

# The effect of eccentric exercise and delayed onset muscle soreness on the homologous muscle of the contralateral limb

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1  
2 **EFFECT OF ECCENTRIC EXERCISE AND DELAYED**  
3 **ONSET MUSCLE SORENESS ON THE HOMOLOGOUS**  
4 **MUSCLE OF THE CONTRALATERAL LIMB**  
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**ABSTRACT**

High intensity eccentric exercise induces muscle fiber damage and associated delayed-onset muscle soreness (DOMS) resulting in an impaired ability of the muscle to generate voluntary force. This study investigates the extent to which DOMS, induced by high intensity eccentric exercise, can affect activation and performance of the non-exercised homologous muscle of the contralateral limb. Healthy volunteers performed maximal voluntary contractions of knee extension and sustained isometric knee extension at 50% of maximal force until task failure on both the ipsilateral exercised limb and the contralateral limb. Surface electromyography (EMG) was recorded from the ipsilateral and contralateral knee extensor muscles (vastus medialis, rectus femoris, and vastus lateralis). Maximal isometric knee extension force (13.7% reduction) and time to task failure (38.1% reduction) of the contralateral non-exercised leg decreased immediately after eccentric exercise, and persisted 24 h and 48 h after ( $p<0.05$ ). Moreover, the amplitude of muscle activity recorded from the contralateral knee extensor muscles was significantly lower during the post exercise maximal and submaximal contractions following high intensity eccentric exercise of the opposite limb ( $p<0.05$ ). Unilateral high intensity eccentric exercise of the quadriceps can contribute to reduced neuromuscular activity and physical work capacity of the non-exercised homologous muscle in the contralateral limb.

**Key Words:** EMG, contralateral, pain, eccentric exercise

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**INTRODUCTION**

11           Musculoskeletal pain can induce cortical reorganization in both somatosensory  
12 and motor area (Flor, 2013), which in turn can reduce motor abilities of both the affected  
13 and unaffected limb. For example, deficits in motor output of the ipsilateral and  
14 contralateral limb have been identified during acute pain (Falla et al., 2007, Hedayatpour  
15 et al., 2008, Schabrun et al., 2016) and /or in chronic pain conditions (Akseki et al., 2008,  
16 Smeulders et al., 2002, Arguis et al., 2008).

17           Pain is also common after high intensity eccentric exercise, most likely due to the  
18 pathophysiological changes within the injured muscle. It has been reported that  
19 pathophysiological changes associated with tissue injuries ((Ebbeling & Clarkson, 1989),  
20 such as progressive necrosis of the contractile elements (Fridén et al. 1998), and the  
21 release of algescic substances ( e.g., prostaglandins ) (Amaya et al., 2013; Tegeder et al.,  
22 2002) enhances the responsiveness of nociceptive endings (Mense, 2003; Tegeder et al.,  
23 2002), large mechanoreceptor afferents, muscle spindles and tendons (Barlas et al., 2000;  
24 Taguchi et al., 2005), which in turn results in delayed onset muscle soreness (DOMS) 24  
25 to 72 hours after the exercise. Although considerable research has been devoted to the  
26 effect of DOMS on muscle activity and the force-generating capacity of the exercised  
27 muscles (Hedayatpour et al., 2009, Hedayatpour & Falla, 2014b), less attention has been  
28 devoted to the effect of DOMS on the functional parameters of non-exercised

1 homologous muscle in the contralateral limb. There are several potential mechanisms by  
2 which pain induced by eccentric exercise may contribute to reduced motor output of the  
3 contralateral non-exercised side.

4         For example, nociceptor sensitization associated with tissue injury can influence  
5 the primary afferents of muscle spindles at superficial layers of the dorsal horn of the  
6 spinal cord which cross to the contralateral side of brainstem and thalamus (Le Pera et al.,  
7 2001; Todd et al., 2003). Moreover, the presence of pain within the damaged muscle  
8 could mediate inhibitory effects on both ipsilateral and contralateral human motor cortex  
9 (Dimou et al., 2013). Accordingly, a ‘cross-over’ effect of muscle adaptations (e.g.,  
10 fatigue) has been reported for the upper and lower limbs after different types of exercise  
11 (Amann et al., 2008; Ruohonen et al., 2002; Todd et al., 2003; Willis, 1985). This  
12 evidence suggests that exercise induced change in motor ability of the exercised limb  
13 could also change motor output of the contralateral non-exercised side, most probably  
14 due to modulation of neural circuits at the level of spinal cord and motor cortex.

