Changes in early and maximal isometric force production in response to moderate and high load strength and power training

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Short Title: Changes in early force production in response to resistance training

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Abstract

The aims of this study were to determine the changes in early (50-, 100-, 150-, 200-, 250 ms) and maximal isometric force production, in response to a four-week period of moderate load resistance training (60-82.5% one repetition maximum [1RM]), followed by a four-week period of high load (80-90% 1RM) resistance training. Thirty-four subjects (age 19.5 ± 2.8 years; height 1.72 ± 0.08 m; body mass 69.9 ± 11.4 kg; maximal power clean 0.92 ± 0.03 $kg.kg^{-1}$) participated in this study. Only trivial to moderate (0.2-2.7%, $d = 0.00\text{-}0.88$) and non-significant ($p > 0.05$) changes in early isometric force production were observed in response to the moderate load training period, while very large (9.2-14.6%, $d = 2.71\text{-}4.16$), significant ($p \leq 0.001$) increases in early isometric force production were observed in response to high load training. In contrast, there was a very large, significant increase in PF across the moderate load phase (7.7 ± 11.8%, $d = 2.02$, $p = 0.003$), but only a moderate significant increase in PF (3.8 ± 10.6%, $d = 1.16$, $p = 0.001$) across the high load phase. The results of this study indicate that high load multi-joint resistance training, that follows moderate load training, results in superior increases in early multi-joint force production, compared to the changes observed after moderate load resistance training.

INTRODUCTION

Maximal strength has been reported to be important for, and strongly associated with, performance in athletic tasks (7, 33). Moreover, increases in force production, as a result of strength training, have been shown to result in improvements in athletic performance (40, 43). While maximal strength may serve as the foundation for improving various athletic performance capabilities, previous literature has indicated that the ability to rapidly produce high levels of force is one of the most important characteristics of an athlete's performance (2, 4), due to a limited duration for the production of force during athletic activities (47). For example, during high velocity sprinting, foot contact times can be much less than 250 ms, with a progressive decline in contact time as velocity increases (27, 37, 50), reaching contact times as low as 80 ms when running at velocities >11 $m.s^{-1}$ (47).

Maximal and rapid force production can be reliably measured during isometric assessments, commonly using single joint setups (10, 21), although variability is greatest at the shortest time periods (i.e. force at 50 ms) (21). Such single joint measures, however, are not closely associated with performance in functional and athletic tasks (9, 38). In contrast, multi-joint assessments of isometric force, especially the isometric mid-thigh pull (IMTP), are closely related to performance in dynamic athletic tasks, including short-distance sprint speed (46, 49), change of direction speed (41, 46) and jump performance (23, 49). Additionally, force at specific time points, assessed using the IMTP, has been related to sprint (49), jump (49) and weightlifting (7) performances, in addition to maximal back squat strength (48). Interestingly, while peak force (PF) (12, 17-19) and force at specific time points, derived using the IMTP, are generally highly reliable (17-19), measures of rate of force development (RFD) have shown varied levels of reliability; partially attributed to the method used to calculate RFD (e.g. mean vs. peak RFD and RFD across different epochs) (22), and the threshold used to identify the onset of the pull (17).

The findings of numerous studies indicate that resistance training results in increased PF, force at specific time points and RFD during single joint isometric assessments (1, 3, 24). While many of these studies state that 'heavy' or 'high' loads were used during the intervention, the majority of the interventions used repetition ranges (6-15) and loads (60-80% one repetition maximum [1RM]) associated with hypertrophy training (i.e. moderate load) (1, 3, 5). Such training interventions reduce the ecological validity of these studies as they were not training specifically to achieve the desired goal (i.e. strength). Andersen et al. (5) observed differential adaptive responses in early phase (≤100 ms) RFD, where there was a reduction in RFD, compared to late phase (≥200 ms) RFD, which increased, during isometric knee extension, after 14 weeks of resistance training. It should be noted however, that the highest loads used during this intervention included 6-8 RM loads, for the last ~3 weeks, with lower loads preceding this. Cormie et al. (14, 16) reported different adaptive responses to high- (75-90% 1RM) and low-load (≤30% 1RM) training on power production during a countermovement jump, with greater improvements in performance in the high-load group. The latter two studies only compared two different training loads between two different groups and did not compare such training loads used consecutively as they would be commonly prescribed. While this approach clearly addressed the researchers questions it does mean that application in a real-world environment may be limited. To the authors' knowledge, differences in the effects of moderate- (60-82.5% 1RM) and high-load (80-90% 1RM) resistance training, in the sequence that they would normally be used (a period of moderate load, followed by a period of high load training, in-season), on PF and force at specific time points during multi-joint isometric assessments, are currently unknown.

