Journal of Strength and Conditioning Research, 2004, 18(2), 377–382

Research Note

MAXIMIZING STRENGTH DEVELOPMENT IN ATHLETES: A META-ANALYSIS TO DETERMINE THE DOSE-RESPONSE RELATIONSHIP

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ABSTRACT. Peterson, M.D., M.R. Rhea, and B.A. Alvar. Maximizing strength development in athletes: A meta-analysis to determine the dose-response relationship. *J. Strength Cond. Res. 18(2):377–382. 2004.*—The efficiency, safety, and effectiveness of strength training programs are paramount for sport conditioning. Therefore, identifying optimal doses of the training variables allows for maximal gains in muscular strength to be elicited per unit of time and also for the reduction in risk of overtraining and/or overuse injuries. A quantified dose-response relationship for the continuum of training intensities, frequencies, and volumes has been identified for recreationally trained populations but has yet to be identified for competitive athletes. The purpose of this analysis was to identify this relationship in collegiate, professional, and elite athletes. A meta-analysis of 37 studies with a total of 370 effect sizes was performed to identify the dose-response relationship among competitive athletes. Criteria for study inclusion were (a) participants must have been competitive athletes at the collegiate or professional level, (b) the study must have employed a strength training intervention, and (c) the study must have included necessary data to calculate effect sizes. Effect size data demonstrate that maximal strength gains are elicited among athletes who train at a mean training intensity of 85% of 1 repetition maximum (1RM), 2 days per week, and with a mean training volume of 8 sets per muscle group. The current data exhibit different dose-response trends than previous meta-analytical investigations with trained and untrained nonathletes. These results demonstrate explicit dose-response trends for maximal strength gains in athletes and may be directly used in strength and conditioning venues to optimize training efficiency and effectiveness.

KEY WORDS. weight training, resistance exercise, sports conditioning

INTRODUCTION

The demands of competition have increased steadily throughout time as sports scientists, coaches, and athletes continue to systematically identify and specify auxiliary elements necessary to succeed in sport as well as surpass predecessors. As these performance demands have increased, so too have the "stakes" associated with success. Winning has become more recognized, admired, illustrious, and lucrative than ever before in history. As a result, sports conditioning and training has developed into a vital component and determinant of success for today's competitive athlete.

During the past half century, innovative exercise disciplinarians and professionals have methodically developed the basic principles of, and instituted new principles for, the practice and implementation of sports conditioning. This growing emergence of the science of sports conditioning, as an exclusive discipline in the field of exercise science, stems from the specific needs of competitive athletes as well as the different training capacities of athletes and nonathletes. The physical demands of sport are generally greater, the training status of the participants is usually much higher, and the possibility of injury is more prevalent. Consequently, the need exists for effective sport conditioning protocols specific to the nature of sport and sport participants.

In contrast to the former unilateral preoccupation with the aerobic energy system that has historically driven exercise science and sport conditioning, a multidimensional approach designed to increase multiple components of fitness is employed in today's strength and conditioning programs. Of the various conditioning aspects, strength training has become one of the most recognized, accepted, and readily implemented conditioning modalities for athletic populations. Furthermore, the study of strength development determinants has subsequently been recognized and embraced as a valid area of investigation in the scientific world at large (22). This concurrent acknowledgment has led to the widespread research and use of different strength training programs for athletic preparation at the recreational, college, and elite levels of sport.

The 2002 American College of Sports Medicine (ACSM) Position Stand, "Progression Models in Resistance Training for Healthy Adults" (21) is significant because it examines, affirms, and reinforces the research that has established various principles that facilitate continued and optimal strength development. Specifically, the position stand emphasizes the necessity of implementing "progressive programs" for healthy individuals seeking to experience muscular conditioning beyond that of general muscular health and fitness. The distinguishing prerequisite of a standard progressive training program is chronic alteration of certain training variables, including resistance, number of sets and repetitions, exercise selection and order, and rest period length (21). Additionally, the statement establishes a requisite increase in resistance training intensity and volume to accompany increased training time and experience.