15         Based on these findings, we hypothesized that pain induced by high  
16 intensity eccentric exercise could contribute to the reduced motor ability not only in the  
17 exercised muscle, but also in the non-exercised homologous muscle in the contralateral  
18 limb. Therefore, the aim of this study was to evaluate whether high intensity eccentric  
19 exercise and subsequent DOMS in the exercised muscle affects neuromuscular activity of  
20 the non-exercised homologous muscle in the contralateral limb. Surface  
21 electromyography (EMG) was recorded from the ipsilateral and contralateral knee  
22 extensor muscles during maximal voluntary contractions and submaximal sustained knee  
23 extension before, 24 h, and 48 h after eccentric exercise.

1

## 2 **METHODS**

3       **Experimental design and approach.** This experiment investigates whether high  
4 intensity eccentric exercise induced DOMS can affect activation and performance of the  
5 non-exercised homologous muscle of the contralateral limb. Time to task failure and  
6 MVC of the non-exercised quadriceps muscle measured, before, immediately after, and  
7 24 and 48 h after eccentric exercise. Moreover EMG activities of the non-exercised  
8 quadriceps muscle were recorded during MVC and over sustained contraction at 50%  
9 MVC before and after eccentric exercise.

10

11

### 12 *Participants*

13       Fifteen healthy men (age, mean  $\pm$  standard deviation; SD,  $20.5 \pm 2.2$  years, body  
14 mass  $70.5 \pm 8.4$  kg, height  $1.75 \pm 0.06$  m) volunteered to participate in the study which  
15 followed a repeated measures design. All subjects were right-leg dominant (self-reported)  
16 and were not involved in regular exercise of their knee extensor muscles for at least 6  
17 months before the experiment. The study was conducted in accordance with the  
18 Declaration of Helsinki and approved by the local ethics committee. Subjects provided  
19 informed written consent before participation in the study.

20

21

### 22 *Warm up*

1           Subjects initially warmed up on a bicycle ergometer (LC4, Monark Exercise AB,  
2 Sweden) for 10 min. After the warm-up, they performed bilateral maximum and  
3 submaximal knee extension contractions and an eccentric exercise protocol on their right  
4 leg as detailed below.

5

#### 6 *Eccentric exercise*

7           Subjects performed eccentric exercise of their right quadriceps using a weight-  
8 training machine (Universal Gym, USA) whilst positioned in supine. The workload was  
9 determined for each subject based on their initial one repetition maximum (1-RM) and  
10 load was defined as 150% of the initial value of 1-RM. One repetition maximum was  
11 defined as the heaviest load that can be moved over a specific range of motion (90 ° -  
12 180°), one time, and with correct performance. The subject performed 4 sets of 25  
13 repetitions with 150% of the 1-RM with three minutes of rest between sets. Timing of the  
14 lowering and lockout phases of the exercise was established using a metronome. The  
15 metronome emitted an audible stimulus at a frequency of 1 Hz. Subjects were asked to  
16 lower the load to the end position in a controlled manoeuvre, in time with the metronome.  
17 The leg press was brought to the starting position (170 ° - 180 ° knee extension, 180 ° =  
18 full knee extension) using two assistants, and the subject lowered the load to the end  
19 position (60 ° knee extension) in a controlled manoeuvre. This allowed the subjects to  
20 perform multiple repetitions against relatively high loads and delayed the onset of fatigue  
21 by eliminating the concentric contraction.

