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SHORT COMMUNICATION

Enhancement of jump performance after a 5-RM squat is associated with postactivation potentiation

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Abstract Weight lifting exercise may induce postactivation potentiation (PAP), thereby enhancing performance of a subsequent biomechanically similar "explosive" movement. However, it has not been shown that weight lifting induces PAP, indicated as potentiation of muscle twitch force. Therefore, the present study tested whether a five repetition maximum squat (5-RM squat) both induced PAP and increased the height of subsequently performed counter-movement jumps (CMJs). Eleven male athletes completed four laboratory sessions on separate days. Two sessions determined whether the 5-RM squat induced PAP: in one, a quadriceps maximal twitch was evoked immediately before and 8 min after a set of five CMJs (control); in the other, a twitch was evoked before a CMJ set, which was followed by a 4-min rest, a 5-RM squat, a 4-min rest, and a second twitch. Another two sessions tested the effect of the 5-RM squat on jump performance: in one session, two sets of five CMJs were performed with an 8-min rest between the sets (control); in the second, a 5-RM squat was performed 4 min after the first set of CMJs, and then after another 4 min the second set of CMJs was performed. Neither twitch torque nor CMJ height changed in the control sessions ($P > 0.05$). In contrast, interpolation of the 5-RM squat increased ($P < 0.05$) both twitch torque (49.5 ± 7.8 to 54.8 ± 11.9 N m; i.e., PAP = 10.7%) and CMJ height (48.1 ± 5.6 to 49.5 ± 5.9 cm; 2.9%). Since PAP was present at the time when CMJ height increased, it was concluded that PAP may have contributed to the increased CMJ height after a 5-RM squat.

Keywords Resistance exercise · Muscle twitch · Jumping · Postactivation potentiation

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Introduction

Muscle activity may enhance subsequent performance by inducing postactivation potentiation (PAP). The mechanism of PAP is considered to be phosphorylation of myosin regulatory light chains, which increases the sensitivity of the myofilaments to calcium ions (Ca^{2+}) (Grange et al. 1993). The most common indicator of PAP is increased evoked isometric twitch force (twitch potentiation) observed following an evoked isometric tetanic contraction (O'Leary et al. 1997) or a maximal voluntary isometric contraction (MVC) (Vandervoort et al. 1983). More relevant to performance of fast movements is that PAP increases the rate of force development of evoked isometric tetanic contractions (Baudry and Duchateau 2007a; MacIntosh et al. 2008; Vandenboom et al. 1995), the force and power of evoked high velocity shortening (concentric) contractions (Abbate et al. 2000), and the maximum velocity attained by evoked shortening contractions under load (Baudry and Duchateau 2007b; MacIntosh et al. 2008). In addition to its effects on evoked (involuntary) contractions, PAP has been associated with enhanced voluntary contraction performance such as increased isometric rate of force development (Baudry and Duchateau 2007a), increased torque of moderately high velocity isokinetic concentric contractions (Miyamoto et al. 2010), and increased shortening velocity attained with various loads (Baudry and Duchateau 2007b).

PAP is typically induced by MVCs (Vandervoort et al. 1983) but has also been induced by velocity-controlled maximal voluntary concentric and eccentric contractions (Baudry and Duchateau 2004; Houston et al. 1985). PAP is also induced by submaximal isometric contractions (Vandervoort et al. 1983); therefore, a set of repetitions of a weight lifting exercise, consisting of alternating submaximal concentric and eccentric contractions, may induce PAP, but the presence and extent of PAP produced by weight lifting exercise has not been determined. Nevertheless, with the assumption that weight lifting exercise induces PAP, several studies have tested whether one or more sets of a weight lifting exercise would enhance subsequently performed "explosive" movements such as vertical jumps (Bishop 2003; Hodgson et al. 2005; Tillin and Bishop 2009). In the present study, we conducted a protocol similar to that used previously to test the effect of weight lifting exercise on subsequent vertical jump height (Jensen and Ebben 2003; Jones and Lees 2003; Khamoui et al. 2009; McCann and Flanagan 2010; Scott and Docherty 2004; Weber et al. 2008; Young et al. 1998). Subjects did five sets of counter-movement jumps (CMJs) before and 4 min after one set of barbell back squats done with the heaviest weight that could be used for five repetitions, referred to as the five repetition maximum or 5-RM. However, unlike previous studies, an additional protocol, in which isometric twitch contractions were evoked in the knee extensor muscles (quadriceps) before and 4 min after a 5-RM squat, tested for the existence and extent of PAP (twitch potentiation) at the time the CMJs were done in the first protocol.