Despite the widespread consensus of the administration of progressive training programs for athletic communities, disparities still exist regarding the most appropriate "dose" of training to elicit maximal gains in muscular strength (i.e., "optimal response"). Most notably, the dose quantifications of intensity, frequency, and volume have emerged as being among the foremost disputed training variables. This explicit dose-response relationship, however currently intangible, would be an invaluable asset to all strength and conditioning professionals as well as sport science researchers. Seasonal time constraints for sport significantly influence the capacity to optimally develop trainable characteristics of an athlete or group of athletes. A consequential, critical need exists to maximize the efficiency and effectiveness of sport conditioning programs.

Establishing and substantiating sport conditioning modalities by way of meta-analytical procedure is at present novel but effectual for optimizing training effect. The need for appropriately designed, specific strength training "prescriptions" in the athletic community is escalating as the competition between today's sport participants steadily increases in quantity and quality. Research has shown that there exists a continuum of trainable adaptations that appropriately correspond to a certain population, based on the training experience and/or training status of that population (21). According to this continuum, the rate of improvement in muscle strength on initiation of a given training prescription decreases with increased training experience and current level of muscle conditioning. Faster rates of muscular strength improvement at smaller doses of resistance training are typical during earlier periods of training or for previously untrained individuals and are likely attributed to neural adaptations resulting in enhanced motor unit activation (11). Furthermore, innovative investigations have begun to discover that there also exists a continuum of the dose-response relationship of certain training variables and associated trainable adaptations for different populations.

The most convincing of these investigations came from a meta-analysis of strength training research (39). In the analysis, 140 research studies, with 1,433 effect sizes, were examined and carried out to ascertain the dose-response relationship for trained and untrained individuals. Effect sizes were calculated and reported for intensity of training (defined as percentage of 1 repetition maximum [1RM]), frequency of training (defined as days per week for a given muscle group), and volume of training (defined as the number of sets performed per muscle group). Effect sizes were used to present different dose-responses per training status of the participants. It was found that untrained individuals demonstrate maximal strength gains when training at 60% of 1RM, 3 days per week, with 4 sets per muscle group. For trained individuals, results showed that maximal strength gains occur when training at 80% of 1RM, 2 days per week, with 4 sets per muscle group. This extensive meta-analysis is significant to the body of literature because it identifies differences in the optimal doses of training to elicit maximal responses in strength between untrained and trained individuals, it strongly supports the recent progression model outlined by the American College of Sports Medicine (21), and it offers objective data that may be directly used for exercise prescription in untrained and trained populations. This type of study is critical, as it essentially eliminates the ambiguity that surrounds the fundamental training prescription variables for specific populations, thus maximizing the potential trainable adaptations.

The recent meta-analysis by Rhea et al. (39) suggests that the dose-response differs based on training status of the participants. In their research, it was demonstrated that the effort-to-benefit ratio is different for untrained and trained individuals, such that maximal increases in strength are attained through different quantities of the training variables. If the principle of progression holds true, the dose-response trends for athletes will differ from those exhibited for lesser-trained populations. The purpose of this investigation was to identify a specific dose-response relationship for intensity, frequency, and volume of training and the resultant strength increases by calculating the magnitude of gains elicited by various protocols in an athletic population.

Methods

Experimental Approach to the Problem

Literature searches were performed for published studies that included strength measurements before and after strength training intervention programs among competitive athletes. Computer searches of Science Citation Index, National Library of Medicine, Sport Discus, ERIC, and Medline were performed. Hand searches of relevant journals and reference lists obtained from articles were conducted. Criteria for study inclusion were that participants must be competitive athletes at the collegiate or professional level, the study must employ a strength training intervention, and the study must include necessary data to calculate effect sizes.

Coding of Studies

A total of 37 studies (1, 3–6, 9, 13–20, 23–35, 37, 38, 40–48) were read and coded for the following variables: descriptive information (gender and age), frequency of training, mean training intensity, number of sets performed, use of creatine, training to failure (use or not of RM training), and periodization of the training program. Frequency was determined by the number of days per week that participants trained a particular muscle group. Intensity was coded as the average percent of 1RM used throughout the training program. Volume was recorded as the number of sets performed (per muscle group) during each workout.