#### 22 *Maximum and sustained knee extension contractions*

1           The subject sat comfortably on a chair fixed with a belt at the hip flexed at 90° and  
2 with the right knee in 90° of flexion. A strap, connected by a chain to a load cell, was  
3 attached to the ankle to measure knee extension isometric force. Force was provided to  
4 the subject as visual feedback on an oscilloscope. The subject performed a total of six 5-  
5 second maximum voluntary contractions (MVC) of knee extension on the ipsilateral and  
6 contralateral limb (three MVCs for each limb) each separated by 2-min rest. During each  
7 MVC, verbal encouragement was provided to exceed the previous force level. MVCs  
8 were performed in random order for the ipsilateral and contralateral leg. The highest  
9 MVC value was considered as a reference value to define the submaximal load.

10           Participants also performed an isometric knee extension contraction at 50% MVC  
11 sustained until task failure on both the ipsilateral and contralateral leg, with the  
12 participant in the same position as in the MVCs. In order to prevent any cross over effect  
13 of muscle fatigue, sustained contractions were performed in a random order for the  
14 ipsilateral and contralateral leg across participants with 25 minute rests in between.  
15 Additionally, EMG signals were recorded from same muscle locations and from same  
16 channels of the EMG amplifier by a single experimenter, factors that can reduce data  
17 variability across a testing session.

18           Submaximal force was defined relative to the highest MVC measured on the same day of  
19 the test. This allowed us to assess the muscles ability to maintain force output over a  
20 sustained contraction with respect to the maximal muscle force produced on the same day  
21 of the test. Task failure was defined as a drop in force >5% MVC for more than 5 s after  
22 strong verbal encouragement to the subject to maintain the target force value  
23 (Hedayatpour et al., 2014b).



1 *Pain assessment*

2 A 10-cm visual analogue scale (VAS), labelled with end points on no pain and  
3 worst pain imaginable, was used to assess the perceived pain intensity measured 24 and  
4 48 h after eccentric exercise. The subjects were asked to rate the average pain intensity in  
5 their quadriceps during their regular activities of daily living (e.g., climbing stairs) since  
6 their last visit to the laboratory (during the past 24 h).

7 *Limb girth*

8 Thigh girth was measured using a tape-measure around the distal portion of the  
9 thigh of the ipsilateral limb (at 10% of the distance between the superior border of the  
10 patella and the anterior superior iliac spine) to monitor changes in limb girth which may  
11 change because of muscle swelling (Soderberg et al., 1996)

12 *Electromyography*

13 Surface electrodes (Ag–AgCl surface electrodes, Ambu Neuroline, conductive  
14 area, 28 mm<sup>2</sup>) were placed bilaterally in bipolar configuration (inter-electrode distance, 2  
15 cm) between the medial border (vastus medialis, VM), superior border (rectus femoris,  
16 RF) and lateral border (vastus lateralis, VL) of the patella and anterior superior iliac  
17 spine, according to the SENIAM recommendations (Hermens et al. 2000)

18 A reference electrode was placed around the right ankle. The positions of the  
19 electrodes were marked on the skin during the first session (day 1) so that the locations  
20 could be replicated 24 h and 48 h after exercise. Surface EMG signals were amplified  
21 (EMG amplifier, EMG-16, OT Bioelettronica, Torino, Italy, bandwidth 10–500 Hz),  
22 sampled at 2048 Hz and stored after 12-bit A/D conversion.

23 *Signal analysis*

1           To assess the amplitude of muscle activation during the MVC, the average  
2 rectified value (ARV) for each individual muscle were calculated over 200-ms windows  
3 within each 5-s MVC. The peak ARV obtained from the highest MVC was retained for  
4 further analysis. For the sustained contractions, the ARV was estimated from the EMG  
5 signals for epochs of 1 s. The values obtained from 1-s-long epochs in intervals of 10%  
6 of the time to task failure were averaged to obtain one representative value for each 10%  
7 interval. This was performed to allow comparison between subjects with different times  
8 to task failure.

