



REVIEW ARTICLE

Impact of Resistance Training on Sports Performance and Muscular Adaptations

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Abstract

Resistance training helps contribute to sports performance and general health benefits. In particular, resistance training is linked to physiological adaptations causing increases in muscular strength, endurance, power, and hypertrophy. These muscular adaptations can be translated to improvements in sports performance. With this concept in mind, sports performance coaches can manipulate training variables in order to optimize athletic performance and help athletes achieve their goals. However, additional research is warranted investigating how certain resistance training variables impact muscular adaptations. Thus, the purpose of this literature review is to explore the impact of resistance training on sports performance through adaptations in muscular strength, hypertrophy, endurance, and power. In addition, this review will study the impact of manipulating resistance training factors, such as rate of force development, frequency, intensity, load, and volume on muscular adaptations.

Introduction

Resistance training contributes to a variety of health and performance-related benefits [1-3]. In fact, Liu, et al. [2] found participating in resistance training as little as once per week, for less than one hour, was associated with a 40-70% reduced risk of cardiovascular disease ($p < 0.05$). Furthermore, resistance training has been linked to improvements in blood pressure [4], bone density [5], and glucose metabolism [6]. In addition to health-related benefits, resistance training has been associated with increases in muscular strength, endurance, power, and hypertrophy, which translates into improvements in athletic performance [1]. With these health and performance benefits in consideration, several organizations have made

resistance training recommendations. The American College of Sports Medicine recommends adults perform resistance training two to three days per week [7]. The National Strength and Conditioning Association also recommends two to three days of resistance training for most athletes, while advanced athletes may safely train up to six days per week [8]. Despite these recommendations, only 30.2% of adults in the United States complete resistance training at least two days per week, and 57.7% report no muscle-strengthening exercise at all [1].

Outcome measures in resistance training studies typically include muscular hypertrophy, strength, endurance, and power. For the purpose of this literature review, hypertrophy is defined as an increase in muscle size [8]. Strength is defined as the maximal amount of force a muscle can produce in a single effort [8]. Endurance is defined as the ability of muscles to repeat contractions over an extended period of time [8]. Power is defined as the ability of muscles to produce force rapidly [8]. A meta-analysis conducted on 111 studies found resistance training significantly increased muscle mass ($\Delta 1.53$ kg; 95% CI [1.30, 1.76], $p < 0.001$). Despite the clear linkage between resistance training and improvements in hypertrophy, there are still gaps in knowledge related to optimizing athletic performance with resistance training. In addition, there are multiple resistance training variables that can be manipulated in order to support the goals of an individual. For example, sports performance coaches will often manipulate the number of repetitions, sets, and rest periods depending on training goals. Training load, frequency, intensity, velocity, and volume are also

important factors involved in muscular adaptations to resistance training. Additional research is warranted investigating how these factors influence muscular adaptations.

Resistance training volume, in particular, appears to be related to muscular hypertrophy [9]. Many resistance training recommendations are based on the belief that greater training volume, defined as sets \times reps \times load, contributes to greater gains in hypertrophy [9]. However, there are discrepancies in previous research findings. For example, some studies indicate higher training volume produces greater muscular adaptations [10,11], whereas other studies have found no differences [12,13]. In addition to muscular hypertrophy adaptations, research indicates improvements in muscular strength are associated with enhanced force/power production, sport-skill performance, and decreased injury risk [3]. However, female athletes are typically not represented in strength training studies. In addition, there is a significant gap in knowledge related to differences in muscular adaptations as athlete's progress through various phases in resistance training programs [3]. Thus, the purpose of this literature review is to explore the impact of resistance training on sports-performance through adaptations in muscular strength, hypertrophy, endurance, and power. In addition, this review will study the impact of manipulating resistance training factors, such as rate of force development, frequency, intensity, load, and volume on muscular adaptations.