Coder drift was assessed (36) by randomly selecting 10 studies for recoding by a separate investigator. Per case agreement was determined by dividing the variables coded the same by the total number of variables. A mean agreement of 0.90 was designated as an appropriate level of reliability in the coding procedures.

Statistical Analyses

Pre/post effect sizes, representing a standardized mean difference, were calculated with the following formula: [(posttest mean − pretest mean)/pretest *SD*] (7). Descriptive statistics were calculated, and 1-way analysis of variance was used to examine differences in effect sizes by variable and training protocol with level of significance set at $p \leq .05$. Trend plots were developed, based on descriptive data, representing a dose-response curve for frequency, intensity, and volume.

Results

Mean effect sizes data are presented in Tables 1–3. These data demonstrate that maximal strength gains are elicited among athletes who train at a mean training intensity of 85% of 1RM, 2 days per week, and a mean training volume of 8 sets per muscle group. Trend plots identified that the magnitude of strength gains decreased with training above 8 sets. Because of the lack of sufficient effect sizes for a mean training intensity above 85% of

Table 1. Mean effect sizes for frequency of training.*

Days/week	Mean	±*SD*	*n*
2	0.70	0.76	158
3	0.69	1.13	173

* Days/week = number of training sessions per muscle group per week; *n* = number of effect sizes.

Table 2. Mean effect sizes for volume of training.*

Sets	Mean	±*SD*	*n*
1	0.32	0.38	6
3	0.36	0.42	54
4	0.90	1.32	119
5	0.64	0.73	37
6	0.68	0.74	26
8	1.22	0.56	6
12	0.69	0.80	46
14	1.06	1.41	8
16	0.41	0.36	22

* Sets = sets per muscle group per workout session; *n* = number of effects sizes.

Table 3. Mean effect sizes for intensity of training.*

% 1RM	Mean	±*SD*	*n*
50	0.24	0.19	34
60	0.24	0.25	20
65	0.10	0.08	12
70	0.07	0.06	16
75	0.73	0.87	27
80	0.57	0.69	94
85	1.12	1.35	96

* RM = repetition maximum; *n* = number of effect sizes.

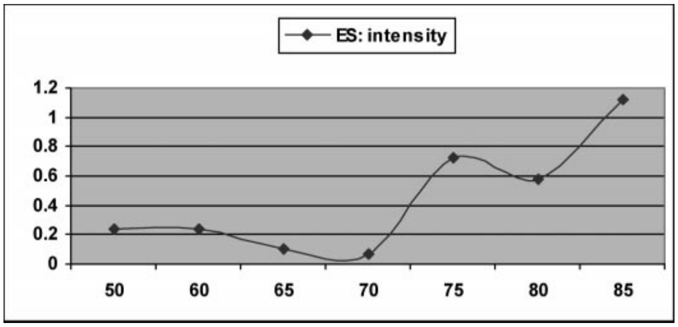

FIGURE 1. Dose-response for intensity.

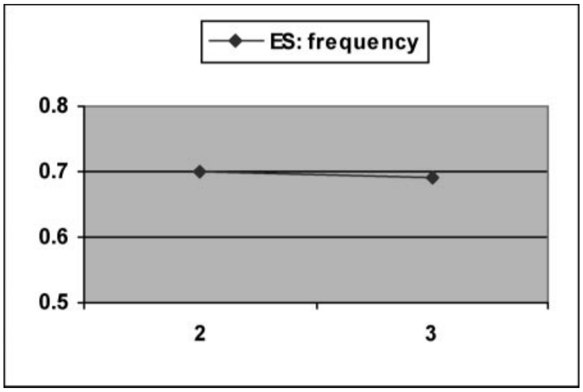

FIGURE 2. Dose-response for frequency.

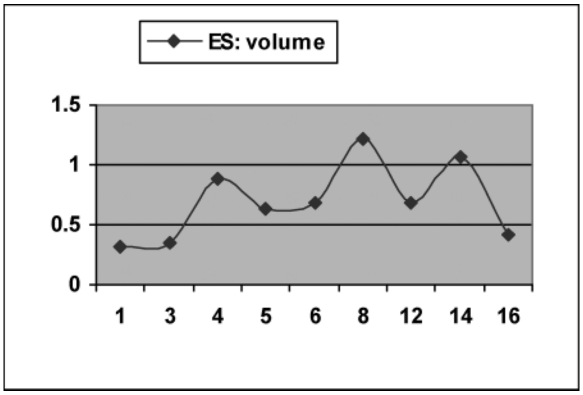

FIGURE 3. Dose-response for volume.

