol ratio, IGF-1, or growth hormone either acutely (pre-exercise to post-exercise) or chronically (pre-training to post-training). This study showed that significant increases in muscular strength and hypertrophy can occur without increases in endogenous anabolic hormones.

It should be emphasized that science does not require researchers to conduct studies that may refute long held opinions. The entire burden of proof is on those who make the claims; the greater the claim, the greater the burden of proof. In their review, Kraemer and Ratamess [55] concluded that acute hormonal responses to resistance exercise “...*may be the most critical element to tissue remodeling*” [p. 356]. They failed to present any evidence to support their claim. In fact, the studies by Migiano and colleagues [63], West and colleagues [65], and Wilkinson and colleagues [67] strongly refute the unsupported opinion of Kraemer and Ratamess.

Wilkinson and colleagues [67] noted that within-subject comparisons provide significantly lower variability between limbs than comparisons between subjects. They cited a study by Hubal and colleagues [68] who reported on a multi-institutional resistance-training study with 585 previously untrained young participants. All the subjects (243 males and 342 females) trained the elbow flexors and extensors of the non-dominant arm two times a week for 12 weeks. They performed three sets for each of five dumbbell exercises (preacher curls, concentration curls, standing curls, overhead elbow extension, and triceps kickback) with 12RM, 8RM and 6RM resistance during weeks 1-4, 5-9 and 10-12, respectively. There was a significant increase in strength (1RM and maximal isometric force) and biceps cross-sectional area (magnetic resonance imaging) in the trained arm. And as noted by Wilkinson and colleagues, the increase in cross-sectional area for the untrained contralateral arm was only 7% of the increase in the trained arm. They noted that such a small increase in size (1.4%) for the untrained limb could be detected only with such a large sample size (N = 585). This small change in hypertrophy for

the untrained limb strongly suggests that it served as a valid internal control for this measure.

Another important result of the study by Hubal and colleagues [68] was the extreme variability in the responses. Although all the participants performed the identical resistance training protocol, the significant increase (18.9%) in muscle cross-sectional area ranged from -2.3% to 59.3%, with a 49.5% coefficient of variation (the size of the standard deviation relative to its mean). The significant increase (54.1%) for the biceps 1RM (preacher curl) also showed great variability that ranged from 0% to 250%, with a 57% coefficient of variation. Hubal and colleagues concluded: “*Men and women exhibit wide ranges of responses to resistance training, with some subjects showing little or no gain, and others showing profound changes, increasing size by over 10cm² and doubling their strength*” [p. 964].

Recently, Erskine and colleagues [69] trained 53 previously untrained young males three times a week for nine weeks. The subjects performed four sets of unilateral knee extension exercise with 80% 1RM. Repetition duration was approximately one second for the concentric phase and one second for the eccentric phase with 2-minute inter-set rest intervals. There was a significant 68% increase in 1RM that ranged from 18% to 113%, with a 45% coefficient of variation. Maximal voluntary contraction torque significantly increased 26% and ranged from -2% to 52%, with a 42% coefficient of variability. There was a significant increase of 5.7% in quadriceps femoris cross-sectional area (ultrasonography) that ranged from -3% to 18%, with a 75% coefficient of variation.

The genetic variability in response to resistance training is not a recent discovery. Over 30 years ago MacDougall and colleagues [70] trained six previously untrained young males three times a week for six months. They focused on training the elbow extensors with the bench press, elbow extension, pullover, and vertical dips between parallel bars. The subjects performed 3-5 sets of 8-10RM for each exercise with 2-minute inter-set rest intervals. Elbow extension strength on a dynamometer significantly increased 91% (+/-23%). Cross-sectional area of the triceps (needle biopsies) significantly increased 33% and 27% for the fast-twitch and slow-twitch fibers, respectively. In a subsequent publication [71] referring to the aforementioned study [70], MacDougall noted: “*Within the group, individual increases in fiber area were as little as 3% and as great as 49% despite the fact that all the subjects followed the same training program*” [p. 502]. These notable studies [68-70] are important because they emphasize the very rarely discussed influence of individual genetic factors affecting strength gains and muscular hypertrophy as opposed to the previously discussed unsubstantiated claims for the obsessive complex manipulation of training variables such as inter-set rest intervals.

After reporting a significant 21.6% decrease in plasma water after exhaustive cycle ergometer exercise in young males and females, Sjogaard and Saltin [72] speculated that increased osmotic pressure (caused by an increased lactate concentration) coupled with elevated capillary pressure produced a filtration of water from the capillaries into the extravascular space and resulted in the high muscle tissue water – both intracellular and interstitial. Some of the aforementioned studies in this section reported estimated changes in plasma volume immediately after resistance exercise [e.g., 51-53, 65] and some studies did not report any estimate of changes in plasma volume [e.g., 57-58, 60-61, 67]. With such significant decreases in post-exercise plasma volume, perhaps the concentration of endogenous hormones is significantly affected.

The lead author (Kraemer) in many of the studies that did estimate the shift in plasma volume [51-53], corrected for the decrease in plasma volume in two of these studies [51-52] but did not report a correction in the other study [53]. In a later study by Gotshalk and colleagues [73] on acute hormonal responses to single set and multiple set protocols, where Kraemer is the corresponding author, they reported a significant decrease in post-exercise plasma volume (10.3-12.2%) that was estimated from the calculations of Dill and Costill [74]. They noted that hormonal concentrations were not corrected for the decrease in plasma volume because the target tissues are exposed to the absolute molar concentrations. The only reference they cited to support this claim was a book chapter by Kraemer [75]. That chapter, which was incorrectly listed in their reference section, contained no mention of molar concentrations. Gotshalk and colleagues [73] concluded: *“Further investigation will be needed to elucidate if a threshold for the amount of work exists with regard to the hormonal responses to heavy-resistance exercise”* [p. 253]. Perhaps future investigations are needed to first elucidate if a threshold exists for hormonal responses to resistance exercise for optimal strength gains or muscle hypertrophy.

Several studies have reported a significant decrease in plasma volume immediately after performing resistance exercise. For example, Kraemer and colleagues [76] recruited seven recreationally trained young males who performed three sets of bench press, lat pull-down, knee extension, and knee flexion exercise with their predetermined 10RM load. There were two minutes rest between sets, five minutes between exercises, and each set was performed to *muscular failure*, which they defined as a 10% decrease in the range of motion. Repetition rate was 15 repetitions per minute and was guided by a metronome. Blood samples were drawn pre-exercise, immediately post-exercise, and 5, 15 and 25 minutes post-exercise. Hematocrit and hemoglobin were used to estimate change in plasma

volume using the calculations of Dill and Costill [74]. Plasma volume decreased 13% immediately post-exercise but returned to baseline within 15 minutes. Kraemer and colleagues concluded: *“The findings demonstrate the magnitude of resistive-exercise-induced plasma volume loss and underscore the importance of accounting for plasma volume change when determining response of a particular blood parameter to resistive exercise”* [p. 251].

