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Volume, intensity, and timing of muscle power potentiation are variable

Anis Chaouachi, Nick Poulos, Fathi Abed, Olfa Turki, Matt Brughelli, Eric J. Drinkwater, and David G. Behm

Abstract: Whereas muscle potentiation is consistently demonstrated with evoked contractile properties, the potentiation of functional and physiological measures is inconsistent. The objective was to compare a variety of conditioning stimuli volumes and intensities over a 15-min recovery period. Twelve volleyball players were subjected to conditioning stimuli that included 10 repetitions of half squats with 70% of 1-repetition maximum (RM) (10 × 70), 5 × 70, 5 × 85, 3 × 85, 3 × 90, 1 × 90, and control. Jump height, power, velocity, and force were measured at baseline, 1, 3, 5, 10, and 15 min. Data were analysed with a 2-way repeated measure ANOVA and magnitude-based inferences. The ANOVA indicated significant decreases in jump height, power, and velocity during recovery. This should not be interpreted that no potentiation occurred. Each dependent variable reached a peak at a slightly different time: peak jump height (2.8 ± 2.3 min), mean power (3.6 ± 3.01 min), peak power (2.5 ± 1.8 min), and peak velocity (2.5 ± 1.8 min). Magnitude-based inference revealed that both the 5 × 70 and 3 × 85 protocol elicited changes that exceeded 75% likelihood of exceeding the smallest worthwhile change (SWC) for peak power and velocity. The 10 × 70 and the 5 × 70 had a substantial likelihood of potentiating peak velocity and mean power above the SWC, respectively. Magnitude-based inferences revealed that while no protocol had a substantial likelihood of potentiating the peak vertical jump, the 5 × 70 had the most consistent substantial likelihood of increasing the peak of most dependent variables. We were unable to consistently predict if these peaks occurred at 1, 3, or 5 min poststimulation, though declines after 5 min seems probable.

Résumé : On démontre systématiquement la potentialisation musculaire lors de l'évaluation des propriétés contractiles évoquées; en contrepartie, la potentialisation des variables fonctionnelles et physiologiques est irrégulière. Cette étude se propose de comparer au cours d'une période de récupération de 15 min les réponses à divers stimuli conditionnants sur le plan de la quantité et de l'intensité. On soumet 12 joueurs de volleyball à des stimuli conditionnants constitués de 10 demi-accroupissements avec une charge correspondant à 70 % du maximum (RM) (10 × 70), puis 5 × 70, 5 × 85, 3 × 85, 3 × 90, 1 × 90 et le contrôle. Au début et 1, 3, 5, 10 et 15 min après la série de répétitions, on évalue la puissance, la vélocité la force et la hauteur de saut. On étudie les données au moyen d'une analyse de variance à deux facteurs et des inférences basées sur l'ampleur des différences. L'analyse de variance révèle des diminutions significatives de la puissance, de la vélocité et de la hauteur de saut au cours de la récupération. Cela ne signifie pas qu'aucune potentialisation ne s'est manifestée. Chaque variable dépendante atteint un sommet à des moments différents : hauteur de saut de pointe (2,8 ± 2,3 min), puissance moyenne (3,6 ± 3,01 min), puissance de pointe (2,5 ± 1,8 min), vélocité de pointe (2,5 ± 1,8 min). L'inférence fondée sur l'ampleur des différences révèle que les protocoles 5 × 70 et 3 × 85 suscitent des modifications dépassant 75 % de la probabilité de la plus petite modification utile (SWC) de la puissance de pointe et de la vélocité. Les protocoles 10 × 70 et 5 × 70 révèlent une probabilité importante de potentialisation de la vélocité de pointe et de la puissance moyenne supérieure à SWC respectivement. Même si aucun des protocoles ne présente de probabilité substantielle de potentialisation de la hauteur de pointe du saut vertical, le protocole 5 × 70 s'avère, d'après les inférences fondées sur l'ampleur des différences, le meilleur pour améliorer la valeur de pointe de la majorité des variables dépendantes. Nous n'avons pu prédire de façon constante si les pointes se manifestent à la première, troisième ou cinquième minute suivant les stimuli conditionnants; néanmoins, la diminution des valeurs après la cinquième minute s'avère probable.

Mots-clés : potentialisation postconditionnante, inférences fondées sur l'ampleur des différences, force, vélocité, récupération.

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Introduction

Postactivation potentiation (PAP) can be defined as an enhancement or increase in force (Baudry and Duchateau 2004; Grange and Houston 1991; Houston and Grange 1990) and rate of force development (Baudry and Duchateau 2004; Sale 2002; Vandenboom et al. 1995) following submaximal or maximal contractions. The potentiation of evoked contractions is consistently reported in the literature (Baudry and Duchateau 2004; Grange et al. 1993; Grange and Houston 1991; Houston and Grange 1990; Stuart et al. 1988; Vandenboom et al. 1995). However, the role of potentiation in enhancing functional performance is not as consistent in the literature (DeRenne 2010; Robbins 2005; Tillin and Bishop 2009).