Methods

Subjects

Eleven men [age 20.5 ± 2.3 years (SD), height 178.3 ± 7.6 cm, mass 87.9 ± 8.7 kg] participated in the study. They were rugby union players who represented their university at the varsity level. They had a minimum of 1 year of experience with resistance training and the barbell back squat exercise that was used in the study. Each subject's training program was adjusted so that no lower body training was done within 3–4 days of a testing session. Written informed consent was obtained from all subjects. McMaster University's Research Ethics Committee approved the study. A medical history questionnaire was used to ensure subjects were free of injury and had no history of lower limb surgery or cardiovascular disease.

Procedures

5-RM squat

'Subjects attempted a set of five squats with their self-estimated 5-RM weight. They were instructed to perform each repetition to 90° of knee flexion. If five repetitions were completed, there was a 5-min rest, after which the weight was increased by a small amount and another attempt was made to complete five repetitions. Because of the subjects' experience with the exercise, only two to three attempts were needed to determine the 5-RM. The subjects' 5-RM squat was 144.5 ± 19.4 kg. The 5-RM squat was only determined on one occasion; therefore, a test of reliability (intraclass correlation) was not done for this measure. The subjects successfully completed a set of five repetitions with the established 5-RM in the experimental sessions.

CMJs

Subjects performed the CMJs on a force-plate (Stratec, Birkenfeld, Germany). The force-plate measured 70 × 50 cm and was divided into left and right halves, each half having strain gauges positioned to detect forces in all three planes of movement (*X*, *Y*, and *Z*). The force-plate was connected to an IBM-compatible computer with a custom-made user interface programmed using LabVIEW (National Instruments, Austin, TX). Jump height was calculated from the "flight" time in the air between take-off and landing. The force-plate software used the equation $h = 1/2at^2$, where h is the jump height, a is the acceleration due to gravity (9.81 m s^{-2}) and t is the flight time in seconds (Linthome 2001). Each CMJ began with the subject standing erect, whereupon he descended to a self-selected depth and immediately jumped upward as high as possible. To exclude the influence of arm-swing on jump height (Harman et al. 1990), the subject was instructed to keep his arms at his sides during each jump. A short rest (3–5 s) was given after each jump until the fifth jump was completed. CMJ height was taken as the average height of the five CMJs. Based on the CMJ height values recorded at the beginning of sessions Jump A and B (Fig. 1), the intraclass correlation (R) was 0.96. The mean CMJ height values obtained (pre values in Fig. 4) were similar those reported previously using a similar methodology in a group of trained subjects that included rugby players (Jones and Lees 2003).

Twitch torque

Peak twitch torque of the right knee extensors (quadriceps femoris) was measured with a custom-made dynamometer

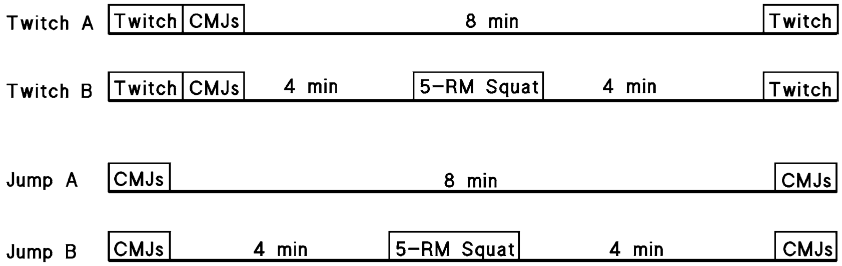

Fig. 1 Protocol. In Twitch A, a baseline knee extensor twitch was evoked, and then after a set of five counter-movement jumps (CMJs) and an 8-min rest, a second twitch was evoked. Twitch B was similar to Twitch A, except that following a 4-min rest after the set of CMJs, a 5-RM squat was done, and after another 4-min rest, a second twitch was evoked. Together, Twitch A and B tested whether PAP was present when the second set of five CMJs was done in Jump B. In Jump A, a set of five CMJs was done, and after an 8-min rest, a second set was done. Jump B was similar to Jump A, except that following a 4-min rest after the first set of CMJs, a 5-RM squat was done, and after another 4-min period, a second set of five CMJs was done. Together, Jump A and B tested whether a 5-RM squat increased the height of a second set of CMJs

