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Symposia

APPLICATIONS OF THE DOSE-RESPONSE FOR MUSCULAR STRENGTH DEVELOPMENT: A REVIEW OF META-ANALYTIC EFFICACY AND RELIABILITY FOR DESIGNING TRAINING PRESCRIPTION

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ABSTRACT. Peterson, M.D., M.R. Rhea, and B.A. Alvar. Applications of the dose-response for muscular strength development: A review of meta-analytic efficacy and reliability for designing training prescription. *J. Strength Cond. Res.* *19(4):950–958. 2005.*—There has been a proliferation in recent scholarly discussion regarding the scientific validity of single vs. multiple sets of resistance training (dose) to optimize muscular strength development (response). Recent meta-analytical research indicates that there exist distinct muscular adaptations, and dose-response relationships, that correspond to certain populations. It seems that training status influences the requisite doses as well as the potential magnitude of response. Specifically, for individuals seeking to experience muscular strength development beyond that of general health, an increase in resistance-training dosage must accompany increases in training experience. The purpose of this document is to analyze and apply the findings of 2 meta-analytical investigations that identified dose-response relationships for 3 populations: previously untrained, recreationally trained, and athlete; and thereby reveal distinct, quantified, dose-response trends for each population segment. Two meta-analytical investigations, consisting of 177 studies and 1,803 effect sizes (ES) were examined to extract the dose-response continuums for intensity, frequency, volume of training, and the resultant strength increases, specific to each population. ES data demonstrate unique dose-response relationships per population. For untrained individuals, maximal strength gains are elicited at a mean training intensity of 60% of 1 repetition maximum (1RM), 3 days per week, and with a mean training volume of 4 sets per muscle group. Recreationally trained nonathletes exhibit maximal strength gains with a mean training intensity of 80% of 1RM, 2 days per week, and a mean volume of 4 sets. For athlete populations, maximal strength gains are elicited at a mean training intensity of 85% of 1RM, 2 days per week, and with a mean training volume of 8 sets per muscle group. These meta-analyses demonstrate that the effort-to-benefit ratio is different for untrained, recreationally trained, and athlete populations; thus, emphasizing the necessity of appropriate exercise prescription to optimize training effect. Exercise professionals may apply these dose-response trends to prescribe appropriate, goal-oriented training programs.

KEY WORDS. progression model, resistance exercise, performance enhancement

INTRODUCTION

Current-day trends have cultivated a steady hierarchical advancement in the professional disciplines of applied exercise science and preventative health. The magnitude of available practitioners, personal trainers, and sport conditioning coaches is increasing not only in sheer number, but also in depth, as subspecialties within these professions emerge. Unfortunately, this progression is not controlled, because our field and the public fails to hold fitness professionals to rigorous standards of knowledge, practice, and/or qualification. The ensuing spread of tangential information leads to confusion and discrepancy of fundamental principles, as well as innovative scientific findings. Equipping students of the exercise sciences with the appropriate tools to convey sound exercise prescription and application in the professional setting is the foremost imperative step. However, by promoting the distribution of research findings to the general exercising public, we can begin to control the integrity and uniformity of this available information, and facilitate its propagation.

Moreover, the other end of the applied-fitness spectrum, which comprises the leaders of sport performance enhancement, is highly specialized, but is also devoid of thorough standardization. The conventional expectation that professional and elite sport will continue to steadily progress in grandeur encourages the ongoing conception and refinement of training technologies and methodologies. This has forced performance-enhancement specialists, coaches, and athletes to build on established training principles, and distinguish auxiliary components, often without the endorsement of scientific investigation. Consequently, athletic performance enhancement has developed into a volatile, yet especially vital institution and determinant for today's sport teams and individual athletes.

Ostensibly, a positive side effect of growth in these professions, and subsequent acknowledgment among the public, is perpetual evolution of exercise-prescription methods and implementation strategies. The design of an effective training program is a complex process, however, involving the application and synergism of established scientific principles, progressive research findings, veteran and modern practices, and professional knowledge to accommodate individual situations, needs, and goals. Whether the program is for a recreational exercise consumer seeking improvements in muscular health and fitness, or a professional athlete working for an advantage on the field of play, ethics demand that sound exercise prescriptions be used. To raise the standards, the National Strength and Conditioning Association has worked to bridge the gap between science and practice by providing disciplinarians and professionals with research-based information that has applicable relevance. In support, the purpose of this paper is to discuss the findings of several recent syntheses of strength development research and to discuss the practical applications of these findings.

A DOSE-RESPONSE FOR MUSCULAR STRENGTH: UNDERSTANDING THE DEBATE

A topic of scientific and professional significance that both the American College of Sports Medicine and National Strength and Conditioning Association have accepted is that of the dose-response for muscular strength training and development (19–21). Historically, a quantifiable relationship between the volume, intensity, and/or frequency of training, and muscular strength improvements, has been elusive and controversial. Although much research has examined strength increases accompanying training interventions, most have examined only 1 or 2 training programs, providing only glimpses of a dose-response relationship. Of the various prescription components, volume of strength training has undoubtedly received the most research attention (i.e., single vs. multiple sets). For many years, personal opinion and the accounts of several unscientific literature reviews were the primary sources of evidence to support training philosophies.