In a landmark study, Ploutz-Snyder and colleagues [77] tested their hypothesis that the reduction in plasma volume induced by high intensity exercise reflects the increase in cross-sectional area of the active muscles. They reported the results of performing six sets of barbell squats with the 10RM resistance in eight young males who had at least three years of resistance training experience. With two minutes rest between sets, the entire session required approximately 20 minutes. The Evans blue dye technique was used to establish an absolute baseline plasma volume and the calculations of Dill and Costill [74] were used to estimate the change in plasma volume from pre-exercise to immediately post-exercise and for up to 60 minutes thereafter. There was a significant 22% decrease (~700 ml) in plasma volume immediately after exercise and it returned to baseline (pre-exercise) within 45 minutes. MRI revealed a significant increase in the cross-sectional area of the active thigh muscles (vastus lateralis, vastus medialis, vastus intermedius, and adductor muscle group), with an estimated increase of ~550 ml of fluid. They speculated that the remaining 150 ml lost from the vascular space could be accounted for by an efflux of fluid into the gluteal and calf muscles, which were not measured in this study but are involved in the squat exercise. There was no significant change pre-exercise to post-exercise in hamstrings or rectus femoris muscle cross-sectional area. There was a similar time after exercise (~45 minutes) for plasma volume and muscle size to return to baseline, which supported their hypothesis that plasma is displaced from the blood into the active muscles. Ploutz-Snyder and colleagues concluded: *“In conclusion, the data support the hypothesis that increased muscle CSA after resistance exercise is primarily reflective of a movement of plasma volume out of the vascular space and into the extravascular space of active muscles”* [p. R541].

In a comprehensive review of exercise-induced changes in plasma volume and its influence on the correct interpretation of biochemical parameters such as hormonal responses, Kargotich and colleagues [78] stated: *“The fields of exercise physiology and training assessment require accurate and valid interpretation of biochemical and hormonal data obtained from the considerable blood sampling performed. However, if plasma volume shifts due to exercise and the corresponding prevailing environ-*

mental conditions are significant, a solute within the plasma which appears to have changed may only reflect these fluid shifts” [p. 102]. “*The effect of plasma volume changes on blood-borne parameters should be considered. If there is no influence of exercise on the plasma volume, uncorrected data may be presented. If significant plasma volume changes have influenced the results, either the corrected or both the measured and corrected data should be presented. It should not be assumed that because plasma volume changes are not discussed they did not occur*” [p. 114]. Furthermore: “*If one is to interpret and make comparisons between various studies examining biochemical and hormonal solutes in the blood after different exercise protocols, it is important to consider whether plasma volume was measured, and whether there were any consequences of shifts in this parameter before arriving at uniform conclusions and recommendations*” [p. 111].

It is important to recognize that there are some rarely addressed questions regarding the reported acute changes in hormonal concentrations and change in plasma volume after resistance exercise. All of the studies that estimated changes in plasma volume cited only the one study by Dill and Costill [74]. However, Dill and Costill derived their calculations from six males who lost ~4% of their body mass (fluid loss) after running on a treadmill for two hours. Are those calculations valid for changes in plasma volume that are primarily the result of fluid shifts – not sweat loss – from the intravascular space into the extravascular interstitial and intracellular spaces of the active muscles immediately following resistance exercise? Could it be that the transient changes reported for endogenous hormone concentrations and their time to return to baseline values (~15-60 minutes) may primarily reflect the shift in plasma volume and the similar time frame for it to return to baseline? Is there really an increase in hormonal production with resistance exercise or are the values elevated because of a greater concentration in the reduced post-exercise plasma volume?

Section Summary

There is a lack of evidence to support the unsubstantiated belief that acute elevations in specific endogenous hormones have any significant effect on strength gains.

Sequence of Exercises

The sequence of performing a series of exercises is related to inter-set rest intervals because several studies have shown a significant reduction in the number of completed repetitions for some exercises that are performed later rather than earlier in an exercise session. The authors of these studies have erroneously claimed that fewer repetitions for an exercise in subsequent sets may result in sub-optimal strength gains.

Simao and colleagues [79] assigned 23 young females with a minimum of two years of recreational resistance training experience to perform two exercise sessions separated by at least 48 hours. Session A consisted of the free-weight bench press, machine military press, elbow extension, leg press, knee extension and knee flexion exercises. The identical exercises were performed in a reverse sequence during session B. The participants completed three sets of each exercise with 80% of their predetermined 1RM until *volitional concentric fatigue*. There were 2-minute inter-set and inter-exercise rest intervals but no control for repetition duration. The total number of repetitions for the three sets was significantly greater for the bench press, military press and leg press exercises in session A; and was significantly greater for the elbow extension, knee extension and knee flexion exercises during session B. The primary conclusion was that the total number of repetitions for the three sets was directly influenced by the sequence of exercise. The authors noted however, that the decrease in the total number of repetitions was caused primarily by a decrease in repetitions on the first set of each exercise. Simao and colleagues concluded that the results of their study are relevant to designing resistance training programs when the goal is to maximize muscular strength and hypertrophy. They did not cite any resistance training studies to support that claim.

Simao and colleagues [79] also claimed that large muscle-group exercises should be performed at the beginning of an exercise session because of the ability to use the heaviest resistance possible, and that the heavier resistance would result in the greatest strength gains for those exercises. They cited four references: the previously discussed 2002 ACSM Position Stand on resistance training [10], two books [16, 80], and one study by Hoeger and colleagues [81] that reported the acute response (number of completed repetitions with different percents of the 1RM) to resistance exercise. Hoeger and colleagues did not mention anything regarding the sequence of exercise or long term strength gains.