built by the engineering department at McMaster University and used previously in our laboratory (Hamada et al. 2000, 2003). The subject sat on the dynamometer with the back and thighs supported so that the thighs were in the horizontal plane with a trunk-thigh (hip) angle of 100°. Velcro straps across the middle and proximal thigh prevented extraneous movement. The right lower leg was strapped to an aluminum plate attached to a steel shaft whose axis was coincident with the axis of the subject's knee joint. The shaft-plate combination was adjusted to set the knee joint angle to 90°. The steel shaft was instrumented with a strain gauge that sensed the knee extension torque developed by isometric actions of the knee extensors in response to percutaneous nerve stimulation. The signal from the strain gauge (sample rate of 3 kHz) was amplified and filtered, AD converted (Model DI420, Dataq Instruments Inc., Akron, OH), and analyzed with both customized and ACODAS (Dataq Instruments Inc., Akron, OH) software on an IBM-compatible personal computer.

Twitch contractions of the right knee extensors (quadriceps femoris) were evoked by percutaneous nerve stimulation. Before attaching the stimulating electrodes, the skin was prepared by shaving, sanding and rubbing with isopropyl alcohol. Electrode gel was then applied to the contact surface. Two self-adhering Ag/AgCl stimulating electrodes were used (5 cm diameter). Self-adhering electrodes were used to prevent shifts in electrode placement during the CMJs that could alter the twitch or M-wave response to stimulation. The cathode was placed on the skin over the femoral nerve in the inguinal crease; the anode was placed over the mid-portion of the thigh. The stimuli were rectangular voltage pulses of 200 µs duration, delivered from a stimulator (DS7A, Digitimer, Letchworth, UK). A maximum twitch response was elicited by delivering a series of single stimuli of increasing intensity until a plateau of twitch torque was obtained. Based on the peak twitch torque values obtained at the beginning of sessions Twitch A and B, the intraclass correlation (R) was 0.86. The mean peak twitch torque values (pre values in Fig. 2) were 15% greater than the mean in a group of untrained men tested with the same protocol (Hamada et al. 2000).

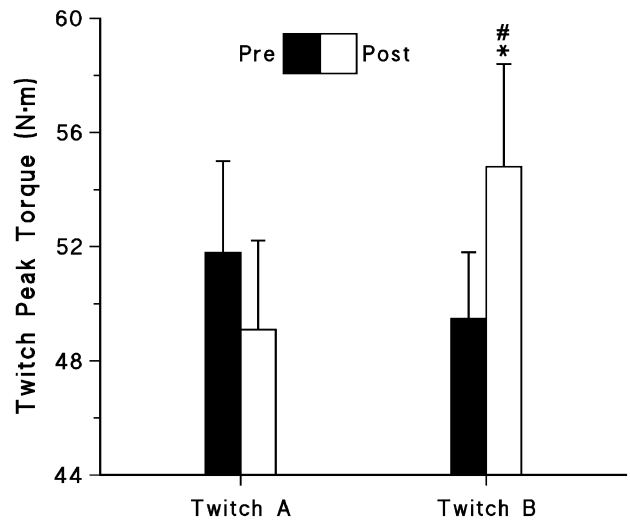

Fig. 2 Twitch peak torque observed in sessions Twitch A and B. Pre refers to the first baseline twitch. Post refers to the second twitch evoked after a set of five CMJs and an 8-min rest (Twitch A), or after an interposed 5-RM squat (Twitch B) (see Fig. 1). *Significant difference pre to post ($P < 0.05$). #Significant difference from Twitch A post ($P < 0.05$)

M-wave

During the twitch torque measurements evoked from the whole quadriceps, muscle compound action potentials (M-waves) were recorded from the distal portion of vastus medialis, one of four heads of the quadriceps muscle. This muscle was chosen because the stimulus artifact was smallest at this site, given the position of the stimulating electrodes. Ag/AgCl electromyographic (EMG) disposable recording electrodes, 3.8 mm diameter, were applied to the skin over the belly of the muscle (stigmatic), about 20 mm distal and medial to the patella (reference), and on the posterolateral aspect of the thigh (ground). EMG signals were amplified (1,000×) and filtered (10 Hz to 2 kHz). AD conversion and analysis was the same as for torque (see above).