Table 1 illustrates the diversity of conditioning stimuli used to induce potentiation, post-intervention testing times, and dependent variables in 22 articles that reported improved performance. There is a similar degree of diversity in Table 2 which highlights 14 articles that reported no change or decreases in subsequent performance. Upon reflecting on both tables, there does not seem to be an obvious pattern of potentiating-inducing interventions, recovery testing times, or measures that would determine the ability to enhance functional athletic performance. Tillin and Bishop (2009) indicated in a review that the PAP-fatigue relationship can be affected by the conditioning or potentiating-inducing stimulus' volume and intensity, recovery period, type of conditioning, and subsequent contractions or activity and subject characteristics. Tables 1 and 2 illustrate the difficulty in assessing the appropriate volume and intensity of the potentiating stimulus as well as the recovery time. Many articles investigate only 1 (Baker 2003; Batista et al. 2007; Baudry and Duchateau 2007; Bevan et al. 2010; Chatzopoulos et al. 2007; Chiu et al. 2003; Duthie et al. 2002; Ebben et al. 2000; Etnyre and Kinugasa 2002; Hrysomallis and Kidgell 2001; Jensen and Ebben 2003; Linder et al. 2010; Matthews et al. 2010; Mitchell and Sale 2011; Miyamoto et al. 2011; Robbins and Docherty 2005; Smith and Fry 2007; Young et al. 1998) or 2 interventions (Boullosa and Tuimil 2009; Burkett et al. 2005; El Hage et al. 2011; Esformes et al. 2010; Hanson et al. 2007; Kilduff et al. 2007; Koch et al. 2003; Markovic et al. 2008; McBride et al. 2005; McCann and Flanagan 2010; Rixon et al. 2007) with a variety of dependent variables and recovery times, making it difficult to evaluate an optimal potentiating stimulus. Brandenburg (2005) and Chattong et al. (2010) examined a wider range of potentiating stimuli (3 and 4, respectively) but only examined recovery at 4 and 2 min, respectively. There are very few studies (2 studies in Table 1) that investigate multiple potentiating contractions with repeated testing over a prolonged period (i.e., 10 min postcontraction) (Iglesias-Soler et al. 2011; Smilios et al. 2005). Since it is difficult to compare between disparate studies that utilize different volumes and intensities, with varying contraction types, populations, dependent variables, and recovery testing times, it is necessary to compare a variety of potentiating stimuli that can provide matching volumes with dissimilar intensities as well as matching intensities with dissimilar volumes. In this manner, it may be possible to differentiate whether a particular volume or intensity or range of volumes and intensities of contractions provide functional benefits over a specified period.

Whereas PAP has a predominant biochemical mechanism involving myosin regulatory light chain phosphorylation (Grange et al. 1993; Houston et al. 1985; Houston and Grange 1990; Vandenboom et al. 1995; Vandenboom and Houston 1996), the potentiation of functional athletic performance can also involve the interplay of fatigue mechanisms (Alway et al. 1987; Behm 2004; Grange and Houston 1991), neural potentiation (Anderson and Behm 2004; Sale 2002), muscle stiffness (Sinkjær et al. 1992), and muscle architecture (Mahlfeld et al. 2004). PAP has been reported to have lower phosphorylation levels and perhaps a minimum threshold around 10 min (Houston and Grange 1990). Muscle stiffness because of residual cross-bridge attachments (Shorten 1987) can contribute to the facilitation or potentiation of contractions and has been shown to persist for 90 min following 5 repetitions of 8-s contract-relax actions (Toft et al. 1989). Following 3 maximal voluntary contractions (MVCs), Mahlfeld et al. (2004) reported a significant change in the pennation angle for up to 6 min as compared with the precontraction and immediately postcontraction measures (0–2 min). This modest modification of the pennation angle (<2°) would allow muscle forces to be transmitted more directly to the tendon. Gullich and Schmidtbleicher (1996) indicated that the short-term increase in explosive force following MVCs could be partially attributed to improved neuromuscular activation as evidenced by increased Hoffman (H) reflexes (indicative of increased afferent excitability of the motoneuron (Enoka et al. 1980)). The potentiation of H-reflexes was significant between 4–11 min following the contractions albeit with considerable interindividual variation. Thenar muscle contractions of 5–30 s provoked increased motor evoked potentials for a period of 60 s after the submaximal contractions indicating enhanced supraspinal excitability (Balbi et al. 2002). Hence, with the interplay and variability of these contributing factors to muscle potentiation, it would be important to test functional measures repeatedly over a prolonged recovery period.

Thus it was the objective of this study to examine the effect of a variety of volumes and intensities of dynamic contractions on subsequent functional muscle performance repeatedly over an extended recovery period of 15 min.

Materials and methods

Subjects

Twelve elite male volleyball players (aged 22 ± 2 years, height 192 ± 8.3 cm, mass 84.1 ± 6.6 kg) volunteered to participate in this study during the early phase of the post-competitive volleyball season. All players were starters in their senior teams participating in the Tunisian national volleyball championship, and had played volleyball continuously for more than 6 years. Before commencing the study, players had a physical examination by a physician in the National Centre of Medicine and Science in Sports of Tunis (CNMSS) and each was cleared of any medical disorders that might limit full participation in the investigation. None of the subjects were involved in a structured resistance or other training program during the time of testing. No players were taking exogenous anabolic-androgenic steroids or other drugs or substances expected to affect physical performance or hormonal balance during this study. All the subjects were informed

Table 1. A sample of published articles employing conditioning stimuli (isometric and dynamic contractions) to induce potentiation of functional activities.

