The effect of dominant index finger fatigue on the force production of contralateral homologous muscle and biceps brachii

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A thesis submitted to the

School of Graduate Studies

In partial fulfillment of the requirements for the degree of

Master of Kinesiology

School of Human Kinetics and Recreation

Memorial University of Newfoundland

June 2018

St. John's Newfoundland and Labrador

ABSTRACT

Non-local muscle fatigue (NLMF) has been examined but the literature is inconsistent. Differences in the protocols contribute to the inconsistent results. Most NLMF studies focus on large muscle groups only (elbow flexors or knee extensors), with few NLMF studies involving small muscles as either fatigued or tested muscles. Furthermore, the NLMF effect from a small fatigued muscle to a larger heterologous muscle is unknown. Hence, the objective of the present study was to examine the effect of small muscle fatigue on the force production and activation of contralateral homologous and a larger heterologous muscles.

ACKNOWLEDGMENTS

First, I would like to express my gratitude to my family for every single amazingly support through my life. My mother, Yamei Zhan and my father, Jianguo Li. It's a great honor to be your daughter.

I would like to thank my supervisor, Dr. David Behm for offering me the opportunity to pursue my Master's degree here at Memorial University of Newfoundland. Your productivity and inspired thoughts have shaped my career.

To Jeannette, thank you for your help and advice for two years. To my fellow graduate students, thank you for providing support through hard times.

Finally, I would like to thank my fiancé, Tianze Chen. I could not have done this without you, you are the best thing happened to me in Newfoundland.

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LIST OF ABBREVIATIONS

EF	Elbow flexor
EMG	Electromyography
ES	Effect size
FDI	First dorsal interosseous
FFT	Fast Fourier transform
FI	Fatigue index
IFA	Index finger abductors
MDF	Median frequency
MVIC	Maximal voluntary isometric contraction
NLMF	Non-local muscle fatigue
RMS	Root mean square

Chapter 1: Review of Literature

1.1 Introduction

Neuromuscular fatigue has been defined as "any exercise-induced impaired ability to exert muscle force or power regardless of whether or not the task can be sustained" (Bigland-Ritchie et al. 1984). Strong evidence for the neural influences on fatigue can be demonstrated with the non-local muscle fatigue (NLMF) effect. NLMF refers to a temporary deficit in the performance of non-exercised muscle groups following a fatiguing protocol (Martin and Ratty, 2007; Halperin et al. 2015). Presently, the NLMF literature remains controversial. The variable protocols might lead to this inconsistency. Most of the NLMF studies focus on large muscles only, whereas there are limited studies that involve small muscles as the tested or fatigued muscle in the protocol. Therefore, the present review will summarize the relevant confounding variables and discuss the mechanisms of the NLMF effect. At the end, this review will discuss the limitation and future studies regarding NLMF effect on small muscles.

1.2 Non-local muscle fatigue (NLMF)

Moritani and De Vries (1979) demonstrated increased maximal voluntary isometric contraction (MVIC) in the biceps brachii which was contralateral to the muscle subjected to resistance training after two weeks. This classic cross education study highlighted the importance of neural factors in strength training. In agreement with this finding, many resistance training studies showed that this “cross-education” effect is evident in contralateral homologous muscles (Cannon et al.1987; Ploutz et al. 1994), as well as in ipsilateral heterologous muscles (Carolan et al. 1992). This “cross-education” or “non-local” effect emphasized the importance of neuromuscular adaptations in strength training, which can be also applied to fatigue. Bangsbo et al. (1996) found that arm-cranking fatiguing exercise could shorten time to exhaustion of lower body cycling and increase the blood lactate at the onset of lower body cycling. Similarly, but not limited to whole body exercise (Bangsbo et al. 1996; Johnson et al. 2014), the NLMF effect can also be found with isometric contraction of specific muscle groups (e.g. elbow flexors and knee extensors). For instance, a number of studies have demonstrated that the voluntary activation or the EMG mean amplitude of the non-exercised knee extensors were significantly reduced after the fatiguing exercise of contralateral knee extensors (Rattey et al. 2006; Martin and Ratty, 2007; Amann et al. 2013; Halperin et al. 2014a; Hamilton and Behm, 2017) as well as elbow flexor fatigue induced inhibition of the contralateral homologogus muscles (Aboodarda et al. 2016). Similarly, Halperin et al. (2014b) showed that elbow flexor force was significantly attenuated after knee extensor fatigue. Also, the motoneuron excitability of the knee extensors was decreased after the fatigue exercise of elbow flexors (Aboodarda et al. 2015, 2017). Although the demonstrations of the NLMF phenomenon continually appear in the literature, conflicting opinions arise and a number of studies have not displayed significant evidence for NLMF (Zijdewind et al. 1998; Todd et al. 2003; Arora et al. 2015). The difference of the protocols likely contributes to the results discrepancy.

1.3 Contraction intensity of fatiguing protocol

Most of the studies demonstrated reduced MVIC (Martin and Ratty, 2007; Doix et al. 2013; Halperin et al. 2014b) or decreased EMG amplitude (Aboodarda et al. 2015) of non-exercised muscles following a maximal contraction protocol of exercised muscles. But this is not the case for submaximal contraction protocols, Paillard et al. (2010) didn't find any change of MVIC of non-exercised knee extensor by using a submaximal fatigue protocol (10% of MVIC) on contralateral knee extensors. Similarly in small muscles, Zijdewind et al. (1998) fatigued the FDI by 30% of MVIC until task failure and no significant NLMF effect was present on the contralateral FDI. Kennedy et al. (2013a) directly compared maximal and submaximal fatiguing protocols. The maximal fatiguing contraction of hand grip muscles resulted in a greater decrement of MVIC and voluntary activation on non-exercised plantar flexor (23% and 15% of reduction, respectively) compared with submaximal contractions (8% and 2% of reduction, respectively).

The differences might be attributed to the higher energy demands with maximal contractions, therefore more severe central changes might be present than with the submaximal contractions (Kennedy et al. 2013a). Also, the motoneuron firing rate during maximal isometric contraction continually decline (Bigland-Ritchie et al. 1983) whereas during the submaximal contraction, additional motoneurons are progressively recruited to maintain the initial target force (Bigland-Ritchie et al.1986). Therefore, motoneuron firing during submaximal contraction is more complex and variable than with maximal contraction (Gandevia, 2001) which might contribute to the inconsistent results in NLMF studies. Some studies showed that during the moderate intensity (40-50% MVIC) submaximal intermittent fatiguing contractions, those first recruited motoneurons showed decreasing firing rates while those recruited during the task presented increased firing rates (Carpentier et al. 2001; Kelly et al. 2013). Others stated that with moderate intensity contractions, motoneuron firing rates tend to decrease or stay the same, while in weaker contractions they tend to increase (Thomas et al. 2001; Kuchinad et al. 2004; Harwood et al. 2012). As a consequence, in NLMF studies, the submaximal contraction protocol may present more fluctuations in motoneuron firing thus may lead to more unpredictable change in non-exercised muscles.

Other than the declined motoneuron firing frequency, it is also reported that the muscle spindle discharge rate decrease 72% during submaximal contractions (up to 30% of MVIC) (Macefield et al. 1991). The muscle spindles provide mechanosensory information about the changes in muscle fiber length and tension (Bongiovanni et al. 1990), which is an excitatory influence to the motoneurons, thus it is reasonable to expect a negative effect on motoneuron firing output from the declined muscle spindle activity (Gardiner, 2001). Consequently, in general, the maximal contraction protocol is more impactful on NLMF effects compared to a submaximal fatiguing protocol.

Halperin et al. (2015) summarized that the influence of contraction intensity to the extent of NLMF also depends on whether the fatigue muscle is in upper or lower body, as it is suggested that higher intensity contractions may lead to greater NLMF compared to lower intensity in the lower body. Whereas in the upper body, both maximal and submaximal contractions may lead to a similar extent of NLMF (Halperin et al. 2015). However, this suggestion was made based on only one upper body NLMF paper (Post et al. 2008). Post et al. (2008) used both maximal and submaximal (30% of MVC) contraction protocols to fatigue the FDI on the same side. Although both fatiguing protocols led to the same (9%) reduction of MVIC, the maximal fatigue protocol resulted in greater reduction of voluntary activation (22% of reduction) on contralateral homologous muscle compared to submaximal protocol (9% of reduction) (Post et al. 2008). Therefore, the maximal contraction protocol actually resulted in a greater NLMF effect than the submaximal contraction protocol. Thus it is arbitrary to conclude that higher intensity may result in more NLMF effect in lower limb rather than in upper limb. Further studies need to conduct to investigate this question.

1.4 Bilateral or unilateral fatigue protocol

The majority of the NLMF studies involved unilateral contraction as the fatigue protocol, whereas results remain controversial. For example, Doix et al. (2013) found significantly reduced MVIC and voluntary activation on non-exercised knee extensors after the fatiguing contraction of contralateral homologues muscles. On the contrary, Arora et al. (2015) investigated the NLMF effect of knee extensors by unilateral fatigue contraction as well but did not find any significant change in MVIC nor EMG on the contralateral non-exercised homologues muscle. There was only one study that directly compared the difference between bilateral and unilateral fatigue protocol in NLMF (Aboodarda et al. 2015). The participants were asked to perform 5 sets of maximal sustained contractions with either one or both elbow flexors and control condition on different sessions. The maximal compound muscle action potential (Mmax), thoracic motor evoked potentials (TMEPs), MVIC and EMG of non-dominant knee extensors were assessed to detect any NLMF effect. The results showed the bilateral fatigue protocol led to significantly lower vastus lateralis (VL) EMG activity compared with the unilateral protocol, but the knee extensors MVIC did not show any statistical significant difference between two protocols. Also, the $TMEP \cdot Mmax^{-1}$ ratio was significantly higher following the bilateral contraction protocol compared with the unilateral contraction protocol, which indicated the motoneuron excitability of non-fatigued VL was increased following the bilateral fatiguing protocol (Aboodarda et al. 2015). It is suggested that the different neural activation between bilateral and unilateral contractions may contribute to the different NLMF effect (Pearce et al. 2005; Aboodarda et al. 2015). Pearce et al. (2005) compared the motor-evoked potentials (MEP) of between-limb (contralateral homologous) and within-limb muscle pairs during voluntary activation and rest. The results showed that the MEP of between-limb muscles pairs was significantly decreased while one muscle was contracted, however, the voluntary activation of a remote muscle did not affect the within-limb muscle pairs MEP correlation while another muscle was non-activated (Pearce et al. 2005). It is proposed that the interhemispheric coupling of corticospinal excitability is suppressed during the voluntary activation (Pearce et al. 2005). In reference to NLMF studies, this implies that the bilateral fatiguing protocol might results in more evidence of decreased corticospinal excitability, which might contribute to produce stronger NLMF effect than the unilateral fatiguing protocol does.

However, it is actually hard to simply state that NLMF is more evident in bilateral fatiguing protocol than unilateral protocol, because it is difficult to differentiate whether the dissimilar NLMF effect is related to the different characteristic of bilateral or unilateral contractions or is it more related to the muscle volume that was involved in the fatiguing protocol. Furthermore, unilateral fatiguing protocol is the only option when the research question is focused on the NLMF effect of contralateral homologous muscles.

1.5 Isometric (intermittent and sustained) or dynamic fatiguing protocol

Isometric contraction fatiguing protocols demonstrated more consistent NLMF effects than submaximal contractions. In a study by Aboodarda et al. (2015), the MVIC and the EMG of non-exercised, unilateral knee extensor was significantly decreased following the elbow flexor fatiguing protocol, which include 5 sets of unilateral or bilateral elbow flexor MVIC until failure. Similarly, 2 sets (Doix et al. 2013) and 1 set (Martin and Rattey, 2007) of 100s MVIC of unilateral knee extensor both led to declined MVIC and ITT on the contralateral non-exercised knee extensor. Similarly in a small muscle, Kavanagh et al. (2016) showed that 4 sets of 4s maximal FDI MVIC (index finger abduction) with 2s rest between significantly decreased the force production (up to 30%) and voluntary activation (up to 90%) of contralateral, non-exercised FDI. This study implied that in addition to maximal sustained isometric contractions, the maximal intermittent isometric contraction fatigue protocols are also able to decreased the force production of non-exercised FDI (Kavanagh et al. 2016).

