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ORIGINAL ARTICLE

Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males

P. W. M. Marshall · M. McEwen · D. W. Robbins

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Abstract The optimal volume of resistance exercise to prescribe for trained individuals is unclear. The purpose of this study was to randomly assign resistance trained individuals to 6-weeks of squat exercise, prescribed at 80% of a 1 repetition-maximum (1-RM), using either one, four, or eight sets of repetitions to failure performed twice per week. Participants then performed the same peaking program for 4-weeks. Squat 1-RM, quadriceps muscle activation, and contractile rate of force development (RFD) were measured before, during, and after the training program. 32 resistance-trained male participants completed the 10-week program. Squat 1-RM was significantly increased for all groups after 6 and 10-weeks of training ($P < 0.05$). The 8-set group was significantly stronger than the 1-set group after 3-weeks of training (7.9% difference, $P < 0.05$), and remained stronger after 6 and 10-weeks of training ($P < 0.05$). Peak muscle activation did not change during the study. Early (30, 50 ms) and peak RFD was significantly decreased for all groups after 6 and 10-weeks of training ($P < 0.05$). Peak isometric force output did not change for any group. The results of this study support resistance exercise prescription in excess of 4-sets (i.e. 8-sets) for faster and greater strength gains as compared to 1-set training. Common neuromuscular changes are attributed to high intensity squats (80% 1-RM) combined with a repetition to failure prescription. This prescription may not be useful for sports application owing to decreased early and peak RFD. Individual responsiveness to 1-set of training should be evaluated in the first 3-weeks of training.

Keywords Single-set · Multiple-sets · Resistance exercise · RFD · Muscle activation · Electromyography · Strength training

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P. W. M. Marshall (✉)
School of Biomedical and Health Science,
University of Western Sydney, Sydney, Australia
e-mail: p.marshall@uws.edu.au

M. McEwen
Department of Sport and Exercise Science,
University of Auckland, Auckland, New Zealand

D. W. Robbins
School of Physiotherapy, Faculty of Health Sciences,
University of Sydney, Sydney, Australia

Introduction

The optimal manipulation of training variables to maximize dynamic strength gains is of significant interest to strength and conditioning researchers and coaches. While it appears that training intensities using loads corresponding to 80–100% of 1-repetition maximum (1-RM) are most effective for increasing maximal strength (Fleck 1999; Fry 2004; Rhea et al. 2003), it is unclear what training volume is required to maximize strength improvements. Resistance training volume is often described in terms of the number of prescribed sets. Within this context, the resistance exercise volume debate revolves around multiple- versus single-set prescription. Many studies provide support for multiple sets of exercise (Humburg et al. 2007; Kraemer et al. 2000; Marx et al. 2001; Schlumberger et al. 2001; Munn et al. 2005; McBride et al. 2003; Rhea et al. 2002). Conversely, some studies suggest that a single set of exercise is just as effective for increasing dynamic strength (Starkey et al. 1996; Ostrowski et al. 1997; Hass et al. 2000; Pollock et al. 1993). This debate has yielded several meta-analyses and narrative reviews that are either pro (Rhea et al. 2003; Peterson et al. 2004; Wolfe et al. 2004; Krieger 2009), or anti (Otto and Carpinelli 2006; Smith and Bruce-Low 2004; Winett 2004; Carpinelli et al. 2004) multiple-set prescription. Thus, the number of sets to prescribe to optimize dynamic strength gains is unclear. The confusion in the literature may in part be owing to the common comparison between one and three sets of exercise. This is not an especially different volume of prescription, and does not tend to reflect the very high volumes of training prescribed and observed in those who are resistance trained. In addition, the majority of studies used untrained subjects. To date, there is an absence of literature examining multiple-set prescription in excess of 3–4 sets in resistance trained individuals.

Previous studies that compared multiple- and single-set resistance training programs in trained individuals are typically between one and three or four sets (Hass et al. 2000; Ostrowski et al. 1997; Rhea et al. 2002; Schlumberger et al. 2001). Only two of these studies found benefits to multi-set prescription in trained individuals (Schlumberger et al. 2001; Rhea et al. 2002). Other studies supporting multi-set prescription in resistance trained individuals are difficult to interpret as long-term periodized prescriptions were utilized that do not provide a clear prescription volume (Kraemer 1997; Kraemer et al. 2000; Kramer et al. 1997), or detail absolute volumes that do not specifically compare a number of prescribed sets (González-Badillo et al. 2005, 2006). The comparison between one and three or four sets does not appear adequate to separate the volume-dependent strength improvements following resistance training and contributes to the confusion present in the strength training literature.