A follow-up study by Hoeger and colleagues [82], which also included resistance trained young females, strongly supports the only really important practical result reported by Simao and colleagues [79]. The number of repetitions completed with 80% 1RM varied considerably among participants and among the different exercises in both studies. For example, Simao and colleagues reported the number of completed repetitions for the first set of exercise ranged from ~7 for the bench press to ~24 for the leg press with 80% 1RM. Hoeger and colleagues reported a similar number of completed repetitions that ranged from ~5 for knee flexion exercise to ~22 for the leg press with 80% 1RM in resistance trained young females. Attempting

to prescribe a specific range of repetitions (e.g., 8-10 repetitions) with a given percentage of the 1RM (e.g., 80% 1RM) will result in a wide range of individual effort among individuals and among exercises. The degree of effort at the end of a set of repetitions is the primary factor that determines the level of motor unit activation [8-9]. Because the degree of effort and subsequent motor unit activation could introduce a significant confounding variable, meaningful comparative resistance training studies should mandate that a similar effort is applied by all participants – rather than an assigned number of repetitions with a specific percent 1RM.

Spreuwenberg and colleagues [83] recruited nine young males with seven years resistance training experience. In session A, the subjects performed four sets of free weight barbell squats with 85% 1RM for as many repetitions as possible. There were 2-minute inter-set rest intervals but no control for repetition duration. The squat was the only exercise performed in session A. In session B, they performed three sets of 8-10RM for the bench press, lunge, rowing, arm curl, deadlift, sit-up, and hang-pull exercises. After a 5-minute rest, they performed the squat exercise as they did in session A (4 sets with 85% 1RM). The participants provided a rating of perceived exertion immediately after completing each of the four sets of squats. The number of completed repetitions was significantly greater in session A compared with session B – but only for the 1st set of squats. There was no significant difference between session A and B in the number of completed repetitions for the 2nd, 3rd or 4th sets.

Perhaps the most important result of this study by Spreuwenberg and colleagues [83] with the greatest practical application to resistance training was that there was no significant difference between session A and B in the rating of perceived exertion following each of the four sets of squats. According to the size principle of motor unit activation, it is the effort at the end of a set – not the amount of resistance or the actual number of completed repetitions – that determines the level of motor unit activation [8-9]. Although not specifically assessed in this study, the motor unit activation was probably similar – near maximal – for each set of squats during both sessions A and B. The authors noted five times in their Discussion section that the total number of repetitions was reduced when the squat was performed after the seven other exercises, but failed to note that this reduction was significant only in the 1st set. They recommended performing multiple joint large muscle mass exercises first in a training session for optimal loading of those muscles. However, the optimal loading of muscles for maximal strength gains is unknown and their recommendation was not supported by the results of their study. Furthermore, they did not cite any resistance

training studies to support their recommendation for performing multiple joint large muscle mass exercises early in a training session.

Monteiro and colleagues [84] recruited 12 young females with at least six months resistance training experience. After assessing their 10RM, the participants performed three sets of bench press, military press and triceps push-down exercises in session A and the reverse sequence in session B. All sets were completed to *voluntary exhaustion* with three minutes rest between sets and exercises. There was no significant difference in the number of completed repetitions between the 1st, 2nd or 3rd sets for any of the exercises in session A. In session B there was a significant difference in repetitions between the 1st and 2nd sets and between the 1st and 3rd sets for the bench press. The authors claimed that if trainees wish to maximize strength gains in a specific exercise (e.g., the bench press), that exercise should be performed first in a training session. They did not cite any resistance training study to support their claim. In fact, they cited one study at least eight times that agreed with their results and another study at least 10 times that conflicted with their results. However, both of these references, which included the 2nd and 3rd authors from this study [84], are not retrievable references as they were cited by Monteiro and colleagues.

Most importantly, Monteiro and colleagues [84] reported a difference of only 1.5 repetitions between the 1st and 3rd sets of the bench press – even when it was performed last in the sequence (session B). The difference between sessions A and B in the average number of completed repetitions with the 10RM for three sets of the bench press was less than one repetition (0.9 repetitions). The authors' belief that this trivial difference in the number of repetitions would have a significant impact on strength gains lacks scientific support and reveals their misinterpretation of the size principle of motor unit activation [8-9].

Simao and colleagues [85] assigned 14 young males and four young females with at least six months of resistance training experience to perform three sets for each of five upper body exercises: bench press, lat pull-down, seated military press, standing biceps curl, and seated elbow extension for the triceps in session A, and the reverse sequence in session B. They performed all sets with their predetermined 10RM and continued each set to *concentric failure*. There were 2-minute inter-set and inter-exercise rest intervals but they did not attempt to control for repetition duration. The average number of repetitions for the three sets was significantly greater for the bench press and lat pull-down in session A. The average number of repetitions was significantly greater for the biceps curl and elbow extension exercises in session B, with no significant difference for the military press in either session.

Within session A there was a significant decrease in the number of completed repetitions for the third set of all the exercises except – oddly enough – for the last exercise in the sequence (elbow extension). There was no significant difference in the number of completed repetitions between the 1st and 2nd sets (with 2-minute inter-set rest intervals) for any of the exercises in either sequence A or B. The authors apparently assume that multiple sets are required for optimal strength gains and are superior to a single set of each exercise, and that if fewer repetitions are completed in the third set because of fatigue, the strength gains will not be optimal. Neither of their assumptions is supported by the preponderance of resistance training studies [see references 5, 8-9, 86-90].

Simao and colleagues [85] correctly concluded that the sequence of exercise in their study affected the number of repetitions performed in upper body large and small muscle groups. However, their claim that the results of this study are relevant to designing resistance training programs when the goal is to maximize muscular strength and hypertrophy is without scientific foundation. They claimed that the use of the heaviest resistance possible for large muscle group exercises would result in the greatest strength gains. They cited three references: the 2002 ACSM Position Stand on resistance training [10], a book [91], and a study (discussed below) by Sforzo and Touey [92].

Perhaps one of the first published studies on manipulating the sequence of exercise was by Sforzo and Touey [92]. They assessed the 8RM for three upper body and three lower body exercises in 17 young males with 4.82 years of resistance training experience. The participants then performed two weight training sessions consisting of four sets for each exercise with their 8RM resistance in a specific sequence: squat, knee extension, knee flexion, bench press, seated military press, and triceps push-down in session A and the reverse sequence in session B, with lower body exercises performed first in both sessions. For some of the exercises – most notably the bench press – there was a significantly greater total force, which the authors described as resistance time the number of repetitions, for each of the four sets in session A compared with session B. Not surprisingly, after performing four sets of triceps push-downs and four sets of military presses to the point of *muscular fatigue* (8RM), the total force in the bench press exercise was significantly lower. Although statistically significant, the effects of exercise sequence were less pronounced for the lower body exercises. The problem with this study is that although the authors' conclusions are valid relative to their results, which showed that performing larger muscle mass exercises prior to smaller muscle mass exercises resulted in a greater total resistance lifted during the session, their claim that this difference would be an

important stimulus for strength development is not supported by the references they cited [93-94].

