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Changes in the force development characteristics of muscle following repeated maximum force and power exercise

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There is some evidence to suggest that ability to develop force in skeletal muscle can be improved for a short period following repeated maximal strength exercise. Some studies have suggested the phenomenon known as post-activation potentiation (PAP) to explain this immediate response to such exercise. However, little is known about the physical and temporal characteristics of the changes in muscle function due to PAP when induced using whole-body maximal strength exercise. The purpose of this study was to establish the physical and temporal characteristics of PAP of muscle function in elite male athletes following maximum strength and power exercise. Fifteen participants performed one of repeated maximal strength exercise or maximal power exercise or a control protocol on separate occasions. Changes in maximum isometric voluntary force (iMF), maximum isometric rate of force development (iRFD) and maximum vertical counter-movement jump (CMJ) were assessed. Results suggest that post-activation potentiation of iRFD occurs but is preceded by an initial suppression of force development capability following repeated maximal strength exercise. Following repeated maximal power exercise, however, post-activation potentiation of iRFD occurs immediately but is not seen over as long a period as that observed following maximal strength exercise. These results suggest that post-activation potentiation does bring about increased force development capability following intense exercise and that the temporal profile of the post-activation potentiation changes with intensity of the exercise used to induce it.

Keywords: Post-Activation Potentiation; iRFD; 1-RM; CMJ; Power; Quadriceps

1. Introduction

The acute enhancement of muscle function after intense muscle activity is referred to as post-activation potentiation (PAP). One mechanism by which PAP is considered to

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operate is phosphorylation of myosin regulatory light chains resulting in increased sensitivity of actin–myosin interaction to Ca^{2+} released from the sarcoplasmic reticulum (Sale 2002). The sensitivity to Ca^{2+} has its greatest effect when Ca^{2+} levels are low in the myoplasm such as in low frequency tetanic contraction. Little effect is seen in high frequency tetanic contractions where myoplasmic Ca^{2+} levels are close to or at saturation (Vanderboom *et al.* 1993, Abbate *et al.* 2000). Another mechanism proposed is the increase in excitability of muscle or more specifically the motor neurone pool. Gullich and Schmidtbleicher (1996) suggested a greater sensitivity of the Hoffman or H-reflex as being a possible cause of PAP.

Despite the mechanisms underpinning PAP being uncertain, the existence of PAP has been demonstrated in functional performance. Young *et al.* (1998) presented evidence of enhanced performance following repeated squat-activity. Loaded counter-movement jump performance (30% of back squat 1-RM) was enhanced immediately after a bout of maximal squatting exercise. Güllich and Schmidtbleicher (1996) reported immediate increases in isometric rate of force development, vertical counter-movement jump height and vertical drop jump height immediately after five maximum isometric voluntary plantar flexor contractions. Gilbert *et al.* (2001) reported an initial decrease in the force development capability of the muscle following five repetitions of the back squat with maximum load. This depression was then followed by a potentiation of the rate of force development capability, which was seen up to **twenty** minutes after the final repetition of the resistance exercise.

Despite there being some evidence to suggest that voluntary induction of PAP results in enhanced functional performance, there still remains a lack of knowledge concerning its physical and temporal characteristics and the effect of contractile history on these characteristics. The aim of this study was therefore to examine the physical and temporal characteristics of changes in muscle function following two types of intense voluntary activity.

2. Methods and procedures

2.1. Participants

Fifteen male athletes volunteered to participate in this study. Mean subject characteristics for age, height and mass (mean $\pm$ SD) are summarised in table 1. All participants were recruited as experienced strength trainers who could perform single repetition in the back squat exercise with a load of at least $2 \times$ body mass (BM). All participants were currently engaged in sporting activities for which power development was essential (power lifting, track and field–throwing events). The study was approved by the Human Ethics Committee of Liverpool John Moores University. Prior to commencement of the study all participants were verbally informed of the experimental procedures before signing an informed consent form.