Neuromuscular adaptation is thought to play an important role in strength development in resistance-trained individuals (Hakkinen et al. 1988). There is limited research comparing measures of neuromuscular adaptation following different sets of resistance exercise in trained individuals. The most common measure of neural adaptation following resistance exercise is the maximal integrated electromyography (iEMG) signal. However, there are conflicting reports regarding changes in maximal iEMG, with some studies showing increases following training (McCarthy et al. 2002; Aagaard et al. 2002; Hakkinen et al. 1985; Moritani and DeVries 1979) while others have shown no change (Garfinkel and Cafarelli 1992; Thorstensson et al. 1976; Cannon and Cafarelli 1997; Robbins et al. 2009). Of particular relevance for resistance-trained populations is the measurement of contractive rate of force development (RFD). RFD has important functional significance for fast and forceful muscle contraction. For example, movements, such as sprint running, boxing, or karate typically involve contraction times of 50–250 ms. Strength training leading to an increased and more rapid rate of neuromuscular activity is accompanied by increases in contractile RFD (Aagaard et al. 2002; Barry et al. 2005; Blazevich et al. 2008; Van Cutsem et al. 1998). Contractile RFD in the initial time period subsequent to contraction onset (<100 ms) is associated with an increased rate of change in muscle activation (Van Cutsem et al. 1998; de Ruiter et al. 2004), as well as muscle twitch contractile properties (Andersen and Aagaard 2006). In the later period following contraction onset, contractile RFD is increasingly related to maximal strength levels (Andersen and Aagaard 2006). Evaluation of changes in RFD in different time periods following contraction onset may provide insight into the underlying adaptation associated with different volumes of resistance exercise. Based on the lack of evidence investigating training volumes in excess of four sets in resistance trained individuals, it was difficult to predict whether a training program consisting of eight sets of exercise performed twice per week would improve or retard contractile RFD in resistance trained individuals.

The aim of this study was to randomly assign resistance-trained individuals to a 6-week training program for increasing maximal strength consisting of either one, four, or eight sets of the squat exercise at an intensity of 80% 1-RM. The primary objective of this study was to examine changes in muscle strength, muscle activation, and contractile RFD of the quadriceps muscle group in response to prescriptions of different number of sets of squat exercise. Although a number of important confounding variables were controlled between groups (diet, training age, absolute age, compliance, initial lean body mass, strength), we expected some variation in the individual strength responses to training considering previous research, which suggests responsiveness is primarily determined by genetic factors (Davidsen et al. 2011; Van Etten et al. 1994). Therefore, a secondary objective of this study was to examine differences in baseline characteristics (demographics, anthropometry, training status) between participants categorized as being high, medium, or low responders in terms of strength gains.

Materials and methods

Subjects

An apriori power calculation was performed based on the estimated difference in effect size for strength gains using either one or eight sets of resistance exercise in athletes, as there was no data for comparison between one and eight sets in resistance trained participants and we believed athletes would be an approximate comparison (Peterson et al. 2004). This provided an effect size for the difference between one and eight sets of $d = 1.33$. An 80% power calculation provided $n = 8$ per group (Faul et al. 2007). Allowing for two drop-outs per group required $n = 10$ in each group. 43 healthy, resistance trained males (28 ± 1.2 years, 178 ± 1 cm, 84 ± 2.3 kg, mean ± SE) initially volunteered to participate in the present study. Inclusion criteria included regular performance (at least twice per week for the last 2 years) of whole body resistance exercise (experience 6.6 ± 1.0 years), no history of knee or low back injury within the last year, and a minimum barbell squat strength of 130% body weight. Subjects were excluded if they reported taking any performance enhancing supplements (creatine, anabolic steroids). All subjects gave informed written consent prior to their participation in the study, which was approved by the local institution's Human Participants Research Ethics Committee, and was conducted in accordance with the Declaration of Helsinki.

Experimental design and training

Participants trained in for a total of 12-weeks. The resistance training program was separated into three primary phases; a 2-week washout from previous training to standardize all programs performed prior to randomization, a 6-week primary training period where participants were randomly assigned to different volumes of the squat exercise, and a 4-week rebound period. Assessments were performed following the washout period (T0), after 3 weeks of training for progress 1-RM squat testing (T1), at the end of the 6-week training period (T2), and at the end of the 4-week rebound period (T3). Training was prescribed in a bodypart split format, to ensure that each muscle group was trained twice per week (Rhea et al. 2003). Testing was performed at least 48-h after a squat exercise session.

Upon providing informed written consent, participants commenced a 2-week washout training program to standardize the type of training performed prior to randomization. This program was a 3-way bodypart split (A program: chest-biceps, B program: back and triceps, C program: legs) based on a standard multi-set (4 sets per exercise) prescription with six primary exercises performed each session, using a 6–12 RM training prescription. Each program was performed three times over the 2-week washout period. No barbell squat exercise was prescribed during the initial 2-week washout. Following the 2-week washout, baseline testing was performed.