Review of Literature

Training volume

Sports performance coaches often manipulate training volume throughout various cycles in order to elicit maximal improvements in athletic performance. Consequently, it is important to review the impact of training volume on physiological markers, such as muscular hypertrophy and strength. Sooneste, et al. [11] compared the effects of three sets versus one set of resistance training on muscular strength and hypertrophy in eight subjects who followed a 12-week resistance training program. Researchers utilized a crossover-style design in which participants' right and left arms were randomly assigned to complete one or three sets of dumbbell preacher curls at 80% one-rep max. Participants followed the program twice per week for 12 weeks. Researchers discovered three sets significantly ($p < 0.05$) increased cross-sectional area more than one set ($13.3 \pm 3.6\%$ vs. $8.0 \pm 3.7\%$). In addition, strength gains were significantly ($p = 0.076$) greater with three sets compared with one set ($31.7 \pm 22.0\%$ vs. $20.4 \pm 21.6\%$). This finding was further supported by Radaelli, et al. [10], who compared the effects of one, three, and five sets of resistance training on muscular strength, endurance, and hypertrophy among young

males with no weight training experience. In this study, participants were randomly assigned to one of three groups and completed three training sessions per week for six months. Researchers discovered five-rep max in the Bench Press (BP) and front Lat Pull Down (LPD) significantly ($p < 0.05$) increased greater for five-sets (BP: $89.6 \text{ kg} \pm 9.6$ pre to $99.6 \text{ kg} \pm 5.5$ post; LPD: $74.2 \text{ kg} \pm 9.5$ pre to $86.5 \text{ kg} \pm 6.5$ post) compared with three-sets (BP: $73.4 \text{ kg} \pm 9.4$ pre to $86.1 \text{ kg} \pm 8.4$ post; LPD: $62.5 \text{ kg} \pm 6.21$ pre to $70.0 \text{ kg} \pm 4.76$ post) and one-set (BP: $64.5 \text{ kg} \pm 9.5$ pre to $73.2 \text{ kg} \pm 9.9$ post; LPD: $57.9 \text{ kg} \pm 10.7$ pre to $68.7 \text{ kg} \pm 9.5$ post). Furthermore, bench press 20-rep max significantly ($p < 0.05$) increased greater with five-sets ($46.5 \text{ kg} \pm 4.7$ pre to $57.6 \text{ kg} \pm 4.3$ post) compared with three-sets ($41.9 \text{ kg} \pm 7.2$ pre to $49.2 \text{ kg} \pm 6.4$ post) and one-set ($34.1 \text{ kg} \pm 3.5$ pre to $35.8 \text{ kg} \pm 5.1$ post). Finally, the effect size for the change in elbow flexor muscle thickness was small for one-set (0.05) and three-sets (0.05), but large for five-sets (2.33). This data indicates a dose-response relationship between the volume of resistance training exercise and improvements in muscular strength, endurance, and hypertrophy [10].

These muscular improvements may be attributed to several physiological adaptations. Greater training volume may be associated with promoting an anabolic environment for muscle growth by increasing anabolic hormones, protein synthesis, and fast-twitch fiber activation [11]. However, it is important to note both of the previously described studies used participants without weight lifting experience [10,11]. When analyzing one-rep max bench press normative values published by the Cooper Institute [14], the one-set group in the Radaelli, et al. [10] study was classified as "poor," with a bench press weight ratio of 0.92. Individuals need to achieve a score of at least 0.99 for "fair," 1.14 for "good," and 1.32 for "excellent" [14]. In addition, untrained individuals may experience greater initial strength gains compared with trained individuals, often attributed to neural adaptations [11]. Thus, future research is needed to investigate the dose-response relationship in training volume and muscular adaptations in trained subjects. Furthermore, multiple studies [12,13] have found conflicting results compared with the findings of Radaelli, et al. [10] and Sooneste, et al. [11], which indicates the need for additional research on this topic area.

