The effect of maximal vs. submaximal contractions on crossover fatigue between limbs

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Abstract

Background: When targeting increased muscle strength, resistance training is revered as the ideal method of achieving this goal. Emerging amounts of evidence indicates that to increase muscular strength, exerting the muscle to a fatiguing point may be required, and that not only the trained muscle can achieve strength increases. When a different muscle than the one being trained achieves a training effect, this phenomenon is known as cross-education. When muscle fatigue is transferred, this is called crossover fatigue, which could link to cross-education, and may not be the same for contralateral limbs as ipsilateral limbs.

Aims: To determine whether the amplitude of crossover fatigue remains the same for both the contralateral and ipsilateral limb, and to compare the effects of maximal versus submaximal fatiguing tasks. Additionally, both central and peripheral factors were investigated.

Method: 18 participants (age 21.8 ± 1.1 years) volunteered for the study, and completed three different testing sessions in the laboratory; a control session, a maximal fatiguing session and a submaximal fatiguing session. Measurements of MVC and electrical stimulation (twitch) were taken prior to (PRE) and after (POST) exercise on the right leg (exercised limb, EL) and left leg (contralateral limb, CL), with only MVC measurements of the right arm (ipsilateral limb, IL).

Results: MVC force output significantly declined by 38 % in the exercised leg during both the maximal and submaximal fatiguing session. During the maximal session, no fatigue was documented in either the contralateral nor the ipsilateral limb. During the submaximal session, a decline of 6 % was found in both the contralateral limb and the ipsilateral limb, although the decline was not statistically significant for the contralateral limb. The twitches were reduced by 21 and 10 % for the exercised limb during the two sessions, while interestingly, the contralateral limb twitch force increased by 20 and 18 %. No significant changes were found in voluntary activation.

Conclusion: This study found a significant difference in effect between the maximal and submaximal fatiguing task in the ipsilateral limb, as well as a trend in the contralateral limb, both being in favor of the submaximal fatiguing session. Central mechanisms appear to be the main cause of crossover fatigue. There is also an implication that a compensating factor, like antagonistic activation, may have played a part in the decreases in force output, which could explain the results.

Abstrakt

Bakgrunn: Når økt muskelstyrke er målet, er styrketrening ansett som den ideelle metoden for å nå dette målet. Fremtredende bevis indikerer at å utøve muskelen til utmattelse kan være nødvendig for å øke muskelstyrken, og at ikke bare den trente muskelen kan oppnå styrkeøkninger. Når en annen muskel enn den som trenes oppnår en treningseffekt, er dette fenomenet kjent som krysningslære. Når muskelutmattelse overføres kalles dette krysningsutmattelse, som kanskje kan kobles til krysningslære, og oppfører seg ikke nødvendigvis likt for kontralaterale og ipsilaterale lemmer.

Mål: Å avgjøre om effekten av krysningsutmattelse forblir den samme for både kontralateral og ipsilateral lem, og for å sammenligne effektene av maksimale versus submaksimale utmattende oppgaver. I tillegg ble både sentrale og perifere faktorer undersøkt.

Metode: 18 deltakere (alder 21.8 ± 1.1) meldte seg frivillig til studien, og gjennomførte tre forskjellige testøkter i laboratoriet i følgende rekkefølge; En kontrolløkt, en maksimalt utmattende økt og en submaksimalt utmattende økt. Målinger av MVC og elektrisk stimulering (twitch) ble tatt før (PRE) og etter (POST) øvelse på høyre ben (utøvd lem, EL) og venstre ben (kontralateral lem, CL), med kun MVC målinger av høyre arm (Ipsilateral lem, IL).

Resultat: MVC kraftutgang opplevde en signifikant nedgang på 38% i utøvd ben under både den maksimale og submaksimale økten. Under maksimal økt ble ingen utmattelse funnet i hverken kontralateral eller ipsilateral lem. Under den submaksimale økten ble det funnet en nedgang på 6 % i både kontralateral lem og ipsilateral lem, selv om nedgangen ikke var statistisk signifikant for kontralateral lem. Twitch ble redusert med 21 og 10% for den utøvde lemmen i løpet av de to øktene, mens det interessant nok økte kontralateral lems verdier med 20 og 18%. Ingen signifikante endringer ble dokumentert ved frivillig aktivering.

Konklusjon: Denne studien fant en effektforskjell mellom den maksimalt og submaksimalt utmattende oppgaven i ipsilateral lem og kontralateral lem, som begge er til fordel for den submaksimalt utmattende økten. Sentrale mekanismer synes å være hovedårsaken til overførbar utmattelse. Det er også sannsynlig at en kompenserende faktor, som antagonistisk aktivering, kan ha spilt en rolle i kraftreduksjonen, noe som kan forklare resultatene.

Acknowledgement

I would like to thank my main supervisor at NTNU, Karin Roeleveld, for guiding me throughout the writing process of this thesis. I also wish to thank my supervisor at the University of Nice Sophia Antipolis, Serge Colson, for all educational (and bureaucratic) help and guidance.

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Abbreviations

EL = Exercised Limb (right leg)

CL = Contralateral Limb (left leg)

IL = Ipsilateral Limb (right arm)

PA = Physical Activity

PRE = Measurements taken prior to the fatiguing task

POST = Measurements taken after the fatiguing task

MVC = Maximum Voluntary Contraction

VA = Voluntary Activation

TTI = Torque-Time Integral

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Background

When targeting increased muscle strength, resistance training is revered as the ideal method of achieving this goal. When a chosen muscle is subjected to increased resistance over time, the muscle in question has been known to increase force output, cross-sectional size, or both (Farup et al., 2012, Gandevia, 2001b, Fimland et al., 2009, Hortobágyi et al., 1997). One would think that this increase in strength only would apply to the muscle being trained. However, there is emerging evidence that not only the trained muscle can achieve strength increases. The phenomenon that occurs when a different muscle than the one being trained achieves a training effect is known as cross-education, and is defined as the event in which the positive effects of resistance training affect the contralateral or ipsilateral equivalent of the muscle receiving resistance training (Howatson et al., 2013).