Table 1. Subject physical characteristics (n = 15).

Age (years)	Height (m)	Mass (kg)	1RM (kg)
24.3 $\pm$ 3.3	1.83 $\pm$ 0.05	112.6 $\pm$ 6.3	236.9 $\pm$ 21.2

2.2. Research design

Participants in the study visited the laboratory on six occasions. Prior to this participants were fully familiarised with the assessment protocols for isometric maximum voluntary contraction (MVC), vertical counter-movement jump (CMJ) and participants' 1-RM (one repetition maximum) and load at which maximum power was developed in the back squat were established. All subsequent visits were used to assess the effects of weight lifting on the force development characteristics of the quadriceps under isometric and eccentric-concentric (stretch-shorten cycle) conditions. The experimental conditions were assigned to participants in a counterbalanced design with a minimum rest period of 7 days.

2.3. Preliminary testing

Participants' age was recorded along with height (m) determined using a wall-mounted stadiometer; body mass (kg) was measured with participants stood still for 3 s on a Kistler force platform. Participants were also asked to report their 1-RM load for the back squat to help minimise the number of attempts required to determine the 1-RM.

2.4. Weightlifting loads and conditions

A standard 20-kg Olympic barbell and calibrated weight discs (Ivanko, Sweden) were used for all load assessments and subsequent experimental protocols. All weight lifting was performed within the confines of a weightlifting safety cage. Participants were permitted to use weightlifting belts as they required. The use of support knee wraps and weightlifting body suits were not permitted for use in this study.

On all occasions a lift was deemed to be successful if the subjects could descend until the inguinal fold was lower than the patella and rise without help as per the International Powerlifting Federation rules (International Powerlifting Federation 2002).

The 1-RM and the load at which participants developed maximum power (P_{max}) were established. Weight lifting loads were assessed on two occasions with a minimum 7 days rest and at the same time of day to minimise time-of-day effects on muscle function (Reilly and Down 1992, Martin *et al.* 1999). Power development during the each lift was recorded on microcomputer via using a Fitrodyne[®] displacement transducer from which velocity and hence power were computed.

2.5. Measurement protocols

2.5.1. Isometric assessment of quadriceps. The force development characteristics of the participant's reported dominant leg were assessed. The participant sat upright with hip and knee angles of 90 degrees. The distal end of the leg was restrained 1–2 cm proximal to the malleolae using a wooden cuff and light padding. The restraining cuff was attached with a solid steel bar to a load cell. Data were collected via analogue to digital converter linked to an Archimedes A5000 computer, and was processed using custom written software. Data were collected using a sample frequency of 1000 Hz for 3 s. Prior to each the measurement the participant was given verbal instruction to 'kick out as hard and fast as possible'. The participant were then given the countdown '3-2-1-GO!' Data acquisition began on the '1' count to ensure data were collected prior to the onset of force.

Maximum voluntary force (iMVF) and maximum rate of force development (iRFD) were calculated from each trial. The iMVF was taken to be the maximum force developed

in the first second of each trial. The iRFD was calculated as the first derivate of the force signal. The iRFD was calculated instantaneously as the change in force per unit of time and averaged over a period of 50 ms using a rolling mean method. Changes in iMVC and iRFD were calculated as the difference between pre- and post-weightlifting values.

2.5.2. Assessment of maximum vertical counter-movement jump. Counter-movement jump performance was assessed using a Kistler force platform (model 9281B, Kistler, Winterthur, Switzerland) mounted flush with the floor of the laboratory. Data were collected at a sample frequency of 1000 Hz for a period of 3 s. Data collection was started prior to the start of the movement in each trail.

2.6. Experimental conditions

Participants reported to the laboratory having abstained from any weightlifting activity for at least 48 hours and from any exercise for 24 hours. Participants were asked to abstain from intake of caffeine or alcohol for at least 12 hours prior to each session of testing and to have eaten no later than 4 hours prior to each visit.