Bottaro, et al. [12] studied the effects of training volume on upper and lower body muscular strength and hypertrophy. Similar to the exercise protocol followed in the Sooneste, et al. [11] study, participants in the Bottaro, et al. [12] study completed resistance training twice per week for 12 weeks. Bottaro, et al. [12] randomly assigned participants to complete either three sets of knee extension and one set of elbow flexion exercise (3K-1E), or one set of knee extension

and three sets of elbow flexion exercise (1K-3E). Elbow flexor muscular thickness significantly increased for both groups, with no significant difference ($p = 0.866$) between groups (3K-1E: 27.9 mm \pm 4.2 pre to 29.9 mm \pm 3.3 post, $p = 0.012$; 1K-3E: 28.8 mm \pm 2.8 pre to 30.5 mm \pm 4.7 post, $p = 0.036$). Changes in knee extensor muscle thickness were not significant for either group (2.5% for 3K-1E and 2.9% for 1K-3E). Elbow flexor peak torque significantly increased in both groups, with no significant difference ($p = 0.47$) between groups (3K-1E: 46.57 Nm \pm 10.56 pre to 51.79 Nm \pm 7.28 post, $p = 0.013$; 1K-3E: 49.67 Nm \pm 10.47 pre to 55.59 Nm \pm 10.61 post, $p = 0.003$). Knee extensor peak torque significantly increased only in the 3K-1E group (203.21 Nm \pm 33.64 pre to 225.39 Nm \pm 32.22 post, $p = 0.006$).

Additional research conducted by Mitchell, et al. [13] supports the aforementioned findings. Participants were randomly assigned to 30% one-rep max with three sets of reps (30%-3), 80% one-rep max with one set of reps (80%-1), or 80% one-rep max with three sets of reps (80%-3), and trained three days per week for ten weeks. Researchers found muscle volume significantly increased with no difference between groups (30%-3 = 6.8 \pm 1.8%, 80%-1 = 3.2 \pm 0.8%, and 80%-3 = 7.2 \pm 1.9%, $p = 0.18$). Based on the findings of Bottaro, et al. [12] and Mitchell, et al. [13], a single-set resistance training program with lower loads may induce muscular hypertrophy and strength in untrained individuals. In addition, lower body muscles may be less responsive to increases in training volume [12]. This finding has significant practical implications for athletes who may have various upper and lower body demands in a particular sport. The discrepancies in research findings may be attributed to differences in samples (trained vs. untrained; male vs. female), frequency of training (two days vs. three days), measurement of muscle size (magnetic resonance imaging vs. ultrasound), and measurement of muscular strength (dynamic vs. isometric). The optimal dose of resistance training is highly variable, depending on the individual's genetics and training background [9]. Therefore, longer-term resistance training studies are required in order to determine the upper limits of the dose-response relationship between training volume and muscular adaptations [9]. Training load is another variable that is manipulated in resistance training programs.

Training load

Training load, the amount of weight lifted for a particular exercise, is often adjusted depending on the athlete's goal. Traditional resistance training recommendations include the use of lighter loads and higher reps for muscular endurance, whereas heavier loads and fewer reps are utilized for muscular strength [8]. Sports performance coaches also use the repetition maximum continuum when prescribing resistance training. According to this concept, optimal strength

gains occur when using loads of one to five repetition maximum, whereas optimal hypertrophy gains occur when using loads of six to twelve repetition maximum [15]. This concept is based on the hypothesis heavier loads are required in order to recruit higher threshold motor units [15].