For example, Sforzo and Touey [92] noted that Goldberg and colleagues [93] concluded that tension was the critical stimulus for muscular hypertrophy. However, in their review of compensatory hypertrophy and retardation of atrophy in rabbits, chickens, frogs, mice and rats (mostly rats), Goldberg and colleagues actually concluded: "*It is suggested that increased tension (either passive or active) is the critical event in initiating compensatory growth*" [p. 248]. They did not suggest how much tension (amount of resistance) is required or how many times the tension should be applied (repetitions or sets) to produce a maximal stimulus for muscular strength gains in humans or other animals.

Sforzo and Touey [92] then claimed that the conclusions of Goldberg and colleagues [93] were supported by studies that employed a maximal or near maximal amount of resistance, which were most effective for improving strength. The only reference they cited for that claim was a review by Atha [94]. However, after Atha cited two resistance training studies [95-96] that reported no significant difference in strength gains as a result of using a very heavy resistance (2-3RM) or a moderate resistance (6-10RM), he concluded: "*From these studies, one begins to believe that the importance of load magnitude may have been exaggerated*" [p. 13].

Neither the review by Goldberg and colleagues [93] nor the review by Atha [94] supports the claim by Sforzo and Touey [92]. Sforzo and Touey also underscore their misunderstanding of *pre-exhaustion* training by incorrectly describing this training protocol and its hypothetical benefit. Pre-exhaustion training is discussed in the next section of this critical analysis.

Miranda and colleagues [97] reported on the potential effects of the sequence of exercise and inter-set rest intervals in 16 young males with at least 6.4 years of resistance training experience. All the participants performed three sets with their predetermined 8RM to *voluntary exhaustion* for each of six upper body machine and free weight exercises: wide grip lat pull-down, close grip lat pull-down, seated machine row, barbell row, dumbbell arm curl and seated machine arm curl in this sequence (SEQ A) or the reverse sequence (SEQ B). In four sessions separated by 48-72 hours, the subjects performed SEQ A and SEQ B with 1-minute and 3-minute rest between sets and exercises. The researchers did not attempt to control repetition duration for the 8RM assessment or the four exercise trials.

Miranda and colleagues [97] reported a significant difference between some of the exercises in the total number of repetitions for the three sets. They noted that the effect of the sequence of exercise on the

number of repetitions was greater than the effect of inter-set rest intervals for two of the exercises (wide grip lat pull-down and machine arm curl) – the first and the last exercises in SEQ A. The effect of inter-set rest intervals was greater than the sequence of exercises for the other four exercises. The authors concluded: *“These results suggest that upper-body exercises involving similar muscle groups and neural recruitment patterns are negatively affected in terms of repetition performance when performed at the end vs. the beginning of a session and the reduction in repetition performance is greater when using 1-minute vs. 3-minute rest interval between sets”* [p. 1575].

Miranda and colleagues [97] cited a study by Kraemer and colleagues [24] who assessed the acute responses in young competitive body builders and power lifters to performing three sets of 10RM for each of ten upper body and lower body exercises with 10 seconds rest between sets. Miranda and colleagues claimed that the body builders demonstrated less of a reduction in repetition performance than the power lifters. As previously discussed in this critical analysis, there was actually no significant difference between groups for any of the measured variables and there are no data reported in that study [24] to support the claim by Miranda and colleagues. In addition, Kraemer and colleagues stated: *“Since there were no perceptual differences [RPE] between the groups performing the exercise protocol, it appears that the perceptual responses to the exercises were independent of differences in clinical symptomatology [nausea and dizziness]”* [p. 251].

The claim by Miranda and colleagues [97] is an excellent example of why authors should seek the primary source – rather than a secondary or tertiary source – to verify a claim. Kraemer [20] made a similar claim about his prior study [24] that the body builders showed a much lower percent decrease in resistance. As previously noted, the data reported in that study failed to support Kraemer’s claim and the claim by Miranda and colleagues regarding a decrease in resistance or repetitions.

Miranda and colleagues [97] claimed that the implications of their study have practical applications in designing programs for resistance trained males. However, their unusual study protocol involved 18 consecutive sets (3 sets of 6 exercises) for the biceps, which are the prime movers for all of these upper body exercises and may have very little practical application to traditional resistance training. If multiple sets of six biceps exercises are desired, perhaps a more productive protocol of alternating each of these exercises with antagonistic exercises may have less of an impact on the performance of subsequent sets and exercises in the sequence. For example, a sequence of wide grip lat pull-down, bench press, close grip pull-down, military press, seated machine row, parallel bars dipping, arm

curls, etc. could mediate the stress of 18 consecutive sets for the biceps.

Regarding inter-set rest intervals, Miranda and colleagues [97] concluded: *“Therefore, when training for upper body strength, longer rest intervals between sets and exercises may provide a superior stimulus because of greater total repetitions performed with a given load and consequently greater workout volume* [p. 1576]. They did not cite any references to support their opinion that a greater volume of exercise produces a greater stimulus for superior strength gains.

Only two resistance training studies [98-99] compared the effect of different sequences of exercise on strength gains. Dias and colleagues [98] randomly assigned 48 young males to train five upper body exercises either progressing from the larger muscle group exercises to the smaller muscle group exercises (group 1), progressing in the reverse sequence (group 2), or a control group. The participants were from the Brazilian Navy Academy, physically active, but had not participated in resistance training at least six months prior to this investigation. The exercise order for group 1 was the barbell bench press, lat pull-down, seated military press, barbell biceps curl, and an elbow extension machine for the triceps. The reverse sequence of exercise was used in group 2. Both groups performed three sets of each exercise with their 8-12RM resistance three times a week for eight weeks. They were encouraged to complete each set to *concentric failure*. There were 2-minute inter-set and inter-exercise rest intervals but the researchers did not attempt to control for repetition duration. Both training groups significantly increased 1RM strength in all five exercises. However, the only significant difference in strength between groups was a greater gain for group 2 in the biceps curl and elbow extension exercises.

The results reported by Dias and colleagues [98] are contrary to the previously discussed studies in this critical analysis where the authors claimed that the sequence of exercise would specifically affect the larger muscle group exercises such as the bench press, lat pull-down and military press rather than the smaller muscle group exercises such as the biceps curl and elbow extension. Dias and colleagues specifically noted: *“The current results revealed no significant difference in strength gains in large muscle group exercises”* [p. 67]. In contrast to that statement, they then claimed: *“If an exercise is important for the training goals of a program, then it should be placed at the beginning of the training session, whether or not it is a large or a small muscle group exercise”* [p. 69]. Their recommendation is not supported by the results of their own study – or by any other resistance training study.