Cross-education has been shown to affect primarily homologous muscles, which means that the contralateral equivalent of the trained muscle group receives a significant strength increase, with the degree of cross-education being roughly half of the strength increase in the exercised muscle (Carroll et al., 2006a). There is, however, emerging evidence which indicate that to increase muscular strength, exerting the muscle to a fatiguing point may be required (Keller-Ross et al., 2014). As such, one can assume that exerting enough force in a muscle group will not only lead to fatigue (in the short run), but increase strength (in the long run), and half of this strength increase could show in a homologous muscle group.

Muscular fatigue is defined as an exercise-induced reduction in the muscles' maximum voluntary force production, which translates to an inability to preserve the strength level required throughout the muscular exercise (Boyas and Guevel, 2011, Barry and Enoka, 2007). A muscle will increasingly reduce its ability to perform a specific task if used to repeated, sustained or intense contractions (Allen et al., 2008). This is called neuromuscular fatigue, and can be described as a decline in the musculature's ability of voluntary force production, caused by extensive muscle use (Enoka and Duchateau, 2008, Rattey et al., 2006, Todd et al., 2003). Simplified, neuromuscular fatigue is a decrease in physical capacity induced by exercise, and carries with it an increased difficulty to perform whatever exercise or task is given. Essentially, when somebody performs a given exercise with sufficient intensity, eventually they will come to a point where they will be unable to continue the task.

During maximal exercise, the consequence of this decline in force production is that the neuromuscular system attempts to compensate for it by using several different nervous- and muscle-related mechanisms to avoid failure to complete the task given, which can also be seen as a means for limiting the potentially harmful ramifications of strenuous muscular exercise. When viewing submaximal exercise, the process is slightly different. Here, the neuromuscular system will attempt to correct the muscular decrements by increasing central drive, thus recruiting additional motor units to help complete the task (Taylor and Gandevia, 2008, Boyas and Guevel, 2011). Although these neuromuscular modifications begin simultaneously with the task and neuromuscular fatigue becomes progressively prominent until failure, most of this decrease in muscular performance capability will recover once the exercise ends (Allen et al., 2008, Boyas and Guevel, 2011). To measure the fatigability of the musculature during a sustained contraction, changes in maximal voluntary contraction (MVC) force is normally evaluated (Enoka and Duchateau, 2008).

There are two subgenres of muscular fatigue; peripheral fatigue and central fatigue. Peripheral fatigue is described as the fatigue located locally within the muscle. Therefore, it is also known as local fatigue. It is caused by a metabolic inhibition of the contractile process and excitation-contraction couple failure, and uses twitch force and tetanic force as markers when measuring (Kent-Braun, 1999, Taylor and Gandevia, 2008, Boyas and Guevel, 2011, Dulhunty, 2006).

Central fatigue is described as a decrease to the motor neurons in the central drive. While peripheral fatigue is based locally in the muscle, central fatigue is not, and is therefore known to be susceptible to the crossover effect. This is the reason why central fatigue is generally associated with crossover fatigue (Kennedy et al., 2015, Gandevia, 2001a). Central fatigue is generally estimated by calculating the level of voluntary activation. This is done by using a formula based on the MVC, potentiated twitch, and superimposed twitch, with the latter two requiring peripheral nerve stimulation (Allen et al., 1995, Herbert and Gandevia, 1999).

The main distinction between central and peripheral fatigue is that central fatigue refers to a failure of nervous system’s ability to evoke and drive motor neurons, thus failing to activate the muscle in question fully, while peripheral fatigue refers to the muscle’s responsive capabilities to neural excitation and force production (Allen et al., 2008, Gandevia, 2001b, Barry and Enoka, 2007). To differentiate between these two forms of fatigue, evaluation of shifts in various responses to electrical nervous stimulation at varied intensities are utilized (Todd et al., 2003).

Crossover fatigue, which also goes by the term non-local muscle fatigue, is described as “muscle performance impairments in a contralateral or non-exercised muscle group following a fatiguing protocol of a different muscle group” (Halperin et al., 2015). This essentially means that the non-exercised muscle group will weaken as an effect from the exercised muscle group

(Rattey et al., 2006, Todd et al., 2003). As previously mentioned, the crossover effect might be a pre-requisite for strength and/or muscle mass. However, the exact nature of how fatigue impacts the crossover effect is not clear (Doix et al., 2013, Zwambag and Brown, 2015). Crossover fatigue has been investigated between ipsilateral and contralateral, homologous and heterogeneous muscles, but the largest amount of research is based on contralateral musculature. Previous studies have reported a decline in force production and voluntary activation after sustained, unilateral exercise when investigating the knee-extensors (Rattey et al., 2006, Halperin et al., 2014b, Doix et al., 2013). When performing similar testing of the elbow flexors however, several studies reported less or no crossover fatigue in the contralateral limb (Grabiner and Owings, 1999, Todd et al., 2003, Halperin et al., 2015). There is less research on the effects of knee-extension fatigue on the elbow flexors, although some studies report fatigue after a lower limb fatiguing protocol here as well (Halperin et al., 2015). Several factors contribute to these polarizing findings, like musculature exercised, duration and intensity of the protocols, as well as what kind of fatiguing exercise the research teams chose for their respective studies (Boyas and Guevel, 2011, Nordlund et al., 2004, Halperin et al., 2015).

These results support the fact that neuromuscular fatigue and the crossover effect could be influential for every-day functionality, which includes balancing and maintaining postural control, stabilization and locomotion for the body (Rattey et al., 2006). The crossover fatigue may be important for this, particularly for the lower limbs, due to their predominant role in performing these functionally specific movements.

The aim of this study was to compare contralateral with ipsilateral crossover fatigue, and to see if the effects differ relating to whether a maximal or submaximal protocol session had been utilized. Therefore, during both a maximal and submaximal testing session, neuromuscular fatigue was quantified in the knee-extensor musculature, and the degree of crossover fatigue from the exercised limb to the contralateral knee-extensors as well as the ipsilateral elbow-flexors was determined with the use of central and peripheral measurements.