Particularly, several narrative reviews (4, 9, 10) were completed in the 1990s that examined the results of a small number of studies using single and multiple-set training programs. This type of review, which may be perceived as more of an art than science, often relies heavily on personal decisions of the reviewer, and contains numerous areas in which bias may persuade the results. Ultimately, such reviews have proven to be of little value in resolving debate or confusion (3, 5). Not in contrast, some of the conclusions and assumptions from the narrative reviews regarding volume of training include: (a) “The opinion that multiple-set protocols are better than a single set of an exercise is not supported by the consensus of scientific evidence” (4); (b) “Multiple set training has not been shown to provide additional benefits in the adult fitness setting” (9); and (c) “The research results show very convincingly that 1 set is generally as effective as 3 sets” (9).

These conclusions, which are in accordance with the philosophies of many low-volume advocates, presume a universal relationship between volume of training and resultant strength development, such that large initial improvements in muscular strength are achieved from the first set of exercise, and very little, if any additional improvements are acquired with successive sets. In essence, this view suggests that the human body is not capable of hierarchical adaptation to greater stresses, beyond 1 set of resistance training performed a few times per week. Interestingly, in 2002, the American College of Sports Medicine issued a position stand which highlighted the topic of “Progression Models” for individuals seeking muscular development beyond that of general health and fitness (14). This position stand was an obligatory re-recommendation of guidelines for resistance-training prescription. In 1998, the ACSM originally issued the suggestion (1) that a single set of 8–10 exercises would result in similar strength improvements as following a training program of higher volume.

Even at that time, such conclusions drastically opposed training prescription practices, and seemed highly speculative to many experienced members of the sport-conditioning field (3). Furthermore, despite the more recent comprehensive position stand on progressive training to accommodate and facilitate higher levels of muscular fitness, the debate continues. In June, 2004, Carpinelli et al. released another narrative review, “A critical analysis of the ACSM position stand on resistance training: Insufficient evidence to support recommended training protocols” (6). The purpose of this subsequent “objective” follow-up was to critically analyze the contents and supportive rationale behind the 2002 ACSM Progression Model. En route to accomplishing this task, the investigators seemingly rebut each and every one of the defining positions set forth by the ACSM. Specifically, regarding training prescriptions for muscular strength, the authors claim a copious failure of the cited evidence to support (a) “The superiority of free weights or machines for developing muscular strength, hypertrophy, power, or endurance” (p. 5); (b) “The superiority of any specific repetition duration for developing muscular strength, hypertrophy, power, or endurance” (p. 9); (c) “The claim in the Position Stand that specific ranges of repetitions produce specific outcomes . . . ” (p. 11); (d) “. . . the superiority of multiple-set training, while strongly supporting the efficacy of single sets” (p. 18); (e) “The claim in the Position Stand that the rest time between sets and exercise is dependent on the specific goals of a particular exercise, that shorter rest periods decrease the rate of strength gains, and that multiple-joint exercises require longer rest periods than single-joint exercises on machines” (p. 19); and (f) “that the planned manipulation of the program variables in advanced trainees can eliminate natural training plateaus and enable higher levels of muscular strength, hypertrophy, power, and local muscular endurance” (p. 35).

Throughout the article, there is a preponderance of the familiar biased dialog that often contaminates narrative and critical reviews, confirming once again, the obvious downfall of this clumsy (7) style of research. Clearly, a more reliable, detailed, quantitative, and objective method for reviewing very large numbers of research studies is needed to shed brighter light on the dose-response for strength, as well as other fitness endeavors.

META-ANALYTICAL INVESTIGATION: QUANTIFYING THE DOSE-RESPONSE

A powerful investigative method that researchers in sport conditioning rarely use, despite proven efficacy in other disciplines, is the meta-analysis. Nevertheless, this statistical review of the literature may potentially become a principal tool to bridge the gap between the science and practice of exercise prescription. The meta-analysis has been used to synthesize treatment effects/effect size (ES) data in many disciplines, including the medical, psychological, sociological, and other behavioral fields, to combine the results of numerous similar studies, under similar circumstances, and with similar participants, into 1 quantitative analysis. Furthermore, the meta-analysis allows for an *objective* assessment of the magnitude of effectiveness for a given treatment or intervention through established, meticulous statistical guidelines. This technique has served as a valuable research tool, facilitating the observance of dose-response trends, wherein a continuum of variable doses elicits a continuum of quantified responses.

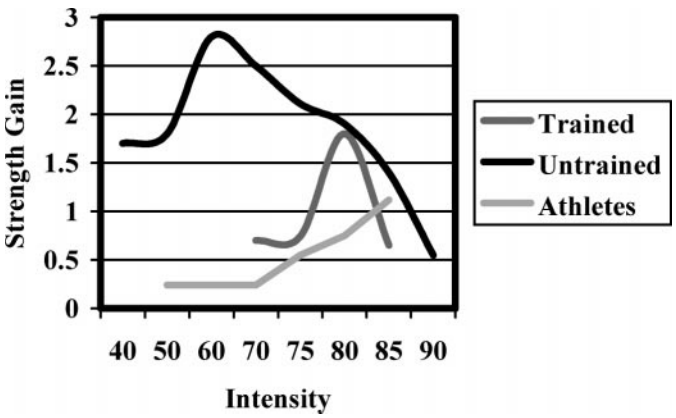

Figure 1. Intensity of training: the average percentage of 1 repetition maximum used throughout the training program.