In order to test this hypothesis, Schoenfeld, et al. [16] recruited 18 young male experienced lifters and randomly assigned them to a Low-Load (LL) or High-Load (HL) group. The LL group completed 25-35 reps per set and the HL group completed 8-12 reps per set. Participants followed a full-body resistance training program, exercising three days per week for eight weeks. Researchers found significant improvements in one rep max (1RM) back squat for HL and LL (HL: 121.0 kg \pm 36.6 pre to 144.7 kg \pm 27.4 post, $p < 0.01$; LL: 122.1 kg \pm 39.7 pre to 132.8 kg \pm 36.5 post, $p < 0.05$). The HL group showed significantly greater strength gains compared with the LL group ($\beta = 28.11$; $p \leq 0.05$). In addition, the HL group showed significant improvements in 1RM bench press (101.5 kg \pm 20.5 pre to 108.1 kg \pm 21.0 post, $p < 0.01$), whereas the LL group showed non-significant improvements (101.0 kg \pm 25.6 pre to 103.0 kg \pm 23.3 post). In regards to hypertrophy, both the HL and LL groups showed significant ($p < 0.01$) growth in elbow flexor thickness by 2.5 mm \pm 2.9 (5.3%) and 3.7 mm \pm 3.2 (8.6%), respectively. No significant between-group differences were found ($p = 0.22$). Both groups also showed significant improvements in quadriceps femoris thickness (HL: 5.3 mm \pm 2.2; LL: 5.2 mm \pm 4.8, $p \leq 0.05$), with no significant between-group differences.

These findings indicate both HL and LL training protocols may contribute to significant improvements in muscular hypertrophy in males with resistance training experience; however, HL protocols may be more effective in stimulating muscular strength [16]. Reflecting back to the dose-response relationship between training volume and muscular adaptations, it could be hypothesized the adaptations in the LL protocol were influenced by the greater training volume caused by an increased number of reps [16]. Furthermore, training with specific loads may influence muscle fiber adaptations. For example, resistance training with lighter loads may be attributed to increases in type I and IIa fibers, which are mainly recruited for muscular endurance [16]. Additional research conducted by Fink, et al. [17] supported the findings of Schoenfeld, et al. [16]. Fink, et al. [17] recruited 21 young male gymnasts who were randomly assigned to one of three groups: 1) High load (H) 8-12 reps at 80% 1RM; 2) Low load (L) 30-40 reps at 30% 1RM; 3) Mixed load (M) switched from H to L every two weeks. Participants completed three sets of preacher curl exercise three days per week for eight weeks. Researchers found significant increases in elbow flexor cross sectional area in all three groups (H: 9.1 \pm 6.4%, $p = 0.001$; L: 9.4 \pm 5.3%, $p = 0.001$; M: 8.8 \pm 7.9%, $p = 0.001$), but no significant difference between groups.

In addition, elbow flexor isometric maximum voluntary contraction, assessed via Biodex, significantly increased in the H group ($26.5 \pm 27.0\%$, $p = 0.028$); however, no significant changes were observed in the L group ($4.6 \pm 23.9\%$, $p = 0.65$) or M group ($11.8 \pm 36.4\%$, $p = 0.26$).

These findings indicate muscular strength, rather than hypertrophy, is more dependent on the training load [16,17]. Of note, the non-linear periodized training protocol of alternating training loads in the Fink, et al. [16] study did not contribute to maximal gains in hypertrophy. Many sports performance coaches use periodized programs when preparing athletes for muscular anatomical adaptations prior to competition. Thus, future studies should evaluate muscular adaptations in periodized programs, particularly in trained athletes over a long duration. This type of study would simulate adaptations that occur as athletes progress through various phases of competition, such as in-season, post-season, and off-season. Although previous literature indicates significant differences in adaptations caused by high and low training load [16,17], other researchers have found no differences between moderate and low training load [18].