Hypothesis: the amount of crossover fatigue will be greater after a maximal fatiguing protocol, as most previous research have found crossover fatigue when using a high intensity protocol. The amplitude of crossover fatigue will be larger for the contralateral limb than the ipsilateral limb, and the effects are caused by central rather than peripheral factors.

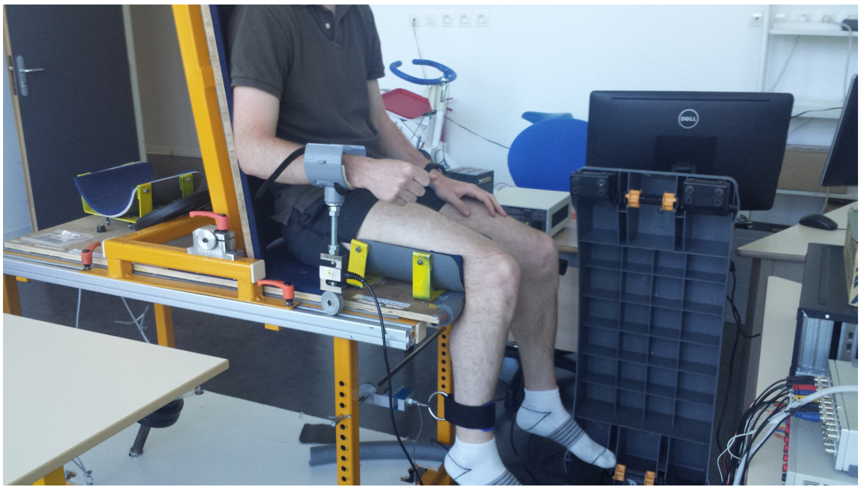
Method

Participants

18 healthy men (n=9) and women (n=9) (age 21.8 ± 1.1 years; height 172.3 ± 9.1 cm; weight 66 ± 11 kg; mean ± SD) were recruited as volunteers for the study. All participants (9 male and 9 female) were students at the faculty of Sports Sciences at the University of Nice Sophia Antipolis. Each participant was informed about the purpose of the study in addition to the potential risks involved. All the participants were physically and/or recreationally active, with at least one specific sport performed by every participant, as well as fitness scores of 9.2 ± 1.4 on the Baecke AQAP for Physical Activity Self-Administered Questionnaire, where the score ranges from 0 to 15 (Bedouet et al., 2011). None of the participants reported any kind of diseases or injuries for the previous three months. Ethical approval was given by the university. They were also informed about the experimental procedure prior to the study, and provided written consent to the university.

Experimental setup

All measurements were made unilaterally on both legs, as well as the right arm. The fatiguing exercise was performed only on the right leg, hereby referred to as the exercised limb (EL). As seen in Figure 1, the participants were positioned in a chair, with their upper body maintaining an individually natural (neutral, ca 100-110°) hip angle, and their knees positioned in a 90-degree angle, as shown in Figure 1. Straps were placed around the waist and chest to hinder upper body movement and shifting of body position during the sessions. The arms of the participant could either hold onto the chair, or cross over the chest and hold on to the chest strap during the leg testing and the fatiguing exercise. Participants were told to attempt to keep the rest of the body. Particularly the right arm (ipsilateral limb, IL) and the non-exercised left leg (contralateral limb, CL), as relaxed as possible during the fatiguing exercise. The position of the body was maintained during the different experimental protocols.



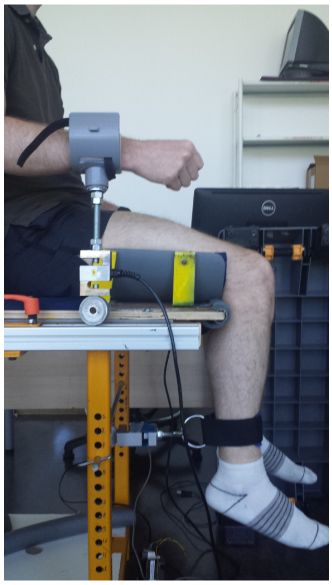


Figure 1A: Body position throughout the experimental protocol. The IL was only in this position while it was being tested.

Figure 1B: setup viewed sideways

Study design

Every participant came by the laboratory three separate days, with the first performed being a familiarization session (control), a second session using 100% MVC (maximal), and a third session using 25% MVC (submaximal) yet the same torque-time integral (TTI,) as the maximal session, occurring in this order. Each testing day/session was separated by at least three days, with the participants getting told to not engage in any straining or otherwise intense activity that could affect the outcome of the testing sessions. The goal of the first session was to familiarize the participants with the protocol, equipment and electrical stimulation of the femoral nerve, and document each participant's individual setup (i.e. chair position/angle, force transducer height, stimulation intensity for each leg), as well as act as a control session when comparing the results to the next two sessions.

The measurements were made before (PRE) and after (POST) the fatiguing exercise.

Experimental procedure

For each session, the participants warmed up with 3 minutes of cycling on a stationary bicycle with 50-watt resistance, before performing 10 bodyweight squats, as a general warmup. After this brief warmup, they got strapped into the chair, the EL was secured to a force transducer located at the frame of the chair, and was moved to the other side of the frame to be attached to the CL when that leg was to be tested.

