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ORIGINAL ARTICLE

Knee extension fatigue attenuates repeated force production of the elbow flexors

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Abstract

Non-local muscle fatigue has been demonstrated with unilateral activities, where fatiguing one limb alters opposite limb forces. Fewer studies have examined if non-local fatigue occurs with unrelated muscles. The purpose of this study was to investigate if knee extensors fatigue alters elbow flexors force and electromyography (EMG) activity. Eighteen males completed a control and fatiguing session (randomised). Blood lactate was initially sampled followed by three maximal voluntary contractions (MVC) with the elbow flexors and two with the knee extensors. Thereafter, subjects either sat (control) or performed five sets of bilateral dynamic knee extensions to exhaustion using a load equal to the dominant limb MVC (1-min rest between sets). Immediately afterwards, subjects were assessed for blood lactate and unilateral knee extensors MVC, and after 1 min performed a single unilateral elbow flexor MVC. Two minutes later, subjects performed 12 unilateral elbow flexor MVCs (5 s contraction/10 s rest) followed by a third blood lactate test. Compared to control, knee extensor force dropped by 35% ($p < 0.001$; ES = 1.6) and blood lactate increased by 18% ($p < 0.001$; ES = 2.8). Elbow flexor forces were lower after the fatiguing protocol only during the last five MVCs ($p < 0.05$; ES = ~0.58; ~5%). No changes occurred between conditions in EMG. Elbow flexor forces significantly decreased after knee extensors fatigue. The effect was revealed during the later stages of the repeated MVCs protocol, demonstrating that non-local fatigue may have a stronger effect on repeated rather than on single attempts of maximal force production.

Keywords: *Crossover fatigue, electromyography, endurance, MVC, quadriceps*

Introduction

Neuromuscular fatigue has been defined as a progressive reduction in the ability of a muscle to produce power or force (Gandevia, 2001). Fatigue is typically attributed to neural and/or muscular origins (Gandevia, 2001; MacIntosh & Rassier, 2002). Neural factors may not only affect the local or target working muscle but also non-local non-working muscles as well. A number of researchers have attempted to investigate this phenomenon by fatiguing a target muscle group and measuring its effects on the contralateral limb or on unrelated non-local muscles (Amann et al., 2013; Doix, Lefèvre, & Colson, 2013; Johnson, Mills, Brown, & Sharpe, 2013). Despite the growing number of studies on this topic, the results are still conflicting. On one hand, it has been demonstrated that fatiguing a certain muscle group can lead to decreases in force and power in the contralateral homologous muscle group (Doix et al., 2013; Post, Bayrak, Kernell, & Zijdewind, 2008), as well as unrelated heterogonous muscle groups (Johnson et al., 2013; Kennedy, Hug, Sveistrup, & Guével, 2013; Nordsborg et al., 2003). For example, it was shown that a constant-load single-leg knee extension exercise to exhaustion of one leg led to subsequent significant decrements in time to exhaustion of the opposite leg (Amann et al., 2013). Similarly, Doix et al. (2013) found that a sustained maximal contraction (MVC) of the knee extensors led to decreased force of the contralateral knee extensors. Kennedy et al. (2013) found that both a maximal and a submaximal isometric fatiguing protocol of the forearm muscles decreased force production with the plantar flexors. It was also demonstrated that a prior arm cranking exercise shortened the time to exhaustion of a lower body cycling task (Bangsbo, Madsen, Kiens, & Richter, 1996; Johnson et al., 2013; Nordsborg et al., 2003).

On the other hand, Todd, Petersen, Taylor, and Gandevia (2003) showed that a sustained elbow flexor MVC was not affected by a previous sustained MVC

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with the contralateral arm. Furthermore, Regueme, Barthèlemy, and Nicol (2007) did not find any contralateral effects in jump performance and force production with the plantar flexors after a fatiguing protocol consisting of repeated jumps with the ipsilateral plantar flexors. It was also demonstrated that an extended aerobic activity such as a marathon run and a cycling activity led to significant decreases in force and power production with the lower limbs, but did not affect maximal grip force (Elmer, Amann, McDaniel, Martin, & Martin, 2013; Millet, Martin, Lattier, & Ballay, 2003; Place, Lepers, Deley, & Millet, 2004; Ross, Goodall, Stevens, & Harris, 2010). Hence these conflicting contralateral and non-local fatigue studies emphasise the need for further investigations.