### 9 *Statistical Analysis*

10           Two-way repeated-measures analysis of variance (ANOVA) was used to analyse  
11 MVC force and time to task failure in the ipsilateral and contralateral leg before and after  
12 eccentric exercise (pre-exercise, immediately after, 24 h and 48 h). A two-way repeated-  
13 measures ANOVA was also used to assess the EMG ARV of the knee extensors  
14 (averaged for VM, RF and VL muscle) with time (pre-exercise, immediately after, 24 h  
15 and 48 h), and leg (ipsilateral and contralateral) as dependent factors. Moreover, three-  
16 way repeated measures ANOVA were used to assess ARV (averaged for VM, RF and VL  
17 muscle) across the sustained contraction at 50% MVC (change from the first to the last  
18 epoch), with time (pre exercise, immediately after, 24 h and 48 h) and leg  
19 (injured/ipsilateral and uninjured/contralateral) as dependent factors.

20           One-way repeated-measures ANOVA was applied to asses muscle inflammation  
21 in the injured leg after eccentric exercise with time as the dependent factor. Pearson  
22 correlation coefficients were obtained to assess the relationship between change in EMG  
23 and change in maximal knee extension force across testing sessions. The significance

1 level was set at  $p < 0.05$  for all statistical procedures. Results are reported as mean and SD  
2 in the text and standard error (SE) in the figures.

3

#### 4 **RESULTS**

5 A significant difference was observed for both maximum force ( $F=9.0$ ,  $p < 0.001$   
6 and time to task failure ( $F=14.0$ ,  $p < 0.0001$ ) between sides with the dominant leg  
7 producing higher force and greater endurance compared with the non-dominant leg ( $p <$   
8  $0.05$ ).

9 A significant reduction in maximum isometric knee extension force was observed  
10 for both the ipsilateral and contralateral leg ( $F=27.7$ ,  $p < 0.001$ ) after eccentric exercise. A  
11 significant interaction was observed revealing that the extent of reduction in the  
12 maximum knee extension force was significantly greater for the ipsilateral injured leg  
13 compared to the contralateral un-injured leg ( $p < 0.05$ ; Figure 1). A significant reduction in  
14 time to task failure was also observed for both the ipsilateral and contralateral leg  
15 ( $F=20.5$ ,  $p < 0.001$ ) after eccentric exercise. A significant interaction was also observed  
16 indicating a greater percentage of decrease in time to task failure observed for the injured  
17 leg compared with the un-injured leg ( $p < 0.05$ ) (Figure 2). MVC and time to task failure  
18 were not significantly different between the three post exercise sessions (immediately  
19 after, and at 24 and 48 h,  $p > 0.05$ ).

20

*Figure 1 about here*

21

*Figure 2 about here*

22

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Additionally, the quadriceps EMG amplitude measured from both the ipsilateral  
and contralateral leg was significantly decreased during the post exercise MVCs ( $F=21.0$ ,

1 p<0.001; Figure 3) and during the sustained isometric contractions (in the final epoch  
2 with respect to the initial epoch) (F=46.0, p<0.0001), compared with the pre-exercise  
3 condition (Table 1).

4

5 *Figure 3 about here*

6 *Table 1 about here*

7

8 In the non-exercised leg, the change in maximal force and change in ARV over  
9 the maximal contraction were significantly correlated (p<0.05; r = 0.39). The positive  
10 correlation indicates that variation in maximal force of the un-injured leg was partially a  
11 result of localised changes in muscle activation.

12

13 *Figure 4 about here*

14 Pain intensity increased over the quadriceps muscle as self-reported by the  
15 participants at 24 h (5.3±1.1/10) and 48 h post exercise (5.5±0.9/10). No difference in  
16 pain intensity was observed between 24 h and 48 h post exercise measurements. Thigh  
17 girth measured on the injured leg during the post exercise sessions was also significantly  
18 larger compared with the pre-exercise session measure (F=4.5, p<0.05).

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23 **DISCUSSION**

1 Unilateral eccentric exercise was associated with an immediate decrease in  
2 strength (13.7%) and time to task failure (38.1%) of the contralateral side, which  
3 persisted for 48 hours. This may indicate that unilateral high intensity eccentric exercise  
4 of the quadriceps can modify neuromuscular activity and physical work capacity of the  
5 non-exercised homologous muscle in the contralateral limb.