On the contrast, dynamic contraction protocols lead to more variable NLMF results (Halperin et al. 2015). Indeed, four studies didn't find significant NLMF effects on non-exercised hand grip muscles after a running fatiguing protocol (Millet et al. 2003; Place et al. 2004; Ross et al. 2007). Alcaraz et al. (2008) reported the number of repetitions and peak power for the bench press after knee extension fatiguing protocol had no significant change. Similarly in the lower limb, the repeated sets of 30 rebound jumps on unilateral plantar flexors until exhaustion did not significantly influence the MVIC of contralateral plantar flexors or the drop jump height (Regueme et al. 2007). But the few other NLMF studies involving dynamic protocol were able to detect NLMF effect on non-exercised upper (Triscott et al. 2008) or lower limb (Amann et al. 2013; Ciccone et al. 2014).

The inconsistent results might be attributed to the variations of dynamic protocols. For instance, Regueme et al. (2007) used rebound jumps to fatigue lower limb but didn't find significant NLMF effect on non-exercised side. However, in the lower limb, Kawamoto et al. (2014) used different intensities of repeated loading knee extension protocols and found significant force decrease on non-exercised homologous muscles. Furthermore, some dynamic fatiguing protocol NLMF studies (Grabiner et al. 1999; Regueme et al. 2007) involved isometric contraction as the post-intervention testing protocol, which even magnified the variations of the research protocol. Together, based on present literatures, the NLMF effect is more evident following the isometric fatiguing protocol compare to the dynamic fatiguing protocol.

1.6 Muscle involved in NLMF study

1.6.1 Fatigued muscle

The majority of NLMF studies involve relatively large muscles as the fatigued muscle in their protocol. Elbow flexors (Halperin et al. 2014a; Aboodarda et al. 2015) and knee extensors (Halperin et al. 2014a, 2014b; Šambaher et al. 2016) are the most common muscle groups that have been fatigued in the NLMF studies. On the contrast, there were few studies that investigated the NLMF effect on relatively smaller muscle (e.g., FDI). Based on our knowledge, there were only three NLMF studies that involved the FDI as the fatigued muscle in their protocols (Zijdewind et al. 1998; Post et al. 2008; Kavanagh et al. 2016) and the results were conflicting. Zijdewind et al. (1998) didn't find any significant NLMF on the non-exercised FDI after fatiguing the contralateral FDI with a submaximal MVIC (index finger abduction) protocol (Zijdewind et al. 1998). On the contrary, Post et al., (2008) used both submaximal and maximal isometric contractions to fatigue the FDI on one side, and found significant NLMF effect on the contralateral FDI for both fatigue protocols. Similarly, Kavanagh et al. (2016) also demonstrated that maximal intermittent contraction of FDI on single side until failure was able to significantly decrease the force production on contralateral FDI.

Since there were very few studies that investigate the NLMF effect using the small muscle fatiguing protocol, it is hard to state whether the NLMF effect is related to the fatigued muscle mass. However, studies have shown that muscle mass is related to the extent of fatigue which may be attributed to the activation of group III/IV muscle afferents (Rossman et al. 2012, 2014). In Rossman et al. (2012), the participants were required to complete both large (bike) and small (knee extensor) muscle mass dynamic exercise at 85% of MVIC. The result showed that the knee extensor exercise led to significantly greater quadriceps fatigue compare to bike exercise

(Rossman et al. 2012). In order to avoid the concerns over task specificity and cardiorespiratory limitations, the same authors conducted another quite similar study, which compared whether the single-leg and double-leg knee extensions elicited different extent of fatigue (Rossman et al. 2014). The results reveled that less muscle mass elicited more peripheral muscle fatigue than greater muscle mass (Rossman et al. 2014). In summary, those two studies suggested that less muscle mass developed greater muscle fatigue, which has been attributed to the greater group III/IV muscle afferents feedback from small muscle mass, enabling the central nervous system (CNS) to tolerate greater peripheral fatigue (Rossmanet et al. 2012, 2014).

Group III/IV muscle afferents are activated by the mechanical and metabolic stimulation which is provided by the muscle contractions (Amann, 2015). The activation of group III/IV muscle afferents can directly inhibit (Amann et al. 2015; Kennedy et al. 2013b) or indirectly influence (Taylor et al. 2016; Sidhu et al. 2017) motoneuron activation and thus contribute to central fatigue (Taylor et al. 2016), potentially spreading to non-exercised limbs (Amann et al. 2013). Therefore, the activation of group III/IV muscle afferents has been recognized as one of mechanisms of NLMF (discussed below). If so, the greater stimulation of group III/IV muscle afferents provided by smaller muscles (Rossman et al. 2012, 2014) may lead to stronger inhibitory influence to CNS and may results in more evident NLMF effect than large muscles. Further NLMF studies should involve small muscle as the fatigue muscle to study about this mechanism.

1.6.2 Tested muscle

It is suggested that lower limb muscles are more susceptible to NLMF than upper limb muscles (Halperin et al. 2015). Indeed, Halperin et al. (2014a) demonstrated decreased force production and EMG activity in knee extensor, but not elbow flexor, after the contralateral knee extensors and diagonal elbow flexors were both fatigued in separate sessions. This result may be attributed to the greater fast twitch muscle fibres composition of knee extensors compared to elbow flexors (Galea et al. 1991; Miller et al. 1993). Fast twitch fibers are more susceptible to fatigue than slow twitch fibers since they have less mitochondria (Berchtold et al. 2000) and rely on glycolytic metabolism as the major energy source (Booth et al. 1991)

However, it is hard to differentiate whether the physiological difference of upper and lower limbs or the muscle volume differences result in the discrepancy. Most of the lower limb muscles have larger muscle volume than upper limb muscles (Janssen et al. 2000), which imply that lower limb muscles have greater number of motor units (McComas, 1991), and potentially more difficult to fully activate than upper limb (Behm et al. 2002), as a result, may lead to greater NLMF effect. For example, Kennedy et al. (2013a) found significant NLMF effects on non-exercised plantar flexor (PF) following a handgrip fatiguing exercise. The NLMF effect on PF, which is a relatively small muscle in lower limb, emphasize that it is possible that the muscle volume, rather than the location of the muscle contribute more to the NLMF effect. However, there were limited papers investigating whether the muscle mass of tested muscle will influence the NLMF effect, especially when the fatiguing protocol involves small muscle only. For instance, all the NLMF studies involved FDI as the fatigued muscle used contralateral homologous as the tested muscle (Zijdewind et al. 1998; Post et al. 2008; Kavanagh et al. 2016), none of them test the NLMF effect from fatigued FDI to a larger muscle. Therefore, further NLMF research needed to involve muscles with different muscle mass as tested muscles.

1.7 Mechanisms for NLMF

1.7.1 Neuromuscular mechanisms

The contribution from corticospinal excitability to the NLMF effect remains controversial. Several studies claimed increased MEP of non-exercised muscles after the fatiguing contraction of exercised muscles (Stedman et al. 1998; Matsuura et al. 2015), meanwhile, other research indicated decreased MEP of non-exercised muscles while presenting NLMF effect (Takahashi et al. 2009). The discrepancy results might due to the difference between bilateral and unilateral fatiguing protocol (Pearce et al. 2005) (discussed above). Also, the different results may be attributed to different contraction strategies (i.e. repeated vs. sustained) in the fatiguing protocol. One possible indirect method to study about the contribution of corticospinal excitability to the NLMF effect could be involving hand or finger muscles as fatigue muscle. Since hand and finger muscles have larger corticospinal projections than many other muscles (Takahashi et al. 2011; Matsuura et al. 2015), thus the alteration of corticospinal excitability that contributes to the fatigue of hand and finger muscles might be greater than other muscles as well (Takahashi et al. 2009; Matsuura et al. 2015). Therefore, if a hand or finger muscles fatiguing protocol results in a stronger NLMF effect, in terms of fatigue of a non-exercised larger muscle, it might be able to explain by corticospinal excitability contribution.

The muscle behavior depends not only on intrinsic muscle properties but also on the influence of neural feedback systems that maintain and control muscle output (Taylor et al. 2016). Muscle contractions provide the mechanical and metabolic stimulation to activate both the thinly myelinated (group III) and the unmyelinated neurons (group IV) (Amann et al. 2011). An emerging line of research has shown that central fatigue has been linked to the feedback from the activation of the group III/IV muscle afferent (Bigland-Ritchie et al. 1986; Gandevia et al. 1996). It is plausible that the activation of group III/IV muscle afferents directly inhibits the activity of motoneurons during voluntary contractions, thus contributing to the central fatigue (Amann et al. 2015). Apart from directly reducing the motoneurons' activity, activated group III/IV muscle afferents may inhibit group Ia terminals presynaptically then disfacilitate motoneurons' activation (Pettorossi et al. 1999); or the activated group III/IV muscle afferent can also indirectly modulate motoneuron firing rate by increasing the reflex inhibition (Garland, 1991). However, it is also suggested that group III/IV muscle afferents exert both facilitatory and inhibitory effects on motoneurons during fatigue (Windhorst et al. 1996), the overall net effect depends on the balance of these inputs.

The maintained firing of these small muscle afferents potentially has more widespread effects in reducing the force production ability of the non-exercised muscles (Amann et al. 2011; Kennedy et al. 2013a, 2013b; Sidhu et al. 2017). Indeed, Kennedy et al. (2013b) demonstrated that post fatigued activated group III and IV muscle afferents from unilateral adductor pollicis may produce significant NLMF effect on the non-exercised elbow flexor. However, the same authors conducted another study (Kennedy et al. 2015) on lower limb two years after, showed that activation of group III and IV muscle afferents from the left knee extensors had no effect on the non-exercised right homologous muscles. Hence, the contribution of group III and IV muscle afferents to NLMF effects remains controversial. Furthermore, most of the NLMF studies focus on large muscle groups only (e.g. elbow flexors, knee extensors), the understanding of the contribution of group III and IV muscle afferents to NLMF effect in small muscles is very limited. There is only one study that demonstrated after the fatiguing contraction of the adductor pollicis, keep firing of the group III/IV muscle afferents would decrease the force production in the ipsilateral elbow flexors (Kennedy et al. 2013b). As mentioned above, it is suggested that a smaller muscle mass evokes stronger, local signals to group III/IV muscle afferents compared to weaker and more diffuse signals from a much larger muscle mass (Rossman et al. 2012; Rossman et al. 2014). Consequently, it might be reasonable to expect more evident NLMF effect from fatigue of a smaller muscle due to stronger feedback from group III and IV muscle afferents than that stimulated by a larger muscle. In conclusion, further investigations need to have a deeper insight into the contribution of group III and IV muscle afferents from the activation of a small muscle to the NLMF effect.

1.7.2 Psychological mechanisms

Physical activity not only involves the neuromuscular components, but also requires attentional resources (Dorris et al. 2012; Pageaux et al. 2014). It is known that the attentional demand needed for physical activity increases with the difficulty of the task (Lajoie et al. 1993; Bisson et al. 2011). In fatigue studies, the fatiguing interventions are generally challenging for participants, not only physically, but also mentally. For example, Vuillerme et al (2002) showed that fatigued gastrocnemius significantly increased the attentional demand to maintain standing. What's more, in order to actually fatigue certain muscles, participants are usually required to maintain the contraction even though it is uncomfortable. This process, was named "response inhibition", refers to the avoidance or inhibition of the unwanted or inappropriate action/emotional responses (Pageaux et al. 2014), that affects physical activity. For example, Pageaux et al. (2014) showed that 30 minutes of mental exertion involving response inhibition was able to significantly decrease the endurance performance during 5km running. Similarly, competitive rowers performed fewer press-ups after a difficult cognitive task than after an easy task (Dorris et al. 2012). Also, knee extensor MVICs were significantly reduced after a mental fatigue task (Budini et al. 2014). It was suggested that mentally fatigued participants generally reported higher perceived exertion (Marcora et al. 2009; Brownsberger et al. 2013), lower potential motivation (Marcora et al. 2009), greater level of fatigue (Smith et al. 2016) and even increased heart rate (Pageaux et al. 2014) and thus potentially attenuated physical performance.

Psychological influence may also contribute to NLMF effect by regulating the pacing strategy during the fatigue test. Tucker (2009) proposed that the physiological system and the environmental factors will provide information to the brain in order to forecast the best pacing strategy to finish the exercise at the onset of the task. Participants may subconsciously decrease the force production in order to cope with subsequent fatiguing contractions (St Gibson et al.