Once strapped in the participants could continue with a specific warmup for the limb in question with submaximal isometric contractions until they were ready to perform the maximum voluntary isometric contractions (MVC). They were told to relax while receiving electrical stimulation on the femoral nerve. Once the participant's optimal stimulation intensity was found, 3 single twitch stimulations were given in a row. Then, the participants were tasked with performing MVCs until plateauing, with the necessary amount of break time given between the MVCs for the participants to be able to achieve their maximum. A doublet stimulation was given at peak MVCs, after which the participants were told to relax. Another doublet stimulation was given 5 seconds after the onset of the first. The EL was tested first, before the force transducer was moved to the CL, and the procedure was repeated. Once both legs had been tested, the IL was strapped to its own force transducer, and received the same treatment as the legs, with submaximal contractions as a specific warmup, before the limb was tested for MVC. Unlike the legs, no electrical stimulation was given for the IL. Between and during the MVC testing, several different measurements were taken, as further described below (see Figure 2 below). After fatiguing task completion, POST-testing commenced immediately. To limit recovery for the CL and IL, POST-tests consisted of a single MVC for each limb, as this would keep the recovery time as short as possible. During each MVC, the participants received a doublet stimulation at peak MVC, with another doublet delivered 5 seconds later, just like during the PRE-measurements. One thing that differed from the PRE-measurements were the single twitches, which were delivered at rest after the POST-MVCs were done. Three single twitch stimulations were given for both legs, with the CL first and EL after, as the force transducer used on the legs would be strapped to the CL after the MVC measurements, as shown in Figure 2.

During both the maximal and submaximal test protocol, the participants received verbal encouragement during the MVCs and fatiguing protocol from the testing experimenter.

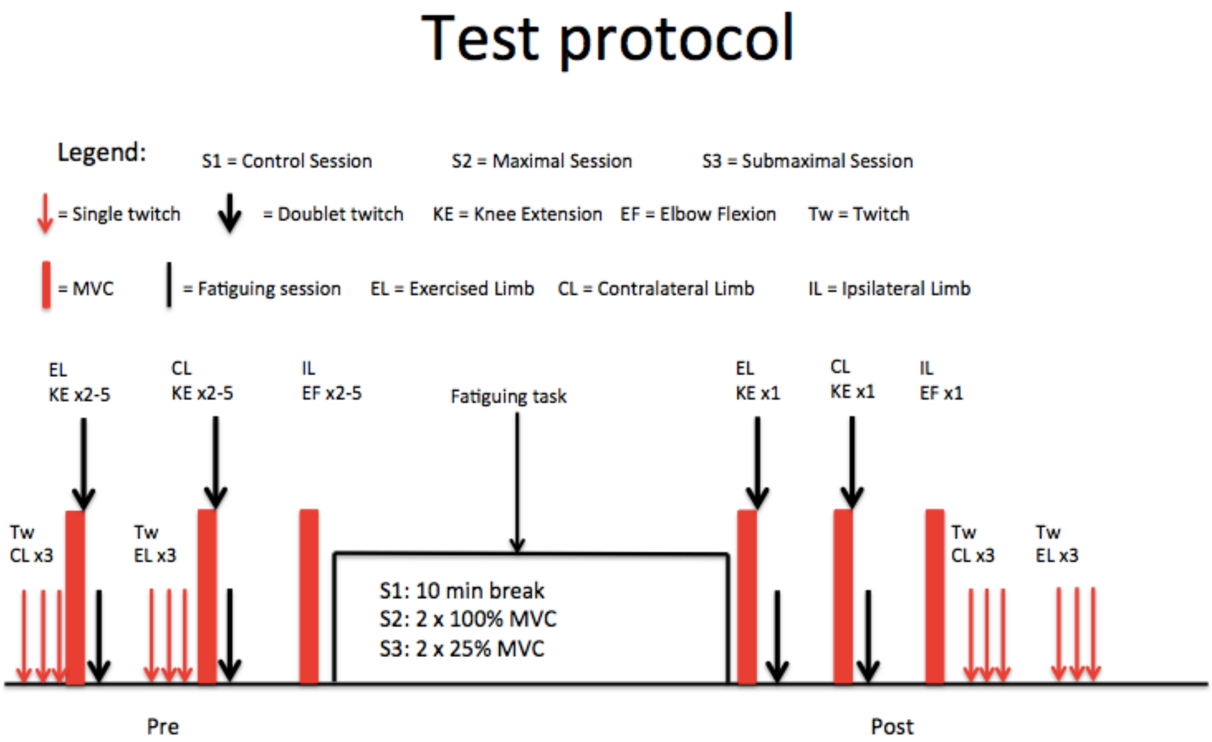


Figure 1: Test protocol. Measurements taken prior to (PRE) and after (POST) the fatiguing task consisted of MVCs, single twitch stimulations at rest, and superimposed and potentiated doublet twitch stimulations. Between PRE and POST, a fatiguing task was given, with a 10 minute break during the control session, 2 x 100 % isometric MVC contractions with 1 minute rest during the maximal session, and 2 x 25 % MVC isometric contractions with 1 minute rest during the submaximal session. During POST testing, MVCs were performed first with superimposed and potentiated doublet twitch stimulation, while single twitch stimulations were performed last.

Fatigue protocol

For the control session, the participants kept still in their position in the chair for 10 minutes. This amount was chosen to keep the time frame as consistent as possible with the maximal and submaximal protocol.

During the maximal session, the participants were tasked with performing 2 × 100 second isometric knee-extension MVCs, with 1 minute of rest between the MVCs. When beginning the task, the participants were told to attempt to reach their PRE-values of MVC to make sure that they indeed performed 100 % MVCs during the fatiguing task. When the fatiguing task was finished, the POST-measuring started immediately, and after the session, the torque-time integral (TTI) was calculated for both bouts.

For the submaximal session, the participants were tasked with performing 2 bouts of isometric knee-extension. Unlike the maximal session, the participants were told to keep their force output at 25 % of their measured PRE-MVC, but to keep contracting until told to stop. During the task, participants were given visual feedback from a monitor, enabling them to keep force output steady. For both bouts, the testing experimenter made sure to tell the participants to stop contracting once the calculated TTI from the maximal session was reached. The first bout of the submaximal session was to be identical to the first bout of the maximal session, with the same applying for the second bout. Between the two bouts in the submaximal session, 1 minute of rest was given.

Force measurements

For measuring isometric force measuring and fatiguing the participants, a force transducer (SM 2000N, Interface, Scottsdale, USA) was secured to one leg at the time, with the EL first and the CL after. Another force transducer (Celtron STC/STC-S 2500N, USA) was secured to the IL during testing and warmup of that limb only. When securing the limbs, two straps with added padding was used on each limb.