Author	*n* (activity status)	Intervention	Recovery time	Results
Etnyre and Kinugasa 2002	12 (NR)	3-s knee extension MVC	0.5, 1, 2, 3 s	Improved reaction, processing, muscle contraction time
Miyamoto et al. 2011	9 (RA)	10-s MVC	5 s, 1, 2, 3, 4, and 5 min	↑ Peak twitch ↑ Isokinetic concentric torque
Baudry and Duchateau 2007	10 (NR)	6-s MVC of thumb adductors	5s, 1, 2, 3, 4, 5, and 10 min	↑ Rate of force development for twitch, tetanus and ballistic contraction Twitch ↑ @ 5 s, ballistic @ 1 min
Burkett et al. 2005	29 (TR)	5 × 75% of CMJ height 5 × weighted CMJ (10% body weight)	2 min	↑ CMJ with weighted CMJ intervention
Chattong et al. 2010	20 (TR)	Jumps onto a box with 5%, 10%, 15%, 20% body weight	2 min	↑ VJ height
Boullosa and Tuimil 2009	12 (TR)	UMTT vs. maximum aerobic speed	2, 7 min	↑ CMJ for both conditions @ 2 min ↑ CMJ height for 7 min with UMTT
Rixon et al. 2007	30 (RA)	3 × 3-s MVC squat vs. 2 × 50% of 3RM dynamic squat;1 × 85% of 3RM dynamic squat; 3 × 90% of 3RM dynamic squat	3 min	↑ CMJ for both conditions MVC > dynamic leg press
Markovic et al. 2008	23 (RA)	1 set × 60% of 1RM bench press vs. 2 sets × 3 × 90% of 1RM bench press	3 min	↑ 4 kg medicine ball throw No effect with 0.55-kg medicine ball throw
Chatzopoulos et al. 2007	15 (TR)	10 × 90% of 1RM squats	3, 5 min	↑ 10–30 sprint speed after 5 min No effect @ 3 min
Gullich and Schmidtbleicher 1996	36 (TR)	2 sets × 1 × >100% 1RM bench press (BP) 3 sets × 1 × 100% 1RM BP; 1 set × 3 × 90% 1RM BP; 5 sets × 5 × >100% 1RM BP; 1 set × 1 × 100% 1RM BP; 3 × 5-s plantar flexor MVC	3, 5 min	↑ Explosive bench press force ↑ VJ for both times but greatest at 5 min
Baker 2007	16 (TR)	6 × 65% of 1RM bench press	3 min	↑ BP throws with 50 kg
McBride et al. 2005	15 (TR)	3 × 90% of 1RM squat vs. 3 × 30% of 1RM loaded CMJ	4 min	↑ Sprint speed following squats Loaded CMJ had no effect
Matthews et al. 2010	11 (TR)	10-s resisted ice skating	4 min	↑ in 25 m skating sprint speed
Mitchell and Sale 2011	11 (TR)	5 × 5RM squats	4 min	↑ CMJ height and peak twitch
Young et al. 1998	10 (TR)	5 × 5RM squat	4 min	↑ Loaded CMJ
McCann and Flanagan 2010	16 (TR)	5 × 5RM squat vs. 5 × 5RM hang clean	4, 5 min	↑ VJ height No difference between interventions or times
Iglesias-Soler et al. 2011	14 (RA)	7 s @ 10% MVC; 7-s MVC; 10 s @ 10% MVC; 10-s MVC	5s, 4 and 10 min	↑ only with 10-s MVC @ 4 min
Batista et al. 2007	10 (RA)	10 knee extensions @ 60% MVC every 30 s	4, 6, 8, 10, 12 min	↑ Isokinetic peak torque persisted for 12 min

Table 1 (*concluded*).

Author	*n* (activity status)	Intervention	Recovery time	Results
Esformes et al. 2010	13 (TR)	3 × 3RM squats vs. 3 × 24 plyometric bounds and hops	5 min	↑ CMJ height for single but not repeated tests
Smilios et al. 2005	10 (TR)	3 sets × 5 × 30% of 1RM half squats; 3 sets × 5 × 30% of 1RM squat jumps; 3 sets × 5 × 60% of 1RM half squats; 3 sets × 5 × 60% of 1RM squat jumps	1, 5, 10 min after each set and 5 and 10 min after the 3 sets	↑ CMJ with both low and moderate loads
Kilduff et al. 2007	23 (TR)	3 × 3RM squat; 3 × 3RM bench press	15s, 4, 8, 12, 16, 20 min	↓ in CMJ and bench press throws @ 15 s ↑ @ 8–12 min
Linder et al. 2010	12 (TR)	4 × 4RM squat	9 min	↑ Sprint speed

Note: BP, bench press; CMJ, countermovement jump; DJ, drop jump; MVC, maximal voluntary contraction; NR, activity status was not reported; RA, recreational athletes (reported to be moderately active but not participating in a structured or consistent training program); RM, repetition maximum; TR, trained (either the subjects have been reported to have resistance trained at least twice a week for 1 year or are competitive athletes); UMTT, University of Montreal Track Test; VJ, vertical jump.

of the methods and risks of the study and gave their informed consent and volunteered to participate in the study, which had the approval of the ethics committee of CNMSS, Tunis, Tunisia.

Procedures

All tests and measurements were conducted in the laboratory of CNMSS in Tunis, Tunisia. One week prior to the commencement of the study, all subjects participated in an orientation session to become familiar with the testing procedure. They were coached on proper back half-squat lifting technique using the bar and were familiarized with the force platform for the vertical jump test. Following this familiarization session, subjects were required to attend the laboratory on 8 separate occasions. The objective of the first session was to determine the subjects 3-repetitions maximum (RM) on the back half-squat, with 3RM defined as a load that caused failure on the fourth repetition without loss of proper technique. Based on this testing day, the value of 1RM was estimated for each subject. According to the percentage 1RM-repetition relationship outlined by Baechle (2000), the load for 3 repetitions is 93% of 1RM. Consequently, the 3RM value was divided by 0.93 to attain a 1RM estimate. The resistance for the different conditioning stimuli of the PAP protocols was then calculated from each subject's 1RM load.

After the first visit, subjects returned to the laboratory on 7 separate occasions for the experimental sessions. Sessions 2–8 were performed over a 3-week period, and all involved the same procedure. Each session began with the subjects performing a standardized dynamic warm-up (Moir et al. 2009) comprising light intensity jogging and dynamic exercises: 10 body weight squats, lunge walks for 15 m, butt kicks for 15 m, and 5 countermovement jumps (CMJ). These exercises were performed twice, and no static stretches were performed during the warm-up. A 3-min rest interval was provided after the end of the warm-up. After this, the subjects performed 3 maximal CMJ, separated by a 2-min rest, and the best of the 3 jumps was used as baseline data. The subjects then performed 1 of the PAP protocols. The conditioning protocols were 10 repetitions of half squats with 70% of 1 repetition maximum (10 × 70), 5 × 70%1RM (5 × 70), 5 × 85%1RM (5 × 85), 3 × 85%1RM (3 × 85), 3 × 90%1RM (3 × 90), 1 × 90%1RM (1 × 90), and the control protocol. Each conditioning stimulus was applied in a counterbalanced, randomized order on separate days. Experienced spotters were present at all times to ensure safety of subjects and appropriate exercise technique execution. Finally, during the recovery interval following the preload stimulus, the participant was required to perform another 5 blocks of 1 to 2 explosive CMJ at the following time points: 1, 2, 3, 5, 10, and 15 min after the potentiating protocol. Testing took place on the same time of day for each subject, and with a minimum of 72 h intervening between testing sessions. Subjects refrained from any strenuous activities, resistance, or plyometric training at least 48 h before each testing session.