Simao and colleagues [99] randomly assigned 31 young males from the Brazilian Navy Sergeants School to one of two resistance training groups or a

control group. All the subjects were participating in the regular military physical activity program but had not performed regular resistance training for at least six months prior to this study. One training group (LG-SM) started each session with the larger muscle group exercises and progressed in the session to the smaller muscle group exercises: barbell bench press, machine lat pull-down, machine triceps exercise, and standing barbell curl. The other training group (SM-LG) performed the same four exercises in the reverse sequence, from the smaller to larger muscle mass exercises. Both training groups performed four sets of 12-15 repetitions for each exercise with 1-minute inter-set rest intervals (weeks 1-4); three sets of 8-10 repetitions with 2-minute inter-set rest intervals (weeks 5-8); and two sets of 3-5 repetitions with 3-minute inter-set rest intervals (weeks 9-12). They trained two times a week with at least 72 hours between sessions. Although the authors did not attempt to control for repetition duration, the participants were verbally encouraged to perform all sets to *concentric failure*. Both training groups showed a significant increase in 1RM for the four exercises. There was no significant difference in strength gains between groups for any of the exercises.

Simao and colleagues' [99] Table 2 [p. 3] revealed that the exercises performed first and last in the reverse sequences showed very similar strength gains (within 2%); that is, the 1RM barbell curl increased ~15% when it was performed last (LG-SM group) and ~17% when it was performed first (SM-LG group). The 1RM free weight bench press increased ~9% when it was performed first (LG-SM group) and ~11% when it was performed last (SM-LG group). The authors noted: "*The absolute strength gains and muscle accretion do not present statistical differences between training groups*" [p. 4].

Section Summary

Several studies that investigated the acute responses to different sequences of specific exercises reported significantly fewer repetitions during the performance of multiple sets for some of those exercises. However, only two studies actually compared strength gains as a result of training with a different sequence of exercise. One study reported a significantly greater increase in the biceps and triceps exercises when they were performed early in the training sessions, but there was no significant difference in strength gains between groups for the larger muscle mass exercises. The other training study reported no significant difference in strength gains between groups for any of the exercises – regardless of the sequence of exercise.

Pre-exhaustion Exercise

Pre-exhaustion exercise is a specific way of performing a sequence of two designated resistance

training exercises for the alleged purpose of creating an optimal stimulus for strength gains. Arthur Jones is probably the person most credited for the original hypothesis and application of pre-exhaustion exercise. In *Nautilus Training Principles, Bulletin No. 1* [100], Jones claimed that the primary purpose of pre-exhaustion exercise "...is to overcome one of the serious shortcomings of almost all conventional exercises...", and that pre-exhaustion exercise "...makes it possible to work a particular muscular structure – almost ANY muscular structure – much harder than is normally possible" [p. 92]. Jones contended that with conventional exercise "...a point of failure is reached when the weakest muscles are no longer able to perform; and in such cases, very little in the way of growth stimulation is provided for the stronger muscles involved in the same exercise" [p. 92]. Jones referred to this topic as the pre-exhaustion principle. However, the word principle denotes a fundamental truth or doctrine. Pre-exhaustion exercise is actually just speculation, and requires rigorous testing to confirm its validity. Consequently, the concept of pre-exhaustion exercise is merely a hypothesis – not a principle.

Jones [100] used several examples of how to perform pre-exhaustion exercise, which was based on his opinion that pre-exhaustion exercise removes or at least minimizes the weak link in a specific exercise. For example, he proposed that the biceps are the weak link between the latissimus muscles and the resistance used in a rowing or lat pull-down exercise. Likewise, he claimed that the triceps are the weak link between the deltoid muscles and the resistance used for overhead pressing exercises, as well as the weak link between the pectoral muscles and the resistance used for bench press exercises. Because it has been misunderstood over the past 40 years, Jones' hypothesis of a weak link requires further explanation.

Assume that the triceps are the weak link in overhead pressing movements – although there is no scientific evidence to support that assumption – and an individual is capable of a 6RM military press at a specific repetition duration (e.g., 4 seconds concentric and 4 seconds eccentric muscle actions) with 50 kg. Jones' assumption [100] would be that the triceps – the weak link according to Jones – are responsible for the inability to complete a 7th repetition.

In order to further simplify this example, one also must assume that the deltoid muscles have 100 motor units available for that particular overhead pressing movement. But, because the triceps were the weak link between the supposedly stronger deltoid muscles, only 75 of the specific deltoid motor units involved in the overhead press were activated and therefore stimulated. Also assume that 100 motor units in the deltoid muscles are available for a lateral raise and that 50 of those motor units also are involved in performing the

overhead press. Performing the lateral raise to a point where an additional repetition is not possible and immediately (fewer than three seconds) followed by the overhead press would require a decrease in resistance (e.g., from 50 kg to 30-35 kg) in order to perform the 6RM overhead press. Because it was estimated that the triceps were capable of a 6RM with 50 kg, and there is now only 30-35 kg of resistance, the triceps should not be the limiting factor in the 6RM overhead press. Therefore, Jones' hypothesis [100] was that a greater number of deltoid motor units available for this specific overhead press exercise would be activated and stimulated.

However, even if all the aforementioned assumptions were correct – and there is no evidence that any of them are valid – there is no empirical evidence (resistance-training studies) to show that any additional motor unit activation would produce greater increases in muscular strength. That does not mean that pre-exhaustion exercise does not elicit better adaptations; it just means there is no evidence at this time to suggest that it would produce greater strength gains.

Several single-joint pre-exhaustion exercises that were suggested by Jones [100] would fall under the same hypothetical scenario: pectoral flies (e.g., dumbbells, pec-deck, arm-cross with pulleys) followed by a multiple joint exercise (e.g., bench press, dips), or the pullover exercise followed by multiple joint rowing or lat pull-down exercises. Hence, Jones developed the Nautilus Double Shoulder, Double Chest, Pull-over Torso-Arm, and Behind-The-Neck Torso-Arm machines.