The aims of this study were to 1) determine in PF and early multi-joint isometric force production (50-, 100-, 150-, 200-, 250 ms), in response to a four-week period of moderate load (60-82.5% 1RM) training and a subsequent four-week period of high load (80-90% 1RM) training, in-season; 2) compare the changes between the two training phases. It was hypothesized that both phases of training would result in increased isometric force production at specific time points, but that the moderate load training would result in the greatest increases in early isometric force production due to the requirement for rapid force production and higher movement velocities during such training. It was also hypothesized that isometric PF would increase at the end of each phase, but that the greatest increase would be observed after the high load training phase. The results of this study should provide strength and conditioning coaches with information regarding the in-season force production adaptations to two different resistance training loading paradigms.

METHODS

EXPERIMENTAL APPROACH TO THE PROBLEM

To determine the effect of two, four-week periods of training on multi-joint early isometric force production (50-, 100-, 150-, 200-, 250 ms) and to compare the differences in changes in early isometric force production and PF between moderate- (60-82.5% 1RM) and high load (80-90% 1RM) training, a within-subjects repeated measures design was utilized. The time points were selected to represent time frames commonly reported for different athletic tasks, including striking (50 ms), contact times during maximal sprint speed (100-, 150 ms) and contact times during sprint acceleration (200-, 250 ms) (4, 27, 37, 50).

All subjects (n = 34) performed baseline testing (week 0), which was repeated after the initial four-week mesocycle (moderate load) (week 5) and repeated after the second four-week mesocycle (high load) (week 10) (Figure 1). A subset of subjects (n = 20) were assessed twice at baseline (48-72 hours apart), to determine the reliability of the dependent variables. All testing and training occurred in-season, at the same time of day, with subjects asked to maintain their normal dietary intake, sport specific training and to avoid strenuous exercise for at least 48 hours prior to testing.

[***Insert figure 1 here***]

Subjects

Male professional youth soccer players (n = 11) and collegiate athletes (n = 23) from a variety of sports (rowing, field hockey, soccer) volunteered to participate in this investigation (age 19.5 ± 2.8 years; height 1.72 ± 0.08 m; body mass 69.9 ± 11.4 kg; power clean 0.92 ± 0.03 kg.kg^{-1}). *A priori* statistical power calculations, using G*Power (version, 3.1.9.2) (20) indicated that for a statistical power of ≥0.90 at an alpha level of p ≤0.05 a sample size of n≥21 was required. All subjects provided written informed consent, or parental assent as appropriate, the study was approved by the Institutional Review Board, in line with the Declaration of Helsinki. Subjects were all experienced (>1-year, 2-3 x week) and competent in each of the lifts performed in the interventions, as determined by a qualified (certified strength and conditioning coach [CSCS] with the National Strength and Conditioning Association and accredited strength and conditioning coach [ASCC] with the United Kingdom Strength and Conditioning association) strength and conditioning coach.

PROCEDURES

Prior to testing, subjects performed a standardized warm up consisting of 10 body weight squats, 10 forward and 10 reverse lunges, and 5 submaximal countermovement jumps. Although all participants were familiar with testing procedures as part of their 'normal' monitoring and training, further familiarization and warm up trials were performed prior to the maximal effort trials, as described below.

Isometric Mid-thigh Pull

For the IMTP, previously described procedures were used (11, 23). Briefly, using a portable IMTP rig (Fitness Technologies, Perth, Australia), an immovable cold rolled steel bar was positioned at a height that replicated the start of the second pull phase of the clean for each individual, with the bar fixed above the force platform to accommodate subjects of different sizes and proportions. This posture resulted in knee and hip angles of 144.3 ± 4.3° and 145.6

± 4.4˚ respectively, with individual joint angles were recorded and standardized between testing sessions (11, 19, 23). Once the bar height was established, the subjects' stood on the force platform with their hands strapped to the bar (11, 23).