A probable reason explaining the conflicting results may arise from the way that the non-localised effects of muscle fatigue are being measured. Most studies thus far have employed either an exhaustive submaximal exercise (Johnson et al., 2013; Nordsborg et al., 2003), a single MVC or repeated MVCs with extended resting periods (Doix et al., 2013; Elmer et al., 2013; Kennedy et al., 2013). Measuring just a single MVC or repeated MVCs with an extended resting period may allow subjects to briefly overcome the non-local effects and produce the same baseline force. Accordingly, the goal of the present study was to further examine if non-local fatigue would be found in the elbow flexors after performing a dynamic fatiguing protocol with the knee extensors by evaluating both muscle fatigue (a single elbow flexor MVC performed after the fatiguing protocol) and fatigue resistance (12 repeated MVCs with short 10 s rest periods). Since Kennedy et al. (2013) examined distal muscle groups (forearms and plantar flexors) in their study, the present study was set to expand on their question and test larger and more proximal muscle groups. The hypothesis was that fatiguing of the knee extensor muscles would lead to muscle fatigue by attenuating force production and electromyography (EMG) activity of the elbow flexor muscles during a single MVC as well as compromising fatigue resistance compared to control conditions.

Methods

Participants

Eighteen healthy resistance trained males (23 ± 4 years, 176 ± 6 cm, 76 ± 9 kg) participated in this study. All of the participants performed resistance training at least three times a week for over 2 years. Subjects were requested to avoid training a day before the testing days. Ethical approval for the study was granted by the institutional Health Research Ethics Board (ICEHR No. 20140650-HK). Before participation, subjects were verbally informed of the procedures and risks associated with the study and then if they agreed, they signed the consent form.

Experimental design

Subjects attended the laboratory on two occasions and performed one of the two conditions in a randomised fashion (Figure 1). Participants were familiarised with the equipment and testing procedures during the first testing day. Then, after 5 min of sitting, blood lactate (Lactate Pro, Arkray, Kyoto, Japan) was collected and analyzed from the index finger of the tested arm. Subjects performed a general warm up of cycling for 5 min at a cadence 70 rpm. This was followed by a specific warm-up for the elbow flexors, which included 10 isometric contractions with the wrist in a supinated position. Intensity level was equal to ~50% of perceived maximum with a work to rest ratio of 2/2 s. One minute after the warm-up, participants performed three pretest elbow flexor maximal voluntary isometric contractions (MVCs) lasting 5 s with 2 min of rest between the trials. Thereafter subjects performed a warm-up for the knee extensors consisting of 12 controlled dynamic bilateral knee extensions using a load equal to 20% of bodyweight. This was followed by two unilateral knee extension MVCs with the dominant leg with 2 min rest between contractions. Following the upper and lower body warm-ups and pretests, subjects either performed the fatiguing protocol or rested for 7 min (control). The load used for the dynamic bilateral knee extension fatiguing protocol was equivalent to the highest unilateral isometric MVC force measured previously. After the load was set, subjects performed the fatiguing protocol, which always consisted of five sets of bilateral dynamic knee extension repetitions to failure with 1 min of rest between sets. Failure was defined as the inability to fully extend the knee, which was measured by touching the shin to an exercise band tied parallel to the ground at full extension, or by not keeping a constant pace of 1 s per contraction dictated by a metronome. Subjects were constantly motivated during the protocol by two experimenters and were reminded to keep their upper body as relaxed as possible during the protocol. All subjects completed the five sets with the number of repetitions decreasing from the first to the fifth set (see Results section). Biceps' EMG activity was monitored throughout the protocol and with any evidence of activation, subjects were reminded to relax their arm. Immediately after the last set of bilateral dynamic knee extension contractions, subjects performed a unilateral isometric knee extension MVC of the dominant limb followed by a second blood lactate concentration test from the same index