3RM procedures

Isoinertial strength assessment

The subjects' 3RM was tested using the procedure outlined by the National Strength and Conditioning Association (Baker and Nance 1999; Cronin and Hansen 2005). Before the start of the strength-testing session, all subjects underwent a standardized general warm-up that comprised light intensity jogging for 5 min, followed by a series of dynamic movements with an emphasis on warming up the musculature associated with the squat. Subjects then performed a weights-specific warm-up involving 8 repetitions at 50% 1RM, 4 repetitions at 70% 1RM, and finally 2 repetitions at 80% of 1RM, with 3-min intervals between them. Each subject used their estimated 1RM as a guide. After the final warm-up set, subjects attempted 3 repetitions of a set load (3RM), and if successful, the lifting weight was increased until the subject could not lift the weight through the full range of motion. A 5-min rest was imposed between all attempts. The 3RM was determined after 3–4 attempts in all subjects. The half-squat movement was carried out according to the International Powerlifting Federation rules (International Powerlifting Federation 2002). Each subject was required to descend to the ''parallel'' position where the greater trochanter of the femur

Table 2. A sample of published articles employing conditioning stimuli (isometric and dynamic contractions) which failed to induce potentiation of functional activities.

Author	*n* (activity status)	Intervention	Recovery time	Results
Jensen and Ebben 2003	21 (TR)	5 × 5RM squats	10 s, 1, 2, 3, 4 min	Jump ↓ @ 10 s No effect at 1–4 min
Ebben et al. 2000	10 (TR)	3 × 5RM Bench press	3 min	No effect on medicine ball power drops (30% of 1RM)
Hrysomallis and Kidgell 2001	12 (TR)	5 × 5RM bench press	3 min	No effect on explosive push-ups
El Hage et al. 2011	17 (RA)	3 × 85% of 1RM squats; 1 × 100% squat	Post, 2, 4 min	↓ DJ height
Robbins and Docherty 2005	16 (RA)	3 × 7 s MVC squat	4 min	No effect
Brandenburg 2005	8 (TR)	5 × 5RM bench press; 5 × 75% of 5RM bench press; 5 × 50% of 5RM bench press	4 min	No change in bench press throws
Till and Cooke 2009	12 (TR)	5 × 5RM dead lift; 5 tuck jumps; 3 × 3 MVC knee extensions	Sprints @ 4,5,6 min; VJ @ 7,8.9 min	No effect on sprints or VJ height
Bevan et al. 2010	16 (TR)	3 × 91% of 1RM squat	4, 8, 12, 16 min	No main effect for time on sprint performance Sig ↑ with individual performances
Duthie et al. 2002	11 (TR)	3 sets × 3RM squats	5 min	No effect
Hanson et al. 2007	30 (TR)	8 × 40% of 1RM squat; 4 × 80% of 1RM squat	5 min	No effect on VJ
Khamoui et al. 2009	16 (TR)	2–5 × 85% of 1RM squat	5 min	No effect on VJ
Chiu et al. 2003	24 (TR, RA)	5 × 90% of 1RM squat	5 and 18.5 min	No overall effect on jump squats but athletes had greater % ↑
Smith and Fry 2007	11 (RA)	10-s MVC knee extension	7 min	No effect on explosive 70% of 1RM knee extension
Koch et al. 2003	32 (TR, RA)	1 set × 3 × speed squats @ 20, 30, 40% of 1RM; 1 set × 3 × squats @ 50, 75, 89,5% of 1RM	Immediately post, 15 min	No effect on broad jump

Note: DJ, drop jump; MVC, maximal voluntary contraction; RA, recreational athletes (reported to be moderately active but not participating in a structured or consistent training program); RM, repetition maximum; TR, trained (either the subjects have been reported to have resistance trained at least twice a week for 1 year or are competitive athletes); VJ, vertical jump.

was aligned with the knee (a line between the lateral epicondyle of the femur and the greater trochanter was approximately parallel to the floor) and ascended until full knee and hip extension. Squat depth was visually assessed by a certified strength and conditioning specialist (second investigator). The investigator was located lateral to the subject and gave a verbal signal ''up'' once the athlete had reached the appropriate depth. Rest periods between trials were 5 min in length. A complete range of motion and proper technique was required for each successful 3RM trial. All subjects had experience with strength training and the back half-squat exercise for at least 2 years before the study.

Jump testing

Vertical jump performance was assessed on a Quattro Jump portable piezoelectric force plate (Kisler Instrument AG, Winterthur, Switzerland) at a sampling rate of 500 Hz. Players performed a CMJ according to the protocol described by Bosco et al. (1983). Subjects were asked to keep their hands on their hips throughout the entire jump to minimize lateral and horizontal displacement during performance, to prevent any influence of arm movements on the vertical jumps, and to avoid coordination as a confounding variable in the assessment of the leg extensors neuromuscular performance (Chaouachi et al. 2009). Players were asked to jump as high as possible and the greatest jump height and associated maximal velocity before take-off, maximal force before the take-off, and peak power was used for analysis. Jump height was determined as the center of mass displacement, calculated from the recorded force and body mass. All variables were determined from the force curves collected from the various vertical jumps using the feedback option of the Quattro Jump Software, version 1.0.9.2 (Kistler software, Switzerland). Body mass was first measured on the force plate, which was calibrated prior to each measurement. Four piezoelectric force sensors in the Quattro Jump force plate measured and relayed vertical force to a laptop. The system software contains mathematical formulae to then calculate acceleration, velocity, displacement, and power. The athlete's body weight was subtracted from the force-time curves. The force-time curves were then integrated with respect to time to obtain the vertical take-off impulse. Vertical takeoff velocity, vertical jump displacement, and power were then calculated as