Each participant performed three warm-up trials, one at 50%, one at 75% and one at 90% of the subject's perceived maximum effort, each separated by one minute of rest. Once body position was stabilized (verified by watching the participant and force trace), the participants were given a countdown of "3, 2, 1, Pull". Any obvious pre-tension was not permitted prior to initiation of the pull, with the instruction to pull against the bar "and push the feet into the ground as fast and hard as possible" which has previously been reported to produce optimal testing results (26). Each IMTP trial was performed for approximately five seconds, and all participants were given strong verbal encouragement during each trial. Participants performed three maximal IMTP trials interspersed with two minutes of rest between trials. If PF during all trials did not fall within 250 N of each other, the trial was discounted and repeated after a further two minutes of rest, in line with previous recommendations (11, 23). All participants completed three successful trials within 3-5 maximal efforts.

Vertical ground reaction force data for the IMTP was collected using a portable force platform sampling at 1000 Hz (Kistler Instuments, Winterthur, Switzerland), interfaced with a laptop computer and specialist software (Bioware 3.1, Kistler Instruments, Winterthur, Switzerland) that allows for direct measurement of force-time characteristics. Raw unfiltered, force-time data was exported for subsequent analysis in a bespoke Excel spreadsheet (11).

1-RM Power Clean

The 1RM power clean performances were determined based on a standardized protocol (35). Briefly, subjects performed warm-up power clean sets using progressively increasing sub-maximal loads prior to performing a maximal attempt, with a progressive increase in loading during the maximal attempts. Any power clean repetition caught >90° knee flexion was ruled as an unsuccessful attempt, by a qualified (CSCS, ASCC) strength and conditioning coach.

Data Analysis

The maximum forces recorded from the force-time curve during the IMTP trials were reported as PF and subsequently ratio scaled (PF / body mass). The onset of force production was defined as an increase in force greater than five standard deviations of force during the period of quiet standing (17), and subsequently force at 50- (F50), 100- (F100), 150- (F150), 200- (F200) and 250 ms (F250) were also determined and ratio scaled (force / body mass). All force data represented net force (maximum force – body weight). Data taken forward for statistical analyses were based on the mean of the three trials.

INTERVENTION

Subjects initially performed a four-week, moderate load mesocycle (Table 1) followed by a testing week and a further four-week, high load mesocycle (Table 2). The loads prescribed for all weightlifting derivatives were based on the subjects' 1RM power clean. The loads prescribed for the remaining exercises were based on predicted 1RM loads from the subject's previous 5RM performances as determined at the end of their previous phase of training. The volume load during the second session of each week was reduced as this was the session closest to the subjects' day of competition. As this period of training was *'in-season'* prescribed loads ensured that the subjects could perform all repetitions without reaching momentary muscle failure, which is likely to induce additional fatigue and does not appear to increase strength or power more than when not reaching failure (30, 34).

All training sessions were supervised by the same qualified (CSCS, ASCC) strength and conditioning coaches, to ensure consistency of technique, coaching, encouragement and exercise sequence. In addition, subjects were instructed to use maximal intent, and complete the concentric phase of the exercises 'as explosively as possible', irrespective of the load, to ensure maximal intent (8). Subjects performed no other resistance training during the intervention and performed between 3.5-4.5 hours of conditioning and skill-based training per week, across 2-3 sessions, depending on their individual competition schedules.

[***Insert table 1 here***]

[***Insert table 2 here***]

Statistical Analyses

Normality of all data was determined via Shapiro-Wilk's test, with all variables normally distributed ($p > 0.05$). Baseline measures were compared to determine between-session reliability, using two-way random effects model intraclass correlation coefficients (ICC) and 95% confidence intervals. The magnitude of the ICC were interpreted as low (<0.30), moderate (0.30-0.49), high (0.50-0.69), very high (0.70-0.89), nearly perfect (0.90-0.99), and perfect (1.0) (29). Percentage coefficient of variation (%CV) were also calculated to determine the between session variability, with <10% being considered acceptable (13). In addition, t-tests were performed, and Cohen's *d* effect sizes calculated to determine if there were any significant or meaningful differences between baseline testing sessions.

A series of repeated measures analyses of variance (ANOVA) were performed to determine differences in dependent variables pre- to post-training phase, with Bonferroni post hoc analysis to determine differences pre- to mid-intervention (moderate load phase) and mid- to post intervention (high load phase). In addition, further t-tests were performed to determine if there were any differences in the percentage change for the moderate- and high load phases, for each variable. An *a priori* alpha level was set at $p \leq 0.05$. Further, the magnitude of any changes were determined via the calculation of effect sizes (Cohen's *d*), classified as trivial (≤0.19), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99), and very large (2.0 – 4.0) (28). All statistical analyses were performed using SPSS (Version 23. IBM, New York, NY).