Upon arrival participants performed a standardised warm up of 10 minutes of sub-maximal cycling (60–70 W) on a cycle ergometer (Monark, Sweden). Due to the strenuous nature of the weightlifting activity the participant was permitted to perform a number of sub-maximal repetitions in the back squat. The participant performed back squats at loads based on the 1 RM established in previous familiarisation sessions; loads were calculated according to Hoeger *et al.* (1990). The participants performed a maximum of a set of 10 repetitions at the predicted 20 RM load, 5 repetitions at the predicted 10 RM load, 3 repetitions at the predicted 6 RM load and 2 repetitions at the predicted load for the 4 RM.

Following this, a baseline assessment of muscle function was undertaken. Three trials with a 1-minute inter-trial rest period were recorded using the either isometric assessment or vertical jump depending on which protocol was being used.

The participant then followed one of three experimental protocols (figure 1). Each participant performed five repetitions of the back squat with either their 1-RM or P_{max}

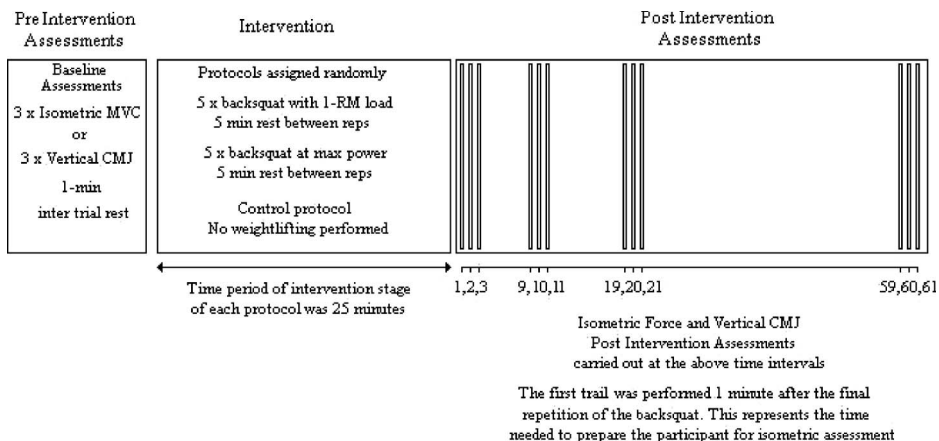


Figure 1. Schematic representation of the pre- and post-intervention assessments and the time line over which they were made.

loads with a 5-min inter-repetition rest period. The participants were also tested under control conditions where no weightlifting was performed. During the control protocol and in between weightlifting repetitions the participant was allowed to move freely about the laboratory. The time taken to complete this phase of the test sessions was 25 min. Immediately after the final repetition or following the 25th minute of the control period a clock was started and MVC or CMJ was recorded at 1,2,3, 9,10,11,19,20,21,59,60,61 min.

2.7. Statistical analysis

Statistical analysis was conducted using The Statistical Package for Social Sciences (SPSS). Sphericity of the data was checked and in the event of violation of sphericity the Greenhouse-Geisser correction was used (Thomas and Nelson 1990). Pre- and Post-treatment changes in iMVC and iRFD were compared using one-way analysis of variance (ANOVA) and the $P < 0.05$ level of significance was used.

3. Results

No participants failed to complete a lift successfully during the test and participants used the same loads during each experimental protocol. No statistical differences were found between the pre-weightlifting assessments of iMF and iRFD for the control, 1-RM and P_{max} protocols. Also no statistical differences were found between pre- and post-weightlifting measurements of iMF and iRFD in the control protocol.