$$v = I/m$$
$$h = v2/2g$$
$$P = Fv$$

where v is vertical velocity at take-off (m·s^{-1}), I is vertical take-off impulse (N·s), m is body mass (kg), h is peak displacement of the centre of gravity above the height of take-off (m), g is gravitational constant of 9.81 (m·s^{-2}), P is power (W), and F is force (N). Jump power was calculated for the concentric phase. Peak force was defined as the highest vertical force reading for the take-off movement. Peak power and peak velocities were determined as the highest values during the concentric phase of the jump. All force and power values were normalized to the athlete's body weight (BW and W·kg^{-1}), respectively. Reliability of the CMJ test has been shown in previous studies from our laboratory to be very high (Chaouachi et al. 2009 2010).

Statistical analysis

A repeated-measures ANOVA was used to compare a pre-intervention (baseline) jump to jumps performed at 1, 3, 5, 10, and 15 min after the intervention for each dependent variable. There were therefore 7 conditions compared across 6 time points for each dependent variable. $p$values in the main effect for time as well as for condition × time interactions were considered statistically significant at <0.05. Repeated measures ANOVAs were calculated using Predictive Analytics SoftWare (version 17.0.2). This analysis was included to illustrate that the method of null hypothesis significance testing may not necessarily be appropriate for this type of experiment (Drinkwater et al. 2008).

Further analysis involved isolating the peak of each dependent variable and comparing it with the baseline, regardless of at which time point the peak occurred. Within subject contrasts were conducted between the baseline and peak for each dependent variable. From the resulting p value, mean difference between comparisons, and total standard deviation of the baseline and peak data, a Cohen's d, smallest worthwhile change (SWC), and likelihood of clinical meaningfulness were calculated (Liow and Hopkins 2003). The Cohen's d is calculated from the mean change divided by the standard deviation of the data; thresholds for qualitative descriptors of Cohen's d were set at <0.20, "trivial"; 0.20 to 0.49: "small", 0.50 to 0.79, "moderate": and >0.80, "large" (Cohen 1988, p.25). The smallest change to be considered worthwhile (SWC) was thus calculated from 0.20 of the standard deviation of the data. The threshold of a clinical meaningful effect was set at 75% (Liow and Hopkins 2003).

Differences in time to peak for each dependent variable were assessed by dependent t tests and expressed as a mean with Cohen's d. Descriptive statistics, p values, 95% confidence limits, and Cohen's d for the within-subject contrasts were calculated by custom-written Excel spreadsheets (Microsoft Office 2007). Magnitude-based inferences were then calculated using a second custom written Excel spreadsheet (Hopkins 2007).

Pearson Product Moment correlations were used to assess the relationship between 1RM and time to peak as well as the relationship between 1RM and amount of change between the baseline and peak. Thresholds for interpreting correlations were 0.1, 0.3, and 0.5 for "small", "moderate", and "large", respectively (Cohen 1988).

Results

Analysis with repeated measures ANOVA

Jump height

There was a significant main effect for time ($p < 0.01$). Across all time points, the time points significantly different to baseline (52.9 ± 4.6 cm) were the decreases at 10 min (51.5 ± 4.85 cm, $p < 0.01$) and 15 min (50.9 ± 4.8 cm, $p < 0.01$). There were no significant condition × time interactions ($p = 0.87$).

Peak power

There was a significant main effect for time ($p < 0.01$). With time, peak power showed a steady, significant decline from baseline (58.0 ± 7.01 W·kg^{-1}) to 5 min (56.7 ± 6.96 W·kg^{-1}, $p < 0.01$), 10 min (55.7 ± 6.6 W·kg^{-1}, $p < 0.01$), and 15 min (54.8 ± 6.5 W·kg^{-1}, $p < 0.01$). There were no significant condition × time interactions ($p = 0.228$).

Force

There was no significant change in force across all time points ($p = 0.317$). There were no significant condition × time interactions ($p = 0.347$).

Velocity

There was a significant main effect for time ($p < 0.01$). There was a significant decrement in velocity between baseline (2.95 ± 0.14 m·s^{-1}) and 10 min (2.91 ± 0.14 m·s^{-1}, $p < 0.01$) and 15 min (2.88 ± 0.15 m·s^{-1}, $p < 0.01$). There were no significant condition × time interactions ($p = 0.429$).

Mean power

There was a significant main effect for time ($p < 0.01$). There was a significant decrease between baseline (31.74 ± 4.68 W·kg^{-1}) and 5 min (31.11 ± 4.29 W·kg^{-1}), 10 min (30.58 ± 4.61 W·kg^{-1}), and 15 min (30.22 ± 4.38 W·kg^{-1}) (all $p < 0.01$). There were no significant condition × time interactions ($p = 0.637$).

Analysis of peaks data

Time to peak

Differences in time to peak jump height (2.83 ± 2.32 min), mean power (3.62 ± 3.01 min), peak power (2.57 ± 1.88 min), and peak velocity (2.57 ± 1.81 min) were all trivial or small (i.e., d < 0.50). This is to say that all of these dependent variables peaked at a similar time of 1, 3, or 5 min. All comparisons with peak force (6.57 ± 5.33 min) were large (d > 0.80), which is to say the peak force reached its peak substantially later than the other dependent variables.

There were no meaningful correlations between 1RM and the time of peak potentiation or the amount of potentiation that was experienced (r = –0.08 to 0.12). Peak power at baseline was also poorly correlated with the amount or timing of the peak (–0.27 to 0.07). There were also no meaningful correlations between time to peak and the amount of potentiation (r = –0.21 to 0.03).