Four studies [92, 101-103] tested the acute responses to what the researchers incorrectly claimed to be pre-exhaustion exercise. The previously discussed study by Sforzo and Touey [92] tested 17 males (age ~20 years) with approximately five years of weight training experience. Subjects were evaluated for the 8RM on six different exercises, and 48-72 hours later each subject performed four sets to *muscular fatigue* with the 8RM on two occasions 48-72 hours apart. The sessions were counterbalanced to minimize any potential order effect of the sessions. In session A they performed the squat, knee extension, knee flexion, bench press, military press, and triceps push-down in that order. In session B the order of performance was knee flexion, knee extension, squat, triceps push-down, military press, and bench press. There were two minutes rest between sets, three minutes rest between exercises, and five minutes rest between upper and lower body exercises.

Sforzo and Touey [92] reported that the *total force* (defined by them as repetitions x resistance) for the first set of bench presses in session A was approximately four times higher (720 kg) compared with the *total force* (179 kg) in the first set of bench presses in

session B. The authors actually reported the total mass – not total force. However, the major flaw in this study was that the researchers probably did not understand the concept of pre-exhaustion exercise. The correct procedure for testing the acute effects of pre-exhaustion exercise is to perform an isolated single-joint movement for the pectoral muscles (e.g., pec-deck, arm-cross, or butterfly exercise) immediately (not three minutes) followed by the bench press. Then, compare the resistance in the bench press during this procedure with the resistance used when performing the bench press without pre-exhaustion, and also compare the motor unit activation of the pectoral muscles on the final maximal repetition of each protocol. The purpose of the experiment should be to pre-exhaust the supposedly stronger pectoral muscles (e.g., with the pec-deck) – not to pre-exhaust the weak link (triceps). The predicted result would be that the resistance in the bench press would be significantly reduced in the pre-exhaustion scenario but the motor unit activity of the pectoral muscles would be greater – hypothetically, receiving a greater stimulus.

Sforzo and Touey [92] reported that the difference in *total force* was not as dramatic for the squat exercise. In session A, *total force* (repetitions x resistance) was 896 kg for the first set and 698 kg for the first set of squats in session B. The subjects exercised – not pre-exhausted – the supposedly weak link (quadriceps) before the stronger gluteal muscles, which actually further weakened the weak link. Sforzo and Touey concluded that their data provide “...a sound platform for a subsequent longitudinal investigation” [p. 24]. In fact, their data contribute nothing to future investigations of pre-exhaustion exercise because none of it was relevant to the actual concept of pre-exhaustion as proposed by Jones [100].

The rationale for the study by Augustsson and colleagues [101] also was based on references by those who apparently did not understand the concept of pre-exhaustion exercise. For example, they cited a book by Fleck and Kraemer [91] as a source. Fleck and Kraemer claimed that by fatiguing smaller muscles before performing the primary exercise, “...the fatigued smaller muscles will contribute less to the movement of later exercises, thereby placing greater stress on the larger muscle groups” [p. 93]. Their claim is baseless because greater stress on the larger muscle groups (pectoral and deltoid) is not possible if the smaller muscles (triceps) – the hypothetical weak link – are made weaker with pre-exhaustion.

Augustsson and colleagues [101] also cited a review by Tan [104] and a book chapter by Schmidtbleicher [105] to support their description of pre-exhaustion exercise. Tan claimed that the objective is to fatigue the smaller muscles “...so that when the larger muscles are exercised, they will have to generate greater forces to

compensate for the fatigued smaller muscles" [p. 293]. Similar to the claim in the book by Fleck and Kraemer [91], Tan's statement is antithetical to the pre-exhaustion hypothesis. Schmidtbleicher only mentioned pre-exhaustion as one of several training variations such as forced repetitions, negative accentuated repetitions, super-sets, burns, and cheated repetitions to provide an intensive training stimulus – none of which has any scientific evidence to show that they have any greater benefit than simple traditional resistance training.

Nevertheless, Augustsson and colleagues [101] evaluated the knee extension and leg press 10RM in 17 young males who had 5.5 years of resistance training experience. Maximal voluntary isometric motor unit activation (MVIA) was estimated with surface electrodes placed over the rectus femoris, vastus lateralis, and gluteus maximus muscles. The average of three 4-second MVIA's was used as a reference value for comparison of muscle activity during the leg press. Electromyographic (EMG) activity during the leg press was normalized relative to the MVIA. The authors stated that the subjects performed one set of knee extensions to the point of *muscular fatigue* or 10RM and within 5-6 seconds performed repetitions to *muscular fatigue* or 10RM on the leg press exercise. The subjects also performed one set of leg presses without the so-called pre-exhaustion exercise. The order of performing the leg press exercise with or without pre-exhaustion was randomly assigned, with 20 minutes rest between trials.

Augustsson and colleagues [101] reported statistically significant, although probably not clinically significant, fewer repetitions on the 10RM leg press (~8 reps) when it was preceded by knee extension exercise compared with just performing the leg press (~9 reps). Clinically significant means that there would be an expectation of a measureable difference in strength gains when comparing 8RM and 9RM resistance training. The surface electromyographic activity (EMG) in the rectus femoris and vastus lateralis muscles during the leg press was significantly lower following the knee extensions compared with just performing the leg press. However, the differences reported for the rectus femoris (70 and 75% MVIA, with and without pre-exhaustion, respectively) and vastus lateralis (100 and 105% MVIA, with and without pre-exhaustion, respectively) are well within the measurements of error for surface EMG, which is apparent with their reporting of the vastus lateralis 5% above MVIA. The authors' claim that these differences were highly significant ($p = 0.001$ and 0.034 , respectively) is questionable.

The gluteus maximus produced similar EMG activity (65% MVIA) under both conditions. Although it was probably difficult from a logistical aspect to move from the knee extension machine to the leg press machine in 2-3 seconds, the time used by Augustsson

and colleagues [101] was double the time interval (5-6 seconds) between exercises that was stipulated by Jones [100]. Consequently, the pre-exhaustion hypothesis was not actually tested in this study.

According to the original pre-exhaustion hypothesis put forth by Jones [100], the quadriceps are the weak link between the larger hip extensors and the resistance. Performing knee extension exercise immediately followed by leg press exercise does not follow his pre-exhaustion hypothesis. It is merely two exercises that primarily activate the quadriceps muscles. The actual purpose of pre-exhaustion would be to use the fresh quadriceps muscles to assist the pre-exhausted gluteal muscles. Hypothetically, the gluteal muscles involved in the leg press or squat exercise would receive a greater stimulus because the involvement of the alleged weak link (the quadriceps) is reduced.