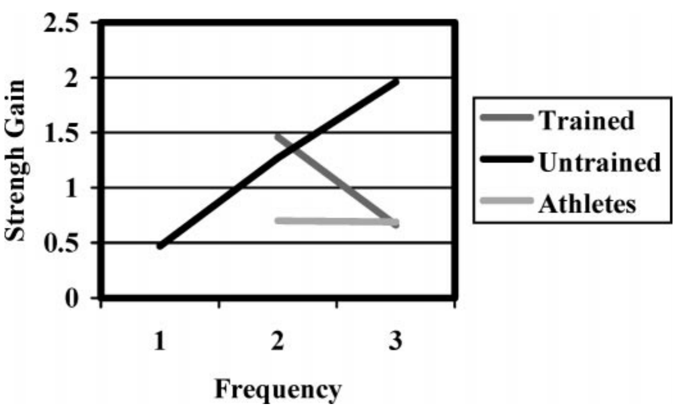

Figure 2. Frequency of training: the number of days per week that participants trained a muscle group.

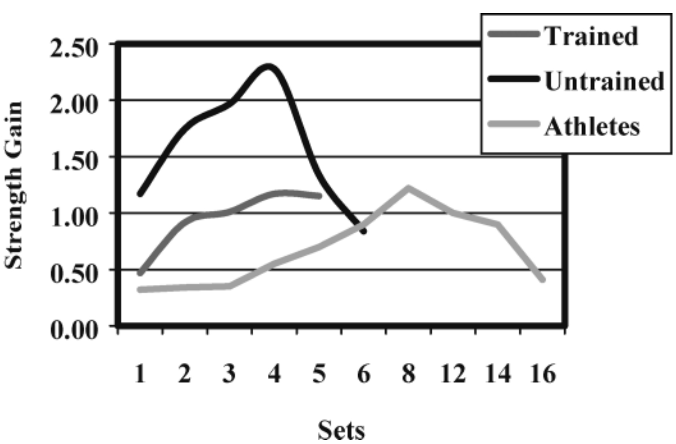

Figure 3. Volume of training: the number of sets performed (per muscle group) during each workout.

Very recently, there have been 2 meta-analyses that have examined and confirmed the existence of a theoretical continuum for strength-training involvement (19, 21). These findings, which were determined by using data from nearly 200 studies, identified a dose-response relationship for the continuum of training intensities, frequencies, and volumes, and resultant strength increases among untrained, trained, and athlete populations (Figures 1–3). Specifically, ES data demonstrated that, for untrained individuals, maximal strength gains are elicited at a mean training intensity of 60% of 1 repetition maximum (1RM), 3 days per week, and with a mean training volume of 4 sets per muscle group. Recreationally trained nonathletes exhibit maximal strength gains with a mean training intensity of 80% of 1RM, 2 days per week, and a mean volume of 4 sets. For athlete populations, maximal strength gains are elicited at a mean training intensity of 85% of 1RM, 2 days per week, and with a mean training volume of 8 sets per muscle group.

Understanding the Data: Application of the Dose-Response

Essentially, this research has confirmed a quantifiable, functional framework whereby the human musculoskeletal system adapts to strength training. Of foremost importance, current data verifies the existence of a dose-response relationship between training stimulus and muscular strength adaptation. Accordingly, single-set and/or very low-volume resistance-training philosophies may no longer be considered adequate for individuals seeking improvement in strength beyond that of general muscular fitness. Significantly greater adaptations are achievable with subsequent sets of training, even for untrained populations (21). Further, and in support of the recent progression model (14), dose-response data demonstrate that muscular strength development requires progressive training, such that smaller doses will elicit greater muscular strength improvement for individuals of inferior muscular fitness than are needed for more highly trained individuals. The effort-to-benefit ratio of resistance training, and associated muscular fitness adaptation, is, therefore, highly contingent on training status (i.e., current strength level and strength-training history). Subsequent training to promote muscular strength improvement must be prescribed on an individualized basis.

Secondly, the rate of improvement in muscular strength, after initiation of a given training prescription, decreases with increased training experience and current level of muscle conditioning. Faster rates of muscular strength improvement are typical during earlier periods of training, especially for previously untrained individuals, and are likely attributed to neural adaptations, resulting in enhanced motor unit activation (2, 24). Moreover, there is a diminished return in sheer magnitude of muscular strength adaptation that accompanies greater levels of muscular development. A novice resistance trainer may have the ability to make vast improvements in short amounts of time, with minimal amounts of training. Alternatively, a recreational athlete with several years of training experience will not only make less improvement in muscular strength, but the improvements will be generated more slowly, and the necessary dose of training to maximize this progress must be subsequently greater. Even a well-trained recreational athlete, however, will be capable of greater strength gains, per unit of time, than would a very experienced, very strong lifter (Figure 4).

