Title:

Effect of an acute bout of plyometric exercise on neuromuscular fatigue and recovery in recreational athletes
Abstract

While plyometric training is widely used by sports coaches as a method of improving explosive power in athletes, many prescribe volumes in excess of the NSCA recommendations. The purpose of this study was to assess voluntary and evoked muscle characteristics to assess the neuromuscular impact of a high volume bout of plyometric exercise that was non-exhaustive. Ten athletes who did not have plyometric training experience and were in their competitive season for club-level sport volunteered for the study. After at least two days without high-intensity activity, subjects were assessed on maximal twitch torque, time to peak torque, rate of twitch torque development, twitch half relaxation time, rate of twitch relaxation, and voluntary activation by the interpolated twitch technique before, immediately after, and 2 hours after a high volume plyometric training program (212 ground contacts). Data were analysed by repeated measures ANOVA and described as mean ± SD and Cohen’s d. Statistically significant decrements appeared immediately after the training protocol in the total torque generated by MVC (p<0.05, d=-0.51) and twitch (p< 0.01, d=-0.92), rate of twitch torque development (p<0.01, d=-0.77), and rate of relaxation (p<0.01, d=-0.73). However, we did not observe any differences that remained statistically different after two hours. There were no significant differences observed at any time point in time to peak twitch, half relaxation time, or voluntary activation. We conclude that high volume plyometric training results primarily in peripheral fatigue that substantially impairs force and rate of force development. We recommend that coaches carefully monitor the volume of plyometric training sessions to avoid neuromuscular impairments that can result in sub-optimal training.
**Key Words:** stretch shortening cycle, training, interpolated twitch technique, muscle activation
Introduction

Plyometric training activities are commonly used by a wide range of athletes to improve explosive power. The principle of Specific Adaptations to Imposed Demands (SAID) illustrates that when training to exert maximal power, improvements will be suboptimal when training at sub-maximal power. Still, many plyometric training sessions for inexperienced participants [17, 30] are administered at volumes well in excess of the recommended maximum of between 80 (novice) to 140 (advanced) ground contacts per session [25]. However, the effects of high-volume plyometric training programs on voluntary and evoked contractile properties such as rate of force development and muscle activation are unknown. Should high volume plyometric training negatively affect muscle contractile properties such as rate processes and force output, researchers and coaches may be training research subject and athletes in a suboptimal fashion.

Plyometric training is intended to maximize the efficient transition from the eccentric to concentric phase of a contraction, a sequence referred to as the stretch shortening cycle (SSC), and depends on using (passive) elastic energy in the muscle as well as the (active) myotatic reflex [15]. Plyometric training can impart on the active muscle groups eccentric loads in excess of 5 times the participant's body weight [20], generating a force well beyond that which could be voluntarily produced. Due to the utilisation of the myotatic reflex, this supra-maximal load occurs at a supra-maximal velocity of less than 60 ms, well beyond the velocity of voluntary actions of over 120 ms for even the simplest of voluntary motor tasks [9, 28]. These mechanisms result in
greater activation of muscles involved in the movement when compared to muscle contractions performed in a non-ballistic way [21].

The magnitude of improvements in performance tests with plyometric training vary widely. Previous research has illustrated no improvement in professional soccer players [26] to up to 60% in previously untrained participants [4]. Previous training status likely plays an important, particularly in sports that naturally involve high levels of SCC activity already (e.g. running, jumping). Therefore, the appropriateness of the training volume and intensity also likely play a determining role in the success of a plyometric training program.

Previous research has investigated the effects of SCC exercise on neuromuscular properties after long-duration (e.g. marathon running) and exhaustive SCC exercise protocols. Decrement in the force of maximal voluntary contractions (MVC) have been consistently shown in such protocols, though results in twitch force are inconsistent [24, 27]. Most studies investigating muscle activation through EMG show substantial decrements after exhaustive activity [16]. The only previous study investigating muscle activation using the interpolated twitch technique (ITT) showed a 9.5% increase in voluntary activation and a 38% increase in EMG. This experiment, however, followed an exhaustive and continuous protocol [27], therefore lacking context validity of a plyometric training session in a sports training environment.
While most coaches are aware the plyometric training sessions should not be exhaustive due to the risk of injury [30] and the acute decrement in power output [12], research has only investigated the local muscular effects of exhaustive SCC exercise [27]. There has been no investigation of the effects of high volume, though not exhaustive, plyometric training sessions on voluntary and evoked muscle properties. Since the “more is better” philosophy in common in the club sport coaching community and training players to high levels of fatigue is often thought to be always beneficial, the purpose of this study is to assess voluntary and evoked muscle characteristics to gauge the neuromuscular impact of a non-exhaustive but high volume bout of plyometric exercise.