Participants were then randomly assigned into one of three groups for the subsequent 6-week training period based on prescription of the barbell back squat exercise. This was the only lower back or leg exercise prescribed to any participant for this 6-week training period, although standard upper body prescription was used throughout this period. Including upper body training improved our ability to blind participants to the intent of the protocol, as well as recruitment and program adherence. We did not choose to manipulate an upper body exercise as we believe that resistance trained males would be less likely to adhere to a one set upper body protocol.

Group assignment in the 6-week training period was to one, four, or eight sets of squats (1-SET, 4-SETS, 8-SETS), which was prescribed at an intensity of 80% of baseline 1-RM squat. For the 6-week training period, a 2-way split program was used (A program: chest-shoulders-arms, B program: back and squat training), so that each muscle group was trained twice weekly (Rhea et al. 2003). All sets of squats were performed to volitional exhaustion, with 3-minutes rest between sets. All squats were performed to a depth of 90° knee flexion. Prior to performance of the primary squat working set/s, a warm-up set of 10 bodyweight repetitions was allowed, followed by a 10 repetition set at 50% 1-RM, then single repetitions at 60 and 70% 1-RM. It was deemed unsafe to immediately perform squat repetitions at the desired training load, as in some cases this would have required participants to immediately load in excess of 200 kg onto the bar and commence squat movements. We believed our warm-up protocol was a realistic method for prescribing high intensity squat exercise. All training loads were recorded into training diaries. Supervision of the training program was provided by experienced exercise scientists.

Following the 6-week training period, all participants performed the same program for the remaining 4-weeks. This program combined low repetition, high load resistance exercise movements (4 exercises per session, 4–12 RM training intensity), with high intensity ballistic exercise movements (two exercises per session of either jump squat, bench press throw, dumb-bell snatch, barbell push-press). Four sessions per week were performed during this period, with each muscle group trained twice weekly. All participants performed the same squat prescription during this phase, with a 3 set × 4-RM prescription. Ballistic strength training was included because it has been shown to enhance explosive strength and speed (Fleck 1999; Izquierdo et al. 2006). In addition, the last 4-weeks were used to produce a similar "rebound effect" for all groups and to avoid overreaching (Fleck 1999; Izquierdo et al. 2006; Fry and Kraemer 1997).

Testing procedures

Squat maximal strength

Participants were required to complete a 1-RM barbell squat as a measure of dynamic lower limb strength. Participants were allowed to complete a warm up set of approximately 10 repetitions at a comfortable load (approximately 50% estimated 1-RM), followed by 1–2 repetitions at approximately 70 and 80% 1-RM. Following this warm-up, 1-RM attempts were performed. The highest achieved weight (kg) prior to failure was recorded as the 1-RM. The squat 1-RM was then normalized to the participant's body weight for data analysis. The 1-RM was always achieved between three and five attempts. Squat depth was standardized by having participants adopt a shoulder width stance and descend until the knee joints were at 90° flexion. Knee angle verification was monitored by a single study investigator throughout the various trials (Hudson et al. 2008; McCaulley et al. 2009; Ostrowski et al. 1997). Periods of approximately 3–5 min rest were allotted between each attempt to ensure recovery. A test was considered valid if the participant used proper form and completed the entire lift in a controlled manner, to the correct depth, without assistance. A 3-point person spot was provided for all trials, as well as the parallel bars. Participants were provided with verbal encouragement throughout 1-RM attempts.

Quadriceps strength, contractile RFD, and muscle activation

Knee extension RFD procedures were based on previous research (Aagaard et al. 2002). Maximal quadriceps muscle strength was measured as maximal isometric knee extension torque exerted in an isokinetic dynamometer (Biodex System 2, Biodex Medical Systems, New York). Subjects were seated in a rigid chair and firmly strapped across the chest, hip, and distal thigh. The rotational axis of the dynamometer was aligned to the lateral femoral epicondyle, and the lower leg was firmly attached to the dynamometer lever arm above the medial malleolus. Subjects were familiarized with the dynamometer and the procedures of the experiment prior to data collection.

Maximal isometric quadriceps contractions were performed with the knee joint set to a static angle of 70° (0° = full knee extension). After a 10-min warm-up consisting of a number of sub-maximal and maximal preconditioning trials, each subject performed three, 3-s isometric knee extensions with maximal voluntary effort. Subjects were carefully instructed to contract "as fast and forcefully as possible". On-line visual feedback of the torque trace was provided to the subjects on a computer screen. Trials with an initial countermovement (identified by a visual drop in the torque trace) were always excluded, and a new trial performed.

Dynamometer strain-gauge signals were sampled at 1,000 Hz using an analog to digital converter (Powerlab, ADI instruments, Australia; 16-bit analog to digital conversion). The strain gauge signal from the dynamometer was calibrated according to equipment standards to calculate the moment of force (torque; Nm). All recorded moments were corrected for the effect of gravity on the lower limb, and lever arm length of each subject. Strain-gauge signals were subsequently smoothed using a fourth order, digital low pass filter at 20 Hz.