6

7

### 8 **Muscle performance before eccentric exercise**

9 Before the eccentric exercise, the dominant leg produced higher muscle force and longer  
10 time to task failure as compared with the non- dominant leg. Previous studies have also  
11 demonstrated a greater force production for the dominant leg with respect to the non-  
12 dominant leg (Noguchi et al. 2014, Lanshammar& Ribom, 2011). This difference  
13 between two leg may be related to higher capacity of the dominant leg to produce force  
14 most likely due to the lower ratio between hamstrings and quadriceps strength in the  
15 dominant leg (H:Q), (Noguchi et al. 2014).

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### 19 **Muscle performance after eccentric exercise**

20 In the current study, participants reported that their quadriceps muscle of the  
21 injured leg was sore 24 and 48 h after eccentric exercise, which might be related to  
22 muscle fiber injuries, which in turn sensitizes the intramyofibril group IV afferents  
23 (Smith, 1991). The average pain intensity reported by participants for the injured leg was  
24  $5.3 \pm 1.1$  and  $5.5 \pm 0.9$  at 24 and 48 h, respectively which is in agreement with the level of  
25 pain reported post eccentric exercise of the quadriceps in previous studies (Hedayatpour

1 et al., 2014a; Vila-Chã et al., 2012). This level of pain intensity has been reported to be a  
2 potential mechanism for the reduced muscle force and time to task failure after eccentric  
3 exercise. The observation of reduced muscle performance after eccentric exercise  
4 indirectly confirms that the muscle was injured by the exercise.

5

### 6 **Cross-over effect of fatigue**

7 In this study, the observed reduction in force output immediately after eccentric exercise,  
8 is most likely explained by a combination of muscle fiber damage and metabolite  
9 accumulation within the exercised muscle. An acute muscle adaptation to eccentric  
10 exercise such as early sarcomere damage (Proske & Morgan, 2001) and/or metabolites  
11 accumulation (e.g., hydrogen ions, lactate and inorganic phosphate) (Wan et al.,  
12 2017), alters contractile process within the exercised muscle, which, in turn reduce  
13 muscle force. Additionally, we also observed a significant reduction in force output for  
14 the non-exercised leg immediately after eccentric exercise. Although direct damage to the  
15 muscle fibers and contractile elements was not present within the non-exercised leg and  
16 therefore these changes in muscle function cannot be explained by changes in the  
17 contractile process. However, neural processes beyond excitation- contraction coupling  
18 such as corticospinal pathways may be involved (Hortobágyi et al., 2003; Sotgiu et al.,  
19 2004).

20 In agreement with our finding, other studies have also reported a ‘cross-over’ effect of  
21 central fatigue for both upper and lower limbs after fatiguing exercise (Ruohonen et al.,  
22 2002; Todd et al., 2003; Zijdwind et al., 1998). Doix et al. (2016) reported that unilateral  
23 fatiguing exercise resulted in a significant torque decline of 10.6% in the contralateral

1 non-exercised limb. Similarly, Martin and Rattey, (2007) found a significant force  
2 decline (<13%) in the non-exercised lower limb after unilateral fatiguing exercise. Others  
3 studies also showed that fatigue induced by exercise, produced a ‘cross-over’ effect of  
4 central inhibition, which in turn resulted in a reduction in force and /or motor output of  
5 the contralateral non -exercised limb (Halperin et al., 2014, Todd et al., 2003).

6

7

### 8 **Cross-over effect of DOMS**

9 Maximal voluntary force and time to task failure in the contralateral non-exercised leg  
10 were also significantly decreased 24 h after eccentric exercise of the opposite limb which  
11 persisted up to 48 h. A significant reduction in maximal isometric force and time to task  
12 failure observed for the contralateral non-exercised leg, indicates that eccentric exercise  
13 contributes to reduced muscle force and physical work capacity not only in the exercised  
14 muscle, but also in the non-exercised homologous muscle in the contralateral limb.

15 Reduction in muscle force observed at 24 and 48 h post eccentric could be related to  
16 fiber injuries of exercised muscle, since muscle can recover from fatigue within 24 h after  
17 exercise.