**Methods**

**Approach to the Problem**

Ten subjects were recruited from local sporting clubs to perform a single bout of high volume (212 ground contacts) plyometric exercise. Prior to the training session, subjects were assessed on maximal voluntary contraction, twitch force and rate properties, and voluntary activation of the right knee extensors. Typical errors of these measures has been previously reported to be less than 8% [5]. Subjects then partook in the plyometric training session. Immediately after the training session, subjects were reassessed for changes in maximal voluntary contraction, twitch force and rate properties, and voluntary activation of the right knee extensors immediately after the
training session and again after two hours of quiet sitting. Such an approach will allow us to elucidate the neuromuscular effects of a high-volume plyometric training session.

Subjects

Ten male volunteers (age: 21.6 ± 1.3 years, height: 178.8 ± 6.3 cm, mass: 81.5 ± 8.1 kg, BMI: 25.5 ± 2.8 kg/m²) who regularly trained high intensity team-sports (e.g. rugby union, rugby league) were recruited from local sporting clubs. Although these activities incorporate SCC movements, subjects had no specific previous history of participation in any structured plyometric training programs. All participants were in-season for their sports with team training twice per week, resistance training twice per week, and competitions on weekends; athletes had not performed any high-intensity activity for at least two days prior to testing. Informed, written consent was obtained from all subjects prior to commencement of the investigation. Subjects were informed they could withdraw from the study at any time without prejudice. The study was conducted with the approval of the Ethics in Human Research Committee of Charles Sturt University.

Data collection apparatus and subject positioning

All assessments were performed on the right knee extensors using a KIN-COM isokinetic dynamometer (Chattanooga Group Inc., Hixon, TN, USA) linked to a BNC2100 terminal block connected to a signal acquisition system (PXI024, National Instruments, Austin, TX). Data were A/D converted at 16-bit resolution and synchronously sampled data at a rate of 1 kHz. All subjects were seated upright on the dynamometer chair and
secured via waist and leg straps. During all tests subjects were required to have their arms crossed against their chest to ensure additional forces did not contribute to performance. The knee was maintained at 90° flexion for all isometric tests. Furthermore, plywood board measuring 20mm thickness (600mm x 700mm) was placed on the dynamometer seat under each subject to improve the stiffness of the seat. The axis of rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the right femur and the lower leg attached to the lever arm 1cm above the lateral malleolus of the ankle.

**Evoked Twitch Properties**

Evoked twitch testing was performed before maximal isometric torque testing (MVC). Six pulses, separated by 10s intervals were delivered to the nerve while the musculature was at complete rest. Activation of the quadriceps muscles was achieved through stimulation of the femoral nerve using two 90 × 50mm reusable self-adhesive gel pad electrodes (Verity Medical Ltd, Stockbridge, Hampshire, UK). The positive electrode was positioned 2cm below the inguinal fold about the medio-anterior aspect of the upper thigh and the negative electrode was placed 5cm above the superior border of the patella on the medial aspect of the lower vastus lateralis/medialis indicated by a low intensity extension of the muscles before placement.

The current applied to the femoral nerve was delivered using a Digitimer DS7AH constant current stimulator (Digitimer Ltd., Welwyn Garden City, Hertfordshire, UK)
linked to a BNC2100 terminal block connected to a signal acquisition system (PXI1024, National Instruments, Austin, TX) using a square wave single pulse with a width of 200μs (400V with a current of 150 - 400mA), driven by a custom designed instrument using Labview software (National Instruments, North Ryde, Australia). Initially, the current was applied manually and ramped until a twitch response of moderate amplitude was achieved. Electrodes were then adjusted either medially or laterally and repositioned where the greatest twitch response occurred. The electrode was then secured and location marked. Stimulus intensity was then gradually increased until a plateau in twitch amplitude was reached. The intensity was then increased by a further 25% to ensure supra-stimulation of the nerve.