Lopes, et al. [18] recruited 16 resistance-trained men who were randomly assigned to a moderate load (10 RM) or light load (20RM) group. Compared with the participants in the Fink, et al. [17] and Schoenfeld, et al. [16] studies, the participants in the Lopes, et al. [18] study exercised at a higher frequency by completing four sessions per week over a shorter duration of six weeks. Fat free mass significantly ($p < 0.05$) increased in the moderate load ($4.7\% \pm 1.0$) and low load group ($3.71\% \pm 1.7$), with no differences between groups. Furthermore, 1RM bench press and 1RM squat significantly ($p < 0.05$) increased in the moderate load ($6.4\% \pm 2.5$; $10.5\% \pm 7.0$, respectively) and light load group ($4.9\% \pm 1.2$; $8.0\% \pm 1.9$, respectively), with no differences between groups. These findings indicate a greater training load may be required in order to elicit greater neuromuscular adaptations, contributing to strength gains [18]. These initial neuromuscular adaptations may not be as evident in trained individuals compared with untrained individuals; therefore, a six-week intervention may not be enough time to find significant differences in various training protocols [18]. Additional research is warranted to investigate specific loading recommendations required to elicit strength gains in trained subjects. These findings are also related to the practice of training to muscular failure during resistance training. As individuals perform repetitions to volitional fatigue, they are potentially activating high-threshold motor units, which may contribute to improvements in hypertrophy [18]. However, this phenomenon deserves further study and evaluation.

Training to failure

Resistance training until failure, the point at which

an additional rep cannot be completed using a full range of motion, has been speculated to maximize muscular strength and hypertrophy [19]. The theory behind this training method states muscular fatigue causes greater activation and recruitment of motor units; however, it remains unclear whether there are specific advantages to using this type of training method [19]. In order to address this issue, Sampson and Groeller [20] recruited 28 untrained males who completed a four-week familiarization phase and were counterbalanced into three groups: 1) Non-failure rapid shortening (RS); 2) Non-failure stretch-shortening (SSC); 3) Failure control (C). Each group used different concentric and eccentric contraction speeds, as well as performed 12 weeks of unilateral elbow flexor exercise three times per week at 85% 1RM. Significant ($p < 0.001$) improvements in pooled 1RM strength were observed, with an 11.4% (8.7-14.2) increase between weeks one-four, 9.4% (7.2-11.6) increase between weeks four-eight, and 7.3% (5.1-9.5) increase between weeks eight-twelve. In addition, a significant ($p < 0.001$) pooled increase of 11.4% (8.7-14.1) was observed in muscle cross sectional area. Finally, a significant ($p = 0.005$) pooled increase of 22.1% (5.9-38.4) was observed in biceps brachii average muscle activation (EMG_{RMS}). Despite these significant pooled improvements, no between group differences were observed.

These results provide evidence to support the theory training until failure may not be necessary to bring about neural and structural adaptations [20]. It should be noted the participants in this study utilized a heavier load at 85% 1RM. Thus, training to failure when using heavier loads may not be necessary to stimulate additional muscle activation [21]. Despite differences in training volume, rapid muscle activation may be a factor involved in the similarities observed in muscular adaptations [20]. Another limitation of the Sampson and Groeller [20] study is the fact participants only completed unilateral exercise. This limitation raises concerns regarding athletic populations who may perform more bilateral or compound movements in order to develop power. Thus, additional research is warranted in order to investigate the effects of training to failure with multi-joint exercises in trained populations [20]. It is also worth highlighting the fact most studies investigating training to failure have focused on studying changes in untrained male subjects. In order to address this limitation, Martorelli, et al. [22] studied muscular strength and hypertrophy changes in 89 young women with resistance training experience.

In the study by Martorelli, et al. [22], participants were randomly assigned to one of three groups: 1) Three sets of reps to failure (RF); 2) Four sets of seven reps not to failure with equalized volume (RNFV); 3) Three sets of seven reps not to failure (RNF). All groups exercised twice per week for ten weeks, using a load of 70% 1RM. The resistance training sessions focused