1RM, it is unclear if higher intensities would result in greater strength improvements. Dose-response curves (Figures 1–3) identified that training at lower volumes (1–3 sets) and intensities (50–70% 1RM) elicited minimal strength improvements among athletes. Effect sizes for training frequency showed no additional benefit to training 3 days per week over 2 days.

Participants using creatine, periodized training programs, and training protocols that involved training to failure elicited greater magnitudes of strength gains ($p < 0.05$). However, these variables did not significantly alter the overall dose-response trends exhibited in the data. Subsequent analysis would be necessary to determine potential dose-response differences between varying creatine supplementation procedures, periodization models, and training programs to failure. In addition, effect sizes were similar ($p > 0.05$) for both men and women. Coder drift was calculated to be 0.94; thus, the coding process was found to be reliable.

DISCUSSION

The results of the present study confirm the existence of a distinct dose-response relationship for strength development in competitive athletes and, accordingly, support the principle of progression for exercise prescription. More specifically, the data offer a quantified description of the magnitude of strength increases elicited per various levels of training intensity, frequency, and volume and demonstrate a differential dose-response relationship from the previous meta-analytical investigation, which considered primarily nonathletes (39). The deliberate significance of this type of investigation becomes apparent when contrasted with individual strength training intervention studies that examine only 1 or 2 training programs. Though critical to the body of knowledge, these studies do little to reveal relationships between a gamut of doses and the associated strength development. The current meta-analytical procedure provides a continuum of quantified strength increases elicited by a continuum of training intensities, frequencies, and volumes.

The results of this investigation demonstrate that competitive athletes experience maximal gains in strength when training at a mean intensity of 85% of 1RM (Figure 1). These results are in line with previous recommendations that have discussed optimal training loads to elicit muscle strength in athletic populations (32).

As can be seen by the dose-response curve, minimal strength increases will be elicited by a mean training intensity of 50–70% of 1RM. Further examination of this curve reveals that when approaching a mean intensity of 85% of 1RM, the trend of strength development increases with increased intensity. However, because of a lack of Effect sizes for mean intensities above 85% of 1RM, the magnitude of strength gains above 85% 1RM was unidentified.

The optimal dose of training intensity for competitive athletes differs from that found for trained and untrained nonathletes by Rhea et al. (39). In their study, maximal gains in strength development were found to be elicited by a mean intensity of 80 and 60% of 1RM for trained and untrained individuals, respectively. This disparity in optimal training dosage per population is likely a result of gradual neural adaptations to lower training intensities that accompany prolonged training experience. Therefore, a progression to higher intensities is required to experience maximal strength gains (Figure 1).

Effect sizes for training frequency (2 and 3 days per week) were similar with no additional benefit to training 3 days per week (Figure 2). An important issue when considering these data is that frequency of training refers to the number of times per week a given muscle group was trained. Many of the training programs included in this meta-analytical investigation incorporated split-strength training programs in which different muscle groups were trained on different days of the week. Therefore, these data demonstrate that each individual muscle groups should be isolated only 2 times per week, but strength training may occur up to 6 times per week if the various muscle groups are separated accordingly.

This analysis demonstrates that maximal strength gains are elicited among competitive athletes who train at a mean 8-set per muscle group training program (Figure 1). These data unequivocally demonstrate the added strength benefits that accompany higher training volumes than is proposed by and used in low-volume training philosophies. Moreover, the data support a quantifiable needs difference in training volume between competitive athletes and nonathletes, such that athletes require a higher volume of training to elicit maximal strength development. In the previous meta-analysis (39), it was determined that a mean volume of 4 sets per muscle group is optimal for maximizing strength gains in a nonathlete population (both trained and untrained individuals). Conversely, for an athletic population, the current investigation would suggest a training volume that doubles this recommendation for maximal gains. This obligatory increase in the training volume for competitive athletes supports the need for progressive training dosages among individuals with more training experience and/or higher initial levels muscular fitness. As athletes adapt to lower-volume training, there is a need for gradual increases in volume to elicit continued overload of the neuromuscular system (10) as well as augmented stimulation of the hormonal system (8, 12).