Maximal Isometric Torque

MVC testing consisted of a minimum of 6 isometric trials where the subject was instructed to achieve peak torque within 2 seconds and maintain maximal effort until instructed to stop, which was typically within 4-5s. A rest period of 30s separated each trial and testing continued until the final three trial data values were within 5%, normally achieved within 6 trials. Verbal encouragement was given during every trial to maximise performance and visual feedback was also provided through graphic display of force on the computer monitor. The MVC value used for analysis was determined as the highest value produced across all trials.

Voluntary Activation
Voluntary activation was assessed for 4 trials, using the twitch interpolation method [13]. For each trial subjects were instructed to produce an MVC. During each maximal contraction the investigator manually primed the trigger 2-3s after the initiation of each contraction. Once primed, the stimulus was automatically triggered using customised software when a decline in force was detected. A 2-3s delay in priming the stimulus trigger was essential to prevent premature stimulation prior to attainment of peak torque in response to normal variations in force that occur during the initial phase of maximal effort. Subjects were instructed to ignore the sensation associated with the stimulus and continue to focus on exerting maximal effort. Within 5s following each isometric MVC contraction, a second stimulus was delivered manually by the investigator with the muscle at complete rest. Strong verbal encouragement again was given to motivate the subject to perform maximally. Each assessment was separated by a 30s timeframe. Automatic triggering for stimulation was performed using a virtual instrument using Labview software version 8.0 (National Instruments, Austin, TX).

Data Processing

Force and stimulation trigger data were recorded during testing were analysed using spreadsheet software for MS Windows (Excel 2007™, Redmond, WA, USA) and corrected for the effect of gravity on the lower leg. Gravity correction was performed through averaging the load applied to the force transducer during the 1s period prior to commencement of the superimposed maximal voluntary contraction and during the 50ms period prior to the evoked twitch contraction while the muscle was at complete rest. The average force during this period was then used to offset the performance data
obtained during testing [6, 7]. Following this, performance data were multiplied by the lever arm length of the dynamometer set to the individual subject, data were then able to be expressed in units of torque (N•m). Peak superimposed torque was determined as the peak isometric torque value produced during the period 50ms before the stimulus and 150ms subsequent to the stimulus delivery.

The level of voluntary activation was calculated by expressing the interpolated twitch torque as a percentage of the peak potentiated evoked twitch torque obtained during rest using the following equation:

\[
\text{Voluntary Activation (\%)} = [1 - \left(\frac{\text{superimposed torque}}{\text{control twitch}}\right)] \times 100
\]

For all evoked twitch trials, torque onset was defined as the point at which torque data following stimulation increased beyond 2 standard deviations of the mean torque value calculated 1s prior to stimulation. Twitch torque-time curves were averaged over all evoked twitch trials within each assessment, with the mean used to determine the following characteristics for analysis; (1) Peak twitch torque (Pt; highest isometric torque value), (2) time to peak torque (TPT; time from torque onset to Pt), (3) half-relaxation time (½ RT; time for Pt to decline by half), (4) contraction duration (CD; TPT plus ½ RT), (5) rate of torque development (RTD; mean tangential slope of the twitch torque-time curve between the onset of torque development and Pt), and (6) rate of relaxation (RR; mean tangential slope of the twitch torque-time curve between Pt and ½
Equations used to calculate mean tangential slope to determine RTD and RR were calculated using GraphPad Prism v3.0 for MS-Windows (GraphPad Software, San Diego, California, USA).

**Plyometric Training Protocol**

The plyometric training session involved 5 specific exercises totalling 212 ground contacts (sets x repetitions): alternate single-leg bounds (3 × 20), jumps over 40cm cones (8 × 5), alternate leg power skips (3 × 20), lateral hopping with two jumps each direction over 30cm cones (4 × 10), and depth jumps from a 60cm height (4 × 3). Subjects were instructed to attain maximal height and/or distance with every repetition performed throughout the session. Subjects were also instructed not to pause between repetitions or pre-load before the following jump. A 30s rest was required between each set of bounds and skips, 20s between each set of box jumps and side hops, and finally, 15s between each set of depth jump. There was a 3min rest period at the completion of each exercise.