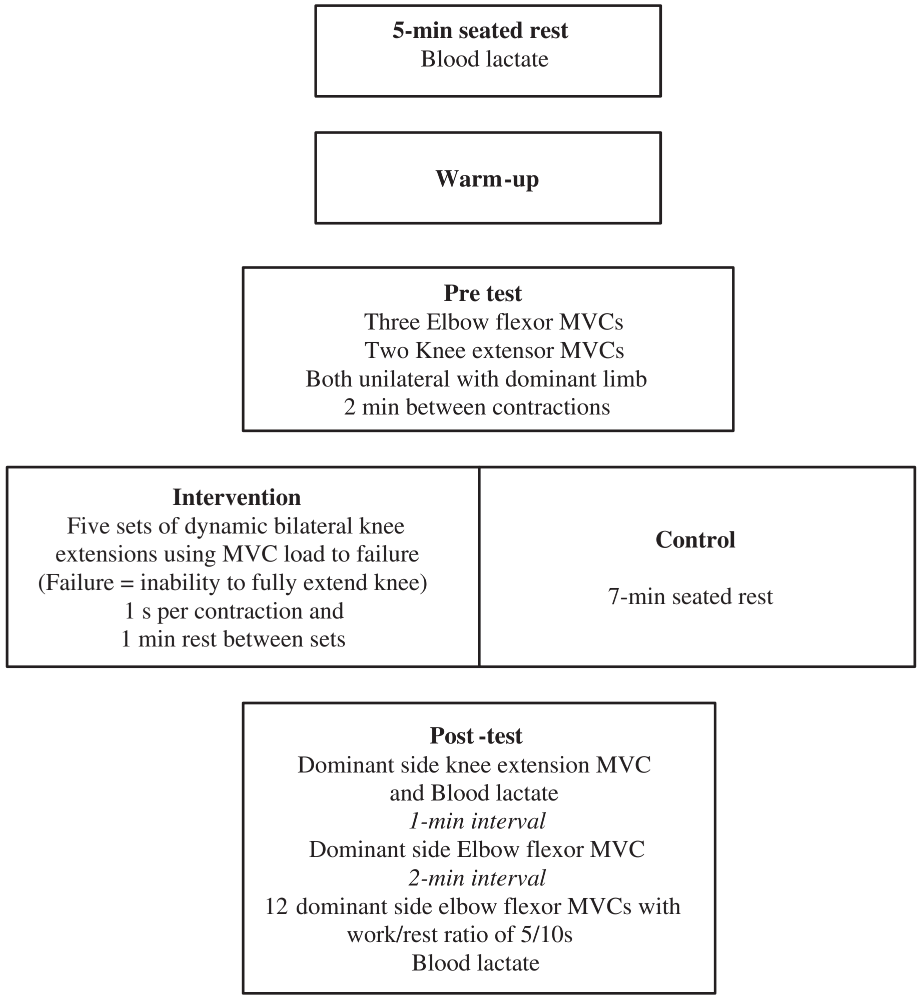

Figure 1. Schematic diagram of the experimental design.

finger. One minute after the lower body MVC, subjects performed one unilateral dominant elbow flexors MVC. Two minutes afterwards, they performed a repeated MVC protocol of the dominant elbow flexors consisting of 12 MVCs at a work to rest ratio of 5/10 s. A third blood lactate test was collected after the last MVC. During the control session, subjects followed the exact same protocol, but instead of performing the fatiguing protocol they sat on the leg extension chair for 7 min, which was the approximate time period to complete the fatiguing protocol.

Maximum voluntary contraction (MVC) force

Subjects were seated on a chair with their upper arm supported and elbow flexed at 90°. The wrist was inserted into a padded strap attached by a high tension wire to a load cell (Omega Engineering Inc., LCCA 500 pounds; sensitivity = 3 mV/V, OEI, Canada) that was used to measure elbow flexion. For the knee extensor MVC and fatiguing protocol, participants were seated in the knee extension machine (Modular Leg Extension, Cybex International, Medway, MA, USA) with the hip and knee fixed at 90° and 83°, respectively. The knee flexion angle was pre-determined by the inclined angle of the seat, which could not be adjusted. To eliminate upper body involvement, a strap was placed around the waist and participants were instructed to relax their arms on their thighs during the protocol. A force transducer was placed behind the leg extensor machine during the MVC tests. Data for elbow flexion were collected and analyzed in a similar fashion to Halperin, Aboodarda, Basset, Byrne, and Behm (2014). The mean force for each MVC was determined over a 3 s window defined as 1.5 s before and following the peak force of each contraction. To account for variability in force production between the three testing days, all mean force data were normalised to the highest mean force recorded during the three pretest trials. As such, force data for elbow flexors are reported as percentage of maximum pretest values. Since only two MVCs were collected for the knee extensors, data are presented in units of Newton.