Electrical stimulation

To measure potentiated twitch torque and calculate voluntary activation, electrical stimulation was utilized, with single stimulation used for the twitch values derived between testing, and doublet stimulation used for superimposed twitch as well as potentiated twitch measured 5 seconds after onset of supramaximal MVC stimulation. The twitch torque values presented in this study are calculated as the mean of the three consecutive stimulation responses. This was achieved using an electrical stimulator (Digitimer DS7AH, Digitimer, Herthforshire, United-Kingdom), which regularly delivered electrical pulses either programmed into the test file, or manually delivered by the testing experimenter.

To stimulate the knee extensors, two bipolar silver-chloride electrodes (10-mm diameter, Contrôle Graphique Medical, Brie-Comte-Robert, France) were placed on the femoral nerve on the EL and the CL. The electrodes were placed by hand by the testing experimenter while the participant lied on their back at a table in the lab.

The participants received electrical stimulation induced manually after the limb-specific warmup had been completed. The stimulus was 400 V and 2 ms rectangular pulse. To determine the individual intensity level required to reach a proper potentiated as well as superimposed twitch, stimulation was increased gradually from 50 mA (with 50 mA increase every time), to the point of a plateau, where the stimulation would no longer increase the amount of force produced in the legs. When this plateau was reached, the stimulation was increased by another 20 % to induce a supramaximal stimulation, ensuring that the true peak was indeed achieved.

During doublet twitch stimuli, this intensity was utilized, with 10 ms at 100 hz separating the two stimuli given.

Data analysis

All data accumulated was analysed using the program Acqknowledge 4.1, Biopac Systems, Inc., Holliston, MA, USA.

Force data

Out of the all MVCs performed, the one with the highest peak force was selected from both the PRE and POST testing for further analysis. In the cases where the peak force occurred at the point of electrical stimulation, the peak force was measured from the selected baseline to just prior to the stimulation. In the cases where peak force occurred before stimulation, the peak force was measured from the selected baseline to the measured peak.

Potentiated twitch was measured as peak-to-peak amplitude from baseline at the point of stimulation, to the peak occurring closest to the 40-60ms interval after onset, as this is considered the normal amount of time it takes for muscle fibers to activate. An example of an MVC and its respective superimposed and potentiated twitch are shown in Figure 3.

All force data was recorded in Volts, and was converted to Newton using the following formulas:

EL and CL: $N = 186{,}98 \times V + 0{,}0056$

IL: $N = 222{,}02 \times V + 0{,}131$

When peak force level occurred at the point of stimulation, the level of voluntary activation was calculated using data derived from the potentiated and superimposed twitch with the following formula:

%VA = (1-superimposed twitch ÷ potentiated twitch) × 100

When peak force occurred before the point of stimulation, a different formula was used to account for this:

%VA = (1-(superimposed twitch × force level just before stimulation ÷ MVC force) ÷ potentiated twitch) × 100

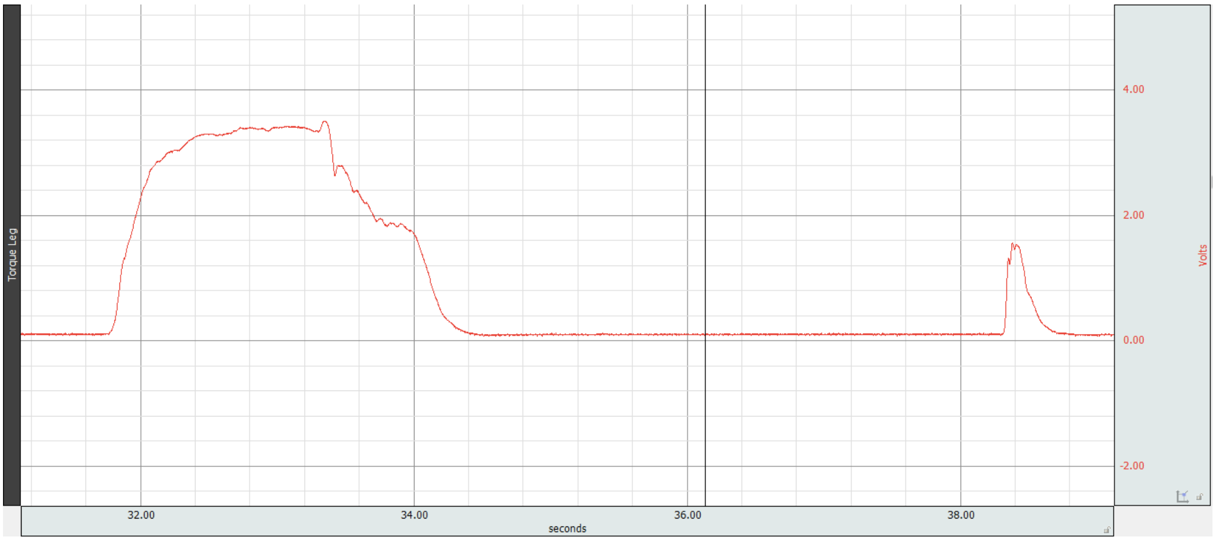


Figure 2: Force and twitch recordings during an MVC. Superimposed twitch occurs here as a response to electrical stimulation at 33.4 seconds, with the potentiated twitch occurring at rest, 5 seconds later.

Statistical analysis

All statistical analysis was conducted using SPSS Statistics, Version 24.0 (IBM Corp., NY, USA). The level of statistical significance was always set to $p \leq 0.05$, meaning that any significance level of $p > 0.05$ was deemed statistically nonsignificant.

Mixed Models tests were used to determine the main effects of session, time and interaction between session × time on each limb, with participants always set as a random factor, and session, time and limb set as fixed factors.

Paired Samples T-tests were used as post hoc tests to evaluate the interactions between the factors.

For the normality of the data, histograms were created for visual assessment. In addition, an automatic one-sample nonparametric analytical test was performed.

All the variables are given as mean ± 95% confidence interval.