2006). Specifically, if the post-test protocol is a repeated contraction protocol, then this phenomenon is highly likely to occur. Additionally, the knowledge of task endpoint also has been shown to be related to the physical performance. Indeed, Hamilton and Behm (2017) demonstrated that the participants who are lacking knowledge of the task endpoint had less force production with the non-exercised muscle than those who knew the endpoint. Overall, the NLMF effect might be partially attributed to the psychological effect as well.

1.8 Limitations and future research

Most of the targeted (fatiguing or testing) muscles in the NLMF studies were large muscle groups of upper and lower limbs, for example, elbow flexors (Todd et al. 2003; Halperin et al. 2014b) or knee extensors (Sidhu et al. 2014; Arora et al. 2015). Even though FDI has been used as the fatigued muscle in previous NLMF studies, the effect was tested between homologous muscles (Zijdewind et al. 1998; Post et al. 2008; Kavanagh et al. 2016). There is no study that has investigated whether fatigue of a distal small muscle is able to alter the force production of large muscle groups. Such an investigation would help provide a better understanding of the contribution of group III and IV muscle afferents to the NLMF. Psychological effects may play a role as well. However, the smaller amount of muscle mass requires less absolute levels of motor drive, which may lead to less central fatigue (Noakes et al. 2005; Amann et al. 2008). Accordingly, the inhibitory influence that projects from the small muscles may be insufficient to manipulate the central drive of bigger muscles. Overall, it would be interesting to investigate the NLMF effect on a large muscle group from the fatigue of a small muscle group. The result will assist in having a better understanding of the NLMF mechanisms.

1.9 References

Aboodarda, S. J., Copithorne, D. B., Power, K. E., Drinkwater, E., & Behm, D. G. (2015). Elbow flexor fatigue modulates central excitability of the knee extensors. *Appl Physio Nutr Metab, 40*(9), 924-930.

Aboodarda, S. J., Šambaher, N., & Behm, D. G. (2016). Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. *Scand J Med Sci Sports,* 26(11), 1301-1312.

Aboodarda, S. J., Šambaher, N., Millet, G. Y., & Behm, D. G. (2017). Knee extensors neuromuscular fatigue changes the corticospinal pathway excitability in biceps brachii muscle. *Neuroscience*, 340, 477-486.

Alcaraz, P. E., Sánchez-Lorente, J., & Blazevich, A. J. (2008). Physical performance and cardiovascular responses to an acute bout of heavy resistance circuit training versus traditional strength training. *J Strength Cond Res*, 22(3), 667-671.

Amann, M., Blain, G. M., Proctor, L. T., Sebranek, J. J., Pegelow, D. F., & Dempsey, J. A. (2011). Implications of group III and IV muscle afferents for high-intensity endurance exercise performance in humans. *J Physio, 589*(21), 5299-5309.

Amann, M., & Calbet, J. A. (2008). Convective oxygen transport and fatigue. *J Appl Physio, 104*(3), 861-870.

Amann, M., Sidhu, S. K., Weavil, J. C., Mangum, T. S., & Venturelli, M. (2015). Autonomic responses to exercise: group III/IV muscle afferents and fatigue. *Auton Neurosci, 188*, 19-23.

Amann, M., Venturelli, M., Ives, S. J., McDaniel, J., Layec, G., Rossman, M. J., & Richardson, R. S. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *J Appl Physio, 115*(3), 355-364.

Arora, S., Budden, S., Byrne, J. M., & Behm, D. G. (2015). Effect of unilateral knee extensor fatigue on force and balance of the contralateral limb. *Eur J Appl Physiol, 115*(10), 2177-2187.

Bangsbo, J., Madsen, K., Kiens, B., & Richter, E. (1996). Effect of muscle acidity on muscle metabolism and fatigue during intense exercise in man. *J Physio, 495*(2), 587-596.

Behm, D., Whittle, J., Button, D., & Power, K. (2002). Intermuscle differences in activation. *Muscle Nerve, 25*(2), 236-243.

Berchtold, M. W., Brinkmeier, H., & Muntener, M. (2000). Calcium ion in skeletal muscle: its crucial role for muscle function, plasticity, and disease. *Physiol Rev, 80*(3), 1215-1265.

Bigland-Ritchie, B., Dawson, N., Johansson, R., & Lippold, O. (1986). Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *J Physio, 379*, 451.

Bigland-Ritchie, B., Johansson, R., Lippold, O., & Woods, J. (1983). Contractile speed and EMG changes during fatigue of sustained maximal voluntary contractions. *J Neurophysiol, 50*(1), 313-324.

Bigland-Ritchie, B., & Woods, J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle Nerve, 7*(9), 691-699.

Bisson, E. J., McEwen, D., Lajoie, Y., & Bilodeau, M. (2011). Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. *Gait Posture, 33*(1), 83-87.

Bongiovanni, L., & Hagbarth, K. (1990). Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man. *J Physio, 423*(1), 1-14.

Booth, F. W., & Thomason, D. B. (1991). Molecular and cellular adaptation of muscle in response to exercise: perspectives of various models. *Physiol Rev, 71*(2), 541-585.

Brownsberger, J., Edwards, A., Crowther, R., & Cottrell, D. (2013). Impact of mental fatigue on self-paced exercise. *Int J Sports Med, 34*(12), 1029-1036.

Budini, F., Lowery, M., Durbaba, R., & De Vito, G. (2014). Effect of mental fatigue on induced tremor in human knee extensors. *J Electromyogr Kinesiol, 24*(3), 412-418.

Cannon, R., & Cafarelli, E. (1987). Neuromuscular adaptations to training. *J Appl Physio, 63*(6), 2396-2402.

Carolan, B., & Cafarelli, E. (1992). Adaptations in coactivation after isometric resistance training. *J Appl Physio, 73*(3), 911-917.

Carpentier, A., Duchateau, J., & Hainaut, K. (2001). Motor unit behaviour and contractile changes during fatigue in the human first dorsal interosseus. *J Physio, 534*(3), 903-912.

Ciccone, A. B., Brown, L. E., Coburn, J. W., & Galpin, A. J. (2014). Effects of traditional vs. alternating whole-body strength training on squat performance. *J Strength Cond Res, 28*(9), 2569-2577.

Doix, A.-C. M., Lefèvre, F., & Colson, S. S. (2013). Time course of the cross-over effect of fatigue on the contralateral muscle after unilateral exercise. *PloS one, 8*(5), e64910.

Dorris, D. C., Power, D. A., & Kenefick, E. (2012). Investigating the effects of ego depletion on physical exercise routines of athletes. *J Sport Exerc Psychol, 13*(2), 118-125.

Galea, V., De Bruin, H., Cavasin, R., & McComas, A. J. (1991). The numbers and relative sizes of motor units estimated by computer. *Muscle Nerve, 14*(11), 1123-1130.

Gandevia, S. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev, 81*(4), 1725-1789.

Gandevia, S., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *J Physio, 490*(Pt 2), 529.

Gardiner, P. F. (2001). *Neuromuscular aspects of physical activity*: Human Kinetics.

Garland, S. (1991). Role of small diameter afferents in reflex inhibition during human muscle fatigue. *J Physio, 435*, 547.

Grabiner, M. D., & Owings, T. M. (1999). Effects of eccentrically and concentrically induced unilateral fatigue on the involved and uninvolved limbs. *J Electromyogr Kinesiol, 9*(3), 185-189.

Halperin, I., Aboodarda, S. J., & Behm, D. G. (2014b). Knee extension fatigue attenuates repeated force production of the elbow flexors. *Eur J Sport Sci 14*(8), 823-829.

Halperin, I., Chapman, D. W., & Behm, D. G. (2015). Non-local muscle fatigue: effects and possible mechanisms. *Eur J Appl Physiol, 115*(10), 2031-2048.

Halperin, I., Copithorne, D., & Behm, D. G. (2014a). Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. *Appl Physiol Nutr Metab, 39*(12), 1338-1344.

Hamilton, A. R., & Behm, D. G. (2017). The effect of prior knowledge of test endpoint on non-local muscle fatigue. *Eur J Appl Physiol, 117*(4), 651-663.

Harwood, B., Choi, I., & Rice, C. L. (2012). Reduced motor unit discharge rates of maximal velocity dynamic contractions in response to a submaximal dynamic fatigue protocol. *J Appl Physio, 113*(12), 1821-1830.

Janssen, I., Heymsfield, S. B., Wang, Z., & Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18–88 yr. *J Appl Physio, 89*(1), 81-88.

Johnson, M. A., Mills, D. E., Brown, P. I., & Sharpe, G. R. (2014). Prior upper body exercise reduces cycling work capacity but not critical power. *Med Sci Sports Exerc, 46*(4).

Kavanagh, J. J., Feldman, M. R., & Simmonds, M. J. (2016). Maximal intermittent contractions of the first dorsal interosseous inhibits voluntary activation of the contralateral homologous muscle. *J. Neurophysiol., 116*(5), 2272-2280.

Kawamoto, J.-E., Aboodarda, S. J., & Behm, D. G. (2014). Effect of differing intensities of fatiguing dynamic contractions on contralateral homologous muscle performance. *J Sports*

Sci Med, 13(4), 836.

Kelly, L. A., Racinais, S., & Cresswell, A. G. (2013). Discharge properties of abductor hallucis before, during, and after an isometric fatigue task. *J Neurophysiol, 110*(4), 891-898.

Kennedy, A., Hug, F., Sveistrup, H., & Guével, A. (2013a). Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors. *Eur J Appl Physiol*, 113(3), 559-566.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013b). Fatigue-related firing of distal muscle nociceptors reduces voluntary activation of proximal muscles of the same limb. *J Appl Physio*, 116(4), 385-394.

Kennedy, D. S., Fitzpatrick, S. C., Gandevia, S. C., & Taylor, J. L. (2015). Fatigue-related firing of muscle nociceptors reduces voluntary activation of ipsilateral but not contralateral lower limb muscles. *J Appl Physio, 118*(4), 408-418.

Kuchinad, R., Ivanova, T., & Garland, S. (2004). Modulation of motor unit discharge rate and H-reflex amplitude during submaximal fatigue of the human soleus muscle. *Exp Brain Res, 158*(3), 345-355.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Exp Brain Res, 97*(1), 139-144.

Macefield, G., Hagbarth, K.-E., Gorman, R., Gandevia, S., & Burke, D. (1991). Decline in spindle support to alpha-motoneurones during sustained voluntary contractions. *J Physio, 440*(1), 497-512.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *J Appl Physio, 106*(3), 857-864.

Martin, P. G., & Rattey, J. (2007). Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. *Pflugers Arch, 454*(6), 957-969.

Matsuura, R., & Ogata, T. (2015). Effects of fatiguing unilateral plantar flexions on corticospinal and transcallosal inhibition in the primary motor hand area. *J Physiol Anthropol, 34*(1), 4.

McComas, A. J. (1991). Invited review: motor unit estimation: methods, results, and present status. *Muscle Nerve, 14*(7), 585-597.

Miller, A. E. J., MacDougall, J., Tarnopolsky, M., & Sale, D. (1993). Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol, 66*(3), 254-262.

Millet, G. Y., Martin, V., Lattier, G., & Ballay, Y. (2003). Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J Appl Physio, 94*(1), 193-198.

Moritani, T., de Vries (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med Rehabil, 58*(3), 115-130.

Noakes, T. D., Gibson, A. S. C., & Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med, 39*(2), 120-124.

Paillard, T., Chaubet, V., Maitre, J., Dumitrescu, M., & Borel, L. (2010). Disturbance of contralateral unipedal postural control after stimulated and voluntary contractions of the ipsilateral limb. *J. Neurosci. Res*, 68(4), 301-306.

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *Eur J Appl Physiol, 114*(5), 1095-1105.

Pearce, S. L., Thompson, P. D., & Nordstrom, M. A. (2005). Interhemispheric coupling of corticospinal excitability is suppressed during voluntary muscle activation. *J Neurophysiol, 93*(4), 2174-2182.

Pettorossi, V., Torre, G. D., Bortolami, R., & Brunetti, O. (1999). The role of capsaicin-sensitive muscle afferents in fatigue-induced modulation of the monosynaptic reflex in the rat. *J Physio, 515*(2), 599-607.