Electromyography (EMG)

Surface EMG recording electrodes were placed approximately 3 cm apart over the proximal, lateral segment of the biceps brachii and over the lateral head of the triceps brachii. Placement of electrodes, skin preparation and data collection and analysis were performed in a similar fashion to Halperin et al. (2014). Using the same 3 s window as applied to the force analysis (1.5 s before and following the peak force), mean rectified root mean square (RMS) EMG was collected and analyzed. The mean amplitude of the EMG RMS was calculated by the software from 50 ms bins within the 3 s window. The absolute mean amplitude measures were then normalised to the highest pretest value and reported as a percentage.

Statistical analysis

Normality (Kolmogorov–Smirnov) and homogeneity of variances (Levene) tests were conducted for all dependent variables. If the assumption of sphericity were violated, the Greenhouse-Geisser correction was employed. First, intraclass correlation coefficients (ICC) were measured for mean force and EMG for the three pretests of both conditions to assess consistency of this data. Second, a two-way repeated measures ANOVA test was used to compare knee extensor force (two conditions × two MVCs) between conditions. Third, two-way repeated measures ANOVA tests (2 conditions × 13 MVCs) were conducted to determine differences between conditions in the following variables: normalised mean force and EMG of biceps brachii and triceps brachii. Lastly, a two-way repeated measures ANOVA test was used to compare blood lactate levels (two conditions × three time periods) between conditions. Paired *t* tests with Holm–Bonferroni corrections were used to decompose significant interactions, and Bonferroni post hoc tests were used if main effects were found. Significance was set at 0.05. Cohen's *d* effect sizes (ES; Cohen, 1988) were also calculated to compare mean force and EMG between conditions. Data are reported as means ± SD.

Results

All subjects were able to successfully complete the knee extension fatiguing protocol. The mean number of repetitions performed in the first and fifth sets were 23 ± 6 and 11 ± 3, respectively. The ICCs of the three pretest elbow flexor MVC values for both conditions were highly correlated ($r \geq 0.96$) for absolute force (control: 404 ± 82 N, fatigue 411 ± 75 N) and EMG of biceps (control: 0.98 ± 0.46 mV, fatigue: 0.92 ± 0.45 mV) and triceps brachii (control: 0.16 ± 0.1 mV, fatigue: 0.15 ± 0.07 mV) measures.

An interaction was found for knee extensors mean force ($p < 0.001$). After the fatiguing protocol, MVC force dropped by ~35% relative to baseline ($p < 0.001$; ES = 1.6), whereas no changes occurred under the control conditions (Figure 2).

An interaction was found for normalised elbow flexors mean force ($p = 0.003$). Paired *t* tests revealed that forces were significantly higher in the control condition only during the last five MVCs (Figure 3). Specifically, the *p* values, effect sizes and percentage differences between the conditions were as follows: #8 ($p = 0.011$; ES = 0.67; 4.7%), #9 ($p = 0.005$; ES = 0.8; 6.2%), #10 ($p = 0.049$; ES = 0.61; 4.4%), #11 ($p = 0.014$; ES = 0.25; 4.6%) and #12 ($p = 0.029$; ES = 0.57; 5.2%).

No interactions or significant main effects were found for normalised biceps and triceps EMG between conditions (Figure 4). However, a main effect of repetitions was found in which EMG amplitude decreased from MVCs #1 to #13 for biceps ($p <$

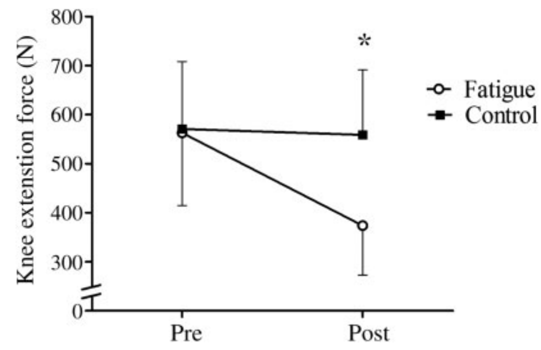

Figure 2. Mean absolute knee extension force values for the two MVCs.
Data are presented in Newton. Asterisk indicates that force was significantly higher ($p \leq 0.05$) in the control condition relative to fatigue condition.