Until now, there has been a paucity in the research and literature of quantification of the construct of this phenomenon. The current meta-analytical investigations were not intended to determine the details of this decrement in training adaptation, but rather, to quantify the

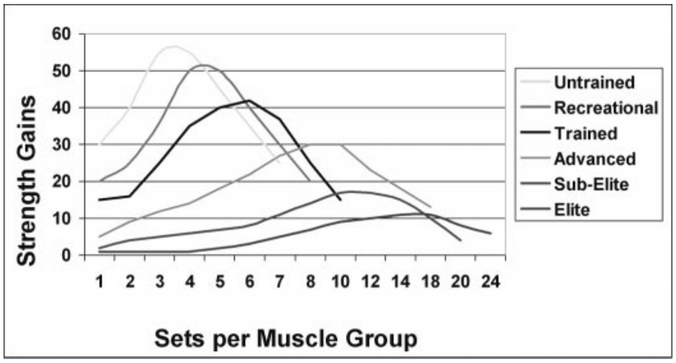

FIGURE 4. Theoretical dose-response progression continuum.

theorized progression continuum by establishing the necessary mean doses to maximize strength development for various populations. To use this data, it is important that the professional understand how to convert these findings to practical entities. Just as an improper prescription of medication may have undesirable effects in a medical setting, so too will the improper dosage of training result in failure of the strength-training program to elicit the desired muscular developmental effect. Clearly, knowledge of how much training is needed to elicit a desired or needed strength improvement would inevitably serve as a valuable point of reference for program design. Most practitioners regard the processes of exercise prescription as a technical, although artistic, endeavor. Accordingly, skillful professionals may use the dose-response data to construct the framework for exercise prescription that, ultimately, may ensure the continued efficiency and effectiveness of a multi-dimensional program.

Although the meta-analyses have greatly reduced the subjectivity of exercise prescription for muscular strength development, the equivocal task of establishing appropriate training doses among specific individuals still exists. An overprescribed protocol will, at minimum, negatively affect the training-to-adaptation (effort-to-benefit) ratio. Unless adjusted, overprescription of the training variables may eventually facilitate strength-gain plateaus or even lead to muscular strength decrements, and cause adverse side effects associated with overreaching and/or overtraining (11). The design of a program must incorporate a systematic method of testing/determining training status and muscular development to ensure proper progression and health. In effect, using the dose-response data may actually demand more time, because careful scrutiny of training progression is constantly necessary.

On the contrary, under prescription of training may be appropriately regarded as training inefficiency. Thus, underprescription becomes less detrimental, or even irrelevant, to most nonathlete populations, than it is for high-level amateur and professional athletes bound by the time constraints of a sport season or the preparation phases of training. Program efficiency for sport conditioning is, therefore, a measure of developmental effect per unit of time. Maximizing efficiency is imperative, because numerous training objectives are set forth during an allotted phase to facilitate safe, successful sport performance. The consummate professional must be cautious in their approach to maximize muscular strength-training efficiency, because the proper prescription is a highly individualistic entity.

OPERATIONAL DEFINITIONS

A respective operational assignment is warranted in further discussing the dose-response relationship for these training variables. Most notably, the designations of training intensity and volume tend to be consistently incongruent among professionals. Intensity of training refers to the percentage of 1RM used for a given exercise. Progressive muscular conditioning necessitates that greater mean intensities of training are necessary to maximize development of strength. For further clarification, the number of repetitions performed should not be considered a component of training volume, because intensity should dictate repetitions, not vice versa. This operational definition for training intensity generates an objective, quantifiable unit, which is contrary to the more subjective measure of training fatigue, often exploited in low-volume programs (8). On a related note, deliberate, slow contraction speed (to accentuate fatigue) is contraindicated for maximal strength development because this method incorporates absolute training intensities lower than necessary for progressive strength adaptation (13).

Training frequency may be defined as the occurrence per unit of time (e.g., calendar week) that a given major muscle group, or prime mover, is trained. Generally, higher-volume training dictates the need to partition a given training program into smaller, less indistinct programs to accommodate greater time requirements. Full-body training, which is often prescribed 2 to 3 days per week, may be reduced to 2 upper-body and 2 lower-body training sessions per week (4 total sessions). Subsequently, an upper-body and lower-body split regimen may be further reduced to target a single muscle or movement in a given training session, twice a week (5–6 total sessions per week for all musculature).

Volume of training refers to the number of sets performed per muscle group, per workout. For example, 5 sets of bench press and 4 sets of incline bench press is equivalent to 9 total sets of training to stimulate strength adaptation of the respective prime-mover musculature. Certainly, all exercises are not created equal regarding limb position, joint articulation, and/or recruitment of synergistic/stabilization muscles. However, rather than defining training volume as the total number of sets per individual exercise, total number of sets per muscle group is a more appropriate measure of the absolute stress applied to a given primary-mover(s). Interestingly, it is apparent that with this designation, many supposed low-volume training philosophies are actually higher-volume training practices.

The inevitable confounding variable that may prevent proper use of the dose-response data is feasibility. Higher-volume workouts that are more strenuous take more time, both as individual training sessions and collectively over time. Many efficiency strategies have been devised that enable more sets of exercise to be performed in a training routine, such as circuit training, complex training, super-setting, drop-setting, tri-setting, etc. Professionals are expected to understand these strategies and be able to implement them at the appropriate place and time. However, there is an unavoidable downfall to most of these strategies: a trade-off must take place with intensity, accompanying higher training volumes and ultimately, fatigue. As the dose-response data demonstrate, the basic strength phase calls for a simultaneous increase in intensity and volume of training. To accomplish both, rest intervals between sets must be accentuated, and single joint, unilateral exercises must become less emphasized.