on performing bilateral biceps curl exercise; however, the participants also completed whole-body exercise as well. Researchers found 1RM in the bilateral biceps curl significantly ($p < 0.05$) increased in all three groups (RF: 17.17 kg \pm 4.20 pre to 22.03 kg \pm 4.45 post; RNF: 17.70 kg \pm 3.87 pre to 22.44 kg \pm 4.32 post; RNFV: 16.44 kg \pm 2.95 pre to 21.09 kg \pm 2.74 post); however, there were no significant differences between groups. In addition, isokinetic peak torque significantly ($p < 0.05$) increased in the RNF group (21.88 Nm \pm 5.21 pre to 22.79 Nm \pm 4.45 post) and RNFV group (19.06 Nm \pm 3.51 pre to 21.68 Nm \pm 4.33 post), whereas no change was observed in the RF group (21.74 Nm \pm 5.93 pre to 21.63 Nm \pm 6.36 post). These findings provide additional evidence to support the theory training until failure does not elicit additional improvements in force production and strength, even among trained female athletes [22]. One potential explanation for the lack of peak torque increase in the RF group may be related to the decrease in muscle action velocity during the final reps completed until volitional exhaustion [22]. Additional research supports this theory in which muscle power output is diminished when strength training until failure [23]. Therefore, training until failure may actually impair the rate of force and muscle action velocity, which could impede muscular power [22]. An additional consideration associated with training until failure is the potential risk of overtraining and overreaching [22]. These two negative effects of training until failure would be detrimental to athletic performance; therefore, athletes should use caution when incorporating this type of training in their sports performance programs. From a practical standpoint, training to failure when performing compound lifts, such as squats and deadlifts, should be used sparingly due to the taxing nature of these lifts [21]. Training frequency is another variable involved in resistance training programming that must be considered when training to failure. When athletes train at a greater frequency, training to failure may lead to slower neuromuscular recovery [21].

Training frequency

Training frequency is often defined as the number of resistance training sessions per week; however, frequency can also be defined as the number of times a specific muscle group is trained per week [24]. Some researchers have proposed spreading out resistance training over several days may enhance muscle protein synthesis, thereby increasing muscular hypertrophy [25]. Furthermore, performing an exercise more frequently may improve neuromuscular efficiency, which increases muscular strength [26]. Aligning with this concept, some athletes choose to follow resistance training split routines in which specific muscle groups are alternately trained on multiple days of the week. This training technique allows for sufficient rest time in between training sessions. A recent meta-analysis of

25 studies conducted by Schoenfeld, et al. [24] found resistance training frequency did not significantly impact hypertrophy when volume was equated. In order to provide more insight on this phenomenon, several researchers have investigated the effects of split routines on hypertrophy and strength in trained individuals [26,27].

Gomes, et al. [27] demonstrated high frequency resistance training was not more effective than low frequency training in stimulating muscle hypertrophy and strength in well trained men. These findings were further supported when Lasevicius, et al. [26] found no significant differences in muscular adaptations in trained men who exercised two days per week compared with three days. In the Gomes, et al. [27] study, 23 resistance trained men were randomly assigned to a low frequency group (split body protocol training each muscle group once per week) or high frequency group (total body protocol training each muscle group every session). Participants completed resistance training exercise on five days per week for eight weeks, with sets and intensity equated. Both groups significantly ($p < 0.001$) improved 1RM bench press [Low frequency: 5.6 kg (95% CI: 1.9-9.4); high frequency: 9.7 kg (95% CI: 4.6-14.9)] and 1RM squat [Low frequency: 8.0 kg (95% CI: 2.7-13.2); high frequency: 12.0 kg (95% CI: 5.1-18.1)]. In addition, both groups significantly ($p = 0.007$) increased lean mass [Low frequency: 0.5 kg (95% CI: 0.0-1.1); high frequency: 0.8 kg (95% CI: 0.0-1.6)]. However, there were no significant differences between groups in any of the outcome measures (1RM bench press, $p = 0.168$; 1RM squat, $p = 0.312$, and lean mass, $p = 0.619$).