18 Additionally, a significant reduction in the amplitude of quadriceps muscle activity was  
19 observed during the post exercise MVCs and sustained contractions for the contralateral  
20 non-exercised leg with respect to the pre-exercise session, indicating that the reduced  
21 muscle force of the contralateral non-exercised leg was partially associated with  
22 decreased muscle activation.

23

1 **Potential mechanisms for cross-over effect of DOMS**

2       There are several potential mechanisms by which DOMS, induced by eccentric  
3 exercise, may contribute to the reduced motor output of the non-exercised leg. Typically,  
4 nociceptor sensitization associated with tissue injury can influence primary afferents of  
5 muscle spindles at superficial layers of the dorsal horn of the spinal cord 24h after  
6 eccentric exercise (Le Pera et al., 2001; Sotgiu et al., 2004). The axons of nociceptive  
7 dorsal horn neurons cross to the contralateral anterolateral quadrant to form an ascending  
8 tract (Carpenter, 1985), which terminates in the brainstem and several distinct areas of  
9 the thalamus (Todd, 2010). These ascending pathways, which mediate nociceptive  
10 information (Willis, 1985), may inhibit motor cortex regions associated with the  
11 contralateral limb which, in turn, reduces neural output (Cotofana et al., 2015; Gossard &  
12 Rossignol, 1990; Barr & Kiernan, 1993 ) and, consequently, reduces maximal force  
13 (Farina et al., 2005; Hedayatpour et al., 2009).

14       Reduced muscle force in the contralateral non-exercised leg could be further  
15 explained by a pain-induced change in motor planning and/or by change in potential  
16 signalling pathways on the contralateral side. The perception of pain within the injured  
17 quadriceps muscle can alter cerebral motor plans (Svensson et al., 1997) and as a  
18 consequence may contribute to reduced muscle performance of the contralateral non-  
19 exercised leg (Byl & Melnick, 1997; Halperin et al., 2014). Finally, damage to muscle  
20 fibers results in the release of a number of immunomodulatory agents that can be  
21 transported to the contralateral part of the body with possible effects on signalling  
22 pathways and consequently changed motor behaviour (Dennis, 1998; Ruohonen et al.,  
23 2002).



1           A number of studies have investigated ‘cross-over’ effect of exercise training and  
2 indicated that both positive and negative effects of exercise can be transferred to the  
3 contralateral non-effected limb, most likely due to the modulation of neural circuits at the  
4 level of spinal cord and motor cortex. For example, previous studies reported that pain  
5 can impair motor performance of the contralateral, unaffected arm of patients with  
6 chronic unilateral tennis elbow (Pienima et al., 1997). Patients with chronic wrist pain  
7 also demonstrated disturbances of fine motor output of the contralateral, unaffected wrist  
8 (Smeulders et al., 2002). Accordingly, deficits in motor function of the contralateral  
9 unaffected side have been identified in some musculoskeletal pain conditions including  
10 osteoarthritis (Cotofana et al., 2015) and patellofemoral pain (Akseki et al., 2008 ) as well  
11 as following some experimental paradigms (Moseley et al., 2005 ). The contralateral  
12 effects of pain have also been demonstrated by earlier electrophysiological studies in  
13 response to laser-evoked somatic and trigeminal pain (Tarkka & Treede, 1993).  
14 Additionally, positive effects of exercise has been reported to be transferred to the  
15 contralateral non-exercised limb. Previous studies reported an increase in muscle force  
16 for the contralateral untrained limb after 4 to 12 weeks of unilateral training (Carroll et al.  
17 2006), and eccentric training resulted in a greater increase in isometric force of the  
18 contralateral untrained limb (39%) as compared to concentric training (22%) (Hortobágyi  
19 et al. 1997).

20           In line with these findings, we also observed for the first time, a decrement in  
21 force output of the contralateral non-exercised leg after a unilateral knee eccentric  
22 exercise, most likely due to cross-over effect of DOMS at the level of spinal cord and /or  
23 motor cortex. This cross-over effect of DOMS may be necessary to reduce force

1 generating capacity of the non-exercised leg through lower voluntary activation to cope  
2 with the weaker force of the exercised leg, and therefore to regulate bilateral coordination  
3 between two limbs during high intensity exercise.