With increasing intensity of stimulation, M-waves from vastus medialis tended to plateau at the same stimulus intensity as twitch torque. It was not feasible to record M-waves from all four heads of quadriceps. Since the twitch torque recordings represented all four heads of quadriceps, whereas M-waves represented only one head, a plateau in twitch torque was considered to be a more reliable indicator of maximal activation of the whole quadriceps muscle group. Based on the M-wave values obtained at the beginning of sessions Twitch A and B, the intraclass correlation (*R*) was 0.78.

Experimental protocol

Each subject completed four experimental sessions spaced 3–4 days apart. The four sessions were organized into two pairs, referred to as Twitch A and B, and Jump A and B (Fig. 1). Session Twitch A was done first by all subjects because it included a familiarization phase. The remaining three sessions were done in random order. Sessions Twitch A and Twitch B tested for the presence of PAP 4 min after the completion of a 5-RM squat. Twitch A was a control session in which two twitch measurements were made without an intervening 5-RM squat. In Twitch B, twitch measurements were made before and after subjects did a 5-RM squat. At the beginning of Twitch A, the subject was familiarized with the dynamometer used to measure twitch peak torque (PAP). The subject then rested for 10 min by sitting on the twitch-testing dynamometer to ensure that any PAP induced by traveling to the laboratory had dissipated, after which a maximal isometric twitch was evoked. The subject then did five practice CMJs on the force platform. After the last CMJ, the subject rested on the twitch-testing dynamometer for 8 min before a second maximal twitch was evoked. After completion of Twitch A, the 5-RM test for the squat exercise was administered. Twitch B was similar to Twitch A, except that 4 min after the first evoked twitch and five CMJs, the subject did a 5-RM squat. After the 5-RM squat, the subject rested for 4 min on the twitch-testing dynamometer and then the second maximal twitch was evoked.

The second pair of sessions, Jump A and B, tested the effect of a 5-RM squat on the height of CMJs. Jump A was a control session in which the subject did a set of five CMJs, and after an 8-min rest, did a second set of five CMJs. Jump B was the same as Jump A, except that 4 min after the first set of five CMJs, the subject did a 5-RM squat. Four minutes after completion of the 5-RM squat, the subject did a second set of five CMJs.

Statistical analyses

Data were analyzed with a two-factor (between, within) analysis of variance (ANOVA). The between factor was the A versus B sessions, and the within factor was time, i.e., the repeated measures of twitch peak torque and CMJ height in the sessions. When a significant session × time interaction was found, the Holm–Sidak post hoc method was used to determine significant differences between mean values. Pearson product moment correlation was used to assess the relationship between percent change in CMJ height and percent change in PAP. Significance was accepted at $P \leq 0.05$. Means are given in the text with standard deviations (SDs) and in figures with standard errors of the mean (SE).

Results

There was a significant ($P = 0.002$) session × time interaction for peak twitch torque in sessions Twitch A and B. Peak twitch torque increased significantly ($P < 0.05$) 4 min after the 5-RM squat in Twitch B (Fig. 2). The percentage increase, based on the pre and post means, was 10.7%. One subject's first (pre) and second (post) twitches evoked in session Twitch B are shown in Fig. 3. Peak twitch torque did not change significantly in session Twitch A (Fig. 2).

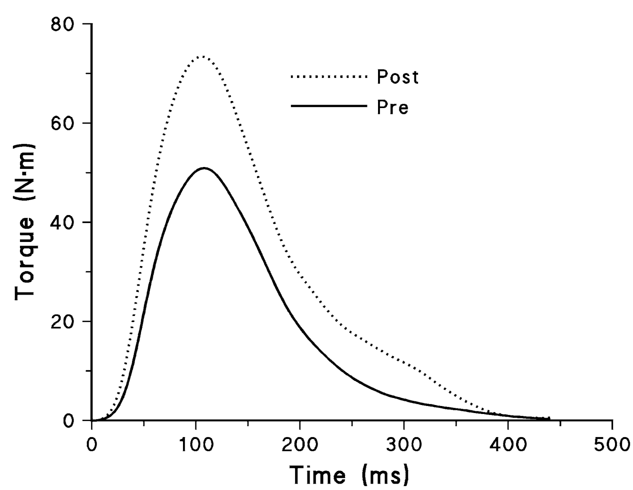

Fig. 3 One subject's evoked twitches during Twitch B. Pre refers to the first baseline twitch. Post refers to the second twitch evoked after a set of five CMJs, a 4-min rest, a 5-RM squat, and another 4-min rest (see Fig. 1). The increased twitch torque pre to post indicates postactivation potentiation (PAP)