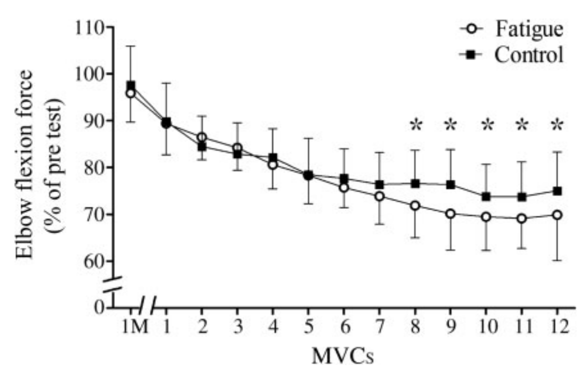

Figure 3. Mean (SD) force profile over the 13 MVCs for the two conditions.
Data are presented in percentage relative to the highest value of the pretest. Asterisk indicates that force was significantly higher ($p \leq 0.05$) in the control condition relative to fatigue condition. 1 M stands for 1 min post fatigue MVC.

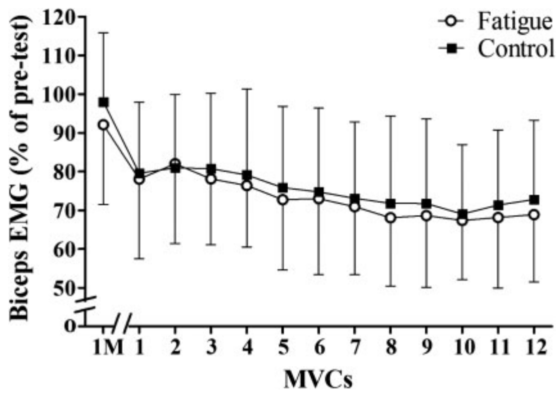

Figure 4. Mean (SD) biceps EMG profile over the 13MVCs for the two conditions.
Data is presented in percentage relative to the highest value of the pre-test. 1M stands for 1 min post fatigue MVC.

0.001; ES = 1.2–1.6; 25–30%) and triceps ($p < 0.001$; ES = 1.3–1.5; 25%) under both conditions.

An interaction was found for blood lactate levels ($p < 0.001$). Paired *t* tests demonstrated that blood lactate levels were not significantly different at pretest between conditions ($p = 0.468$), but were higher after the fatiguing protocol at post-test 1 ($p < 0.001$; ES = 2.3; 18%) and post-test 2 ($p < 0.001$; ES = 2.5; 19%) compared to control conditions (Figure 5).

Discussion

The main finding of the present study was that a decrease of elbow flexors' fatigue resistance occurred as a result of knee extensors' fatigue. Interestingly, relative to the control conditions, the force decrements with the elbow flexors were only observed in the last five MVCs during the repeated MVCs protocol (Figure 3). In contrast, no differences were found between conditions with the single elbow flexion MVC performed 1 min after the fatiguing protocol. This finding may explain some of the discrepancies in the literature. That is, the effects

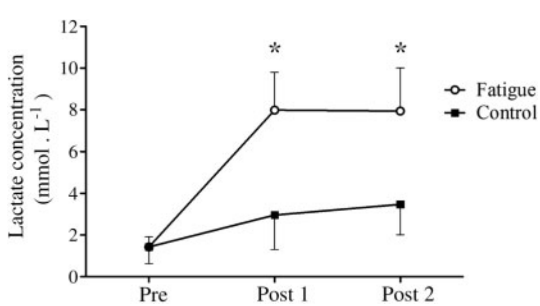

Figure 5. Mean (SD) blood lactate levels over the three time periods.
Data are presented in units of mmol L^{-1}. Asterisk indicates that blood lactate was significantly higher ($p \leq 0.05$) in the fatigue condition relative to control condition.

are more evident in the later stages during repeated maximal effort contractions (fatigue resistance) and not so consistent with single maximal intent contractions. To the best of our knowledge, the present study is the first to examine the non-localised fatigue effects measured with repeated MVCs with short rest intervals. Indeed, most studies have used either submaximal fatiguing protocol to exhaustion (Johnson et al., 2013; Nordsborg et al., 2003) or a single or repeated MVCs but with extended rest period between (>30 s) (Doix et al., 2013; Elmer et al., 2013; Regueme et al., 2007).