Place, N., Lepers, R., Deley, G., & Millet, G. Y. (2004). Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc, 36*(8), 1347-1356.

Ploutz, L. L., Tesch, P. A., Biro, R. L., & Dudley, G. A. (1994). Effect of resistance training on muscle use during exercise. *J Appl Physio, 76*(4), 1675-1681.

Post, M., Bayrak, S., Kernell, D., & Zijdewind, I. (2008). Contralateral muscle activity and fatigue in the human first dorsal interosseous muscle. *J Appl Physio, 105*(1), 70-82.

Rattey, J., Martin, P. G., Kay, D., Cannon, J., & Marino, F. E. (2006). Contralateral muscle fatigue in human quadriceps muscle: evidence for a centrally mediated fatigue response and cross-over effect. *Pflügers Archiv, 452*(2), 199-207.

Regueme, S., Barthelemy, J., & Nicol, C. (2007). Exhaustive stretch-shortening cycle exercise: no contralateral effects on muscle activity in maximal motor performances. *J Med Sci Sports, 17*(5), 547-555.

Ross, E. Z., Middleton, N., Shave, R., George, K., & Nowicky, A. (2007). Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Exp Physiol, 92*(2), 417-426.

Rossman, M. J., Garten, R. S., Venturelli, M., Amann, M., & Richardson, R. S. (2014). The role of active muscle mass in determining the magnitude of peripheral fatigue during dynamic exercise. *Am. J. Physiol. Regul. Integr. Comp. Physiol., 306*(12), R934-R940.

Rossman, M. J., Venturelli, M., McDaniel, J., Amann, M., & Richardson, R. S. (2012). Muscle mass and peripheral fatigue: a potential role for afferent feedback? *Acta Physiol, 206*(4), 242-250.

Šambaher, N., Aboodarda, S. J., & Behm, D. G. (2016). Bilateral Knee Extensor Fatigue Modulates Force and Responsiveness of the Corticospinal Pathway in the Non-fatigued, Dominant Elbow Flexors. *Front Hum Neurosci, 10,18.*

Sidhu, S. K., Weavil, J. C., Mangum, T. S., Jessop, J. E., Richardson, R. S., Morgan, D. E., & Amann, M. (2017). Group III/IV locomotor muscle afferents alter motor cortical and corticospinal excitability and promote central fatigue during cycling exercise. *Clin Neurophysiol, 128*(1), 44-55.

Sidhu, S. K., Weavil, J. C., Venturelli, M., Garten, R. S., Rossman, M. J., Richardson, R. S., . . . Amann, M. (2014). Spinal μ-opioid receptor-sensitive lower limb muscle afferents determine corticospinal responsiveness and promote central fatigue in upper limb muscle. *J Physio, 592*(22), 5011-5024.

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Med Sci Sports Exerc, 48*(2), 267-276.

St Gibson, A. C., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med, 36*(8), 705-722.

Stedman, A., Davey, N. J., & Ellaway, P. H. (1998). Facilitation of human first dorsal interosseous muscle responses to transcranial magnetic stimulation during voluntary contraction of the contralateral homonymous muscle. *Muscle Nerve, 21*(8), 1033-1039.

Takahashi, K., Maruyama, A., Hirakoba, K., Maeda, M., Etoh, S., Kawahira, K., & Rothwell, J. C. (2011). Fatiguing intermittent lower limb exercise influences corticospinal and corticocortical excitability in the nonexercised upper limb. *Brain Stimul, 4*(2), 90-96.

Takahashi, K., Maruyama, A., Maeda, M., Etoh, S., Hirakoba, K., Kawahira, K., & Rothwell, J. C. (2009). Unilateral grip fatigue reduces short interval intracortical inhibition in ipsilateral primary motor cortex. *Clin Neurophysiol, 120*(1), 198-203.

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural contributions to muscle fatigue: from the brain to the muscle and back again. *J. Med. Sci. Sport Exerc*.

Thomas, C. K., & Del Valle, A. (2001). The role of motor unit rate modulation versus recruitment in repeated submaximal voluntary contractions performed by control and spinal cord injured subjects. *J Electromyogr Kinesiol., 11*(3), 217-229.

Todd, G., Petersen, N. T., Taylor, J. L., & Gandevia, S. (2003). The effect of a contralateral contraction on maximal voluntary activation and central fatigue in elbow flexor muscles. *Exp Brain Res, 150*(3), 308-313.

Triggs, W. J., Yathiraj, S., Young, M. S., & Rossi, F. (1998). Effects of task and task persistence on magnetic motor-evoked potentials. *J Contemp Neurol, 2*, 2-7.

Triscott, S., Gordon, J., Kuppuswamy, A., King, N., Davey, N., & Ellaway, P. (2008). Differential effects of endurance and resistance training on central fatigue. *J Sports Sci, 26*(9), 941-951.

Tucker, R. (2009). The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *Br J Sports Med, 43*(6), 392-400.

Vuillerme, N., Forestier, N., & Nougier, V. (2002). Attentional demands and postural sway: the effect of the calf muscles fatigue. *Med Sci Sports Exerc, 34*(12), 1907-1912.

Windhorst, U., Kirmayer, D., Soibelman, F., Misri, A., & Rose, R. (1996). Effects of neurochemically excited group III–IV muscle afferents on motoneuron afterhyperpolarization. *Neuroscience, 76*(3), 915-929.

Zijdewind, I., Zwarts, M. J., & Kernell, D. (1998). Influence of a voluntary fatigue test on the contralateral homologous muscle in humans? *Neurosci Lett, 253*(1), 41-44.

Chapter 2: Co-Authorship Statement

The following details my role in the preparation of the manuscript.

Research Design

Methodology was developed based on previous research by Dr. David Behm in combination with work from non-local muscle fatigue. Discussions with Dr. David Behm and Dr. Israel Halperin helped to refine details of the experiment. With assistance from Dr. David Behm I was able to obtain approval from the Health Research Ethics Authority (HREA) to conduct this research.

Data Collection

I collected all data with assistance from Dr. David Behm.

Data Analysis

I performed all data analysis procedures.

Manuscript Preparation

I wrote the manuscript with assistance from Dr. David Behm.

Chapter 3: Manuscript

The effect of dominant index finger fatigue on the force production of contralateral homologous muscle and biceps brachii

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3.1 Abstract

Introduction: Non-local muscle fatigue (NLMF) has generally focused on large muscle groups. It is unclear whether fatigue of a small muscle can result in NLMF of a large muscle. The purpose of the present study was to examine the effect of a small muscle (first dorsal interosseous, FDI) fatiguing protocol on the force production of contralateral homologous and larger heterologous muscles (biceps brachii, BB). **Method**: Fifteen right-handed male subjects participated in the study. Subjects performed three pre-test maximum voluntary isometric contractions (MVICs) of index finger abduction or elbow flexion on the non-dominant side. Subsequently, they performed two 100s index finger abduction MVICs on the dominant side (fatiguing protocol) or rested for 5 minutes (control). Afterwards, a single MVIC and a 12-MVIC fatiguing protocol were completed with index finger abduction or elbow flexion on the non-dominant side. Force and electromyography (EMG) were measured from both sides. **Results**: The force and EMG median frequency (MDF) of non-exercised index finger abductors (IFA) /FDI and elbow flexors (EF) /BB significantly decreased after the fatiguing protocol. Compared with control condition, the non-exercised IFA had a significant greater fatigue index than the

EF's force and EMG MDF. There were no significant force differences with the single MVIC test between conditions. **Conclusion:** The small muscle fatiguing protocol produced NLMF effects on both contralateral homologous and larger heterologous muscles, with the force decrements greater with the homologous muscle. The results suggested that both physiological and psychological factors may have contributed to the small muscle NLMF effect.

Key words: non-local muscle fatigue (NLMF), muscle mass, hand muscle.

3.2 Introduction

Neuromuscular fatigue is not limited to the working muscle but also may present on non-exercised muscles both ipsilateral and/or contralateral to the muscle where fatigue was induced. This phenomenon is known as crossover fatigue or non-local muscle fatigue (NLMF) (Martin and Ratty, 2007; Halperin et al. 2015). There is substantial evidence demonstrating crossover effects on contralateral upper (Aboodarda et al. 2016; Sidhu et al. 2014) and lower (Doix et al. 2013; Kennedy et al. 2013a; Halperin et al. 2014a; Hamilton and Behm, 2017) non-exercised limbs following a fatiguing protocol. However, the literature is not consistent. For example, Arora et al. (2015) did not find any changes in the maximal voluntary isometric contraction

(MVIC) force of non-exercised knee extensors after a unilateral knee extensors fatiguing protocol. Alcaraz et al. (2008) also reported that there was no NLMF effect on non-exercised upper body muscles followed a dynamic lower body fatiguing protocol.

Presently, most NLMF studies focus on large muscle groups (e.g. elbow flexors (EF) or knee extensors (quadriceps)), with few studies involving small muscles (e.g. finger muscles). For instance, only three papers have examined NLMF effects on the unilateral first dorsal interosseous (FDI) after the fatigue of the contralateral homologous muscle, and the results were inconsistent (Zijdewind et al. 1998; Post et al. 2008; Kavanagh et al. 2016). This inconsistency may be attributed to the differences between protocols. Zijdewind et al. (1998) reported that a unilateral submaximal contraction fatigue protocol of the FDI did not elicit NLMF effects on the contralateral FDI, whereas Post et al. (2008) demonstrated significant NLMF effects on FDI from both sustained maximal and submaximal protocols. Kavanagh et al. (2016) also showed NLMF effects on the FDI by using a maximal intermittent contraction protocol to fatigue the contralateral FDI. Despite the different fatigue protocols, the most important similarity of the three papers is that the tested, non-exercised muscles were the contralateral homologous muscle.

However, the NLMF effect from fatigue of the FDI to a non-exercised heterologous muscle has not been investigated. Furthermore, since most of the NLMF studies have investigated larger muscle groups, the NLMF effect of a smaller muscle group upon a larger heterologous muscle group is also unknown.

Activation of group III/IV muscle afferents from the prolonged maintenance of muscle contractions provides inhibitory feedback to the central nervous system (Bigland-Ritchie et al. 1986; Gandevia et al. 1996). This negative influence potentially could have a widespread effect to non-exercised muscles (Amann et al. 2011; Kennedy et al. 2013b; Sidhu et al. 2017). Indeed, Kennedy et al. (2013b) demonstrated that post-fatigued firing of group III/IV muscle afferents of the adductor pollicis, decreased the force production of ipsilateral non-exercised EF. Furthermore, studies showed that a smaller muscle mass evokes stronger, local signals to group III/IV muscle afferents compare to weaker and more diffuse signals from a much larger muscle mass (Rossman et al. 2012, 2014). Therefore, it is reasonable to speculate that a small muscle fatiguing protocol would produce NLMF effects not only to a non-exercised homologous muscle, but also to larger heterologous muscles.

Psychological effects can also impair physical performance (Marcora et al. 2009). The fatiguing protocol can be perceived as a high level of exertion with the focus and attention needed to maintain such a demanding and uncomfortable activity, which could result in mental fatigue (Pageaux et al. 2014). Previous studies have shown that the mental fatigue can directly deteriorate physical performance (Budini et al. 2014; Pageaux et al. 2014) and increase the perceived exertion (Marcora et al. 2009; Van Cutsem et al. 2017) during the exercise. Therefore, the NLMF elicited from a small muscle may also partially be attributed to the psychological influence.

The primary aim of the present study was to investigate the effect of small muscle (FDI) fatigue on the force production of the contralateral homologous and a larger heterologous muscle (biceps brachii: BB). Specifically, we hypothesized that the fatiguing contraction of the FDI could result in the NLMF effect on both contralateral non-exercised FDI and BB.

3.3 Methodology

Participants

A power analysis (G*Power 3.1.9.2) was used to calculate the sample size of this study using a statistical power of 0.80, and alpha level of $p < 0.05$. This was based on samples of four studies (Zijdewind et al. 1998; Post et al. 2008; Kennedy et al. 2013b; Kavanagh et al. 2016) that had participants engaged in NLMF with fatiguing hand muscles. The mean sample size was calculated to be 8 participants. However, 15 participants from the university population were recruited to compensate for the possibility of any drop outs and ensure the power of study. All subjects were right hand dominant males, none of who had a history of musculoskeletal or neurological diseases. Subjects were verbally informed of the procedures. They were then asked to read and sign the consent form if they were in agreement. Subjects were asked to refrain from ingesting caffeine and participating in vigorous physical activity at least 1 day before attending each experimental session. The study was conducted in accordance with the declaration of Helsinki and approved by the Interdisciplinary Committee on Ethics in Human Research of Memorial University of Newfoundland (20181017-HK).