Consequently, by using knee extension as the pre-exhaustion exercise, Augustsson and colleagues [101] actually pre-exhausted the hypothetical weak link (the quadriceps) rather than pre-exhausting the hip extensors. It should be recognized that Jones also was incorrect in stating that the knee extension was the pre-exhaustion exercise for the leg press. He subsequently manufactured a particular machine (the Nautilus Compound Leg Machine) that ironically did not serve the purpose (pre-exhaustion) for which he originally hypothesized. As correctly noted by Augustsson and colleagues, testing the pre-exhaustion hypothesis for the leg press would necessitate pre-exhausting the hip extensors with a single-joint hip extension exercise. Of course that statement raises the question of why they did not use hip extension for the pre-exhaustion exercise in their study.

In addition, according to Jones' pre-exhaustion hypothesis [100], the resistance for the leg press should have been reduced (~25-30%) to allow the performance of a similar number of repetitions (ten). The purpose is to avoid fatiguing the quadriceps before the larger hip extensors. Augustsson and colleagues [101] used the same resistance for the leg press with and without their so-called pre-exhaustion.

Augustsson and colleagues [101] concluded that because fewer repetitions were performed after the pre-exhaustion (~8 vs ~9 repetitions), trainees should reconsider its effectiveness for increasing muscular strength. Their statement is without any foundation because there is no evidence that a maximal effort on the 9th repetition is a greater stimulus for muscular strength than a maximal effort on the 8th repetition for any exercise. They also stated that they did not attempt to control for repetition duration. When repetition duration is not controlled, the additional momentum created with shorter repetition durations can significantly affect the number of completed repetitions. The conclusions of Augustsson and colleagues are not

relevant to resistance training because it is extremely difficult to test a hypothesis and draw any conclusions about the results when the authors apparently did not fully understand the pre-exhaustion hypothesis.

Gentil and colleagues [102] reported the effects of the sequence of exercise on the number of completed repetitions and EMG activity of three upper body muscles. Thirteen young males with 7.37 years of resistance training experience were assessed for their 10RM on the chest press and pec-deck exercises. In one session they performed one set of the pec-deck exercise to *muscular failure*, and within 20 seconds performed one set of the chest press to *muscular failure*. In another session they performed the same exercise protocol in the reverse sequence. The researchers used a metronome to guide the repetition duration (2 seconds concentric and 2 seconds eccentric muscle actions). They recorded EMG activity of the triceps brachii, anterior deltoid, and pectoralis major. Pectoralis activity was significantly greater than the triceps for the chest press exercise during both sequences of exercise. However, the triceps activity was significantly greater during the chest press when that exercise was performed after the pec-deck exercise. The number of completed chest press repetitions was significantly greater when performed before the pec-deck exercise, and the number of pec-deck repetitions was significantly greater when it was performed before the chest press. There was no significant difference between protocols in the total number of repetitions or total work (repetitions x resistance) for both exercises combined.

Although Gentil and colleagues [102] claimed that they compared the pre-exhaustion system with the *priority system* of resistance training, the pre-exhaustion system specifically stipulates that the time between the primary pre-exhaustion exercise (e.g., the pec-deck) and the secondary exercise (e.g., the chest press) should be three seconds or less. The inter-set rest interval used by Gentil and colleagues was approximately 10 times longer (~20 seconds) than what was recommended by Jones [100]. One should question why the authors did not seek the original source of Jones' pre-exhaustion hypothesis, which is easily accessible on the internet (www.arthurjonesexercise.com/bulletin1/37.pdf). Instead, they cited a book by Fleck and Kraemer (80) as their source, which failed to correctly state the concept of pre-exhaustion exercise.

The second flaw in Gentil and colleagues' study [102] – as in the study by Augustsson and colleagues [101] – was that they did not decrease the resistance (~25-30%) for the secondary exercise (chest press) so that the triceps would not be the hypothetical weak link. This may have allowed a similar number of completed repetitions (ten) for that exercise. As previously noted in this section of the critical analy-

sis, the pre-exhaustion hypothesis predicts that by reducing the resistance for the chest press exercise, the pre-exhausted pectoralis would experience a greater stimulus; that is, a significantly greater EMG activity compared with the triceps.

Brennecke and colleagues [103] recruited 12 young males with 8.81 years of resistance training experience who were assessed for the 10RM barbell bench press and dumbbell fly exercise. Surface EMG activity was recorded for the pectoralis major, anterior deltoid and the long head of the triceps brachii during the bench press for two conditions: performing one set of 10RM bench press in one session, and performing the 10RM bench press approximately 11 seconds after one set of 10RM dumbbell flies in another session. The EMG during the bench press was compared with the MVIA of the aforementioned muscle groups. The EMG for the triceps was significantly greater when the bench press was preceded by the dumbbell flies. The number of completed bench press repetitions was significantly fewer when performed after the dumbbell flies.

According to the pre-exhaustion hypothesis, Brennecke and colleagues [103] should have limited the time between exercises to less than 2-3 seconds. Their time of 11 seconds was too long to actually test the pre-exhaustion hypothesis. Although they did not reference the original source by Jones [100], they did cite an article on pre-exhaustion by Darden [106] who also recommended fewer than 2-3 seconds between exercises. It is interesting that Darden's article is a repeat – almost verbatim – of the chapter by Jones on pre-exhaustion, without actually citing Jones' chapter. And most importantly, Darden never challenged or questioned any of the so-called pre-exhaustion exercises.

For example, Jones [100] and Darden [106] contended that the lower back – not the quadriceps or the gluteal muscles – is the weak link during the performance of the barbell squat. They did not cite any scientific evidence to suggest that a healthy person will fail because of lower back fatigue while correctly performing the squat exercise. In fact, if the squat is performed properly throughout the set, the lower back should be performing an isometric muscle action to help stabilize the torso, while the gluteal, quadriceps, and hamstrings muscles are contracting dynamically to extend the hip and knee joints. Even if the lower back were the weak link in some individuals, the Nautilus Compound Leg machine, which is the only compound machine developed by Jones for lower body pre-exhaustion exercise, consists of knee extension and leg press exercises. The lower back is supported by the machine and not significantly stressed during either exercise.

Other examples given by Jones [100] and Darden [106] are barbell curls immediately followed by close grip chining exercise, and triceps curls immediately

followed by a dipping exercise on parallel bars. These resistance training protocols are merely examples of two exercises that activate the prime movers (elbow flexors and elbow extensors, respectively) with very little rest between exercises. However, they are not examples of pre-exhaustion exercises originally hypothesized by Jones.