Results

Reliability of all IMTP variables was very high to nearly perfect (ICC = 0.863-0.951) between sessions (Figure 1), with acceptable variability (CV = 3.46-7.95%). Furthermore, differences between sessions were trivial (d = 0.002-0.13) and non-significant (p >0.05).

[***Insert figure 1 here***]

Sphericity was assumed via Mauchly's test for all variables. There were significant ($p < 0.001$, power ≥ 0.978) increases in F50, F100, F150 and F200 across the entire duration of the intervention. The results of post-hoc analysis highlighted a small, non-significant increase (0.7 ± 12.5%) in F50 across the moderate load phase (d = 0.53, p = 1.000; 15.07 ± 0.37 $N.kg^{-1}$ vs. 15.27 ± 0.39 $N.kg^{-1}$), although there was a very large, significant increase (13.2 ± 17.4%) across the high load phase (d = 4.16, p = 0.001; 15.27 ± 0.39 $N.kg^{-1}$ vs. 17.00 ± 0.44 $N.kg^{-1}$) (Figure 2). Similarly, there was a trivial, non-significant increase (0.9 ± 14.4%) in F100 across the moderate load phase (d = 0.00, p = 1.000; 19.01 ± 0.67 $N.kg^{-1}$ vs. 19.01 ± 0.63 $N.kg^{-1}$), while in contrast there was a very large, significant increase (14.6 ± 21.7%) across the high load phase (*d* = 3.55, *p* = 0.002; 19.01 ± 0.63 $N.kg^{-1}$ vs. 21.49 ± 0.76 $N.kg^{-1}$) (Figure 2). F150 also showed a small and non-significant increase (2.7 ± 13.7%) across the moderate load phase (*d* = 0.54, *p* = 1.000; 23.49 ± 0.95 $N.kg^{-1}$ vs. 24.00 ± 0.91 $N.kg^{-1}$), while there was a very large, significant increase (14.6 ± 21.7%) across the high load phase (*d* = 3.05, *p* = 0.004; 24.00 ± 0.91 $N.kg^{-1}$ vs. 26.81 ± 0.93 $N.kg^{-1}$) (Figure 2).

[***Insert figure 2 here***]

Post-hoc analysis also highlighted a small, non-significant increase (2.5 ± 13.7%) in F200 across the moderate load phase (*d* = 0.49, *p* = 1.000; 26.80 ± 0.95 $N.kg^{-1}$ vs. 27.25 ± 0.88 $N.kg^{-1}$), while in contrast there was a very large, significant increase (10.9 ± 17.6%) across the high load phase (*d* = 2.77, *p* = 0.001; 27.25 ± 0.88 $N.kg^{-1}$ vs. 29.74 ± 0.92 $N.kg^{-1}$) (Figure 3). Only a small, non-significant increase (2.0 ± 12.4%) in F250 occurred across the moderate load phase (*d* = 0.33, *p* = 1.000; 28.20 ± 0.92 $N.kg^{-1}$ vs. 28.49 ± 0.81 $N.kg^{-1}$), although there was a very large, significant increase (9.2 ± 15.2%) across the high load phase (*d* = 2.71, *p* = 0.002; 28.49 ± 0.81 $N.kg^{-1}$ vs. 30.81 ± 0.90 $N.kg^{-1}$). PF also increased significantly ($p < 0.001$, power = 0.963) across the duration of the study. In contrast to the time specific force variables, there was a very large, significant increase (7.7 ± 11.8%) in PF across the moderate load phase (*d* = 2.02, *p* = 0.003; 35.70 ± 1.17 $N.kg^{-1}$ vs. 38.05 ± 1.16 $N.kg^{-1}$), but only a moderate and significant increase (3.8 ± 10.6%) across the high load phase (*d* = 1.16, *p* = 0.001; 38.05 ± 1.16 $N.kg^{-1}$ vs. 39.50 ± 1.34 $N.kg^{-1}$) (Figure 3).