Results

All participants performed the control session, as well as the maximal and submaximal fatiguing tasks successfully on their respective days, and the participants managed to maintain roughly 25% of their MVC during the submaximal fatiguing session until told to stop. This resulted in the same amount of total force exerted during the submaximal fatiguing session as the maximal fatiguing session.

There was reason to believe that one of the participant did not perform the task as required during Post- and Recovery testing. This participant's calculated Voluntary Activation level was 21% during POST, which is below values supported by literature. Therefore, this participant was excluded from further analysis in this study.

MVC

Figure 4 displays the produced peak force conducted during the participants' MVCs, with the EL, CL and IL prior to and after the fatiguing exercises. The EL reduced force output during the maximal and submaximal fatiguing sessions, resulting in 38% lower mean MVCs after the fatiguing exercise (p=0.000). The IL also experienced a statistically significant (p=0.014) decrease in force output by 6 %, though this only occurred during the submaximal fatiguing session. During the same session, there was also a trend (p=0.06) towards fatigue in the CL, of 6 %. The maximal fatiguing session provided no statistically significant decrease in force output for neither the IL, nor the CL.

A paired samples T-test of the differences between the changes in MVC during the maximal and submaximal sessions, revealed that there was a trending (p=0.065) difference between the two sessions for the CL, and a statistically significant difference (p=0.047) between the sessions for the IL.

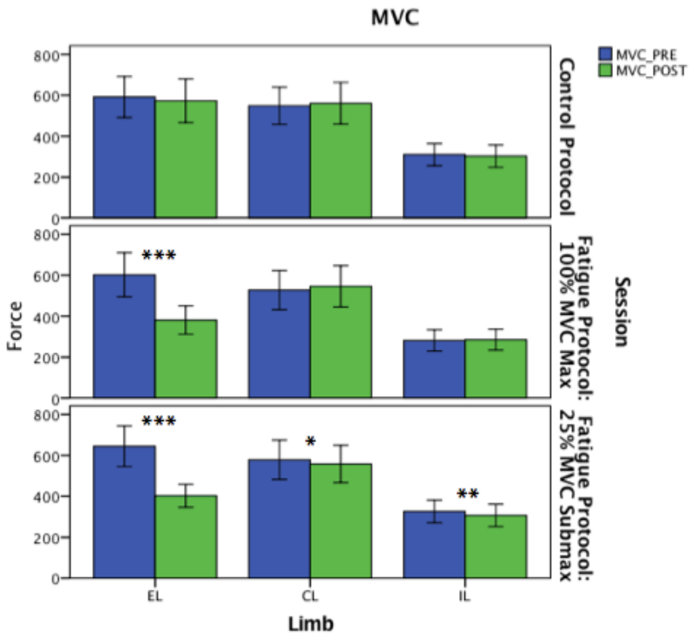


*Figure 3: MVC force given in Newton prior to(PRE) and after (POST) fatiguing task for the exercised limb (EL), contralateral limb (CL), and the ipsilateral limb (IL) for all three sessions. ***p<0.001 **p<0.05 *p<0.1. Error bars represent 95 % Confidence Interval.*

Twitch Torque

Figure 5 displays the produced twitch torque derived after the participants' MVCs, with the EL and CL prior to and after the fatiguing exercise. The mixed model test showed no difference between the sessions, and the EL and CL had similar twitch torque values, but it showed a significant limb × pre-post interaction ($p<0.001$). The EL reduced twitch torque during the maximal and submaximal fatiguing sessions, with 20-25% lower mean twitch after the fatiguing exercise during the maximal session ($p<0.001$), and 10-15% during the submaximal session, though this decrease was not statistically significant.

The CL experienced a statistically significant ($p<0.001$) increase in twitch torque by 10-15%, with the increase in values during both sessions being similar to one another.

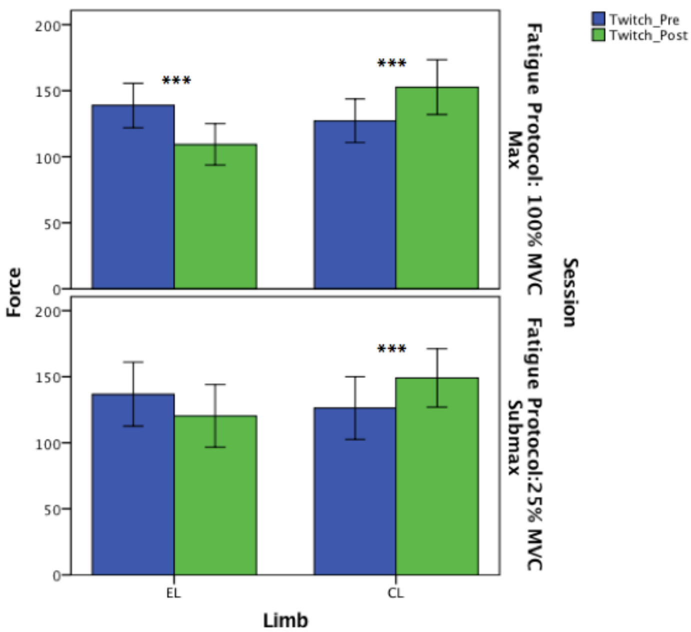


*Figure 4: Twitch torque given in Newton prior to(PRE) and after (POST) fatiguing task for the exercised limb (EL) and contralateral limb (CL) for all three sessions. ***p<0.001 **p<0.05 *p<0.1. Error bars represent 95 % Confidence Interval.*

Voluntary Activation

Figure 6 displays the voluntary activation level of the participants, with the EL and CL prior to and after the fatiguing exercise. Neither of the legs experienced any statistically significant changes between PRE and POST. The EL experienced a trend toward decline in VA level during the maximal session, however (p=0.072). There was also uncovered no difference between the sessions.