In addition, Brennecke and colleagues [103] probably should have reduced the resistance for the bench press so that the hypothetical weak link (the triceps) would not be the limiting factor in the bench press. From a methodological aspect it would appear to be very difficult to move from one machine to another and begin exercising in two seconds unless one were exercising on a Nautilus Double Chest machine, which incorporates both the primary single joint pectoral exercise and the secondary multiple joint bench press exercise in one compound function machine. Of course this raises another important concern regarding pre-exhaustion exercise: even if future research found a significant advantage to this type of exercise over traditional resistance training, not many trainees would have access to this specific machine or some similarity for training.

Section Summary

Four studies reported that when two exercises for similar muscle groups (e.g., pec-deck and bench press) were performed in reverse sequence, the number of completed repetitions was significantly greater for the exercise performed first compared with the second exercise. However, none of these studies actually tested the acute effects of the original hypothesis for pre-exhaustion exercise. And, more importantly, no study has tested the chronic effects of pre-exhaustion training; that is, potential increases in muscular strength. Consequently, there is no evidence to suggest that pre-exhaustion training is superior to simple traditional resistance training.

Scientific Integrity

When he spoke about scientific integrity, the Nobel Prize winning physicist Richard Feynman [107] stated that if a claim is made or results of an experiment are reported in a scientific journal “...then you must also put down all the facts that disagree with it, as well as those that agree with it. In summary, the idea is to try to give all the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another” [p. 11].

Unfortunately, many of the reviews and studies cited in this critical analysis failed to present all the information available on specific topics. For example, Willardson [1] cited a meta-analysis [4] in an attempt to support his claim for the superiority of multiple

set resistance training over single set training, but he failed to cite the critical analysis [5] that clearly showed that meta-analysis to be a highly flawed document. In another review, Willardson [2] cited the ACSM 2002 Position Stand on resistance training [10] to support his claim that the manipulation of inter-set rest intervals significantly affects strength gains. However, he failed to cite the critical analysis [11] of the Position Stand that unequivocally demonstrated how the majority of claims and recommendations – including those regarding inter-set rest intervals – were without any scientific foundation. Willardson [2] also claimed that advanced lifters must perform an increasingly greater volume of exercise to increase strength and he cited another meta-analysis [17]. But again he failed to cite the critical analysis [5] that showed – ironically – that their own data did not support the conclusions in the meta-analysis.

In their review, de Salles and colleagues [3] claimed that the performance of a single set of each exercise is not as effective as multiple sets for strength gains in advanced trainees. They cited the meta-analysis by Rhea and colleagues [4] and another meta-analysis by Peterson and colleagues [108]. However, they failed to cite the critical analysis [5] that revealed numerous mathematical and statistical errors in both of those meta-analyses and their lack of any significant practical application to resistance training.

Most of the studies cited in this critical analysis did not define important but ambiguous terms such as *muscular failure* or *fatigue*, *volitional exhaustion*, etc. Some authors made statements in their Discussion or Conclusions sections that were antithetical to their own reported results. Several authors incorrectly reported the results of other studies; that is, in some instances they reported only those results from a specific study that supported their own training philosophy and failed to report the other results from that study that conflicted with their opinions on resistance training. In some of those studies the overwhelming results that were omitted are contrary to their opinions. Other reviews and studies cited references that failed to support the authors’ opinions or references that were unobtainable or invalid.

Feynman [107] astutely noted: “The first principle is that you must not fool yourself – and you are the easiest person to fool. So you have to be very careful about that. After you’ve not fooled yourself, it’s easy not to fool other scientists. You just have to be honest in a conventional way after that” [p. 12]. Perhaps the stronger the belief or bias, the harder it is not to fool yourself.

A much more important issue than how much rest is required between sets or the sequence of exercise is how all the aforementioned unsubstantiated claims made their way through the supposedly rigorous peer-review process of all those scientific journals. The

ultimate responsibility for detecting bias, negligence and incompetence in peer review lies with the editors-in-chief of those journals.

Conclusions

As shown in previous critical analyses [5, 8, 11], this critical analysis demonstrates how most of the claims and opinions in the resistance training peer-reviewed literature remain unsubstantiated.

- Several studies that assessed the acute responses to various inter-set rest intervals have reported significantly fewer repetitions during subsequent sets of some exercises when shorter inter-set rest intervals were employed. However, most of the authors failed to support their claims that fewer repetitions or a decrease in resistance for subsequent sets will significantly affect strength gains when the final repetition is a maximal effort (RM).
- Nine studies reported the strength gains as a result of training with different inter-set rest intervals. Only three of these nine studies reported significantly greater strength gains for some exercises when longer inter-set rest intervals were employed. However, the differences were only when more traditional inter-set rest intervals such as 2, 3, 4 and 5 minutes were compared with unconventionally brief inter-set rest intervals such as 30, 40 and 60 seconds.
- None of the studies cited in this critical analysis recruited subjects older than their mid-thirties. Therefore, the acute and chronic effects of the different resistance training interventions discussed in this critical analysis are unknown in this large population of older trainees.
- There is no evidence to support the widely-held unsubstantiated belief that acute elevations in specific endogenous hormones such as testosterone and growth hormone have any significant effect on strength gains.
- Two resistance training studies compared strength gains as a result of training with a different sequence of exercise. One study reported a significantly greater increase in two small muscle group exercises when they were performed early in the training sessions, but there was no significant difference in strength gains between groups for the larger muscle mass exercises. The other training study reported no significant difference in strength gains between groups for any of the exercises.
- No study actually tested the acute effects of the original hypothesis for pre-exhaustion exercise. And more importantly, no study has tested the chronic effects of pre-exhaustion training on the potential increases in muscular strength. Consequently, there is no evidence to suggest that pre-exhaustion training is superior to traditional resistance training.

- Science places the entire burden of proof on those who make the claims. Most of the studies cited in this critical analysis failed to meet the burden of proof to support the claims regarding specific inter-set rest intervals, sequence of exercise, pre-exhaustion exercise, or acute endogenous hormonal responses for optimal strength gains.
- Even very strong, sincere, widely held opinions should not take precedence over the actual science when those opinions – sometimes clandestinely disguised as science – are published in scientific journals.

Acknowledgements

I would like to thank Arty Conliffe for improving the readability of the manuscript and consistently challenging the conceptual and technical aspects of this critical analysis. I also sincerely appreciate the unwavering support of my wife Sandee and my son Rocco during the entire preparation of this document.

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Received: May 10, 2010

Accepted: August 10, 2010

Published: August 23, 2010

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