Furthermore, if the goal or necessity of training is to maximize muscular strength development, the dose-response data must be used in conjunction with a plan that also specifically accommodates muscular endurance, hypertrophy, and muscular power, as well as addresses the vital skill-related components of fitness, including acceleration, speed, balance, coordination, reaction time, and nonlinear movement. Whether it is for recreational- or elite-level training, the deliberate fluctuation of training dosages to pursue specific muscular fitness objectives allows for continued progression over time. In fact, participating in a given training regimen that is *devoid* of variation may well lead to suppression of physiological and neurophysiological adaptations. It is very important that the dose-response data refers to mean intensities, frequencies, and volumes. Within a training microcycle, the daily, or even weekly, values of these doses may be altered, as long as the average remains at the necessary predetermined level to optimize training effect over the duration of the immediate strength program/phase.

As with traditional periodization, this manipulation process typically necessitates that the intensity of training be gradually increased, and volume decreased, over time, allowing for adequate opportunity to adapt to the higher intense training protocol. To concurrently increase both volume and intensity of training, without overtraining, it must be done indirectly. Conceptually, volume performed per unit of time may be increased while decreasing the volume performed per training session, simply by altering training frequency. In other words, there may still be a trade-off with volume and intensity in a given training session, as long as there is a subsequent trade-off between frequency of training per week and volume per workout.

The Law of Diminishing Returns

The law of diminishing returns states that as the quantities of an input increase, the resulting rate of output-increase eventually decreases (12). Often known as the law of diminishing marginal returns in economics, this law is used to determine the optimal working relationship between total and marginal values of a production system. Concerning muscular development, we may consider strength improvement as the product, and dose of training, the input. The change in strength adaptation associated with a 1-unit change in training dosage per unit of time is, therefore, known as the marginal product of strength.

Figure 5 represents a hypothetical snapshot of the continuous relationship between absolute strength, marginal strength, and training dose for a given individual. The strength increase per unit of training dose is greatest at, and denoted by, the inflection point A (the point at which the slope of the line is greatest) on the marginal strength curve. It is at this point on the curve that "Increasing Returns" peaks and transitions into "Diminished Returns." The marginal strength curve in Figure 5 is synonymous with the dose-response trends in that it submits a quantified magnitude of effect for a specific dose of training relative to other doses. Muscular strength development is maximized at the point A. Point A is also

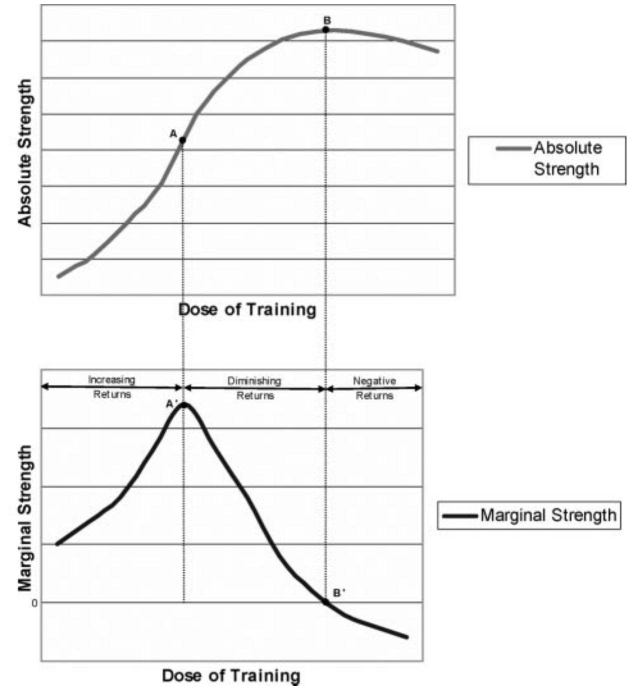

Figure 5. (a) Absolute strength function curve. (b) Marginal strength function curve.

the point wherein the most efficient training takes place, because strength change and training dosage are functions that exists per unit of time. If training dosage is expanded past point A, absolute strength gain continues to progress, but with a diminished return of effort to benefit. Eventually, the increased diminished return becomes "Negative Returns," because absolute strength plateaus at point B and begins to decrease (intersects the zero-value of marginal strength).

Regarding diminishing returns, a prevalent argument against progressive training contests the need for additional volume beyond that of the initial set, citing a marked drop-off in strength adaptation outcome with *any* subsequent training. If, in fact, it is true that the first set elicits a purported 90% of the potential gains in strength, multiple sets may seem inherently unnecessary, and ultimately not worth the time and effort. Interestingly, with simple extrapolation of the coded volume data within the meta-analyses, it is actually possible to examine and quantify this theory with an objective measuring tool and to report the data in relation to an overall percentage of strength gains.

Specifically, as may be seen in Figure 6, when the data for an athletic population is examined it seems that, approximately, a mere 26% of strength-gain potential is elicited with 1 set of training. In fact, dose-response data suggests that an athlete does not satisfy the requirement for 75% of strength developmental propensity until an average of 4 sets of training are completed. Finally, the data also reveals that for the athlete population, a mean of 8 sets of training per muscle group is a requisite to ensure maximal strength-training effect. As an important point of clarification, these data do not confer that a single specific volume of training be an appropriate recommendation for every athlete or nonathlete individual, nor should it encourage the prescription of a particular volume for an extended time. However, the findings do soundly up-

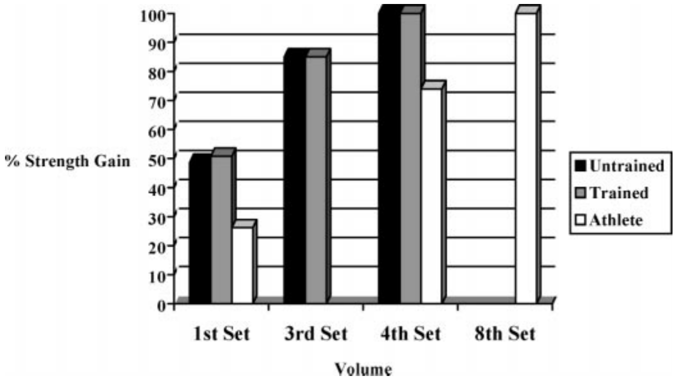

FIGURE 6. Using effect size to extrapolate to percent gains in muscular strength.