The difference in training frequency among participants in the Gomes, et al. [27] study could be considered somewhat extreme, as researchers essentially compared the effects of training the same muscle group once per week versus five days per week. In order to address this concern, Lasevicius, et al. [26] compared the effects of resistance training performed two days per week versus three days. Researchers recruited 36 trained men who were randomly assigned to a split routine (training each muscle group twice per week) or full-body routine (training each muscle group three times per week). Participants completed three exercise sessions per week over ten weeks. Muscle thickness in the rectus femoris significantly ($p < 0.001$) increased in the total body group (22.7 mm \pm 2.5 pre to 4.5 mm \pm 2.7 post) and split group (22.7 mm \pm 2.6 pre to 25.5 mm \pm 2.2 post). Muscle thickness in the elbow extensor also significantly ($p < 0.001$) increased in the total body group (30.0 mm \pm 5.6 pre to 32.6 mm \pm 8.1 post) and split group (29.9 mm \pm 6.5 pre to 34.6 mm \pm 5.8 post). In terms of muscular strength, 1RM squat significantly increased in the total body group (156.5 kg \pm 26.5 pre to 184.3 kg \pm 31.2 post, $p = 0.011$) and split group (159.7 kg \pm 27.7 pre to 190.0 kg \pm 29.3 post,

$p = 0.006$). In addition, 1RM bench press significantly increased in the total body group ($78.1 \text{ kg} \pm 19.8$ pre to $86.1 \text{ kg} \pm 21.6$ post, $p = 0.034$) and split group ($80.9 \text{ kg} \pm 15.6$ pre to $90.5 \text{ kg} \pm 17.3$ post, $p = 0.03$). There were no significant differences between groups in any of the outcome measures.

Based on the findings of Gomes, et al. and Lasevicius, et al. [26,27], weekly resistance training frequency does not significantly impact muscular strength or hypertrophy when training volume is equated. Although these findings seem to contradict the motor learning theory, which states performing an exercise more frequently contributes to better skill acquisition, researchers speculate training as little as twice per week may be sufficient to stimulate neural adaptations [26]. Thus, training volume, rather than frequency, may be a predominant factor involved in maximizing strength and hypertrophy [26]. Many studies have used different assessments of muscle thickness, such as ultrasound, dual-energy X-ray absorptiometry, and magnetic resonance imaging, which makes it difficult to compare changes in hypertrophy. Another limitation in previous research is the duration of training. Previous studies typically utilized training protocols ranging from eight weeks [27] to ten weeks [26]. Therefore, additional research is warranted investigating the long-term effects of training frequency on muscular adaptations. Moreover, previous research has not compared the effects of training frequency while performing single-joint versus multi-joint exercises [24]. This limitation aligns with the gaps in knowledge associated with training to failure using compound exercises. In addition to muscular hypertrophy and strength, the rate of force development is associated with athletic performance. The rate of force development is an indicator of muscular power; therefore, this factor deserves consideration when designing sports performance programs.

Rate of force development

Rate of Force Development (RFD), often referred to as explosive strength, is a critical component in sports performance [3]. Explosive strength refers to the muscle's ability to increase force rapidly. From a practical standpoint, explosive strength is frequently used in sports requiring rapid movements, such as jumping and sprinting [3]. Research provides evidence explosive and heavy-resistance strength training has a positive effect on RFD and rapid force capacity [28]. In fact, a previous study found maximal muscle strength may account for up to 81% of the variance in voluntary RFD [29]. Despite this knowledge, there are gaps in existing literature related to the specific effects of different strength training programs on maximal and explosive force production.

In order to address this deficiency, Tillin and Folland [30] recruited 19 active males who were assigned to

either Maximal Strength Training (MST) or Explosive Strength Training (EST). Both groups completed four sets of ten isometric knee extensor contractions four times per week for four weeks. However, the EST group was instructed to contract "as hard and fast as possible" for one second, while the MST group was instructed to progressively contract up to 75% Maximal Voluntary Force (MVF) and hold for three seconds [30]. Researchers discovered improvements in MVF were significantly ($p < 0.001$) greater in the MST group ($21\% \pm 12$) compared with the EST group ($11\% \pm 7$). Early phase explosive force significantly ($p < 0.01$) increased in the EST group ($3.94 \text{ N/kg} \pm 0.61$ pre to $4.53 \text{ N/kg} \pm 0.62$ post); however, there was no change in the MST group ($4.21 \text{ N/kg} \pm 0.78$ pre to $4.34 \text{ N/kg} \pm 0.72$ post). These findings support the theory neuromuscular adaptations are specific to the training stimulus. Therefore, explosive strength training appears to be more effective at improving early phase explosive strength [30]. Researchers hypothesized the differences were attributed to greater neuromuscular activation at MVF with MST, whereas EST was associated with greater neuromuscular activation in the early phase of contraction [30].