The results are in partial agreement with Kennedy et al. (2013) who found 23% and 9% decrements in plantar flexors MVC after a maximal and submaximal fatiguing protocol with the forearm muscles. In line with their findings, the present study also found non-localised fatigue effects. However, the effects were not immediate, and the magnitude of decrement was ~5% and evident only during the last five elbow flexion MVCs. The different results can be explained by the fatigued and tested muscle groups. In the present study, the fatigued muscle group was larger and more proximal (biceps brachii versus forearm flexors), and the fatiguing protocol consisted of dynamic rather than isometric contractions. Additionally, despite the different nature of the activities, the results of the current study match those of Johnson et al. (2013) and Nordsborg et al. (2003) who reported shorter time to exhaustion in a lower body cycling task when it was preceded by an arm cranking exercise. In contrast, other studies were not able to find a non-local effect measured with grip MVCs tested after, or during an extended aerobic activity (Elmer et al., 2013; Millet et al., 2003; Place et al., 2004). This discrepancy may be explained by the MVCs being tested only once or repeatedly with longer resting periods (>30 s), allowing the participants to overcome the non-local fatiguing effects (Elmer et al., 2013; Martin & Rattey, 2007). Additionally, in the present study a dynamic knee extension with medium load (~50% of MVC for each limb) was performed until exhaustion with short breaks between sets, whereas in the previously cited studies the fatiguing protocols were continuous, cyclical and of longer duration.

The fatiguing protocol altered the metabolic milieu in the lower limbs, which could have influenced the central projection of type III and IV muscle afferents (Amann, 2011, 2012). Through a feedback loop, these neurons provide an inhibitory effect to the central nervous system leading to decrements in the magnitude of the neural drive to the working muscles (Amann, 2011, 2012), which in this case were the elbow flexors. Indeed, the blood lactate levels measured at the fingertips of the tested arm after the lower body fatiguing protocol were 18% higher compared to control conditions (Figure 5). Hence, it is also possible that that the increased blood lactate influenced the local milieu of the elbow flexors peripherally affecting fatigue resistance. Additionally, it could also be hypothesised that a psychological strain was induced by the lower body fatiguing protocol leading to mental fatigue and hindering fatigue resistance (Marcora, Staiano, & Manning, 2009).

Biceps' EMG activity did not differ between the two conditions (Figure 4). This could be explained by a number of possibilities. First, despite asking the participants to keep their wrist in a supinated position throughout the protocol, minor shifts towards pronation with the wrist could have influenced biceps' EMG readings with possible changes in synergistic contributions (e.g. brachialis and brachioradialis). Second, it has been demonstrated the force-EMG relationship is not always linear (Lawrence & De Luca, 1983). This is particularly the case at the high force portion of the EMG-force relationship (Kamen & Gabriel, 2009). At last, it could be that the surface EMG was not sensitive enough to capture the differences between conditions, which were relatively small (~5%). However, despite the fact that biceps brachii EMG did not differ between conditions, it followed a similar pattern to that of force across conditions (Figure 4). A similar pattern was found for triceps, in which no significant differences were found between conditions. Hence, the decreased elbow flexor MVC force could not be attributed to increased co-activation level activity.

Limitations

A major limitation of the present study was the inability to distinguish between central and peripheral fatigue since techniques such as interpolated twitch technique and evoked contractile properties were not employed. Rather than a purely neural mechanism for the impaired fatigue resistance, the increased blood lactate from the knee extension fatiguing protocol could have negatively affected elbow flexor force output. Accordingly, it is suggested that similar future studies identify more clearly the locus of fatigue. Additionally, as was already discussed, EMG was collected from only one of the elbow flexors (biceps brachii), which could explain the lack of significant difference between the conditions.

Conclusion

Fatigue effects were found in which a prior knee extension fatiguing protocol negatively affected elbow flexors force during the last five MVCs during a repeated MVC protocol. In contrast, the single elbow flexors MVC performed after the lower body fatiguing protocol was not affected. The results may help explain some of the discrepancies in the literature, as it demonstrated that the effects were revealed only in later stages during a repeated maximal effort protocol with short rest periods. The practical applications of this study are as follows; performing a fatiguing lower body exercise may hinder the later stages of a repeated maximal force production with the upper body.

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