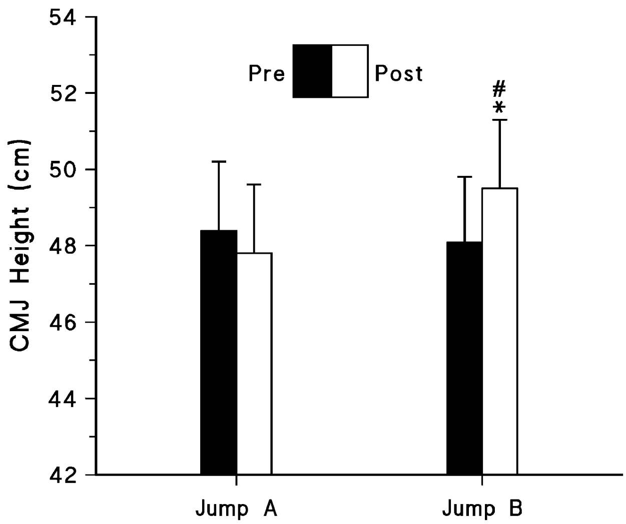

Fig. 4 CMJ height attained in sessions Jump A and B. Pre refers to the first set of five CMJs. Post refers to the second set of five CMJs after either an 8-min rest (Jump A) or 4 min after a 5-RM squat (Jump B) (see Fig. 1). *Significant difference pre to post ($P < 0.05$). #Significant difference from Jump A post ($P < 0.05$)

M-wave amplitude recorded from vastus medialis during the peak twitch torque measurement did not change significantly (time main effect and session × time interaction, $P > 0.05$) in sessions Twitch A and B. In Twitch A, the pre and post values were 11.2 ± 6.2 and 13.3 ± 5.5 mV, respectively. In Twitch B, the pre and post values were 9.1 ± 5.2 and 12.0 ± 6.0 mV, respectively.

There was a significant session × time interaction ($P < 0.001$) for CMJ height in sessions Jump A and B. CMJ height increased significantly ($P < 0.05$) 4 min after the 5-RM squat in session Jump B (Fig. 4). The percentage increase, based on the pre and post means, was 2.9%. CMJ height did not change significantly in session Jump A (Fig. 4). Among the subjects, the correlation between the percentage increases in twitch torque (PAP) and CMJ height was not significant ($r = 0.24$, $P > 0.05$).

Discussion

In agreement with some (McCann and Flanagan 2010; Weber et al. 2008; Young et al. 1998) but not all previous studies (Jensen and Ebben 2003; Jones and Lees 2003; Khamoui et al. 2009; Scott and Docherty 2004), we found that CMJ height increased significantly 4 min after a 5-RM squat. The observed 2.9% increase in CMJ height was similar to the previous reports showing a positive effect, and represents a notable enhancement of performance that could, e.g., affect ranking in a jump competition.

The present study is the first to test the assumption that a set of weight lifting exercise induces PAP, indicated as potentiation of twitch torque. In session Twitch B, a 5-RM squat induced the PAP mechanism, which based on the potentiated twitch response (PAP) persisted for at least 4 min and was therefore likely present when CMJs were performed 4 min after the 5-RM squat in session Jump B. PAP in quadriceps averaged 10.7% 4 min after the 5-RM squat, a magnitude within the range reported in quadriceps 4 min after a 10-s MVC (Folland et al. 2008; Hamada et al. 2000; Houston and Grange 1990; Rassier and Herzog 2001).

The mechanism of PAP increases rate of force development (Baudry and Duchateau 2007a) and the shortening velocity attained under load (Baudry and Duchateau 2007b); therefore, PAP may have contributed to the increase in CMJ height in the present study. However, among the subjects, the correlation between the magnitude of PAP and the percentage increase in CMJ height was not significant. One interpretation of the non-significant correlation is that PAP made no contribution to the increase in CMJ height, but the following should be considered. First, knee extensors (quadriceps), hip extensors, and ankle plantar flexors are all active in a 5-RM squat and contribute to CMJ performance. We measured PAP only in the knee extensors. It is possible that across subjects the 5-RM induced a varying extent of PAP in the three muscle groups; furthermore, there may have been a cumulative effect of PAP across the muscle groups. Secondly, PAP and changes in CMJ height were measured in separate sessions conducted at least 3 days apart. In each subject, the magnitude of PAP may have differed between session Twitch B, when PAP was measured, and Jump B when CMJ height but not PAP was not measured. Thirdly, other factors in addition to PAP may have contributed to the increase in CMJ height. For example, the 5-RM squat likely increased muscle temperature, which is known to increase jump height (Bergh and Ekblom 1979). Given these considerations, the non-significant correlation between PAP in quadriceps and the percentage increase in CMJ height is perhaps not surprising, and the lack of correlation does not warrant dismissal of induced PAP as a potential contributor to enhanced jump performance.