Contractile RFD was determined from the trial with the highest maximal torque (maximal voluntary torque, MVT). RFD was calculated as the average slope of the torque-time (Δtorque/Δtime) curve over time intervals of 0–30, 0–50, 0–100, 0–200, and 0–400 ms relative to the onset of contraction. The onset of contraction was defined as the time point on the torque-time curve that exceeded the baseline torque by >7.5 Nm (Aagaard et al. 2002).

Electromyography

After careful skin preparation including shaving excess hair, abrading the skin with fine sandpaper, and cleaning the skin with an isopropyl alcohol swab to reduce impedance below 5 kΩ (measured using an analog multimeter), pairs of silver–silver/chloride electrodes (3M Red Dot, St. Paul, MN; contact diameter 20 mm, center to center distance 20 mm), were placed over the muscle bellies of vastus lateralis (VL) and vastus medialis (VM). VL electrodes were located one quarter of the distance proximal to the lateral tibial condyle on a line connecting this and the anterior superior iliac spine. VM electrodes were located at a position approximately 20% of the distance along a line connecting the medial gap of the knee and the inguinal ligament. EMG electrodes were connected to a G.tec (Guger Technologies OEG Herbersteinstrasse 60, 8020 Graz, Austria) BSamp biosignal amplifier system (common mode rejection ratio 110 dB, input impedance >110 MΩ), and were sampled at 1,000 Hz with 16-bit analog to digital conversion (Powerlab, ADI instruments, Australia). EMG signals were bandpass filtered between 20 and 500 Hz, and smoothed using a moving root-mean-square (RMS) filter with a time constant of 50 ms.

The following parameters were determined from the maximal torque trial: (1) peak RMS EMG amplitude (MVC) within the entire contraction phase, (2) integrated EMG (iEMG) in time intervals of 0–30, 0–50, 0–100, 0–200, and 0–400 ms relative to onset EMG integration, and similarly (3) average EMG (aEMG), and (4) average rate of EMG rise (RER) determined from the ΔEMG/Δtime curve over the corresponding time intervals. The onset of EMG integration was initiated 70 ms before the identified onset of the torque-time curve, which accounts for electromechanical delay (Aagaard et al. 2002; Blazevich et al. 2008).

Anthropometric assessments

Caliper skinfold measurements were obtained prior to testing to allow estimates of lean body mass and body fat percentage. Skinfold measurements were obtained from seven sites on the right side of the body (triceps, subscapular, mid-axillary, chest, suprailiac, abdomen, and thigh) as described previously for body composition analyses (Jackson and Pollock 1978).

Participant sub-grouping

Participants were sub-grouped as either high, medium, or low responders based on the observed gains in strength (% increase in bodyweight normalized squat strength) following the different training programs. High responders were classified as strength gains >20%, medium 10–19%, and low responders <10%. It is notable that high responders were identified in all three randomized groups (1-SET $n = 3$; 4-SETS $n = 5$; 8-SETS $n = 5$), and low responders were also identified in all three groups (1-SET $n = 6$; 4-SETS $n = 5$; 8-SETS $n = 2$).

Statistical analyses

Dependent variables were normally distributed, therefore parametric analysis methods were used. Main training effects between the three randomized training groups were assessed by a two-way ANOVA with repeated measures (group × time), with training age (years) used as a covariate. Baseline characteristics (demographics, anthropometry, RFD, strength, muscle activity) and training variables (average repetitions per set, total repetitions performed, average repetitions per first set) were compared between high, normal, and low responders by single factor ANOVA, with randomized training group (1-SET, 4-SETS, 8-SETS) entered as an additional between-subjects factor. When a significant F value was identified from the ANOVA procedures, Tukey's post hoc tests were performed to locate the pairwise differences between means. Cohen's effect sizes were calculated using G-Power statistical software, where $d = 0.8$ is a large effect, $d = 0.5$ is moderate, and $d = 0.3$ a small effect size (Faul et al. 2007). Data are presented as mean ± SE. $P < 0.05$ was considered statistically significant.

Results

Eleven participants withdrew from the study for the following reasons (injury = 6, not specifically related to the training intervention; interference with sport = 3; time demands = 1; job interference = 1). Seven withdrew during the wash-out period, and four withdrew during the initial 3-weeks of training. At completion of the study, each participant was questioned as to whether they knew what was manipulated in the study. Of the 32 subjects who completed the study, 14% said they had not thought about what was manipulated in the study, 28% had no idea, 33% thought they had an idea and 14% said they knew exactly what was manipulated. Of the participants who thought had an idea or knew exactly what was manipulated, seven correctly identified the volume of squat exercise as the variable being manipulated (22%). This shows that participants were well blinded to the manipulation of the study and results would not have been influenced by a placebo effect.

Training repetitions

Training volume was successfully manipulated in the experimental period from T0 to T2, with incremental increases in total repetitions and training volume from the 1-SET group to that accumulated by the 4-SET and 8-SET groups (Table 2).