Vila-Chã, et al. [31] provided further evidence to support the effects of strength training on improving Maximal Voluntary Contraction (MVC) and RFD. In this study, participants were randomly assigned to either a Strength Training (ST) or Endurance Training (ET) protocol for six weeks of training. The ST group completed lower body resistance training at 60-85% 1RM. The ET group completed cycle ergometer training at 50-75% heart rate reserve. The ST group showed significant ($p < 0.05$) improvements in MVC and RFD ($17.5\% \pm 7.5$ and $33.3\% \pm 15.9$, respectively) after six weeks of training; however, there were no changes observed in the ET group. With that being said, the ET group showed significant ($p < 0.05$) increases in time to task failure ($29.7\% \pm 13.4$), while no changes were observed in the ST group. Based on these findings, it can be inferred different types of training may elicit specific neuromuscular adaptations, as well as variations in motor unit discharge rates [31].

This research has important practical implications for sports performance coaches designing resistance training programs for athletes. It appears strength training improves RFD through a cascade of effects, involving motor unit discharge rates, muscle activation, muscle fiber type composition, muscle size, muscle-tendon stiffness, and maximum force production [28]. Thus, if the athlete's goal is to increase RFD, explosive type training may improve early phase rises in force, whereas heavy resistance training may improve late phase rises in force [28]. When athletes are working to increase explosive strength, they should be instructed to contract the working muscle group quickly, using loads of 60-85% 1RM, in order to generate rapid force [30,31]. Additional research is warranted in order to investigate

the optimal contraction velocity required to maximize explosive strength. In addition, the two previous studies focused on neuromuscular adaptations in knee extensor muscles alone. Therefore, additional research should investigate these adaptations in various muscle groups among different training backgrounds [30,31].

Conclusion

In conclusion, neuromuscular adaptations, stimulated by resistance training, can significantly impact athletic performance [1,3]. In particular, improvements in muscular hypertrophy, strength, power, and endurance all play a role in athletic development and achieving peak performance [3]. Despite these benefits, Kraemer, et al. [32] state misinformation still exists in the sports performance field. Sports performance coaches and athletes can manipulate certain resistance training variables in order to optimize their results. There appears to be a dose-response relationship between training volume and muscular adaptations; however, it is important to consider individual differences in response to resistance training [9]. Athletes should use heavier loads with fewer reps in order to maximize neuromuscular adaptations required for strength gains [15,18]. Sports performance coaches must also carefully monitor training intensity, as training until failure may actually impede muscle recovery [21,22]. Although some coaches may promote split routines, these programs may not actually provide additional improvements in muscular strength and hypertrophy [26,27]. Training two days per week may be sufficient in order to stimulate neuromuscular adaptations in certain populations [26]. Finally, explosive strength can be targeted by utilizing loads of 60-85% 1RM and contracting the working muscle group as quickly as possible [30,31]. Explosive strength training helps athletes develop power and force production, which is particularly useful during explosive movements, such as jumping and sprinting [3].

It is well established in the literature athletes should perform sports-specific exercise, simulating movements and velocities used during competition, in order to optimize the effects of resistance training [32]. However, there are multiple gaps remaining in the literature that should be addressed by future studies. For example, future research needs to evaluate neuromuscular adaptations to periodized programs, particularly in trained athletes over a long duration. These long-term studies could also help determine the upper limits of the dose-response relationship between training volume and muscular adaptations, without leading to overtraining and overreaching [9]. This research would help provide resistance training guidelines for both elite and recreational athletes.

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