4

## 5 **CONCLUSION**

6 Maximal knee extension force and time task failure during sustained knee  
7 extension contractions of the contralateral non-exercised leg were significantly reduced  
8 immediately after unilateral eccentric exercise, and this persisted 24 and 48 h post  
9 exercise. This original finding indicates that DOMS induced by eccentric exercise at 24  
10 and 48 h post eccentric may partly contribute to reduced muscle force and physical work  
11 capacity in the unaffected homologous muscle of the contralateral limb. This change  
12 should be taken into consideration when developing training and rehabilitation  
13 programmes since these changes may leave the limb at risk of greater injury if the  
14 training volume is not adjusted according to the reduced motor capacity. Further studies  
15 are needed to determine the underlying mechanisms of reduced motor output in the  
16 contralateral non-exercised limb and to identify the time required for motor function to  
17 return to normal.

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**TABLE**

Table 1- Mean  $\pm$  SD (n=15) for the percent change in the EMG average rectified value (ARV) recorded from the quadriceps during sustained knee extension contractions at 50% MVC (change from the first to the last epoch), and measurement of thigh circumference.

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| <b>ARV (% decrease)</b>  | -1.5 ± 0.09   | -15.5 ± 3.4 * | -14.8 ± 2.7 * | -12.9 ± 3.8 * |
|--------------------------|---------------|---------------|---------------|---------------|
| <b>Ipsilateral leg</b>   |               |               |               |               |
| <b>ARV (% decrease)</b>  | - 0.85 ± 0.02 | -10.7 ± 2. 5* | -9.5 ± 2. 3*  | -7.7 ± 1.8 *  |
| <b>Contralateral leg</b> |               |               |               |               |
| <b>Thigh girth (cm)</b>  | 40.7 ±2. 4    | 41.6 ± 3.1 *  | 41.5 ± 2.8 *  | 41.5 ± 3. 1*  |

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\*Indicates significant difference to baseline (p<0.05).

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### 3 **FIGURES**

4

5 **FIGURE 1-** Maximal isometric knee extension force (mean  $\pm$  SE, N.m, n = 15) recorded  
6 before the eccentric exercise (pre exercise), immediately after, 24 H and 48 h after the  
7 eccentric exercise. Ipsilateral leg (black circle) and contralateral leg (white circle). \*p  $\leq$   
8 0.05.

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10 **FIGURE 2-** Time to task failure (mean  $\pm$  SE, s, n = 15) during sustained isometric knee  
11 extension 50% of the maximal voluntary contraction (MVC) measured before the  
12 eccentric exercise (pre exercise), immediately after, 24 h and 48 h after the eccentric  
13 exercise. Ipsilateral leg (black circle) and contralateral leg (white circle). \*p  $\leq$  0.05.

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15 **FIGURE 3-** Average rectified value of EMG (ARV; mean  $\pm$  SE,  $\mu$ V , n = 15) recorded  
16 from the knee extensors muscles (average for the VM, RF and VL muscles) during  
17 maximal voluntary contraction of the knee extension before the eccentric exercise (pre  
18 exercise), immediately after, 24 h and 48 h after the eccentric exercise. Ipsilateral leg  
19 (black circle) and contralateral leg (white circle). \*p  $\leq$  0.05.

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21 **FIGURE 4.** Scatter plot of change in average rectified value of EMG (average for vastus  
22 medialis, vastus lateralis and rectus femoris) versus change in maximal isometric muscle  
23 force, performed at pre-exercise compared with the post- exercise sessions (average for

1 all post- exercise sessions). In the non-exercised leg, the change in maximal force and  
2 change in ARV over the maximal contraction were significantly correlated ( $p < 0.05$ ;  $r =$   
3  $0.39$ ). The positive correlation indicates that variation in maximal force of the non-  
4 exercised leg was partially a result of changes in muscle activation.

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