Pearson Product Moment

There were no substantial correlations between 1RM and time to peak (r = –0.02 to 0.12) of any dependent variable assessed or the relationship between 1RM and amount of change (r = –0.07 to 0.12) between the baseline and peak jump.

Magnitude-based Inferences

The peak of jump height was unaffected by any of the stimulus protocols with no protocol eliciting a 75% likelihood of exceeding the SWC from the baseline, even when all protocols were combined (Table 3).

For peak power, both the 5 × 70 and 3 × 85 protocol elicited changes that exceed 75% likelihood of exceeding the SWC (89% and 80%, respectively, Table 4). The 5 × 70 protocol also had an 80% likelihood of exceeding the SWC in mean power (Table 4). Neither peak nor mean power were substantially increased when all independent variables were pooled (>75% likelihood of the observed difference being trivial).

The peak force was substantially increased above the SWC in the 10 × 70 protocol (91% likely), 3 × 85 (92% likely) and 3 × 90 (89% likely) protocols as was the control condition (99% likely). There was also a pooled influence of all protocols (95% likely, Table 5).

The 10 × 70, 5 × 70, and 3 × 85 protocols substantially increase peak velocity above the SWD (0.034 $m \cdot s^{-1}$). The improvements were 75%, 77%, and 87% likely, respectively (Table 5)

Discussion

The most important finding of the present study was the interindividual variations in the potentiation of mean and peak power and peak velocity. Most dependent variables peaked at 1, 3, or 5 min, though this peak was often not greater than the SWC. Overall, the 5 × 70 and 3 × 85 protocols presented the most consistent substantial likelihood (i. e., >75%) of increasing the peak of most dependent variables (i.e., peak power and velocity). However, there was sufficient inconsistency in the timing of the peaks that "statistical significance" was lost in the repeated measures ANOVA aside from the decrement between baseline and the 10-min and 15-min time points. Table 6 provides a sample of the varying time points when force potentiation was achieved for each individual. The use of only a traditional ANOVA with an α of 0.05 led to the conclusion that the intervention protocols provided no evidence of potentiation and in fact led only to fatigue effects. The ANOVA indicated that jump height and velocity experienced decrements at 10 and 15 min of recovery while mean and peak power were impaired at 5, 10, and 15 min of recovery. However, the statistical limitation was that the variability in the timing of the potentiation could not be detected by an ANOVA.

Alternatively, the data of the current study were also analysed in a way that reflects the likelihood of the observed effect exceeding the SWC (i.e., 20% of the between-subject standard deviation). Analysing results in this way firstly reflects that a result that is "statistically significant" may still have a low likelihood of playing a meaningful role. For example, while the pooled effect of having a stimulus activity before vertical jumping significantly increases vertical jump ($p < 0.01$), the observed mean increase is so small (0.7 cm) that it seems unlikely (<10%) to have impacted to any meaningful degree in performance. Conversely, an effect may have a high likelihood of having a meaningful effect on performance though not reach statistical significance. For example, the 1.89 $W \cdot kg^{-1}$ peak power increase elicited by the 3 × 85 protocol did not reach statistical significance (p = 0.054) but still has an almost 80% likelihood of having a nontrivial increase in performance.

A number of studies have commented on the extent of individual variability in muscle potentiation studies (Bevan et al. 2010; Smith and Fry 2007; Till and Cooke 2009). Other studies have encountered similar results and used analyses other than ANOVAs and t tests to analyse the data. McCann and Flanagan (2010) used ANOVAs, γ squares, and radar plots to analyse and illustrate the individual variability in the potentiation of vertical jumps in their study. The use of an ANOVA by Till and Cooke (2009) resulted in no significant group effects for any PAP treatment on sprint and vertical jump measures. Consequently, they still illustrated and discussed the substantial improvements made by the majority of subjects. The few subjects in that study who showed negative responses to all conditions and the others who showed decreases with select conditions nullified the possibility of finding statistical significance with an ANOVA. At the level of the muscle, Smith and Fry (2007) reported that following a 10-s MVC, 7 subjects had elevated regulatory light chain phosphorylation while 4 subjects were nonresponders. Thus, whereas an ANOVA would indicate no significant potentiation, the positive responders in the aforementioned studies definitely did increase performance because of the potentiating stimulus.

It is commonly reported that strength trained individuals respond more positively to PAP than untrained individuals (DeRenne 2010; Sale 2002; Tillin and Bishop 2009). Table 1 illustrates that 16 of the 23 studies demonstrating potentiation used trained individuals. However, there is no guarantee that trained individuals will always experience potentiation. Table 2 list studies where potentiation did not occur. Ten studies with trained subjects did not report significant potentiation in addition to the 5 studies that included recreationally active subjects. Hence, the variability of the elite trained volleyball players in the present study is representative of many potentiation studies.

There are a number of factors that can contribute to the variability within studies and individuals. In addition to the trained state of the individuals influencing the extent of potentiation, the fibre composition of the muscle also plays a role. A greater PAP response is reported to be elicited with greater fast twitch fiber compositions (Tillin and Bishop 2009). Fatigue resistance would also play a role as potentiation mechanisms attempt to balance fatigue responses (Behm 2004; Tillin and Bishop 2009). Whether a subsequent activity presents with fatigue or potentiation will depend on whether the potentiation or the fatigue responses predominated. An individual with greater fatigue resistance (i.e., greater buffering, higher phosphocreatine stores, more oxidative enzymes and mitochondria) would allow the potentiating mechanisms to dominate. Alternatively, an individual with less fatigue resistance may still exhibit potentiation but at a delayed onset

Table 3. The influence of different stimulus protocols on jump height.