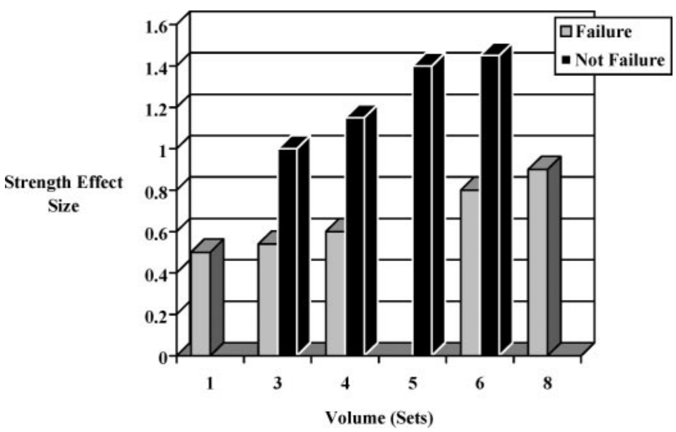

FIGURE 7. Training-to-failure vs. not training-to-failure: implications to volume of training.

hold the conception that a dose-response for strength adaptation exists, and that trends demonstrate a required progression of training volume to approach an eventual average of 8 sets of training to accompany progressive muscular strength adaptation. As a notable corollary, Figure 6 also demonstrates that virtually no differences exist between trained and untrained populations as they respond to variation in volumes of strength training. Once again, the first set of training is only responsible for producing approximately 50% of the overall net potential gain in strength for these 2 populations, needing approximately 4 sets to ultimately achieve the desired maximal effect. Clearly, both athletes and nonathletes require multiple sets of strength training to promote optimization of muscular strength development per unit of time. Low-volume and single-set protocols drastically restrict the potential strength adaptation of athletes and nonathletes, respectively.

DEFENSE OF THE META-ANALYSIS AND DOSE-RESPONSE

Of course, these meta-analyses (19, 21) and dose-response trends have not been devoid of critical scrutiny. In fact, since the publication of the first of these meta-analyses (21) there have been several consistent areas of concern regarding the efficacy of the dose-response for muscular strength program prescription. Accordingly, the following are several standard arguments that have been used against the meta-analyses and proposed dose-response data, as well as the authors' collective defense.

Adherence

Two frequently cited issues relative to the implementation of the dose-response data for athlete populations are increased time commitment per training session, and subsequent training adherence. It has been argued that programs that approach the upper end of the dose-response continuum (which, again, suggest 8 sets of training per muscle group) will surely last longer than 1 hour, and, thus, inevitably fail to produce desired results. Seemingly, this argument stems from a limited body of research advising that 60-minute training sessions be the definitive upper limit in time commitment for exercise programs.

The 1998 ACSM Position Stand states that "Programs lasting more than 60 minutes per session appear to be associated with higher dropout rates" (Ref. 1, p. 983). A critical question must be raised: will strength adaptation and adherence diminish if training sessions last longer than this seemingly simplistic 60-minute rule? The answer to this question becomes less definitive if we consider athletic populations of higher training status. Athletes are truly different than the general populations regarding adherence concerns. However, when taking the athletic population out of the equation, it is interesting to note that the 1998 Position Stand references a study that shows that the average time required to complete a 3-set resistance-training program is approximately 50 minutes (1, 18). Thus, for trained and untrained nonathletes, it is highly probable that a training session may be accomplished in 1 hour, especially if the recommended training volume for trained and untrained populations is used at an average of 4 sets per muscle group.

In reality, there is an upper limit to the amount of time athletes can dedicate to strength-training programs. The true limit is an individualistic entity, however, and it becomes the tedious job of the strength and conditioning professional to use time to optimize the conditioning benefits for each athlete. Motivational factors must be considered for this population. One global and resounding motivational factor is evident as positive results of the actual strength-training intervention. If we understand the theory that governs the dose-response, and what it takes to optimize muscular strength adaptation, credence is lent to additional intensity and volume in program prescription. One of the prime motivators in sport performance training is to produce the desired result of maximal strength improvement. The dose-response offers scientific credibility to the design and implementation of appropriate frequency, volume, and intensity of program prescription.

An additional means of increasing strength-training adherence would be through the processes of systematic goal setting. Several renowned psychologists and sport psychologists have discovered that specific and challenging goals lead to higher intrinsic motivation and performance outcomes than easily attainable goals (15–17, 22). Further, this investigative rationale has also recently been advocated for use in sport performance programs (26). If we are to follow the research and postulated applications, it is evident that multiple-set programs may be used as given explicit, challenging process-oriented goals. Program design may rely on systematic increases in volume and intensity of training as additional motivational factors. To do this, specific alterations in the intensity and volume may be computed and, thus, the training sessions (i.e., process) become part of the goals and ultimate strength development (i.e., product).