[***Insert figure 3 here***]

Discussion

The aims of this study were to compare the changes in early (50-, 100-, 150-, 200-, 250 ms) and peak isometric force production, after four weeks of moderate load training and after four weeks of high load training. In contrast to the hypotheses, only trivial to small increases were observed in response to the moderate load training period, while large increases in early force production were observed in response to the high load training period. Also, in contrast to our hypotheses, PF increased to a greater extent across the moderate load training phase (7.7%) compared to the high load training phase (3.8%). During the moderate load training phase only trivial to small increases (0.7-2.7%) in early force production were observed, while very large increases in in early force production (9.2-14.6%) occurred across the high load phase.

In contrast to the moderate load phase, early force production showed very large increases during the high load training phase. While beyond the scope of this study, such adaptations may be as a result of increases in motor neuron recruitment, firing frequency, myosin heavy chain isoform composition and sarcoplasmic reticulum calcium kinetics, in line with previous findings (2). Although very large increases in early force production occurred, only moderate increases (3.8%) in isometric PF were found, which were greater than the smallest detectable difference (1.3%) previously reported for this assessment (12). It must be acknowledged that that the adaptations experienced in the first block of training likely influenced adaptations to the second block, which may be expect based on the phase potentiation observed during periodized training, especially with a reduction in volume during the high load phase. In addition, James et al. (31) previously suggested that there may be a delayed training effect for weaker, less experienced lifters, which may explain some of the individual variation in the results of this study (Figures 2 & 3). This is further explained by the model proposed by Minetti (36) where large changes in rapid force production in stronger athletes are likely a result of timing, whereas in weaker athletes these are likely due to increases in cross sectional area and strength.

Assessment and development of rapid force production, across such time-points, are important in the context of the time constraints of a variety of athletic tasks, with field sports requiring force to be produced over shorter durations as sprint speed increases (27, 37, 47, 50). In addition, ground contact times are generally <250 ms during jumping tasks, such as long jump (~120 ms) and high jump (140-190 ms) (47). The results of this study indicate that, high load resistance training results in increased rapid multi-joint force production, similar to the findings of numerous investigations that have demonstrated increases in RFD and force at specific time-points during single-joint isometric assessments (1-3, 5, 24, 25). In addition, Bazyler et al. (6) reported similar adaptations in rapid force production characteristics in response to high load multi-joint strength training (85-92% 1RM).

This study is not without limitations; for example, while the loads used for the exercises are within the 'normal' ranges recommended for this type of training. More recently, however, researchers have suggested during weightlifting pulling derivatives higher loads (≥100% 1RM) to maximize force and RFD and lower loads (≤60% 1RM) to maximize power and movement velocity (44, 45). It is also worth noting that there was clear variability in the individual responses to the training stimulus, as illustrated in figures 3 and 4, which may be due, in part, to range in relative strength (1RM PC = 0.65 – 1.36 $kg.kg^{-1}$) levels prior to participating in the study. Such variability in responses to training have also recently been reported with subjects divided in to responders and non-responders (39), while other researchers have also reported differential adaptations between week and strong athletes (15, 31, 32). In addition, some of the individual variation evident in the results of this study (Figures 3 & 4) may be explained by the individual demands of competition and sport-specific trainings, as this study was conducted in-season.

While the sequence of training phases was not randomized, and a cross-over design was not used, moderate loads followed by high loads was used to ensure ecological validity, as this is recommended as standard practice in the training and development of athletes (42). Future research, however, should consider a cross-over design, possibly across a series of three or four mesocycles to determine the potential effect of such training procedures, to determine whether the current practices are optimal. Additionally, a cross-over design may allow researchers to determine the effect of a moderate load phase preceding a high load phase has on the adaptations in the subsequent adaptations during the high load phase.

Practical Application

The findings of the study illustrate the benefits of training with high loads, with the intention to move quickly, to enhance early force production. These results also demonstrate that higher movement velocities associated with moderate load training do not result in greater adaptations in rapid force production when compared to the high loads, which results in a lower movement velocity. Based on the results of this study, it is suggested that coaches and athletes focus on higher load (>80% 1RM) training, using multi-joint exercises, including squats and weightlifting derivatives, when the aim is to increase rapid force production, but that this is preceded with an appropriate period of moderate load training, which may facilitate the adaptations observed during the high load phase. Appropriate phasing of these loads may result in preferential adaptations, in terms of rapid force production.

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Table and Figure Legends

Table 1: Moderate load (60-82.5% 1RM) training sessions, weeks 1-4.

Table 2: High load (80-90% 1RM) training sessions, weeks 6-9.