Following the weightlifting with 1-RM load statistically significant differences were found between pre- and post-weightlifting assessment of iRFD. The temporal profile of the changes in iRFD can be seen in figure 2. Significant reductions from a pre-weightlifting baseline of $4867 \pm 881 \text{ N s}^{-1}$ were found at the 2 min ($F_{1,2,15} = 20.67$, $P = 0.0023$) and 10 min ($F_{1,11,15} = 12.41$, $p = 0.035$) assessment times. Following this, significant increases were found at the 15 min ($F_{2,1,15} = 11.38$, $p = 0.021$) and 20 min ($F_{1,11,15} = 12.41$, $p = 0.006$) assessment times representing a functional peak increase of 11.8%. No significant difference was found between pre-weightlifting and post-weightlifting assessment of iRFD at 20 and 60 minutes.

These results contrast with that of the changes found following repeated maximum power exercise. The temporal profile of the changes in iRFD (figure 2) showed a significant increase ($F_{1,11,15} = 12.41$, $p = 0.038$) representing a functional peak increase of 6.7% immediately after the final repetition of the back squat (2 min after weightlifting). All subsequent assessment did not differ significantly from pre-treatment assessment.

Similar changes were also found in maximum vertical countermovement jump height following with both 1-RM and P_{max} loads. Significant increases in jump height were seen after both types of weightlifting. Following weightlifting with the 1-RM load the increases in vertical jump height peaked at 20 minutes.

4. Discussion

From the results presented it is evident that intense exercise can be used to induce short-term changes in neuromuscular performance. The positive effects observed in participants express themselves in improved force development capabilities.

The results for the assessment of force development capabilities for the control protocol indicate that the repeated iMVC assessment was not in itself sufficient stimulus

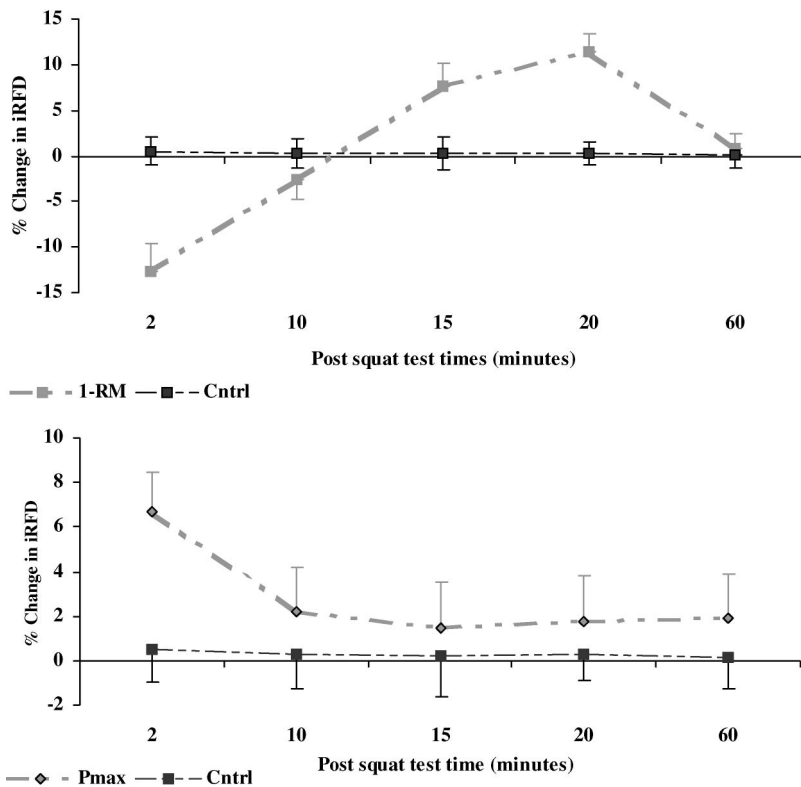


Figure 2. Changes from baseline in isometric rate of force development following five single repetitions of back squat at 1-RM (above) and at maximum power (below) with 5-min inter-repetition rest (conditions used were 1-RM=1 repetition maximum; Pmax = maximum power and cntrl = control. See text for details).

to induce changes. The protocol, followed as a control to the weightlifting protocols, differed only in that no weightlifting was performed. Participants remained active for the same period of time as that taken to complete the weightlifting (i.e. 5 repetitions with a 5 min inter-trial rest = 25 min). Participants were allowed to move about the laboratory or cycle sub-maximally on a cycle ergometer at the same intensity as that used in warm up (60 W) but were not allowed to perform any intense exercise. Typically participants performed a combination of cycling, walking and jogging.