Before the commencement of each exercise, a visual demonstration was given to ensure the correct technique was performed. Continuous feedback during performance was also given. Subjects were given strong verbal encouragement throughout the entire exercise session.
Statistical Analyses

Descriptive data are presented as the mean ± standard deviation. Statistical differences within subjects associated with plyometric training were determined by repeated measures ANOVA (α=0.05) using SPSS™ for MS-Windows version 16.0 (Statistical Package for the Social Sciences, Chicago, Il). In the event of overall significance in the ANOVA, pairwise comparisons were made between time points to assess which time points were significantly different. The magnitudes of differences are expressed in standardized (Cohen) effect sizes (d) [6].

Results

Statistically significant differences were found immediately after the training protocol in the total torque generated by MVC (p<0.05, d=0.51, ‘moderate’) and twitch (p<0.01, d=0.92, ‘large’), rate of twitch torque development (p<0.01, d=0.77, ‘moderate’), and rate of relaxation (p<0.01, d=0.73, ‘moderate’). However, we did not observe any differences that remained statistically different than the pre-training results after two hours.

There were no significant differences observed at any time point in time to peak twitch, half relaxation time, or voluntary activation.

Discussion
The purpose of this study was to examine the extent of neuromuscular fatigue associated with an acute bout of high volume, but not exhaustive, plyometric exercise. We further assessed the extent of recovery of any changes two hours after exercise. Using voluntary and evoked muscle characteristics, we found that while there was no significant change in muscle activation immediately after the plyometric training session, there was evidence of peripheral but not central fatigue. We also observed a moderate decline in the rate of twitch torque development, thus indicating a slowing of contraction velocity. We conclude that high volume plyometric training results in substantial peripheral fatigue and slows contraction velocity, even when the training session is not exhaustive.

The use of voluntary and evoked contractile properties is often used to determine the site of fatigue (i.e. central or peripheral). By electrically stimulating a muscle, the voluntary (central) components of activation are bypassed, thereby leaving only the peripheral components [3]. The moderate to large decrements observed here in MVC and twitch torque with a lack of change in voluntary activation indicate that, while the subject was still able to activate any muscle fibres capable of being activated (i.e. lack of central fatigue), there are muscle fibres not capable of being activated, even by electrical stimulation (i.e. peripheral fatigue). In other types of fatigue protocols [2, 8] there are decreases in both MVC and voluntary activation. In such a case, the decline in MVC is at least partially related to central mechanisms since the muscle fibres are still capable of being activated by electrical stimulation, even though the subject is not able to voluntarily activate them. The lack of significant change in peak twitch to MVC ratio
observed here, a mark of motor unit activation under maximal contraction [23], also indicates a lack of central change. Therefore, these results indicate that a high, but realistic volume of plyometric training reduces the torque generating capacity of muscle through events in the afferent or efferent neurons, or peripherally mediated events in the muscle.

The effects of fatigue on voluntary and evoked muscle characteristics have been extensively studied [2, 8, 27]. The sources of fatigue are dependent upon, among other things, the fiber type composition of the active muscle group, the duration of the exercise period, the type of muscle contraction, the rest period between contractions, the intensity of the contraction, and the length of time per contraction [2]. Metabolically, the accumulation of hydrogen ions [7], inorganic phosphates [14], and potassium [19] are major contributors to muscular fatigue. Hydrogen ions directly inhibit cross-bridging or competitively binding with troponin-C thus inhibiting the binding of calcium [7] while potassium is linked to impairing the action potential along the neuron or sarcolemma [19] or dihydropyridine receptors thereby inhibiting calcium release [10]. Slightly longer duration fatigue may also result from decreased energy source within the muscle, such as creatine phosphate [11]. Additionally, often postulated to be the source of impaired force output after eccentric muscle action is damage to the contractile mechanisms [18, 29].
While any of these mechanisms could be used to explain the immediate reduction in MVC and voluntary activation, one would expect that muscle injury would not have improved in the span of two hours, though an accumulation of metabolic by-products could have been cleared in two hours and CP could have replenished. Therefore, the acute fatigue observed here is likely to be related to an accumulation of by-products rather than muscle injury related, though this is not to say that lingering effects of muscle injury is not present. It is not unusual to observe full recovery in two hours and then a secondary decrement up to two days later [16]. In this sense, the recovery from SCC exercise can be described as bimodal [22].