Condition	Jump height (baseline, cm)	Jump height (peak, cm)	95% Confidence limits of change		Cohen's d	Likelihood of the observed effect exceeding the smallest worthwhile change (%)	
			Lower	Upper		Trivial	Potentiate
Total	52.91	53.63	0.36	1.10	0.15	90.59	9.41
10×70	52.56	53.62	0.20	1.91	0.22	42.49	57.49
5×85	52.26	53.38	–0.17	2.41	0.27	30.96	68.69
1×90	52.98	53.35	–0.12	0.86	0.08	98.91	1.09
Control	53.02	53.72	0.08	1.32	0.15	78.12	21.87
5×70	52.81	53.70	0.26	1.52	0.20	50.11	49.88
3×85	53.40	53.85	–0.05	0.95	0.08	99.18	0.82
3×90	53.33	53.78	–0.65	1.56	0.09	85.11	14.23

Note: Ninety-five percent confidence limits describe the lower and upper limits of the change from baseline vertical jump (VJ) of the peak vertical jump. The Cohen's d describes the magnitude of the observed change. The percent likelihoods describe the likelihood that the observed effect may be either trivial or exceed the smallest worthwhile change (VJ SWC = 0.95 cm).

Table 4. The influence of different stimulus protocols on peak and mean power.

Condition	Mean power (baseline, $W \cdot kg^{-1}$)	Mean power (peak, $W \cdot kg^{-1}$)	95% Confidence limits of change		Cohen's d	Likelihood of the observed effect exceeding the smallest worthwhile change (%)	
			Lower	Upper		Trivial	Potentiation
Total	31.74	32.25	0.02	0.99	0.11	96.28	3.71
10×70	32.11	32.86	–0.37	1.87	0.13	78.12	21.73
5×85	33.52	34.08	–0.81	1.93	0.11	76.32	22.40
1×90	34.00	33.68	–1.31	0.67	–0.06	94.14	0.44
Control	30.59	31.02	–0.09	0.94	0.12	88.62	11.36
5×70	30.16	31.43	0.09	2.46	0.32	18.95	80.91
3×85	31.07	31.98	–0.05	1.89	0.24	37.59	62.27
3×90	30.75	30.68	–1.39	1.25	–0.02	77.72	9.30
Total	58.01	58.69	0.18	1.20	0.10	99.51	0.49
10×70	57.76	59.50	–0.18	3.67	0.21	47.30	52.58
5×85	61.43	61.54	–1.12	1.35	0.01	98.50	1.02
1×90	61.84	61.22	–1.64	0.40	–0.07	98.63	0.01
Control	56.61	56.37	–1.16	0.67	–0.05	93.95	0.69
5×70	55.15	57.21	0.21	3.91	0.42	11.04	88.75
3×85	56.42	58.31	0.03	3.74	0.33	20.12	79.67
3×90	56.85	56.66	–2.05	1.68	–0.03	76.94	7.82

Note: Ninety-five percent confidence limits describe the lower and upper limits of the change from baseline mean power of the peak of mean power. The Cohen's d describes the magnitude of the observed change. Cohen's d were set at <0.20, "trivial"; 0.20 to 0.49, "small"; 0.50 to 0.79, "moderate"; and >0.80, "large" (Cohen 1988, p. 25). The percent likelihoods describe the likelihood that the observed effect may be either trivial or exceed the smallest worthwhile change (peak power SWC = 1.38 $W \cdot kg^{-1}$, mean power SWC = 0.94 $W \cdot kg^{-1}$). The threshold of a clinical meaningful effect was set at 75% (Liow and Hopkins 2003).

once the fatigue mechanisms have dissipated. Although the subjects in the present study were elite volleyball players, differences in anaerobic fatigue resistance and fiber composition could have contributed to the variety of recovery potentiation times.

Furthermore, potentiation of functional activities involves more than a single potentiating mechanism. An augmentation of subsequent activity can be influenced by increased myosin regulatory light chain phosphorylation, afferent excitability of the motoneuron (increased H-reflex), cortical excitability (increased motor evoked potentials), muscle stiffness (decreased compliance), and changes in muscle architecture (decreased pennation angle). Each of these responses have been reported to peak and diminish at different times following the potentiating contraction. While cortical excitability can begin to diminish within 1 min (Balbi et al. 2002), afferent excitability of motoneurons may persist for 4–11 min (Gullich and Schmidtbleicher 1996), changes in muscle architecture for 6 min (Mahlfeld et al. 2004), myosin regulatory light chain phosphorylation for 10 min (Houston and Grange 1990), and muscle stiffness up to 90 min (Toft et al. 1989). Moore et al. (1990) demonstrated gradual dephosphorylation over an approximately 5-min period. Thus the variability in potentiation recovery times can be dependent upon which mechanism(s) is more predominant at a particular time for each individual.

Withstanding the extensive individual variability, in general, the 5 × 70 and 3 × 85 protocols had the most consistent substantial likelihood (i.e., >75%) of increasing the peak of most dependent variables, in particular peak power and peak velocity. The 5 × 70 protocol also seems likely to have a

Table 5. The influence of different stimulus protocols on peak force and velocity.

Condition	Peak force (baseline, *N*)	Peak force (peak, *N*)	95% Confidence limits of change		Cohen's d	Likelihood of the observed effect exceeding the smallest worthwhile change (%)	
			Lower	Upper		Trivial	Potentiation
Total	2090.06	2171.17	130.00	81.37	0.38	4.20	95.80
10×70	2081.17	2159.00	17.03	138.64	0.41	8.84	91.09
5×85	2147.09	2169.90	–76.05	121.67	0.11	58.58	32.94
1×90	2127.50	2223.73	–93.93	286.40	0.41	22.52	71.15
Control	2021.23	2168.28	70.57	223.54	0.67	0.64	99.35
5×70	2096.45	2157.38	9.33	112.52	0.25	29.69	70.27
3×85	2114.45	2183.04	28.06	109.12	0.35	7.14	92.85
3×90	2042.52	2136.86	23.39	165.28	0.36	10.90	89.06
Total	2.95	2.98	0.01	0.06	0.21	41.50	58.50
10×70	2.93	2.98	0.00	0.09	0.30	24.50	75.30
5×85	2.95	2.97	–0.01	0.06	0.20	49.19	50.48
1×90	2.98	2.98	–0.02	0.02	0.01	98.65	0.91
Control	2.94	2.96	0.00	0.04	0.13	82.96	17.00
5×70	2.93	2.96	0.01	0.06	0.28	22.66	77.31
3×85	2.95	3.05	–0.03	0.23	0.63	10.62	87.39
3×90	2.96	2.97	–0.04	0.05	0.05	80.08	14.88