Experimental setup

Subjects were seated in a chair, elbow slightly flexed (120°-130° angle) (Kavanagh et al. 2016) with their pronated forearm supported on the table. All fingers were fully extended with the palm facing down, placed on a custom-designed device for measuring index finger abduction force. The elbow, distal forearm, digits 3-5 and the thumb were secured with Velcro straps to prevent any movements during the contractions. The index finger metacarpophalangeal joint was positioned at 0° abduction and 0° flexion, and the interphalangeal joints were maintained in extension. The proximal interphalangeal joint was pressed against a calibrated strain gauge (Transducer Techniques Inc., MLP-300-CO; sensitivity = 2mV/V, CA, USA) during the experiment, which was connected to the custom-designed device. (Fig.1)

Maximal voluntary isometric contractions (MVIC)

The index finger abduction forces were recorded from the dominant side during the fatiguing intervention and from the non-dominant side during the pre- and post-tests. The forces were sampled by the Daytronic conditioner (Daytronic, Model 3270, OH, USA). The conditioner was connected to the Biopac MP150 (Biopac System Inc., DA 100: analog-digital converter MP150WSW; Holliston, MA) for force analysis. Before starting the contractions, subjects were instructed to maintain contact with the strain gauge.

The elbow flexion forces from the non-dominant side were collected during the pre- and post-test. Forces from the EF were collected by having subjects sit on a chair with hips and knees flexed to 90° with the elbow flexed at 90° and supported by an arm-rest, the forearm was in a supinated position while the wrist was inserted into a padded strap attached to a high tension wire attached to a load cell (Omega Engineering Inc., LCCA 500 pounds; sensitivity = 3 mV/V, Quebec, Canada), which was used to measure elbow flexion force. The forces were sampled by Biopac data collection system (Biopac Systems Inc. DA 100, Holliston, MA).

Surface electromyography (EMG)

Surface electromyography (EMG) was recorded from the non-dominant FDI or BB during the pre- and post-tests. Following the skin preparation, bipolar Ag/AgCl electrodes (Ag/AgCl; Kendall MediTrace H69P foam electrodes, Holliston, Massachusetts, USA) were placed over the muscle belly of the superficial head of FDI, and over the distal tendon at the second metacarpophalangeal joint. The reference electrode was placed over the ulnar styloid process (Post et al. 2008; Kavanagh et al. 2016). For the BB, bipolar Ag/AgCl electrodes (Kendall130 MediTrace foam electrodes, H69P, Holliston, Massachusetts, USA) were placed over the midpoint of the muscle belly. The inter-electrode spacing was 10 mm. All the EMG signals were collected by the Biopac data acquisition system (AcqKnowledge III, Biopac System Inc. Holliston MA. USA) at a sample rate of 2000 Hz (impedance = 2 MΩ, common mode rejection ratio >110 dB min (50/60 Hz), noise >5 µV). A bandpass filter (10–500 Hz) was applied prior to digital conversion. (Fig.2)

Experimental protocol

Subjects were required to attend the lab for four sessions and performed one of the following four conditions: 1) fatigue the FDI and test the contralateral FDI (Fatigue-FDI); 2) fatigue the FDI and test the contralateral BB (Fatigue-BB); 3) no fatigue intervention and test the contralateral FDI (Control-FDI); 4) no fatigue intervention and test the contralateral BB (Control-BB). The conditions were randomized and at least one day of rest was allowed between testing days. Subjects were familiarized with the testing procedures during the first testing day.

Subjects initially performed the warm-up for all the conditions. The warm-up included 10 isometric contractions at an intensity level equating to approximately 50% of their perceived maximum on either index finger abductors (IFA) and/or EF. Work to rest ratio was 2s/2s.

(1) Pre-test

A minute after the warm-up, participants were required to perform 3 MVICs on the non-dominant IFA or EF for 5s with 1 minute of rest between contractions.

(2) Fatiguing intervention

Following the warm-ups and pre-tests, subjects performed the fatiguing intervention which included 2 MVICs of the IFA on the dominant side, 30s of rest was provided between repetitions. For the control condition, they were asked to be seated and rest for 5 mins, which was the estimated duration to complete the fatiguing protocol. To ensure consistency, verbal encouragement involved the same wording and timing. Participants were not informed of the end point of any test.

(3) Post-Intervention test

Immediately after the intervention, subjects performed a single and then a repeated MVIC protocol with either IFA or EF (same movement as the pre-test). The repeated MVIC protocol consisted of 12 MVICs at a work to rest ratio of 5s/10s (Halperin et al. 2014a, 2014b). Standardized verbal encouragements included the same wording and timing during the repeated MVIC protocol.

Data analysis

Force and EMG data were recorded and analyzed with a commercially designed software program (Acq-Knowledge III, Biopac Systems Inc., Holliston MA, USA). The mean force for each MVIC during pre- and post-test was determined over a 3s window defined as 1.5s before and following the peak force of each contraction. All mean force data were reported as the percentage of highest pre-test values. The mean amplitude of the rectified root mean square (RMS) EMG was calculated by the software from 50 ms bins within the same 3s window as applied to the force analysis. The absolute mean amplitude measures were then normalized to the highest pre-test value and reported as a percentage. The fast Fourier transform (FFT) was also applied to EMG signal for the pre- and the post-test. The FFT median frequency (MDF) was computed and normalized to the highest pre-test value and reported as a percentage.

The fatigue index (FI) was calculated for both force and FFT MDF during the post-test using following formula: FI (%) = (maximal – minimal) * 100/maximal (Adam, 2002).

Statistical analysis

First, normality (Kolmogorov–Smirnov) and homogeneity of variances (Levene) tests were conducted for all dependent variables. If the assumption of sphericity was violated, the Greenhouse-Geisser correction was employed. Secondly, two sets of two-way repeated measures ANOVA tests were conducted. The analysis of the mean force, the FFT MDF and the EMG RMS involved the 2 conditions (fatigue vs. control) x 12 repeated MVICs for IFA/FDI and EF/BB. The analysis of a) single MVIC, b) the force differences between the single MVIC and the first MVIC of the 12-MVIC protocol, and c) the fatigue indexes (force, FFT MDF) involved a 2 conditions x 2 muscles analysis. 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. An alpha level of 0.05 was used to determine statistical significance. Cohen's effect size (*d*) was calculated, and results evaluated on the following criteria: < 0.35 trivial; 0.35-0.80 small; 0.80- 1.50 moderate; and >1.50 large, for recreationally trained subjects (Cohen, 1988). Data was reported as mean ± standard deviation (SD).

3.4 Results

Mean force during the post-tests.

A significant main effect was found for conditions ($p = .036$; $d = 0.49$) and repetitions (p

$< .001$; $d = 0.54$) but no interactions were found ($p = .370$; $d = 0.14$) for the IFA (Fig. 3a). The averaged forces of non-exercised IFA in the control session were 10.63 ± 4.28% greater compared with the fatigue session. Also, the averaged forces significantly dropped 27.17 ± 2.31% from the single MVIC to the last post-test MVIC (#12) across both conditions.

A significant main effect was found for conditions ($p = .044$; $d = 0.46$) and repetitions ($p = .004$; $d = 0.41$) for the EF (Fig. 3b). The averaged forces of non-exercised EF in the control session were 14.79 ± 10.46% greater than the fatigue session. Also, the averaged forces were significantly decreased 14.72 ± 3.10% from the single MVIC to the last post-test MVIC (#12).

EMG FFT MDF during the post- tests

A significant main effect was found for repetitions ($p = .041$; $d = 0.41$), but no significant differences between conditions ($p = .281$; $d = 0.10$) or interactions ($p = .288$; $d = 0.15$) were found for the FDI (Fig.4a). The mean MDF of non-exercised FDI EMG were significantly decreased from the single MVIC to the last repeated MVIC (#12) across two conditions by 8.27 ± 4.01%.

A main significant main effect was found for conditions ($p = .045$; $d = 0.42$), but no significant main effect was found for repetitions (*p* = .252; *d* = 0.22) or interactions for the BB (*p* = .178; *d* = 0.23) (Fig.4b). The mean MDF of non-exercised BB EMG were 4.35 ± 2.88% higher in the control session than in the fatigue session.

Single MVIC

No significant main effect was found for conditions (*p* = .945; *d* = 0.01), muscles (*p* = .589; *d* = 0.04) or interactions (*p* = .696; *d* = 0.02) (Fig.5).

Force differences between the single MVIC and the 1st MVIC of the 12-MVIC protocol

A significant main effect was found for conditions (*p* = .021; d = 0.49) and muscles (*p* = .047; *d* = 0.43) but no interactions were found (*p* = .773; *d* = 0.01) (Fig. 6). After the fatiguing protocol, the force differences between the single MVIC and the first repetition of the repeated MVICs protocol increased by 10.16 ± 7.18%, the EF (12.7 ± 18.99%) had greater force decrease than the IFA (6.25 ± 8.76%).

Force Fatigue index

A significant main effect was found for conditions (*p* = .021; *d* = 0.49) and muscles (*p* = .029; *d* = 0.43) but no interactions were found (*p* = .754; *d* = 0.03) (Fig. 7). After the fatiguing protocol, the force fatigue index increased by 8.86 ± 6.27%. The IFA fatigue index (12.54 ± 8.87 %) increased more than the EF (5.18 ± 3.66%).

FFT MDF fatigue index

A significant main effect was found for conditions (p = .041; d = 0.38) and muscles (p = .039; d = 0.33) but no interactions were found (p = .658; d = 0.03) (Fig.8). After the fatiguing protocol, the MDF fatigue index increased by 3.66 ± 2.40%. The FDI MDF fatigue index (5.72 ± 1.89%) increased more than the BB (1.69 ± 3.47%).

RMS

After the fatiguing protocol, no significant FDI (Fig. 9a) or BB (Fig. 9b) RMS EMG main effect were found for conditions (FDI: p = .724; d = 0.02; BB: p = .672; d = 0.03), repetitions (FDI: p = .462; d = 0.12; BB: p = .581; d = 0.11) or interactions (FDI: p = .748; d = 0.09; BB: p = .230; d = 0.16).

3.5 Discussion

The primary findings of the present study were that unilateral fatigue of the dominant index finger led to significant decrements in the force production and EMG MDF of contralateral non-exercised homologous and a larger heterologous muscle group (EF). The contralateral non-exercised IFA/FDI exhibited a greater force and EMG MDF fatigue index than the non-exercised EF/BB after the unilateral fatigue protocol.

Although NLMF effects have been examined, results are conflicting and the possible mechanisms are still debatable (Halperin et al. 2015). Most of the NLMF studies focus on large muscle groups such as knee extensors and EF (Halperin et al. 2014a, 2014b; Kawamoto et al. 2014; Aboodarda et al. 2015, 2016, 2017; Šambaher et al. 2016). Even though there were a few studies that fatigued a small muscle, the tested muscles were homologous only (Zijdewind et al. 1998; Post et al. 2008; Kavanagh et al. 2016). Based on our knowledge, the present study is the first study that examined NLMF effects on both a homologous and a larger heterologous muscle from the fatiguing of a contralateral small volume muscle.

The force reduction of non-exercised IFA after fatiguing of contralateral IFA is in agreement with Post et al. (2008) and Kavanagh et al. (2016). Although the fatiguing protocols in these two studies and the present study were not precisely similar, all three studies included a maximal contraction fatiguing protocol. On the contrary, submaximal contraction fatiguing protocols resulted in more variable changes. For example, Zijdewind et al. (1998) did not find any NLMF effect on non-exercised FDI after fatigue of the contralateral FDI with an isometric submaximal contraction (30% of MVIC), but Post et al. (2008) presented significantly reduced non-exercised IFA force production after both submaximal (30% MVIC) and maximal fatiguing contractions of the contralateral IFA. Based on a limited scope of studies, maximal contraction protocols have produced more consistent NLMF effect in small muscles.