Training-to-Failure

One of the most vehement arguments against the dose-response for strength training has come from high-intensity advocates. Accordingly, as theory would suggest, a high-intensity (i.e., single set or very low volume often combined with deliberate, low movement velocity) program can be just as effective as a multiple-set program if sets are performed to the point of absolute muscular failure (8). However, again, with simple extrapolation of training-to-failure data from the meta-analyses, a small sample of data and ES were analyzed ($n = 75$ studies). Each study had to include training-to-failure as a component of the overall data set, and control for the magnitude of training frequency and intensity.

As can be seen in the Figure 7, training-to-failure does not elicit greater gains than not training-to-failure. This is true even when multiple sets of training-to-failure are compared with training sessions that are not training-to-failure.

The Meta-Analyses

Lastly, it is necessary to briefly address the content of several recently published reports on the Internet (23, 27) that have appraised the value of the meta-analyses. Certainly, these critiques were reasonably predictable because there is a long-standing discord between groups of conflicting strength-training philosophies. Unfortunately, whereas dissimilar opinions and viewpoints should, and often can, foster development and refinement of the sciences and practices within a field, from time to time, innovative research inquiry is touted as undisciplined and/or "questionable" if findings are not in support of a particular individual's or group's agenda. Specifically, there are several notorious, self-appointed experts who have made a name by aimlessly denigrating the work of others while supporting an obstinate bias, with critiques that lack scrutiny, justification, and accuracy.

The majority of the initial critique (27) focuses on methodological issues relating to the meta-analysis. Methodological debates have existed since the creation of meta-analytic procedures, as have existed regarding methodologies of narrative reviews and experimental research. Any suggestion that there is a single correct method for conducting a meta-analysis is as imprudent as suggesting that there is only 1 correct method for conducting experimental research. In fact, the checklist wherein a given meta-analysis is evaluated is highly variable and is dependant on whichever of the nearly 100 resources that scrutinize the topic of meta-analytic procedure for the various social, behavioral, and health sciences is chosen. Any suggestion that the findings of the analyses are of "little value" as a result of not including some of the methodological steps that this particular reviewer presents and references is extremely shortsighted. Although we have, as conscientious investigators, acknowledged that each of our analyses has its respective limitations, the critique in question provides no quantitative evidence that the methodological criticisms would actually have any influence on the findings and conclusions presented.

The following are several examples of uncalculated observations. Ultimately, dissection of this critique from Dr. Winnett (27) actually helps to demonstrate the soundness with which the meta-analyses substantiate a dose-response for strength training. The reviewers reported that the 2 meta-analyses proclaimed to have analyzed "all" existing strength-training research articles, to date (Ref. 27, p. 12; Ref. 23, p. 56). First, there have been *no* such claims made wherein "all" studies examining strength development were secured; the only claim was to have conducted a search for studies including a strength-training intervention. Indeed, many more studies have been conducted on strength development than were included in the meta-analyses. Securing every study ever conducted would be unreasonable, because countless more exist. However, we have continued to add studies to the database as we secure them, and have yet to observe any alteration in the dose-response trends presented in our published analyses (19, 21). Based on the size of our current database (>250 studies), it would take literally thousands of ES, all showing drastically different strength outcomes than the studies included in the meta-analyses to have a significant impact on the proposed dose-response data. Such a situation is unlikely to exist.

The analyses were also criticized for the inclusion of multiple ES from a single study, suggesting again that such methodological issues should result in rejection of the findings presented. This is an issue that has received significant discussion and debate in meta-analytic groups, and, for the most part, there has been an acceptance of the inclusion of multiple ES from each individual study, especially when large numbers of studies are included in the analysis. If, for instance, a small number of studies were included, and 1 or 2 of those studies included many ES, then those studies would have a greater impact on the findings of the analysis. However, our analyses included 37 (19), and 140 (21) studies, respectively, with very few studies only contributing a single ES. Most studies reviewed included multiple, dissimilar measures of strength (i.e., squat, bench press, etc.). There is no reason to expect, based on the large number of studies included, that our findings were in any way biased by such methods. Further, once again the reviewer has provided no evidence to otherwise support the claim that such methodological issues render the findings worthless.

Several additional criticisms were raised regarding our statistical analyses. Shockingly, there were considerable concerns regarding the findings for training volume. By performing a simple t-test of 2 sets vs. 4 sets, the reviewer concluded that 4 sets do not elicit greater strength gains because a nonsignificant p value was obtained. However, sole reliance on probability values to make statistical decisions has received a great deal of criticism among researchers recently, because numerous potential errors arise, especially in low-power studies (25). One of the benefits of calculating, and combining ES, is the ability to examine the actual *magnitude* of the treatment effect instead of relying solely on p values to examine differences between treatments. The use of the reviewer's t-test (and nonsignificant p value) was the only source of evidence to support any of the claims made that prompted the conclusion that the meta-analyses do not support the performance of multiple-set training. Interestingly, this t-test was performed between 2 sets and 4 sets—both of which represent multiple-set programs. When analysis of covariance is performed, with intensity and frequency as covariates on the different volumes of training, it is strongly demonstrated that multiple sets of training are more effective at eliciting strength improvements than single-set training. Further, whereas 2-, 3-, and 4-set programs did not result in significantly different effects sizes ($p > 0.05$), it should be noted that, in a number of the studies within the analyses, control groups (no training at all) demonstrated improvements in strength (ES = 0.30), which, based solely on probability values, were found to be similar to the amount of strength improvement with 1 set of training ($p > 0.05$). Therefore, if reliance on probability values is the only source of valid information achieved by the research process (as suggested by opponents of the meta-analyses we have conducted), then those same p values reject the notion that single-set resistance training is any better than no training at all and do not result in the same degree of strength development as multiple-set programs.