In 1998, the ACSM addressed this issue of strength training volume in the position stand "The Recommended Quantity and Quality of Exercise for Developing and Maintaining Cardiorespiratory and Muscular Fitness, and Flexibility in Healthy Adults" (2). This position stand presented an initial benchmark for the strength training prescription of healthy adult populations, offering a training recommendation of 1 set per muscle group and 8–10 exercises per workout. The 2002 ACSM position stand (21) revised this recommendation to accommodate those individuals interested in attaining muscular conditioning beyond that of general muscular health and fitness. The subsequent purpose of ACSM's follow-up was "to extend the initial guidelines established by the ACSM for beginning resistance training programs and provide guidelines for progression models that can be applied to novice, intermediate, and advanced training" (21 p. 365).

Clearly, the progression models now advocate increased dosages of training to accompany increased training experience and/or initial level of muscular fitness. Low-volume training programs may be sufficient to elicit strength development in untrained individuals but will eventually lead to diminished returns as these individuals adapt and become more experienced (21). It is a subsequent necessity to establish the optimal doses of resistance training to facilitate maximal strength development for given populations of more training experience. Current data are consistent with the progression model in that higher volumes of training are necessary for athlete populations than is even needed for trained nonathletes. For athletes, effect size data demonstrate a relatively small mean effect size for 1-set-per-muscle-group training interventions (mean effect size = 0.32), a moderate effect size for 5-sets-per-muscle-group interventions (mean effect size = 0.64), and a high effect size for 8-sets-per-muscle-group training interventions (mean effect size = 1.22). Consequently, these data demonstrate that the 8-set training interventions elicit strength increases of nearly 1 standard deviation above that of 1-set interventions in regard to magnitude of effect (Figure 3).

A note of clarification is warranted when discussing the dose-response relationship for training intensity and volume. This elucidation is crucial, as ambiguity and divergence exists within the strength and conditioning community regarding "intensity" and "volume" designation. In each of the studies analyzed, training intensity was coded as the average percent of 1RM used throughout the training program and training volume as the number of sets performed per muscle group. This operational definition for training intensity generates an objective, quantifiable unit that is contrary to the more subjective measure of training fatigue, often exploited in "H.I.T." programs. Additionally, rather than designating volume as the total number of sets per specific exercise, total number of sets per muscle group is a more appropriate measurement of the absolute stress applied to a given muscle group. It should be noted that in accordance with this classification, many purported 1-set training programs/philosophies may, in effect, be multiple-set training practices.

As previously mentioned, progressive training programs are marked by variation of resistance training determinants (21). Many of the studies analyzed in the present meta-analytical investigation incorporated periodized training models in which training volumes and intensities fluctuated over the duration of the intervention (i.e., 3–7 sets at 70–100% 1RM). Therefore, it is necessary to qualify current effect size data in that the dose-response curves signify the *mean* training dosages. It is the position of the authors that strength and conditioning professionals should not facilitate the implementation of resistance training programs that employ prolonged durations of constant training volumes and/or intensities.

PRACTICAL APPLICATIONS

Depending on the athletic venture, considerable degrees of muscular strength, power, and endurance, as well as neuromuscular control, aerobic capacity, agility, and mental acuity, are often needed as an athlete competes and progresses through the ranks. When applying the current dose-response relationship for exercise prescription among athletes, it is necessary to take into account a "needs analysis" and assessment of the sport in question as well as the individual athlete (32). It is essential for the strength and conditioning professional to consider the most appropriate training approach based on the fundamental limb movement patterns, energy system requirements, and potential injury analysis for a given sport. Further, for an individual athlete, initial training status and training experience must be regarded, and specific fitness limitations should be emphasized. An exercise specialist or strength and conditioning coach can look to the dose-response trends identified in this analysis to prescribe the appropriate level of training for eliciting the desired or needed strength increase.

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