The force reduction of non-exercised EF after fatiguing of unilateral IFA is in agreement with our hypothesis. Although there are few studies investigating the NLMF effect on a larger muscle from fatigue of a small muscle group, the present results were in partial agreement with some similar studies (Rossman et al. 2012, 2014; Kennedy et al. 2013b). For example, Kennedy et al. (2013b) found that maintained firing of group III/IV muscle afferents after a fatiguing adductor pollicis contraction could significantly reduce the force production of non-exercised ipsilateral EF. Contrary to the present study, instead of testing the NLMF effect on contralateral EF immediately after a hand muscle fatiguing protocol, Kennedy et al. (2013b) subsequently blocked the circulation of the hand for two minutes to keep firing of group III/IV muscle afferents, in order to investigate the contribution of post-fatigued activated group III/IV muscle afferents on the NLMF effect. Similar to the present study, the force production of EF deteriorated after hand muscle fatigue (Kennedy et al. 2013b). Indeed, the inhibitory feedback from activated group III/IV muscle afferents to the central nervous system has been shown to provide a negative influence on exercise performance (Amann et al., 2011, 2012; Kennedy et al. 2013b; Sidhu et al. 2017). Kennedy et al. (2013b) demonstrated that this inhibitory feedback plays an important role in NLMF effect, even when the effects are transferred from a small fatigued muscle to a larger non-exercised muscle. Consequently, in the present study, the force decrement of a larger non-exercised muscle from the unilateral fatigue of a small muscle (without ischemia) might also be attributed to muscle afferent inhibition. Moreover, it has been proposed that the less muscle mass involved in the exercise, results in a greater relative contribution of peripheral fatigue (Rossman et al. 2014). This is attributed to a smaller muscle mass evoking stronger, local group III/IV muscle afferent signals compared to more diffuse signals provided by a larger muscle mass (Rossman et al. 2012, 2014). Together, our results support the contention that group III/IV muscle afferents of a small muscle group may contribute to NLMF.

The results also demonstrated that non-exercised IFA/FDI had a greater rate of fatigue index for both force and EMG MDF compare to non-exercised EF/BB after the contralateral fatiguing of the IFA. This implies that the NLMF effect elicited from the IFA on non-exercised heterologous larger muscles was not as substantial as with a homologous muscle. This may be attributed to alterations of corticospinal excitability. Since hand and finger muscles have larger corticospinal projections than many other muscles (Takahashi et al. 2009), the alteration of corticospinal excitability that contributes to the fatigue of contralateral hand and finger muscles might be greater than other muscles (Takahashi et al. 2009; Matsuura et al. 2015).

It has been suggested that there is movement coordination between homologous muscles when a person moves limbs simultaneously, in other words, a tendency to synchronize movement between homologous muscles (Swinnen, 2002). Furthermore, this phenomenon is most common in fingers, for instance, bimanual index finger oscillation paradigm has been a classical model to study about coactivation of homologous muscles (Kelso, 1984; Haken et al. 1985). One possible explanation is that contralateral homologous muscles share a common neural pathway (Carson, 2005), thus there might be mediating bilateral interactions between limbs (Ridderikhoff et al. 2005; Post et al. 2008). However, it is also believed that the coactivation between homologous muscles might due to perceptual anticipation, which refers to the visualization of the movement of the unilateral limb, participants may prepare the contralateral homologous muscle as a way of anticipating the perceptual consequences of movements (Mechsner et al. 2004). This might result in unintended muscle contractions of contralateral non-exercised muscle that start even before the post-test occurs, which lead to more evident NLMF effects than with heterologous muscles. Indeed, Post et al. (2008) found that during the unilateral FDI fatiguing protocol, the coactivation of contralateral non-exercised FDI increased, and NLMF effect also presented after the fatiguing protocol. Therefore, in the present study, the anticipatory response might account for greater force and EMG MDF decrease of homologous than heterologous muscles.

Fatiguing studies are not only highly physically demanding, but also mentally challenging (Dorris et al. 2012; Pageaux et al. 2014). In the present study, participants were required to perform the fatiguing protocol with maximal intensity on a muscle group (index finger abductor) that is not frequently subjected to such a protocol. This more uncommon action could produce more response inhibition (Pageaux et al. 2014) and require greater perception of effort (Marcora et al. 2009), thus imposing a greater mental challenge. Furthermore, high perceived exertion demanding tasks can increase the mental fatigue (Pageaux et al. 2014), decrease motivation (Marcora et al. 2009), and thus deteriorate physical performance (Pageaux et al. 2016). According to the psychobiological model of exercise performance (Marcora, 2008), a fatigue test is a motivated behavior ultimately determined by perceived exertion and potential motivation (Wright, 2008). It has been previously noted that muscle mass may affect perceived exertion (Sweet et al. 2004; Mayo et al. 2014). Faigenbaum et al. (2004) demonstrated that a smaller muscle mass may elicit greater perceived exertion compare to larger muscle mass while contracting at the same intensity. Therefore, the small muscle fatigue protocol induced NLMF effects on a non-exercised larger muscle may also be attributed to a psycho-physiological effect to a certain extent.

Our results also showed that, after the fatiguing protocol, no significant force decrements were observed with a single MVIC of non-exercised EF and IFA, whereas significant force decreases for both muscles were presented in the first MVIC of the repeated MVICs protocol. This is partially in agreement with Halperin et al. (2014b), who demonstrated that the EF only had force decrement in the last five MVICs during the repeated MVICs protocol after knee extensor fatigue. Thus it has been suggested that the NLMF effect is more evident during repeated MVICs protocol rather than a single MVIC (Halperin et al. 2015). Similar results also have been shown in different NLMF studies with EF (Triscott et al. 2008) or knee extensors (Amann et al. 2013).

Interestingly, our results found a significant and substantial force decrease from the single MVIC to the first repetition of the MVICs repeated protocol. In anticipation of the subsequent series of contraction, the participants may subconsciously decreased their initial MVIC force output in order to cope with the subsequent fatiguing task possibly to avoid a future catastrophic event (St Gibson et al. 2006; Tucker, 2009). Also, the setting of initial work rate is based on previous experience and the knowledge of exercise duration (St Gibson et al. 2006). In the present study, all the participants were informed that they had to perform a repeated (12 repetitions) MVICs fatigue protocol immediately after they finished the single MVIC test. In this case, as a pacing strategy, exercise performance would be subconsciously attenuated from the beginning of exercise (St Gibson et al. 2006; Tucker, 2009). Further, during the test, most of the participants were not accurately aware of how many MVICs remained and they were not informed when the final repetition was to be performed. Hence, the participants lacked knowledge of the task endpoint. Knowing the endpoint is crucial for the brain to generate an appropriate strategy during the exercise (St Gibson et al. 2006). Lacking this knowledge could result in an inefficient pacing strategy which may lead to greater peripheral fatigue (St Gibson et al. 2006; Hamilton and Behm, 2017). Indeed, Hamilton and Behm (2017) showed that not knowing the endpoint decreased the force production of non-exercised knee extensors after the fatiguing contraction of contralateral knee extensors compare to knowing the endpoint. Also, it has been suggested that the most considerable effect of the knowledge of the endpoint occurs during the initial and the final stage of the task (Billaut et al. 2011; Hamilton and Behm, 2017). Since the participants were not reminded when the final contraction was to occur, there was no pacing influenced increase in the final MVIC.

There were no significant changes in EMG RMS neither between conditions nor repetitions for both tested muscles. This is in accordance with Halperin et al. (2014a, 2014b) who also didn't find significant NLMF-induced changes in EMG RMS of non-exercised muscles. It has been suggested that EMG RMS is less sensitive to changes in muscle force compared to MDF so it is a less reliable indicator of muscle fatigue (Dimitrova et al. 2003; Bartuzi et al. 2014). Similarly, in the present study, while there were no significant changes in EMG RMS, there were significant decrease of MDF which somewhat paralleled the muscle fatigue.

To the best of our knowledge, this is the first study to demonstrate that a small muscle fatiguing protocol is able to elicit NLMF effects both on homologous and larger heterologous muscles. Future studies may take a deeper insight into the relationship between muscle mass and the extent of NLMF effect by conducting similar protocol in lower limbs. Also, further investigations may include the objective measures of motivation or perceived exertion during and/or after fatiguing protocol to test the contribution of psychological effect to NLMF effect.

3.6 References:

Aboodarda, S., Šambaher, N., & Behm, D. (2016). Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. *Scand J Med Sci*

Sports 26 (11), 1301-1312.

Aboodarda, S. J., Copithorne, D. B., Power, K. E., Drinkwater, E., & Behm, D. G. (2015). Elbow flexor fatigue modulates central excitability of the knee extensors. *Appl Physiol Nutr Metab, 40*(9), 924-930.

Aboodarda, S. J., Šambaher, N., Millet, G. Y., & Behm, D. G. (2017). Knee extensors neuromuscular fatigue changes the corticospinal pathway excitability in biceps brachii muscle. *Neuroscience, 340*, 477-486.

Adam G.M. (2002) Exercise Physiology: Laboratory Manual. Champaign, IL: McGraw Hil, 107–119

Alcaraz, P. E., Sánchez-Lorente, J., & Blazevich, A. J. (2008). Physical performance and cardiovascular responses to an acute bout of heavy resistance circuit training versus traditional strength training. *J Strength Cond Res*, 22(3), 667-671.

Amann, M. (2012). Significance of Group III and IV muscle afferents for the endurance exercising human. *Clin. Exp. Pharmacol. Physiol, 39*(9), 831-835.

Amann, M., Blain, G. M., Proctor, L. T., Sebranek, J. J., Pegelow, D. F., & Dempsey, J. A.

(2011). Implications of group III and IV muscle afferents for high- intensity endurance exercise performance in humans. J. Physiol., 589(21), 5299-5309.

Amann, M., Venturelli, M., Ives, S. J., McDaniel, J., Layec, G., Rossman, M. J., & Richardson, R. S. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *J Appl Physiol, 115*(3), 355-364.

Arora, S., Budden, S., Byrne, J. M., & Behm, D. G. (2015). Effect of unilateral knee extensor fatigue on force and balance of the contralateral limb. *Eur J Appl Physiol, 115*(10), 2177-2187.

Bartuzi, P., & Roman-Liu, D. (2014). Assessment of muscle load and fatigue with the usage of frequency and time-frequency analysis of the EMG signal. *Acta Bioeng Biomech, 16*(2), 31--39.

Bigland-Ritchie, B., Dawson, N., Johansson, R., & Lippold, O. (1986). Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *J. Physiol, 379*, 451.

Billaut, F., Bishop, D. J., Schaerz, S., & Noakes, T. D. (2011). Influence of knowledge of sprint number on pacing during repeated-sprint exercise. *Med Sci Sports Exerc, 43*(4), 665-672.

Budini, F., Lowery, M., Durbaba, R., & De Vito, G. (2014). Effect of mental fatigue on induced tremor in human knee extensors. *J Electromyogr Kinesiol, 24*(3), 412-418.

Carson, R. (2005). Neural pathways mediating bilateral interactions between the upper limbs. *J Electromyogr Kinesiol, 49*(3), 641-662.

Dimitrova, N., & Dimitrov, G. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol, 13*(1), 13-36.

Doix, A.-C. M., Lefèvre, F., & Colson, S. S. (2013). Time course of the cross-over effect of fatigue on the contralateral muscle after unilateral exercise. *PloS one, 8*(5), e64910.

Dorris, D. C., Power, D. A., & Kenefick, E. (2012). Investigating the effects of ego depletion on physical exercise routines of athletes. *J Sport Exerc Psychol, 13*(2), 118-125.

Faigenbaum, A. D., Milliken, L. A., Cloutier, G., & Westcott, W. L. (2004). Perceived exertion during resistance exercise by children. *Percept Mot Skills, 98*(2), 627-637.

Gandevia, S., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *J.Physio,490*(Pt 2), 529.

Haken, H., Kelso, J. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biol Cybern, 51*(5), 347-356.

Halperin, I., Aboodarda, S. J., & Behm, D. G. (2014b). Knee extension fatigue attenuates repeated force production of the elbow flexors. *Eur J Sport Sci, 14*(8), 823-829.

Halperin, I., Chapman, D. W., & Behm, D. G. (2015). Non-local muscle fatigue: effects and possible mechanisms. *Eur J Appl Physiol, 115*(10), 2031-2048.

Halperin, I., Copithorne, D., & Behm, D. G. (2014a). Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. *Appl Physiol Nutr Metab, 39*(12), 1338-1344.