Body composition

At the beginning of the program (Table 1), no significant differences were observed between groups in age, height, body mass, or percent body fat. A significant increase in body mass was observed at T3 for the 8-SET group compared to T0. A significant decrease in body fat was observed at T2 and T3 compared to T0 for all groups.

Maximal squat strength

Maximal squat strength results are presented in Fig. 1. Training age was not a significant covariate in the analysis.

Table 1 Physical characteristics during the experimental period

	1-SET ($n = 11$)	4-SETS ($n = 11$)	8-SETS ($n = 10$)
Age, years	25.5 ± 1.4	31.0 ± 3.2	26.0 ± 1.5
Height (cm)	177 ± 1.5	178 ± 1.8	179 ± 2.1
Body mass (kg)			
T0	79.5 ± 3.3	84.8 ± 3.8	85.2 ± 5.9
T1	79.5 ± 3.3	84.7 ± 3.6	85.5 ± 5.9
T2	79.8 ± 3.3	84.5 ± 3.5	85.8 ± 6.0
T3	80.0 ± 3.4	84.3 ± 3.4	86.7 ± 6.0*
Body fat (%)			
T0	13.6 ± 1.6	14.6 ± 1.9	12.8 ± 1.5
T2	12.2 ± 1.7*	13.1 ± 1.6*	11.2 ± 1.6*
T3	11.6 ± 1.4*	12.8 ± 1.5*	11.2 ± 1.6*
1RM squat (kg)			
T0	149.0 ± 7.8	157.3 ± 12.2	162.0 ± 11.8
T1	155.7 ± 8.8	174.1 ± 12.0	179.5 ± 13.9*[,a]
T2	165.5 ± 9.2*	178.2 ± 11.8*	194.0 ± 14.3*[,a]
T3	166.4 ± 12.0*	179.1 ± 11.8*	199.0 ± 13.7*[,a]

Data are mean ± SE

T0 baseline measurement, *T1* after 3-weeks of training, *T2* after 6-weeks of training, *T3* after 10 weeks of training

* $P < 0.05$ from time point T0, [a] $P < 0.05$ from 1-SET

Table 2 Squat exercise training variables measured during the 6-week training period (from T0 to T1)

	1-SET	4-SETS	8-SETS
1st set repetitions (average per session)	10.9 ± 0.7	9.0 ± 0.9	8.2 ± 0.8[a]
Average repetitions per set	10.9 ± 0.7	7.7 ± 0.8[a]	7.0 ± 0.6[a]
Total repetitions	131.3 ± 8.5	370.2 ± 40.7[a]	669.7 ± 58.9[ab]
Total volume (kg; reps × sets × weight)	16160 ± 1117	49689 ± 6034[a]	92026 ± 12488[ab]

Data are mean ± SE

[a] $P < 0.01$ from 1-SET, [b] $P < 0.01$ from 4-SETS

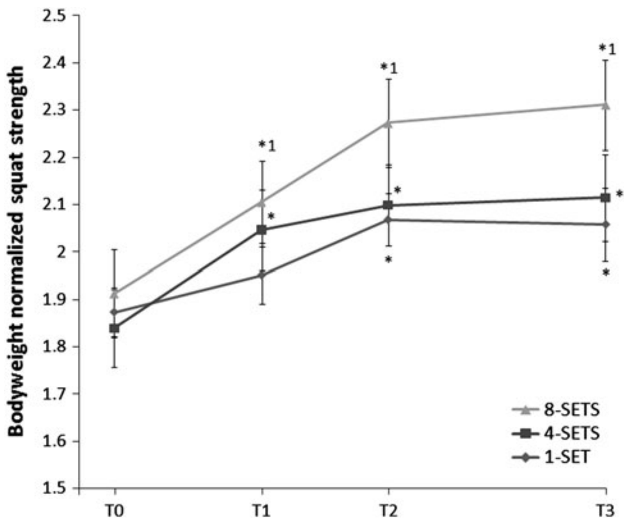

Fig. 1 Maximal squat strength normalized to body weight during the experimental period ($n = 32$). *T1* is after 3 weeks of training, *T2* after 6 weeks, and *T3* is after 10 weeks. *$P < 0.05$ from time point T0 (baseline measurement), [1]$P < 0.05$ from 1-SET group. Data are mean and SE