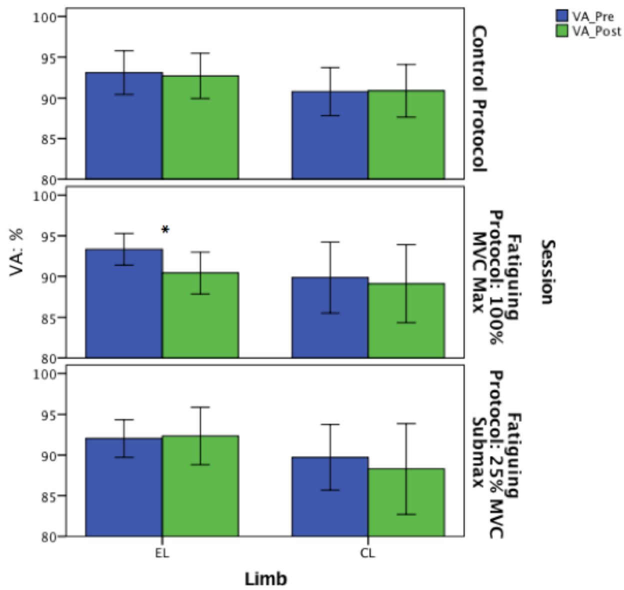


*Figure 5: Voluntary activation given in percent prior to(PRE) and after (POST) fatiguing task for the exercised leg(RL), non-exercised leg(LL) for all three sessions. ***p<0.001 **p<0.05 *p<0.1. Error bars represent 95 % Confidence Interval.*

Discussion

Main findings

In this study, the aim was to ascertain any changes in maximal voluntary force production in the contralateral knee extensors (CL) and the ipsilateral arm flexors (IL) after performing two different fatiguing tasks, and to determine which fatiguing task, if any, would induce greater amounts of fatigue in the contralateral and ipsilateral limbs. To achieve this, both the central and peripheral mechanisms of the crossover effect were examined. In this study, the main findings were that both sustained MVCs and sustained submaximal contractions led to fatigue in the exercised limb, but only submaximal contractions led to crossover fatigue in the contralateral and ipsilateral limbs. The effect was statistically significant for the IL, while for the CL, the effect was statistically non-significant, yet trending. There was no significant difference between the CL and IL. These findings are in contrast with the hypothesis that a maximal session would induce greater amounts of crossover fatigue, and that the contralateral limb would achieve greater amount fatigue than the ipsilateral limb. This crossover fatigue could only be attributed to central mechanisms, as the twitch torque (which is a peripheral measurement) increased in the CL rather than decrease. This is in accordance with the hypothesis, but is not confirmed by the voluntary activation levels of the participants, as these were expected to decrease, yet did not. There is an overarching tendency of non-significant results in the current study, which makes concluding difficult, especially as the lack of crossover fatigue using a maximal fatiguing protocol is in contrast with previous studies.

Changes in force and crossover-fatigue

During both the maximal and submaximal fatiguing sessions, MVC force production in the EL was reduced by approximately 38 %, a reduction level that is consistent with previous studies investigating isometric fatigue of the knee extensors of the right leg, with previous studies reporting between 20-50 % decrease in force production, sometimes based on muscle fiber composition (Hamada et al., 2003).

The maximal fatiguing protocol did not lead to crossover fatigue. This is in contrast with the hypothesis and previous studies reporting greater crossover fatigue resulting from a maximal protocol rather than a submaximal one (Taylor and Gandevia, 2008). Previous studies have mainly used repetitive MVCs for maximal protocols, while submaximal protocols have generally used light intensities until exhaustion, making them hard to compare (Halperin et al., 2015). A possible explanation for the lack of crossover fatigue after the maximal fatiguing protocol in the present study could simply be that the submaximal fatiguing protocol lasted longer than the maximal one, as prolonged contractions consistently demand more neural input, which according to Behm could augment global neural fatigue as well as afferent inhibition of cortical and spinal motoneurons (Behm, 2004).

The CL had a trending decrease in force production by approximately 6 % during the submaximal fatiguing session. This decrease in the contralateral limb is similar to that achieved in other studies focusing on the fatiguing of limbs and the resulting crossover effect, with decreases in voluntary force production ranging from 4 % to 14 % (Rattey et al., 2006, Doix et al., 2013, Martin and Rattey, 2007).

The IL had a significant decrease of approximately 6 % during the submaximal fatiguing session. This decrease is in line with previous studies reporting decreased force production ranging from 4 % to 12 % in the ipsilateral elbow flexors after a knee-extension fatigue protocol, although some results are conflicting (Šambaher et al., 2016, Ben Othman et al., 2016, Halperin et al., 2014a, Halperin et al., 2014b). The hypothesis was that the contralateral limb would achieve greater crossover fatigue than the ipsilateral limb, yet the results are similar between the two. There have been indications that crossover fatigue affects the ipsilateral elbow flexors to a lesser degree than the contralateral knee extensors, although the amount of research on the former is currently lacking compared to the latter (Halperin et al., 2015).

The crossover fatigue presented in the present study may not lead to any detectable cross-education in either the contralateral or ipsilateral limb, as the decline of 6 % in both limbs is in the lower end of the spectrum, and there is little research investigating the link between the two. Research suggests that cross-education is caused by increased motoneuron output, meaning that central mechanisms are the cause (Carroll et al., 2006b). This suggests that crossover fatigue could correlate to cross-education. As such, it would have been interesting to measure any strength increases resulting from the present study, and determine which of either; the total fatigue of the exercised musculature or the crossover fatigue of the contra/ipsilateral musculature show stronger correlation with cross-education.

Peripheral mechanisms

In this study, peripheral fatigue was assessed by investigating changes in twitch torque between PRE and POST. The EL’s decreases of 21 % (significant) during the maximal session and 10 % (nonsignificant) during the submaximal session in twitch torque are consistent with previous reports of decline percentages in the knee-extensors after exercise (Doix et al., 2013, Martin and Rattey, 2007). The CL had a statistically significant increase of 20 % during the maximal session and 18 % during the submaximal session in twitch torque, indicating that a potentiated phenomenon sometimes experienced by other studies, could have occurred. This post-activation potentiation phenomenon can occur along with fatigue, and is attributed to: phosphorylation of myosin regulatory light chains, which increases myosin and actin sensitivity to calcium, or increases in α-motoneuron excitability (Hodgson et al., 2005, Colson et al., 2009). As the CL was expected to decrease its twitch torque values as well due to this being the case in previous studies, this increase was surprising.