Hamilton, A. R., & Behm, D. G. (2017). The effect of prior knowledge of test endpoint on non-local muscle fatigue. *Eur J Appl Physiol, 117*(4), 651-663.

Johnson, M. A., Polgar, J., Weightman, D., & Appleton, D. (1973). Data on the distribution of fibre types in thirty-six human muscles: an autopsy study. *J. Neurol. Sci, 18*(1), 111-129.

Kavanagh, J. J., Feldman, M. R., & Simmonds, M. J. (2016). Maximal intermittent contractions of the first dorsal interosseous inhibits voluntary activation of the contralateral homologous muscle. *J Neurophysiol, 116*(5), 2272-2280.

Kawamoto, J.-E., Aboodarda, S. J., & Behm, D. G. (2014). Effect of differing intensities of fatiguing dynamic contractions on contralateral homologous muscle performance. *J Sci Med Sport, 13*(4), 836.

Kelso, J. (1984). Phase transitions and critical behavior in human bimanual coordination. *Am. J. Physiol. Regul. Integr. Comp. Physiol., 246*(6), R1000-R1004.

Kennedy, A., Hug, F., Sveistrup, H., & Guével, A. (2013a). Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors. *Eur J Appl Physiol, 113*(3), 559-566.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013b). Fatigue-related firing of distal muscle nociceptors reduces voluntary activation of proximal muscles of the same limb. *J Appl Physiol*, 116(4), 385-394.

Marcora, S. M. (2008). Do we really need a central governor to explain brain regulation of exercise performance? *Eur J Appl Physiol, 104*(5), 929.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *J Appl Physiol, 106*(3), 857-864.

Martin, P. G., & Rattey, J. (2007). Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. Pflugers Arch, 454(6), 957-969.

Matsuura, R., & Ogata, T. (2015). Effects of fatiguing unilateral plantar flexions on corticospinal and transcallosal inhibition in the primary motor hand area. *J Physiol Anthropol, 34*(1), 4.

Mayo, X., Iglesias-Soler, E., & Fernández-Del-Olmo, M. (2014). Effects of set configuration of resistance exercise on perceived exertion. *Percept Mot Skills, 119*(3), 825-837.

Mechsner, F., & Knoblich, G. (2004). Do muscles matter for coordinated action? *J. Exp. Psychol. Hum. Percept. Perform., 30*(3), 490.

Pageaux, B., & Lepers, R. (2016). Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front Physiol, 7*, 587.

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *Eur J Appl Physiol, 114*(5), 1095-1105.

Post, M., Bayrak, S., Kernell, D., & Zijdewind, I. (2008). Contralateral muscle activity and fatigue in the human first dorsal interosseous muscle. *J Appl Physiol, 105*(1), 70-82.

Ridderikhoff, A., Daffertshofer, A., Peper, C. L. E., & Beek, P. J. (2005). Mirrored EMG activity during unimanual rhythmic movements. *Neurosci Lett, 381*(3), 228-233.

Rossman, M. J., Garten, R. S., Venturelli, M., Amann, M., & Richardson, R. S. (2014). The role of active muscle mass in determining the magnitude of peripheral fatigue during dynamic exercise. *Am. J. Physiol. Regul. Integr. Comp. Physiol., 306*(12), R934-R940.

Rossman, M. J., Venturelli, M., McDaniel, J., Amann, M., & Richardson, R. S. (2012). Muscle mass and peripheral fatigue: a potential role for afferent feedback? *Acta Physiol, 206*(4), 242-250.

Šambaher, N., Aboodarda, S. J., & Behm, D. G. (2016). Bilateral Knee Extensor Fatigue Modulates Force and Responsiveness of the Corticospinal Pathway in the Non-fatigued, Dominant Elbow Flexors. *Frontiers in human neuroscience, 10*.

Scott, W., Stevens, J., & Binder–Macleod, S. A. (2001). Human skeletal muscle fiber type classifications. *Phys Ther, 81*(11), 1810-1816.

Sidhu, S. K., Weavil, J. C., Mangum, T. S., Jessop, J. E., Richardson, R. S., Morgan, D. E., & Amann, M. (2017). Group III/IV locomotor muscle afferents alter motor cortical and corticospinal excitability and promote central fatigue during cycling exercise.*Clin Neurophysiol, 128*(1), 44-55.

Sidhu, S. K., Weavil, J. C., Venturelli, M., Garten, R. S., Rossman, M. J., Richardson, R. S., . . . Amann, M. (2014). Spinal μ-opioid receptor-sensitive lower limb muscle afferents determine corticospinal responsiveness and promote central fatigue in upper limb muscle. *J Physiol, 592*(22), 5011-5024.

St Gibson, A. C., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med, 36*(8), 705-722.

Sweet, T. W., Foster, C., McGuigan, M. R., & Brice, G. (2004). Quantitation of resistance training using the session rating of perceived exertion method. *J Strength Cond, 18*(4), 796-802.

Swinnen, S. P. (2002). Intermanual coordination: from behavioural principles to neural-network interactions. *Nature Rev Neurosci, 3*(5), 348.

Takahashi, K., Maruyama, A., Maeda, M., Etoh, S., Hirakoba, K., Kawahira, K., & Rothwell, J.

C. (2009). Unilateral grip fatigue reduces short interval intracortical inhibition in ipsilateral primary motor cortex. *Clin Neurophysiol, 120*(1), 198-203.

Thorstensson, A., & Karlsson, J. (1976). Fatiguability and fibre composition of human skeletal muscle. *Acta Physiol, 98*(3), 318-322.

Triscott, S., Gordon, J., Kuppuswamy, A., King, N., Davey, N., & Ellaway, P. (2008). Differential effects of endurance and resistance training on central fatigue. *J Sports Sci, 26*(9), 941-951.

Tucker, R. (2009). The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *Br J Sports Med, 43*(6), 392-400.

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: a systematic review. *Sports Med, 47*(8), 1569-1588.

Wright, R. A. (2008). Refining the prediction of effort: Brehm's distinction between potential motivation and motivation intensity. *Soc Personal Psychol Compass, 2*(2), 682-701.

Zijdewind, I., Zwarts, M. J., & Kernell, D. (1998). Influence of a voluntary fatigue test on the contralateral homologous muscle in humans? *Neurosci Lett, 253*(1), 41-44.

3.7 Figures

Figure 1

FIGURE 1: Experimental set-up

Figure 2

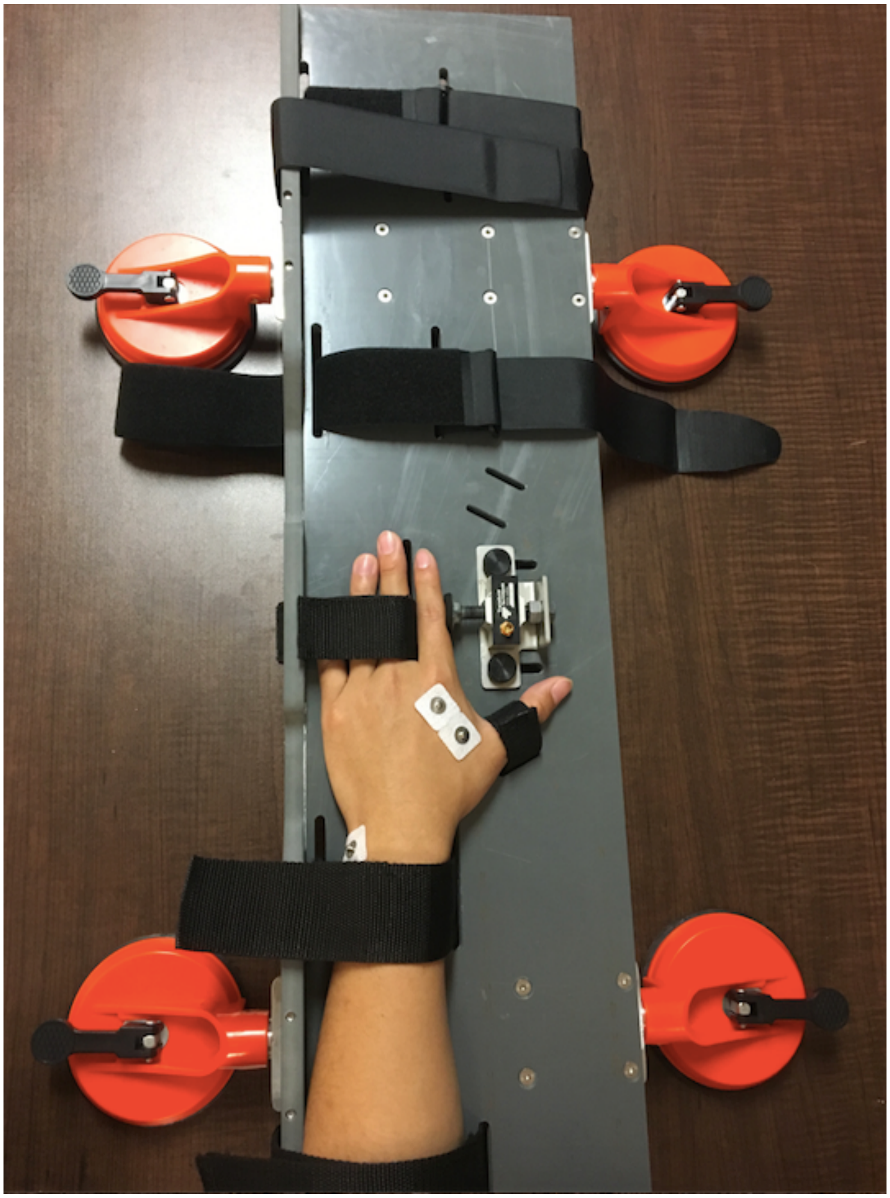

FIGURE 2: FDI electrodes placement.

Figure 3a.

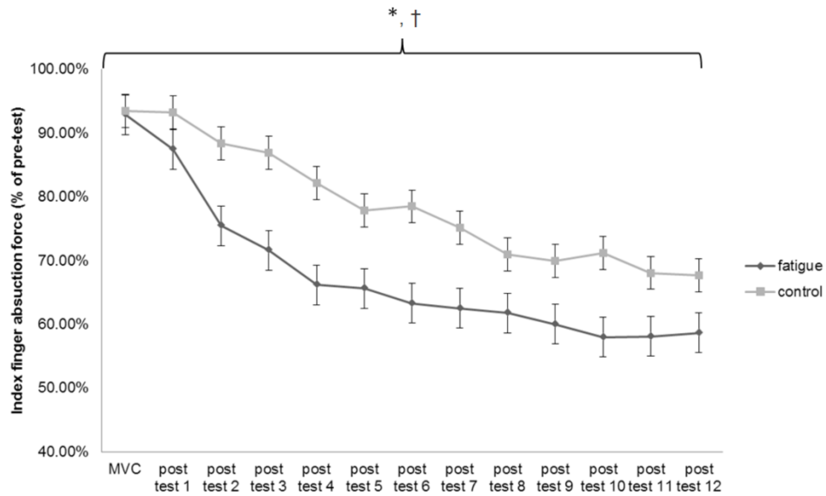

Figure 3b.

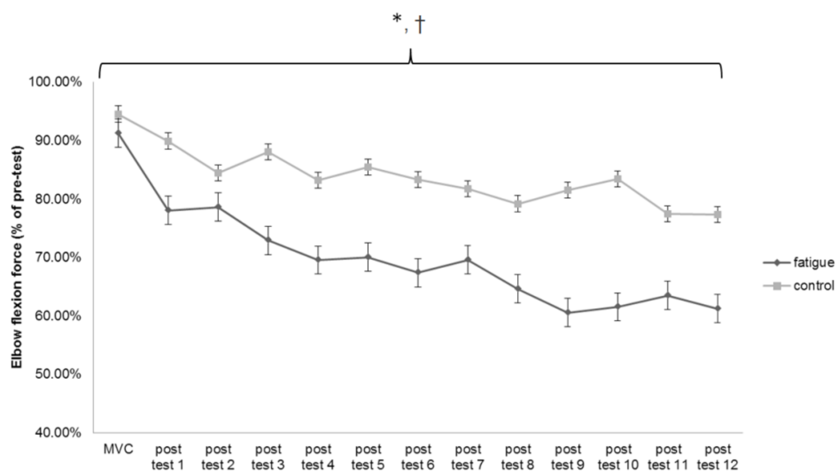

FIGURE 3: Mean force of IFA and EF over the post-tests for two conditions. Data is presented in percentage relative to the highest value of the pre-test.3a: Index finger abduction. 3b: Elbow flexion. * indicates significant differences for repetitions and † indicates significant differences between conditions ($p < 0.05$).