Following repeated weightlifting with 1-RM and P_{max} loads no significant changes in iMF between pre- and post-weightlifting isometric assessments were found. Previous studies (Vanderboom 1993, Güllich and Schmidtbleicher 1996, Abbate 2000) all reported similar findings regarding the maximal force or high frequency tetanic contractions in skeletal muscle. It has been suggested that phosphorylation of myosin regulatory light chains causing increased sensitivity to Ca^{2+} released from the sarcoplasmic reticulum could explain the effects of PAP in skeletal muscle. No significant change in iMF is consistent with this theory as high frequency tetanic contractions typically occur where the levels of Ca^{2+} are close to or at saturation. Under these circumstances an increased sensitivity would have little effect (Sweeney 1993, Rassier and MacIntosh 2000, Sale 2000).

There were significant changes in iRFD following repeated weightlifting with 1-RM and P_{max} loads. Following weightlifting with the 1-RM load, a significant increase in iRFD

was found at 15 and 20 minutes after the final repetition but iRFD had returned to baseline levels by 60 minutes (figure 1). Functionally the changes represented an increase of up to 11.8% but this was preceded by a significant reduction of up to 12.6% found immediately after the final repetition. Following repeated weightlifting with the P_{max} load, an immediate increase in iRFD was found. Assessment of iRFD 2 minutes after the final repetition showed a functional increase of 6.7% but subsequent assessment showed a return to baseline levels. Similarly the theory that increasing sensitivity of myosin regulatory light chains to Ca^{2+} could explain the effects of PAP in skeletal muscle. The low frequency component of tetanic contraction where peak iRFD is typically found occurs at low levels of myoplasmic Ca^{2+} . Under these circumstances an increased sensitivity would have its greatest effect (Sweeney 1993, Rassier and MacIntosh 2000, Sale 2000).

Similarities can also be seen when comparing the temporal profiles for the changes in iRFD and CMJ performance for the 1-RM and P_{max} protocols. The changes for both parameters showed an initial depression followed by a potentiated response. Furthermore the temporal profiles show similarities in the timing of the extent of the responses. Following heavy weightlifting (1-RM) the iRFD and CMJ profiles indicated a maximum response 20 min after the final repetition of heavy weightlifting. And an almost immediate effect following the final repetition performed at maximum power. Though further investigation is needed to indicate the profile of changes between 20 min and 60 min, these