Finally, numerous blatant discrepancies between actual facts from the published analyses and allegations found in the critiques must be exposed. First, the meta-analysis on muscular strength for competitive athletes (19) is not a "subset" of the previously published meta-analysis on untrained and trained populations (21), as was suggested (Ref. 27, p. 16). Between the 2 analyses, less than 10 references contributed to both analyses, whereas nearly 200 references in total—with a combined 1,800 ES—were used. A simple reference check could have pinpointed this fact and alleviated any related confusion. Furthermore, inclusion criteria for the 2 meta-analyses dictated a rigorous elimination process, whereby more than 1,000 articles were searched for and coded by the primary authors, during the course of almost 4 years. Each research article was expected to contain a controlled strength-training intervention and include a detailed description of the following information for viable inclusion in the meta-analyses: (a) number of participants (n); (b) duration of training (i.e., number of weeks for the training intervention); (c) periodization (coded as: 1 = traditional linear periodization, 2 = undulating periodization, 3 = no variation-progressive resistance, and 4 = nonperiodized); (d) mode (coded as 1 = free weights, 2 = machines, and 3 = both); (e) volume of training (coded as sets per muscle group per workout); (f) intensity of training (coded as percent of 1RM); (g) frequency of training (coded as number of days trained per week per muscle group); (h) training-to-failure (coded as 1 = yes, 2 = no, and 3 = not specified); (i) status (coded as 1 = untrained: less than 1 year of consistent strength training, 2 = recreationally trained: more than 1 year of consistent strength training or high school athlete, and 3 = college, professional, and/or elite athlete); (j) creatine use (coded as 1 = yes, and 2 = no); (k) sex (coded as 1 = male, and 2 = female); (l) age (coded for mean age); (m) preintervention and postintervention strength measures (coded as means and standard deviation descriptive statistics).

Additionally, in contrast to the claim that we failed to address the issue of differing numbers of ES among varying training volumes and intensities, each of the papers actually contained a clear cautionary statement. In fact, we have pointed out several times throughout our analyses that this limitation should be noted, and that, if all levels were equated, the dose-response trends may have been different. However, as previously mentioned, we have been consistently adding articles and ES calculations to our databases, with no tangible alterations to date. Should there be a change, it would certainly be our duty—as ethical investigators—to present that information. Further, and related to this issue, the review claims that we have neglected to present any physiological or theoretical rationale to explain the data and conclusions. Paradoxically, in every published paper, we have discussed the concepts of overload and progression, two physiological principles of training adaptation that support, and are supported by, our analyses, whereas opponents of these principles (i.e., single-set advocates) continually fail to present a physiological rationale for the opinion that single-set training will elicit maximal strength gains.

Without doubt, the field of exercise and sport sciences will continue to evolve only if there is constant critical examination of the knowledge disciplines and methods that govern the respective research. Nevertheless, if an impact is to be made on the rising number of professionals that administer exercise and sport-conditioning prescriptions, and more importantly, the general consumer who seeks education in pursuit of fitness aspirations, there must be a shift in paradigm to acquiesce to "common goals" by means of "different roles." Much of the clinical credibility lost during the early part of the last 40 years, with the emergence of the first scientific-*reminiscent* literature on strength training, has been regained. Relatively speaking, however, the science behind the principles of strength training and disciplines of sport conditioning is still very much in an infancy stage. As a result, the professional frontlines of the field have, by necessity, preceded the scientific community for quite some time. Hence, any all-encompassing blanket arguments against the principles that are advocated by the National Strength and Conditioning Association and the American College of Sports Medicine, because of a "lack of empirical support" (23), should be viewed merely as spiteful. Moreover, with the availability of today's training technologies and methodologies, a persistent reliance on age-old beliefs that ignore valuable and innovative empirical evidences, so as to oversimplify and over generalize strength-training prescription, is clearly illogical.

Practical Applications

A principal objective in sport conditioning includes maximizing training effect per unit of time to allow multiple goals to be met simultaneously. Current dose-response data establishes the point at which marginal strength is maximized for various inputs (i.e., volume, intensity, and frequency). It should be a primary objective of all professionals to determine the point at which a given athlete, or group of athletes, maximizes progress. The collaborative results of the 2 meta-analyses demonstrate that development of muscular strength through resistive exercise may be optimized through careful prescription and manipulation of the training variables, such that distinct dose-response relationships correspond to specific populations. Furthermore, training status (i.e., training history and level of current muscular fitness) directly dictates these optimal doses and influences the potential magnitudes of the responses. In particular, for healthy individuals seeking to experience muscular strength development beyond that of general health, a requisite increase in resistance-training dosage must accompany increases in training time and experience. These investigations further demonstrate that the effort-to-benefit ratio is different for untrained, recreationally trained, and athlete populations; thus, emphasizing the necessity of appropriate exercise prescription to optimize training adaptation. The meta-analytic procedure is a scientific, rigorous, objective, and quantifiable synthesis of a given treatment and resultant treatment effect. Relying on such scientific evidence, combined with professional experience and competency, may result in the most effective and reliable training prescriptions.

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