The mechanism of PAP, myosin regulatory light chain phosphorylation, is most pronounced immediately after muscle activity, and then declines (Houston and Grange 1990; Houston et al. 1985; Vandenboom et al. 1995). In response to relatively brief muscle activity, such as a 10-s MVC of the knee extensor muscles, the manifestation of the PAP mechanism, twitch potentiation, is also greatest immediately after the MVC and then declines exponentially (Folland et al. 2008; Hamada et al. 2000; Houston and Grange 1990; Rassier and Herzog 2001). In contrast, following relatively prolonged activity such as a 60-s MVC, the mechanism of PAP is most pronounced immediately after the MVC, but twitch force is initially depressed due to fatigue and is not maximally potentiated until after 4 min of recovery at a time when the PAP mechanism is in decline (Houston and Grange 1990). Thus, the twitch response reflects not only the PAP mechanism but also fatigue (Rassier and Herzog 2001; Sale 2002). Furthermore, even when twitch potentiation is at or near its highest level soon after muscle activity, maximal contraction performance may be impaired as a result of fatigue (Gossen and Sale 2000; Hamada et al. 2003). Prior weight lifting exercise has depressed isometric rate of force development for 10 min (Gilbert and Lees 2005). A 5-RM squat takes about 30 s to complete and therefore likely induced considerable fatigue in addition to activating the PAP mechanism. Recovery from a 5-RM squat, defined as being able to complete a second 5-RM set, would take a minimum of 4–5 min (Willardson and Burkett 2005). Moreover, previous research has shown that after very short intervals (10–30 s) following weight lifting exercise, jump performance is depressed rather than enhanced (Comyns et al. 2006; Jensen and Ebben 2003; Kilduff et al. 2007). On this basis, we and previous investigators (McCann and Flanagan 2010; Weber et al. 2008; Young et al. 1998) chose a rest interval of 4 min between the end of the 5-RM squat and performance of jumps. Twitch potentiation may have been greater at intervals shorter than 4 min after the 5-RM squat, but CMJ height would likely have been suppressed due to fatigue (Comyns et al. 2006; Jensen and Ebben 2003; Kilduff et al. 2007). Nevertheless, in future studies, inclusion of measures of both and PAP at rest intervals shorter and greater than 4 min could be tested to determine the optimal rest interval between weight lifting exercise and dynamic performance. Furthermore, the optimal rest interval may vary based on subject characteristics such as state of training (Jo et al. 2010).

Muscle activity may also induce potentiation of the muscle compound action potential (M-wave) that develops during and persists after activity (Hamada et al. 2000; Hicks et al. 1989). The mechanism of potentiation is likely hyperpolarization of muscle fiber membranes resulting from increased Na^{+}–K^{+} pump activity (McComas et al. 1994). The time course of M-wave potentiation often differs from that of twitch potentiation (Hamada et al. 2003; McComas et al. 1994), suggesting that the former has little effect on the latter. In the present study, M-wave amplitude increased in both sessions Twitch A and B, more so in Twitch B perhaps because this session included more activity (both CMJs and 5-RM squat) between pre and post M-wave measurements. However, the changes in M-wave amplitude were not statistically significant, possibly partly the result of the lower reliability of the M-wave measurement ($R = 0.78$) compared to that of the twitch torque ($R = 0.86$) and CMJ ($R = 0.96$) measurements. The lower reliability of the M-wave measurement may be related to sessions Twitch A and B having been done on different days. Despite best efforts, there was likely some variation in the placement of the recording electrodes in the two sessions. Within sessions Twitch A and B, there may have been slight movement of the recording electrodes between the pre and post M-wave measurements, as a result of performing the CMJs (Twitch A) and the CMJs plus 5-RM squat (Twitch B). Electrode movement may have increased the variability in the M-wave measurements.

Conclusions

PAP was present and CMJ height was increased 4 min after a 5-RM squat. Since PAP is known to increase isometric rate of force development and the shortening velocity attained under load, PAP induced by the 5-RM squat may have contributed to the increase in CMJ height.

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