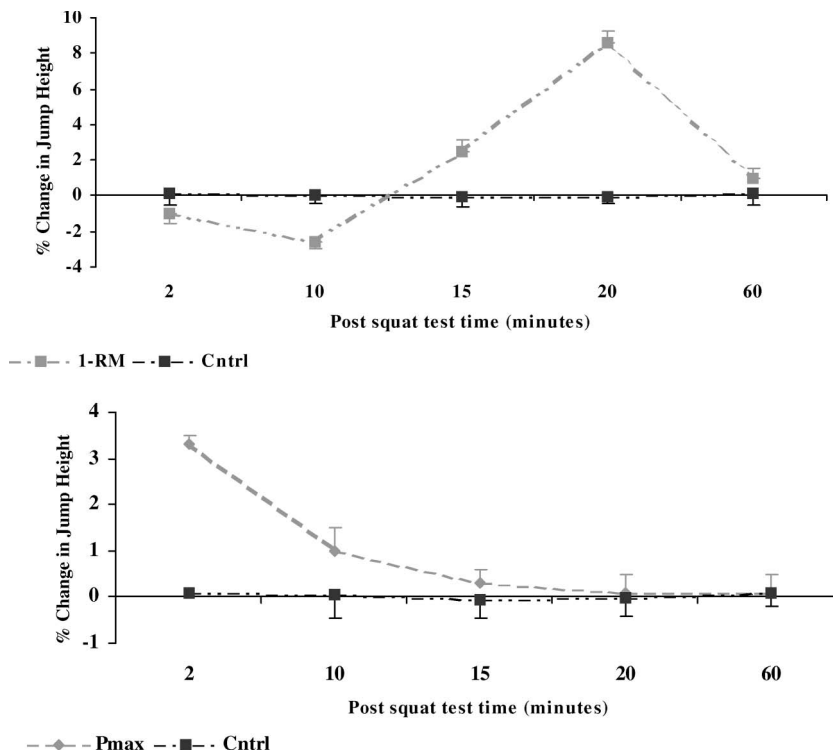


Figure 3. Changes from baseline in maximum vertical countermovement jump height following five single repetitions of back squat at 1-RM (above) and at maximum power (below) with 5-min inter-repetition rest (conditions used were 1-RM = 1 repetition maximum; Pmax = maximum power and cntrl = control. See text for details).

results are consistent with previous findings (Güllich and Schmidtbleicher 1996, Abbate *et al.* 2000). This finding indicates the practical significance of PAP in the preparation of athletic performers prior to competition and is noteworthy from the perspective of modified warm up strategies employed prior to maximal performance or competition.

The initial depression of the rate of force development may be attributed to fatigue induced by the repeated maximum squats. Previous studies (Güllich and Schmidtbleicher 1996, Gilbert *et al.* 2000) have examined the effects of maximal repeated strength exercise and have done so using an inter-trial rest of 5-min and not reported fatigue effects. When examining the effects of inter-trial rest periods in maximal back squatting, Matuszak *et al.* (2003) reported that an inter-trial rest interval of one minute was sufficient to ensure adequate recovery when performing repeated maximal squatting in weightlifters with a back squat 1-RM of at least $1.5 \times \text{BW}$. For inclusion in this study, participants were required to demonstrate a 1-RM of at least $2 \times \text{BW}$ and therefore fatigue can reasonably be discounted as a contributory cause of this depression.

When the results of the two weightlifting protocols are compared, the changes in iRFD following repeated lifting with 1-RM and $P_{\max}$ loads indicate that differences in the magnitude of and time to peak PAP exist. The PAP peaks at least 20 min after the final repetition following weightlifting with the 1-RM load as compared to 2 min following weightlifting with the $P_{\max}$ load. Further, the magnitude of the PAP is 11.8% (1-RM load) and 6.7% ($P_{\max}$). Clear differences therefore can be seen between the effects of the two weightlifting protocols. The existing literature (Güllich and Schmidtbleicher 1996, Young *et al.* 1998, Gilbert *et al.* 2001) has shown significant changes in iRFD existing over a period of up to 20 min but little is known regarding the mechanisms mediating the control of PAP under these circumstances.

Güllich and Schmidtbleicher (1996) noted immediate increases in the excitability of the motor neurone pool of the exercise skeletal muscle following repeated isometric MVC. They suggested that the increased Hoffman or H-reflex could be a possible mechanism to explain the effects of PAP.

Only Sale (2002) and Gilbert *et al.* (2001) have noted the presence of an initial decrease in force development characteristics following intense exercise. In suggesting a strategy to exploit the effects of PAP, Sale claimed that the fatigue induced by the conditioning activity would dissipate more quickly than the PAP and that therefore there would be an optimal time to utilise the effects of PAP. Further research into the optimal time and conditions for use of PAP is needed, as it appears that the effects of PAP change with the conditioning stimulus used to induce it.

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