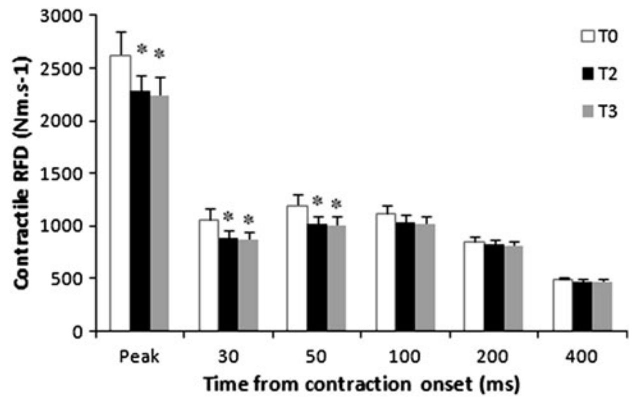

Fig. 2 Contractile RFD during the experimental period ($n = 32$). RFD was calculated in time intervals of 0–30, 50, 100, 200, and 400 ms from the onset of contraction. In addition, peak RFD was determined during the entire contraction. *$P < 0.05$ from T0 (baseline assessment). T2 is after 6-weeks of training, and T3 is after 10 weeks. Data are mean and SE

No significant differences were observed between groups at T0 (baseline assessment). At T1 the 4 and 8-SET groups had increased squat strength from T0 ($P < 0.05$), and squat strength was 7.9% higher in the 8-SET compared to the 1-SET group ($P < 0.05$). At T2, all groups had increased squat strength from T0 ($P < 0.05$). Squat strength in the 8-SET group was 9.9% higher than the 1-SET group ($P < 0.05$). During the peaking phase (from T2 to T3), no significant changes in squat strength were observed for any group. At T3, squat strength in the 8-SET group was 12.3% higher than the 1-SET group ($P < 0.05$). There were no differences in squat strength between the 4-SET and 8-SET, or between the 4-SET and 1-SET groups at any time point.

Maximal quadriceps strength, contractile RFD, and muscle activation

Maximal quadriceps torque output did not change for any group during the training program (T0 251 ± 11.2 Nm, T1 249.2 ± 10.9 Nm, T2 252.3 ± 10.5 Nm). Maximal contractile RFD (Fig. 2) was reduced by 14.1% at T1 ($P = 0.026$) and 15.4% at T2 ($P = 0.012$). Contractile RFD at time intervals of 30 and 50 ms post contraction onset was observed to be reduced at T1 and T2 compared to T0 (Fig. 2). No group or group × time effects were observed for contractile RFD.

No difference between VL and VM activation was observed at any point, therefore, muscle activity was averaged between VL and VM to represent overall quadriceps femoris activity for data analysis. There were no observed changes during the experimental period for maximum quadriceps EMG amplitude (T0 735 ± 56 μV, T2 709 ± 52 μV, T3 727 ± 52 μV). There were no changes during the experimental period for iEMG and aEMG measured at any time interval post contraction onset. RER increased between 43 and 58% in the initial phase of muscle contraction (0–30 and 0–50 ms) during the experimental period (Fig. 3). There were no group or group × time effects observed for RER.

High, medium, and low responders

Prior to training, there were no differences between high, medium, and low responders in terms of training age, chronologic age, absolute body weight, lean body mass,

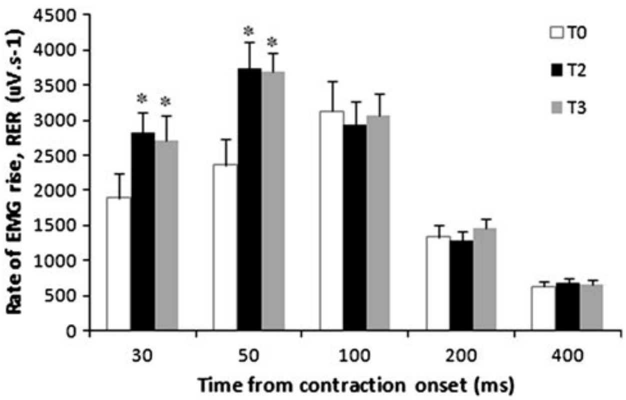

Fig. 3 Rate of EMG rise (*RER*) during the experimental period ($n = 32$). RER (ΔEMG/Δtime) was calculated in time intervals of 0–30, 50, 100, 200, and 400 ms relative to onset of EMG integration. *$P < 0.05$ from T0 (baseline assessment). T2 is after 6 weeks, and T3 after 10 weeks of training. Data are mean and SE

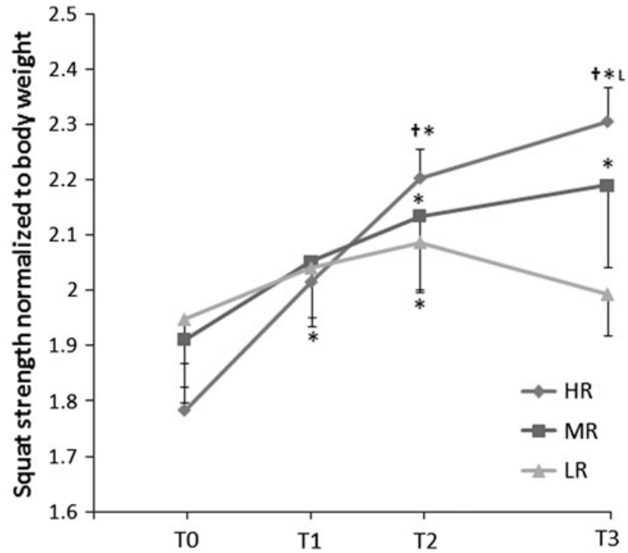

Fig. 4 Maximal squat strength normalized to body weight during the experimental period for the high (HR; $n = 13$), medium (MR; $n = 5$), and low (LR; $n = 13$) responder sub-groups. *$P < 0.05$ from T0, $^{\dagger}P < 0.05$ from preceding time-point, $^{L}P < 0.05$ from low responder group. Data are mean and SE