In accordance with the hypothesis, the results indicate that only the EL was subject to peripheral fatigue, with lowered twitch torque values pointing to a deterioration in excitation-contraction coupling, while the CL was only subjected to deterioration in force output while increasing twitch torque values, thus pointing to central mechanisms as the main factor of the present crossover fatigue (Enoka and Duchateau, 2008, Barry and Enoka, 2007, Nordlund et al., 2004, Behm and St-Pierre, 1997, Neyroud et al., 2012, Duchateau and Hainaut, 1985).

Since the force reduction in the EL was roughly twice the reduction reported in twitch values for the maximal session, and about four times greater than the reduction in twitch values during the submaximal session, there is an indication that the nervous system or other bodily mechanisms have attempted to compensate for the decrease in force production. What could be the case is that the central nervous system reacted to the peripheral fatigue by increasing the neural drive. Alternatively, a different explanation for the reduction in measured force could be the activation of antagonistic musculature, i.e. the hamstrings. This is likely to have affected the present results, as co-activation of antagonistic musculature has been known to increase with progressive fatigue in the knee extensors (Rothmuller and Cafarelli, 1995, Bouillard et al., 2014).

Central mechanisms

For this study, central fatigue was assessed by investigating changes in voluntary activation between PRE and POST. The VA levels of the EL and CL, which were determined using MVC data and twitch interpolation, experienced no changes between PRE and POST. This was unexpected, and not in accordance with the hypothesis or other studies investigating crossover fatigue, as these reported a significant decrease in VA levels for both limbs after fatiguing exercise (Rattey et al., 2006, Doix et al., 2013, Halperin et al., 2014b, Post et al., 2008, Martin and Rattey, 2007). As no changes seemingly occurred, one cannot conclude that the compensatory mechanisms that should be attributed to the limitation of peripheral fatigue, originate from the central nervous system. However, it should be noted that among all data collected (MVC, twitch torque, voluntary activation), the measurement with the largest amounts of missing data is the voluntary activation levels, as quantifying these levels meant utilizing a formula that requires both twitch and force data. Also, there is precedent to think that exercise-induced fatigue caused by continuous contractions at lower levels (≤30% MVC), is mainly caused by central rather than peripheral mechanisms (Place et al., 2009). This supports this study's findings, although it seems central mechanisms played an important role during the maximal session as well.

Methodological considerations

This study utilized both maximal and submaximal isometric contractions of the knee-extensors and elbow-flexors. Other studies have used many different protocols, yet sustained isometric maximal contractions of the knee-extensors and elbow-flexors appear to be the most common (Halperin et al., 2015). In this study, submaximal and maximal contractions were compared to either confirm what seems to be the current norm (maximal contractions work better), or to show that there could be a better option. The reason submaximal contractions were considered was due to a theory that since slow-twitch muscle fibers are under constant neural firing and fast-twitch fibers are constantly switching between work and rest, then a submaximal protocol would prove more efficient in inducing fatigue, as the nervous system would get more drained by this. This study's findings support this theory, as the only statistically significant fatigue of the elbow flexors was found during the submaximal session, with the non-significant results of the knee-extensors trending towards statistical significance here too.

Even though there were no statistically significant changes in voluntary activation, the trend in the maximal session supports what is seen in other studies, as the only studies that reported changes in VA all used maximal contractions. One study which investigated submaximal versus maximal fatiguing task differences found that VA levels decreased in both the exercised and non-exercised limb when using the maximal fatiguing task, while only the VA levels of the exercised limb decreased when using a submaximal fatiguing task, although this study tested the intrinsic hand muscles, not the knee-extensors (Post et al., 2008).

Threats to validity

Time delay when shifting the position of the force transducer could affect the results, as there was a time delay of 15-30 seconds between testing of the EL and the CL, as well as between the CL and the IL.

It should be noted that there was no measurement of twitch torque or voluntary activation of the IL, which was the only limb with statistically significant amounts of crossover fatigue. However, as the CL experienced a trend towards fatigue during the same session, it seems that central mechanisms played the main part in fatiguing the IL.

The VA levels of the participants did not experience any statistically significant changes between PRE and POST, but these results were also the ones most affected by missing data, which could explain why no statistically significant changes occurred.

Relevance of study

Like previously mentioned, crossover fatigue might play a crucial role in everyday life, as motoric behavior like locomotion, balancing and stabilizing the body requires a balance in the strength prospects of both sides of the body. This could be especially true for the lower limbs due to their prominent role when performing these activities. As such, crossover fatigue could be necessary to maintain this balance of strength between the limbs.

Further research

As this study only measured twitch torque values and voluntary activation levels, making any claims about the fatiguing aspects of the ipsilateral elbow flexors is difficult. For future research, making the same measurements on the arm should be considered in addition to the legs.

Conclusion

This study found a decline in voluntary force production after subjecting the right knee-extensors to two different fatiguing protocols; one maximal, one submaximal, with only the submaximal protocol resulting in crossover fatigue. This study found a difference in effect between the maximal and submaximal fatiguing task in the ipsilateral and contralateral limb, both being in favor of the submaximal fatiguing session. This confirmed that crossover fatigue had indeed taken place during the submaximal session, and suggest that submaximal fatiguing tasks may be more efficient at inducing crossover fatigue, and this could be attributed to the length of the contractions. The magnitude of crossover fatigue was similar in the contralateral and ipsilateral limb. The mechanisms causing this crossover effect appear to be central rather than peripheral, with the decline in force production differing from the increase in peripheral measurements caused by post-activation potentiation. However, the results are not completely reliable, as the measurements of central mechanisms could not explain the fatigue. It is likely that antagonistic musculature activation, or another factor not accounted for in the present study, was present during POST testing, which could explain the results.

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