Figure 1: Reliability (intraclass correlation coefficients and 95% confidence intervals) of force-time variables.

Figure 2: Comparison of percentage change in early force production a) force at 50 ms, b) force at 100 ms, c) force 150 ms, between periods of training.

Figure 3: Comparison of percentage change in early force production a) force at 200 ms, b) force at 250 ms, and c) peak force between periods of training.

Figures & Tables

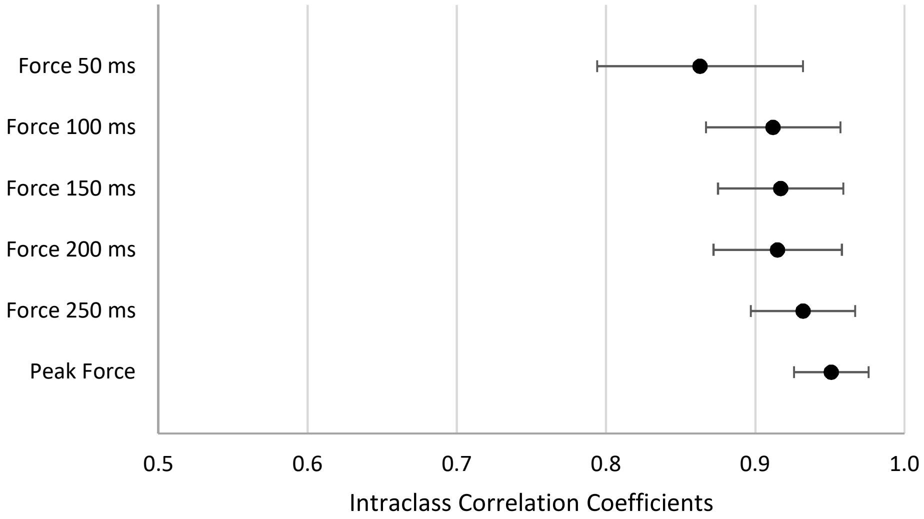

Figure 1: Reliability (intraclass correlation coefficients and 95% confidence intervals) of force-time variables

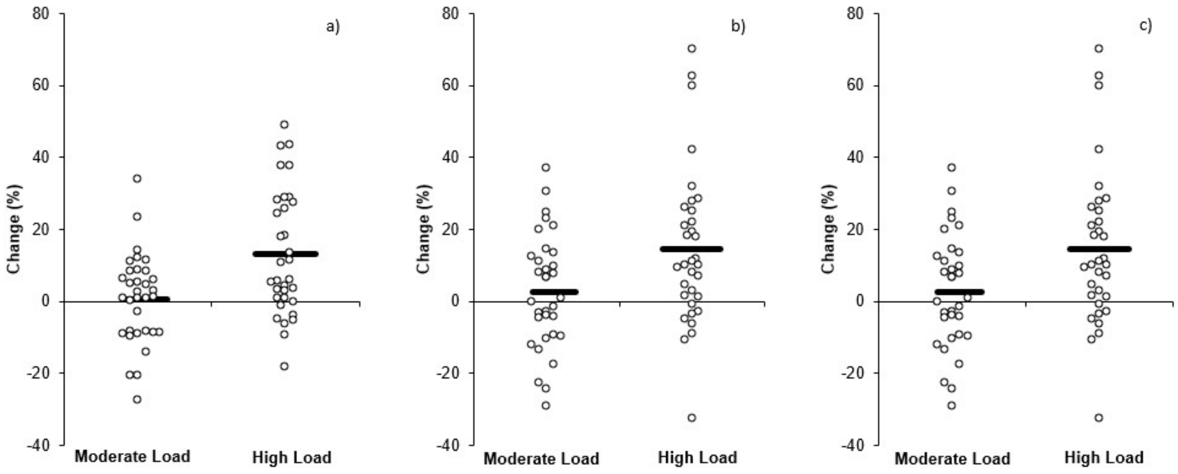

Figure 2: Comparison of percentage change in early force production a) force at 50 ms, b) force at 100 ms, c) force at 150 ms, between periods of training