body fat %, thigh and leg length, absolute and normalized squat strength, muscle activation, and RFD measurements (data not shown). We also analyzed diet records and observed no significant differences in energy intake at baseline, or during the study. Significant differences were observed between all responder groups for the change in strength ($P < 0.01$). High responders ($n = 13$) increased their squat strength by 29.4 ± 2.2% compared to 14.3 ± 0.9% for medium responders ($n = 6$), and 2.6 ± 2.0% for low responders ($n = 13$). No training group interaction was observed within high, medium or low responder sub-groupings. A post hoc repeated measures ANOVA found that high responders increased their squat strength between each time point (Fig. 4). Medium and low responders had increased their squat strength from T0 at T2. However, at T3, only the medium responders had elevated squat strength from T0. No differences were observed between responder groups for average repetitions per set, or average repetitions per first set of squat exercise. Responder analysis of muscle activation and RFD changes were similar to the trends observed for the overall group effects (Figs. 2, 3).

Discussion

The main findings of this study were that: (1) 1-RM squat strength was significantly increased in the eight set compared to the one set group throughout the training period, (2) maximal muscle activation did not change during the study for any group, (3) peak and early (<100 ms) contractile RFD decreased and the rate of rise in muscle activation in the early phase of contraction increased for all groups, (4) high and low responders were identified from all randomized training groups, although a greater number of high responders were from the 4 and 8-SET groups, while six participants from the 1-SET group were classified within the low responder group.

Of particular interest in this study is that the overall group result for the 8-set group was significantly different from 1-set after only 3 weeks of training. In addition, the improvement after 3 weeks in the 4-set group was significantly greater than baseline. This result suggests that for very short-term strength gains, multiple-set prescription should be used. At the end of 10 weeks training, low to moderate effect sizes were identified for the difference in improvement between eight and four sets ($d = 0.52$), and four and one sets ($d = 0.39$). In the resistance training environment, despite being small to moderate effect sizes (and therefore indicating type II error in not detecting significant differences in this study), these differences represent clinically relevant differences in strength gains for trained individuals, and provide further support for the conclusion of this study that multiple-set prescription, preferably in excess of three or four sets, should be pursued for greater and more rapid strength improvements.

Evaluation of individual strength gains found high, medium, and low responders in each of the randomized groups. Of interest, 11 of the 13 low responders were from the 1 and 4-set groups. We cannot be sure whether or not prescription of greater volume (i.e. 8-sets) would elicit improvement in these individuals. Conversely, we cannot be sure whether or not the ten high responders from the 4 and 8-set groups would achieve the same improvement with reduced training volume, or that the three high responders from the 1-set group would achieve more success with greater volume. Nonetheless, that the numbers are so clearly skewed to associate high volumes with responsiveness lends some weight to the argument that regardless of categorical variables, high training volumes are preferred in order to develop strength. Finally, the 4-week peaking program prescribed after the 6-week randomized training period was only effective for high responding participants. We are unsure of the reason for this. Although speculative, it is possible that the cumulative effects of the various training volumes achieved under the three protocols, when combined with the exercise prescription in the peaking phase, were sufficient stimuli to evoke strength development in high responders. That is, regardless of previous 6-week protocol, in high responders, the volume-manipulated phase set the stage for further strength gains during the peaking phase. Alternatively, perhaps the training prescribed (e.g., combination of high intensity and ballistic lifts) in the peaking phase is sufficient to realize gains in high responders, but not low or medium responders.

Maximal quadriceps muscle recruitment did not change following training in any randomized group, or when subgrouped according to responsiveness. This supports previous findings showing that maximal EMG does not increase following resistance training (Garfinkel and Cafarelli 1992; Thorstensson et al. 1976; Cannon and Cafarelli 1997; Robbins et al. 2009). It may be likely that resistance trained individuals are already maximizing their motor unit recruitment during a maximal effort, and therefore further improvement is unlikely. Furthermore, neural adaptation may be most likely to manifest at sub-maximal contraction intensities, where it has been identified that resistance training leads to improvements in contraction efficiency through increased corticospinal gain (Carroll et al. 2002; Jensen and Marstrand 2005; Carroll et al. 2009). Peak and early contractile RFD (0–30, 0–50 ms) decreased following the 6-week training period in all groups (and subgroups, results not shown), and did not exhibit a 'rebound' following the peaking period. This result suggests that the type of training program used in this study impairs explosive force production, which has important consequences for sporting application. In addition, the rate of rise in early muscle activation (RER) increased following training. The similar between group neuromuscular changes can be attributed to the commonalities in the exercise prescription; high intensity squats (80% 1-RM) and a repetition to failure training model. Possible explanatory factors for the decreased early RFD include low frequency fatigue, specific muscle architectural changes, and changes in muscle morphology.