Note: Ninety-five percent confidence limits describe the lower and upper limits of the change from baseline peak force of the peak of peak force. The Cohen's d describes the magnitude of the observed change. Cohen's d were set at <0.20, "trivial"; 0.20 to 0.49, "small"; 0.50 to 0.79, "moderate"; and >0.80, "large" (Cohen 1988, p.25). The percent likelihoods describe the likelihood that the observed effect may be either trivial or exceed the smallest worthwhile change (peak force SWC = 42.8 N, peak velocity SWC = 0.032 $mol{\cdot}L^{-1}{\cdot}s^{-1}$). The threshold of a clinical meaningful effect was set at 75% (Liow and Hopkins 2003).

Table 6. A sample of the variability in the timing of peak force potentiation.

Baseline	1 min	3 min	5 min	10 min	15 min
2184.01	2139.98	2079.01	2106.58	2166.03	2120.01
2041.00	2118.00	2077.10	2041.00	1970.68	2067.96
2016.57	2063.11	2061.96	2051.58	2108.01	2116.00
2207.02	2185.03	2176.13	2285.93	2196.73	2144.00
1656.07	1900.01	1768.89	1813.12	1714.01	1727.00
2374.68	2329.00	2436.42	2386.04	2414.03	2438.17
2061.00	2018.13	2067.86	1984.00	1952.51	2118.00
2085.98	1800.13	2160.57	2149.00	2108.79	2108.95
2280.30	2270.00	2228.00	2183.00	2111.72	2308.03
2154.33	2069.05	2106.00	2069.98	1996.00	2017.98
2083.00	2293.72	2143.41	2228.03	2228.23	2164.86
1947.14	1806.99	2007.75	2026.63	2127.88	2039.69

Note: Shaded cells indicate the greatest potentiation. Ten of 12 participants were potentiated in this intervention but the potentiation was distributed over the 5 recovery periods.

substantial effect on mean power, and is the only protocol to do so. DeRenne (2010) recommends a heavy preload warm-up protocol consisting of 3–10 sets of 1 repetition at 90% of 1RM for elite men and 1 set of 4 repetitions with a 4RM load for elite women. Table 1, however, exhibits a wider range of potentiating possibilities with interventions typically ranging from a minimum of 5RM or 60% of 1RM up to 1RM or 100% MVCs. The present study's findings of most consistent results with 5 × 70 and 3 × 85 protocols concurs with most studies that successfully potentiated the subsequent activity using moderately high to high intensity resistance with moderate to low volumes.

There was no protocol in the present study that had a substantial likelihood of potentiating the peak vertical jump above the smallest worthwhile change. Table 2 similarly illustrates 7 studies that did not report any potentiating effects on jump performance. While McBride et al. (2005) reported no improvement of loaded countermovement jumps and Kilduff et al. (2007) reported a decrease in countermovement jumps at 15-s recovery — both studies using 3 repetitions of heavy squats — 11 other studies in Table 1 report potentiation of jump performance. Hence, jump potentiation is quite variable between studies as well as between individuals. The question arises, though, as to why power and velocity had a substantial likelihood of potentiating in the present study but vertical jump did not. A countermovement vertical jump involves not only power and velocity but the coordination and sequencing of the power and velocity of each limb segment. It may be possible to increase the primary components of power and velocity but if segmental coordination is altered there may not be an appropriate summation of forces leading to no improvement of vertical jump height.

Kean et al. (2006) demonstrated that a balance training program can improve vertical jump height. They hypothesized that a decrease in body sway with improved balanced would contribute to a more vertical takeoff allowing the power and forces to be directed in an optimal direction. Fatigue can have an adverse effect on balance (Bizid et al. 2009; Surenkok et al. 2006). According to the ANOVA analysis, overall, the intervention protocols utilized in the present study led to fatigue-induced deficits. While the general fatigue effect was not consistent as evidenced by the variable potentiation of power and velocity, it could have had an effect on balance and coordination resulting in no benefit for the vertical jump height.

Conclusion

The timing of potentiation for power and velocity in the present study were variable among individuals which is compatible with the comments found in a number of other potentiation studies (Bevan et al. 2010; Rixon et al. 2007; Smith and Fry 2007; Till and Cooke 2009). With such variability, a traditional ANOVA analysis proved ineffective in highlighting the likelihood of such potentiation occurring. However, there was evidence that the 5 × 70 and 3 × 85 protocols had the most consistent substantial likelihood (i.e., >75%) of increasing the peak of most dependent variables. The 3 × 85 protocol succeeded in potentiating peak power, force, and velocity, while the 5 × 70 protocol had a substantial likelihood of potentiating peak and mean power and peak velocity. These dependent variables were most likely to peak at a similar time of 1, 3, or 5 min. While keeping the aforementioned likelihoods in mind, it is recommended that potentiation schemes should be personalized to the individual. An approach using a single potentiating workload and recovery will not provide the optimal benefits for each individual due to individual differences in physiological characteristics and trained state. As jump height was not potentiated in the present study, it should also be kept in mind that a conditioning stimulus is a physiological balance between potentiation and fatigue (Behm 2004). Thus while characteristics such as power, force, and velocity can be augmented, there could also be fatigue-related impairments to coordination, resulting in no net gain in jump height.

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