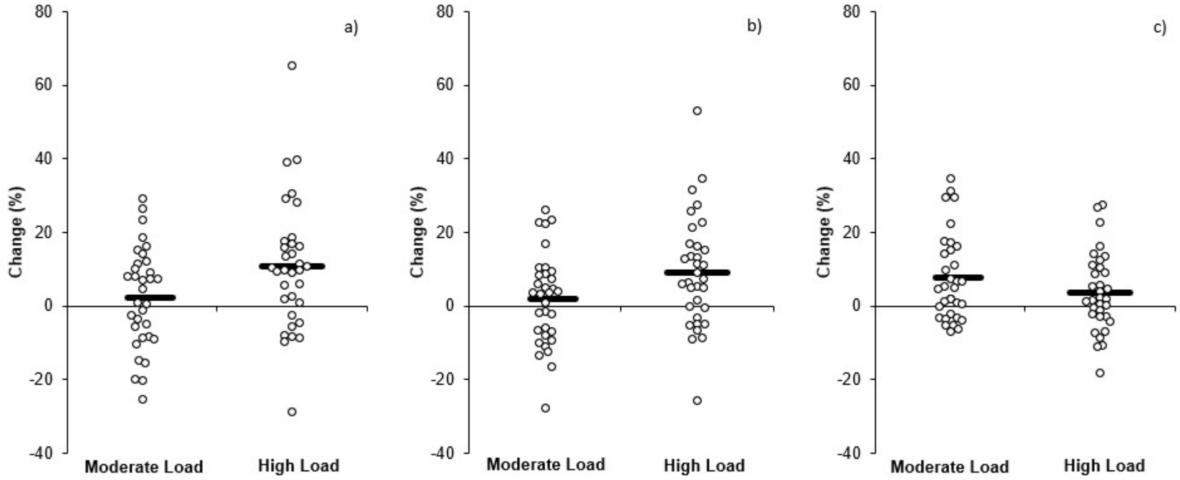

Figure 3: Comparison of percentage change in early force production a) force at 200 ms, b) force at 250 ms, and c) peak force, between periods of training

Table 1: Moderate load (60-82.5% 1RM) training sessions, weeks 1-4

Mesocycle 1: Day 1				
Exercise	Week 1	Week 2	Week 3	Week 4
Back Squat	3 x 5 @ 75%	3 x 5 @ 80%	3 x 5 @ 82.5%	3 x 5 @ 67.5%
Power Clean	3 x 5 @ 75%	3 x 5 @ 80%	3 x 5 @ 82.5%	3 x 5 @ 67.5%
Push Press	3 x 5 @ 70%	3 x 5 @ 72.5%	3 x 5 @ 75%	3 x 5 @ 60%
Nordic Lowers	2 x 3 BW	3 x 3 BW	3 x 3 BW	3 x 3 BW
Mesocycle 1: Day 2				
MTPC	3 x 5 @ 60%	3 x 5 @ 65%	3 x 5 @ 70%	3 x 5 @ 55%
RDL	3 x 5 @ 70%	3 x 5 @ 75%	3 x 5 @ 77.5%	3 x 5 @ 65%
Push Press	3 x 5 @ 60%	3 x 5 @ 65%	3 x 5 @ 70%	3 x 5 @ 55%

Sets x Repetitions @ 1RM%
MTPC – Mid-thigh Power Clean
RDL – Romanian Deadlift
BW = Body Weight

Table 2: High load (80-90% 1RM) training sessions, weeks 6-9

Mesocycle 2: Day 1				
Exercise	Week 1	Week 2	Week 3	Week 4
Power Clean	3 x 3 @ 82.5%	3 x 3 @ 85%	3 x 3 @ 90%	3 x 3 @ 75%
Push Press	3 x 3 @ 80%	3 x 3 @ 82.5%	3 x 3 @ 85%	3 x 3 @ 75%
Back Squat	3 x 3 @ 85%	3 x 3 @ 87.5%	3 x 3 @ 90%	3 x 3 @ 75%
Nordic Lowers	2 x 3 BW	3 x 3 BW	3 x 3 BW	3 x 3 BW
Mesocycle 2: Day 2				
MTPC	3 x 3 @ 80%	3 x 3 @ 82.5%	3 x 3 @ 85%	3 x 3 @ 70%
RDL	3 x 3 @ 80%	3 x 3 @ 85%	3 x 3 @ 87.5%	3 x 3 @ 70%
Push Press	3 x 3 @ 80%	3 x 3 @ 82.5%	3 x 3 @ 85%	3 x 3 @ 70%

Sets x Repetitions @ 1RM%
MTPC – Mid-thigh Power Clean
RDL – Romanian Deadlift
BW = Body Weight