Low frequency fatigue (LFF) is a type of fatigue characterized by reduced force at low stimulation frequencies, whereas force at high frequencies is not, or only reduced to a minor extent (Edwards et al. 1977; Westerblad et al. 1993). It is thought that LFF impairs calcium release from the sarcoplasmic reticulum, which would impair the muscle's ability to move from a low to high generating force state (Westerblad et al. 1993). Therefore, it has been reasoned that LFF is most likely to affect early but not later RFD (Gordon et al. 2000; Chiu et al. 2004), as observed in this study. Thus, the increased rate of rise in muscle activation (RER) in the corresponding early time periods post contraction onset may be a compensatory neuromuscular adaptation for LFF. Alternatively, increased muscle fiber pennation angle in response to resistance training may shift the joint torque–angle relationship (Seynnes et al. 2007). Changes in the torque–angle relationship may have a negative or positive impact on early contractile RFD measured at a consistent angle between sessions (Blazevich et al. 2009). Finally, recent research found that decreases in early phase RFD (<140 ms) following 14 weeks of training (in previously untrained individuals) were associated with reduced relative proportion of type IIX muscle fibers (Andersen et al. 2010) that are characterized by a high intrinsic RFD (Harridge 2007). We cannot determine which of the three aforementioned explanatory factors best explains the decline in early and peak RFD observed in this study, although it is reasonable to speculate that the most negative factor, LFF, has interfered with improvements.

It is clearly a limitation of this study that neuromuscular adaptation during the squat exercise itself was not measured. However, other studies have documented significant improvements in isometric knee extension strength, muscle activation and RFD, subsequent to squat based resistance programs (Aagaard et al. 2002; Blazevich et al. 2009; Andersen et al. 2010). We cannot discount that significant neuromuscular adaptations may have been observed in other muscles that are significant contributors to the squat movement, such as the hamstrings, erector spinae, and gluteal muscle groups.

Mechanisms responsible for strength development are numerous. It is likely that a number of underlying mechanisms contribute to the outcome in most, if not all, cases exhibiting increases in strength. That no positive changes in neuromuscular measures were observed in the present study should not be mistaken to indicate that increases in squat strength are independent of neuromuscular adaptation. Rather, it is likely that neuromuscular adaptation is at least partially underlying the observed strength increases in this study, but, for reasons such as those described above, the employed methodology did not reveal as much. Recent studies suggest that higher resistance training volumes are important for eliciting a greater acute protein signaling response that may lead to greater protein accretion over time (Terzis et al. 2010; Burd et al. 2010). While body fat decreased in all groups during the current study, more direct methods are required to elucidate the histomorphological changes that may explain the success of higher volume training.

Conclusion and practical applications

Of interest to practitioners and coaches is the clear advantage increased volumes of high intensity squat exercise have with respect to lower limb strength development in resistance-trained individuals. This advantage may be exploited in as little as three weeks, thus providing an opportunity to realize gains in a relatively short time period. Practitioners should be aware of the neuromuscular implications of high intensity squat training. It is possible that prolonged use of high volumes of high intensity resistance exercise performed at maximal effort is not beneficial to ballistic movement. If the intention of a given training program is to develop power via neural adaptation, sub-maximal intensity prescription may be warranted.

Individual responsiveness to resistance exercise poses a complex conundrum for practitioners. Resource constraints make it difficult to determine optimal prescriptions aimed at strength development on an individual basis. Nonetheless, within resource constraints, attempts to consider individual responsiveness to different volumes of exercise should be made. Although some interesting possibilities exist with respect to individual-specific responses to resistance training, the present research suggests that, independent of an individual-response constituent, increased volumes are preferred in order to develop strength in the lower body.

In conclusion, training at 80% 1-RM for 1, 4, and 8-sets of squats, twice per week, resulted in gains in 1-RM squat strength. Strength improvements were significantly greater for the 8- compared to the 1-set group. This study has demonstrated benefits to multi-set training in excess of 4-sets in resistance-trained males. We recommend that responsiveness to single-set training be evaluated in the early stages (<3-weeks) of a training program, with progression to higher volumes of training in those who are not responsive to lower training volumes. The results of this study support multi-set prescription as a recommendation for strength training in exercise programs for resistance-trained individuals. One specific proviso for this recommendation is that the prescription should exceed four sets to ensure gains are superior to a single set.

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