The study that most resembles our study also investigated evoked and voluntary contractile properties of the knee extensors, though they investigated continuous, repeated, exhaustive SCC exercise [27]. We observed a 23% decrement in twitch torque with no significant difference in time to peak twitch or ½ RT immediately after the training session, results nearly identical to those observed by Strojnik and Komi [27]. However, while Strojnik and Komi [27] observed a 16.5% increase in estimation of voluntary activation by ITT and a 34.9% increase in EMG of the vastus lateralis, we observed no change in estimation of voluntary activation. Unusually, Strojnik and Komi [27] report their increase was from 69% to 78.5% voluntary activation, results that are much lower than those reported here and those reported by other authors (i.e. >90%) [1, 8].
The decrement in the rate of twitch torque development with the lack of change in time to peak twitch torque may initially appear contradictory: How could one twitch rate process change while the other not? The lower twitch torque is reached in the same amount of time as the previous higher twitch torque due to the slower rate of twitch torque development. A similar explanation exists for the slower rate of relaxation though unchanged half relaxation time. Furthermore, the lower rate of twitch torque development occurs as the stimulus occurs in a fixed time period (i.e. 200μs), so with a slower rate of twitch torque development, a lower torque is developed. Therefore, the more relevant variable here is the rate of force development and rate of relaxation as it reflects the slowing of the velocity of contraction from high volume plyometric training.

While previous research has used twitch interpolation to investigate exhaustive SCC exercise [15], there has not been any previous investigation of high volume but non-exhaustive plyometric exercise. It is that the exercise was high volume but not exhaustive that gives the current study its validity within common training environments. There is a reduction in voluntary force from high volume plyometric exercise. The observed decrements observed in MVC and twitch torque with a lack of change in voluntary activation indicate that these results are likely related to peripherally mediated events. We also observed a slowing of the evoked contraction velocity and lack of significant change in peak twitch to MVC ratio, thereby also implicating peripherally mediated events. We conclude that high volume plyometric exercise can cause substantial performance decrements, even when not performed to exhaustion.
Practical Applications

This research has illustrated that even when plyometric training sessions are not exhaustive, high volume plyometric training sessions (212 ground contacts) can substantially impair a muscle’s ability to generate force and slows evoked contraction velocity. The results of this research indicate that coaches should carefully monitor the volume plyometric training sessions, even if athletes do not feel fatigued as poorly controlled volume of plyometric training results in impaired force and velocity, thereby reducing the effectiveness of the training session.
References


Table 1 - Knee extensor MVC and evoked twitch properties pre, post, and 2 hours post plyometric exercise

<table>
<thead>
<tr>
<th>Variable</th>
<th>Pre-training</th>
<th></th>
<th>Post-training</th>
<th></th>
<th>2 hours post</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>sd</td>
<td>mean</td>
<td>sd</td>
<td>mean</td>
<td>sd</td>
</tr>
<tr>
<td>Maximal Voluntary Contraction (Nm)</td>
<td>262.2*</td>
<td>45.7</td>
<td>232.5</td>
<td>66.2</td>
<td>259.9</td>
<td>59.5</td>
</tr>
<tr>
<td>Peak twitch torque (Nm)</td>
<td>51.5*</td>
<td>12.02</td>
<td>39.7</td>
<td>9.6</td>
<td>49.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Time to peak twitch torque (ms)</td>
<td>112.0</td>
<td>14.8</td>
<td>104.9</td>
<td>7.2</td>
<td>113.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Rate of Twitch Torque Development (Nm/s)</td>
<td>112.0*</td>
<td>14.8</td>
<td>104.9</td>
<td>7.2</td>
<td>113.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Half twitch relaxation time (ms)</td>
<td>69.6</td>
<td>10.5</td>
<td>66.9</td>
<td>8.4</td>
<td>74.5</td>
<td>15.9</td>
</tr>
<tr>
<td>Rate of twitch relaxation (NM/s)</td>
<td>422.2*</td>
<td>98.8</td>
<td>340.6</td>
<td>93.0</td>
<td>382.9</td>
<td>133.1</td>
</tr>
<tr>
<td>Peak twitch to maximal voluntary contraction ratio (%)</td>
<td>20.0</td>
<td>4.8</td>
<td>18.2</td>
<td>6.9</td>
<td>19.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Voluntary activation (%)</td>
<td>92.3</td>
<td>5.2</td>
<td>91.1</td>
<td>4.5</td>
<td>93.9</td>
<td>3.6</td>
</tr>
</tbody>
</table>

* Indicates the pre-training session result is significantly different (p<0.05) to immediately post-training