Figure 4a

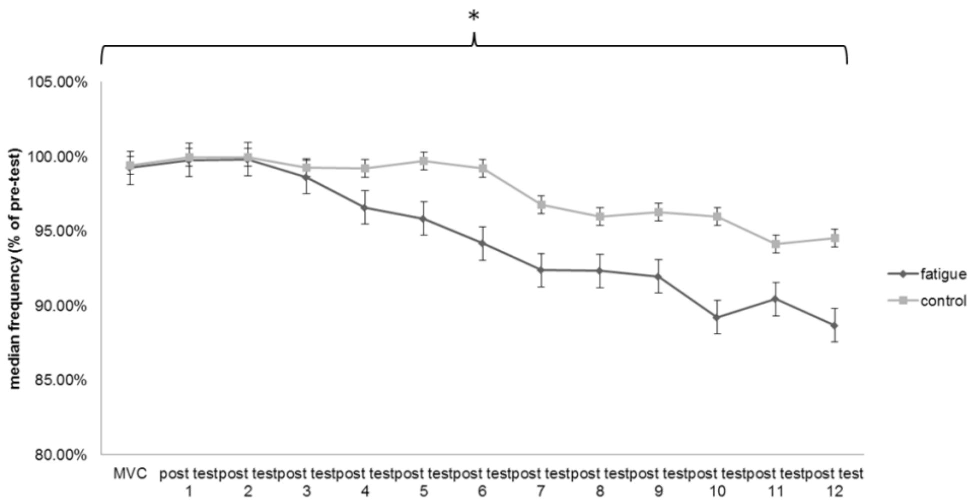

Figure 4b

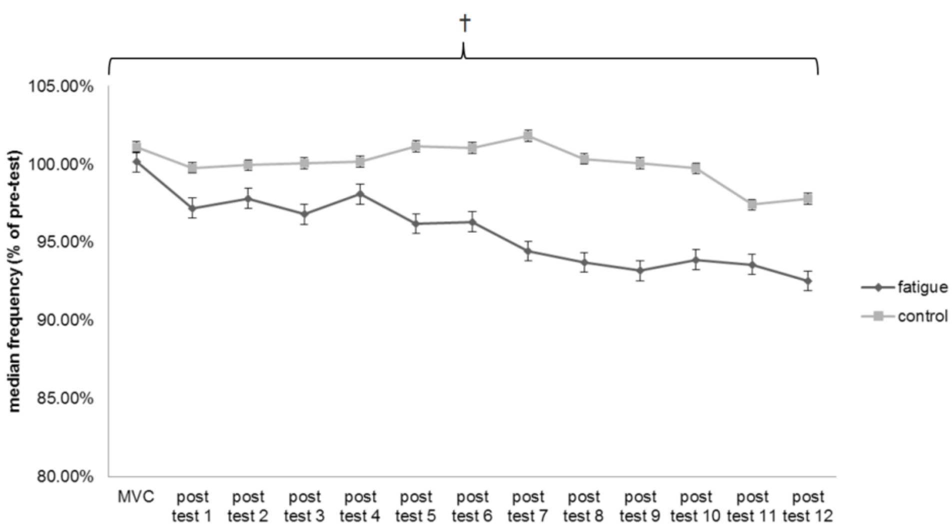

FIGURE 4: EMG FFT MDF of FDI and BB over the post-tests for two conditions. Data is presented in percentage relative to the highest value of the pre-test. 4a: FDI FFT MDF. 4b: BB FFT MDF. † indicates significant differences between conditions ($p < 0.05$).

Figure 5

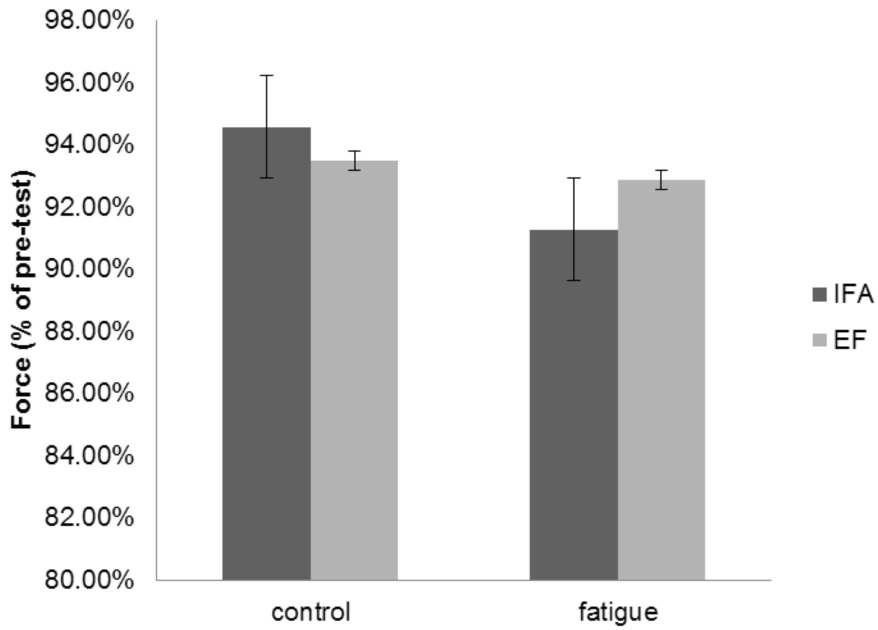

FIGURE 5 Mean force of IFA and EF over the single MVIC test for two conditions. Data is presented in percentage relative to the highest value of the pre-test.

Figure 6

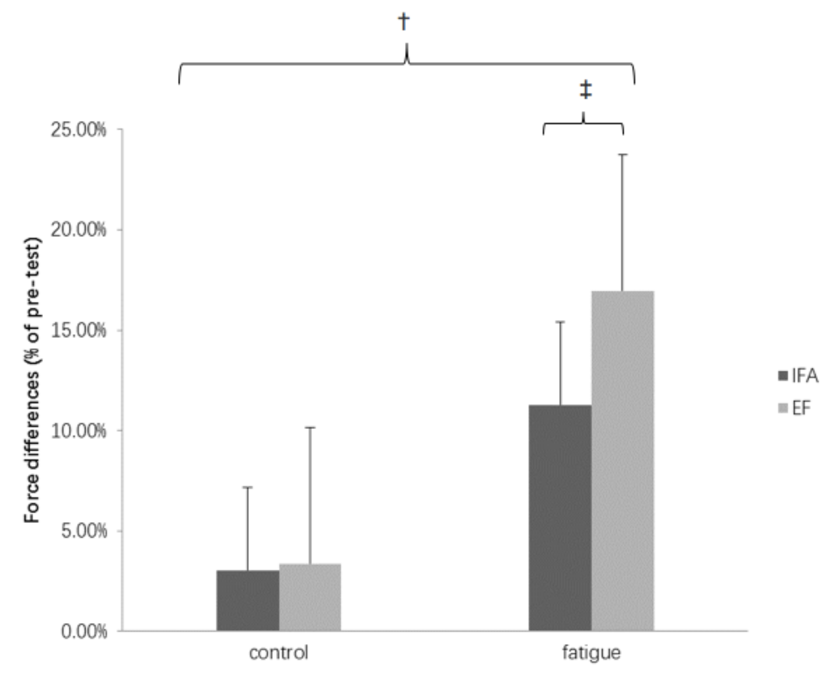

FIGURE 6 Force differences between the single MVIC and the first repetition of the repeated MVICs protocol. Data is presented in percentage relative to the highest value of the pre-test. † indicates significant differences between conditions and ‡ indicates significant differences between muscles ($p < 0.05$).

Figure 7

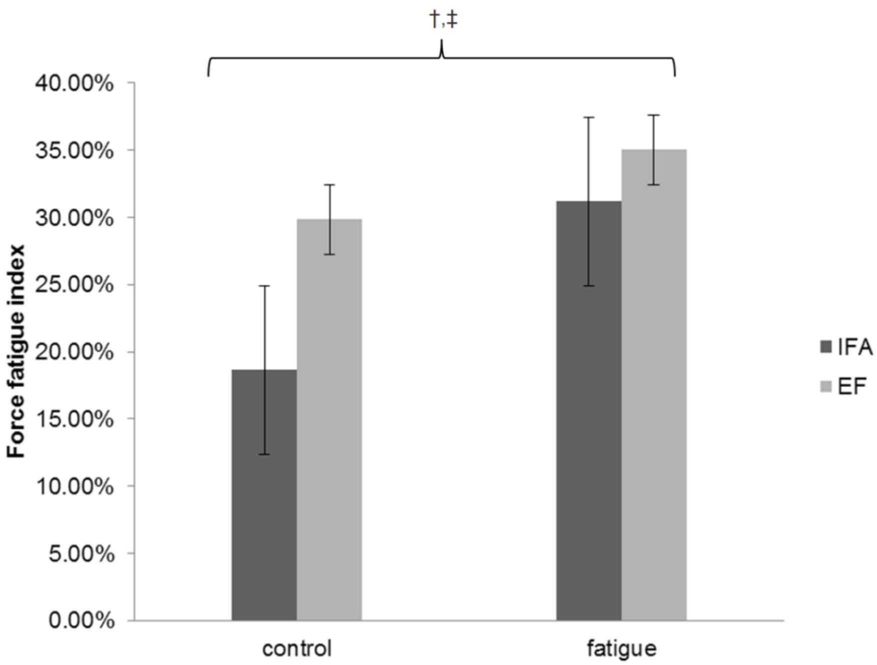

FIGURE 7 Force fatigue index of the IFA and the EF for two conditions. † indicates significant differences between conditions and ‡ indicates significant differences between muscles ($p < 0.05$).

Figure 8

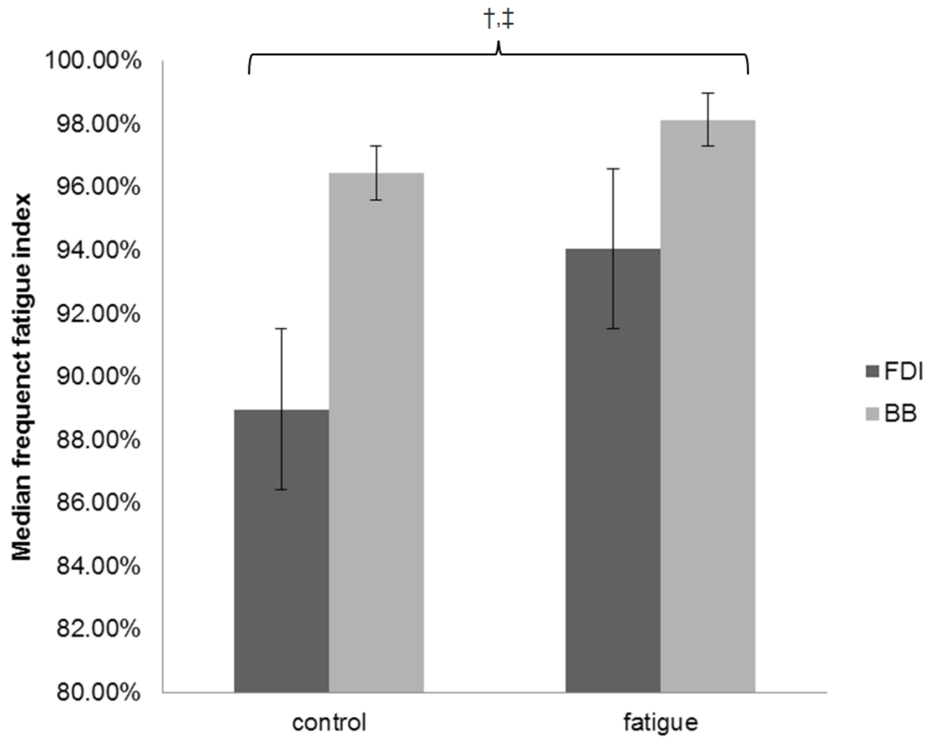

FIGURE 8 EMG FFT MDF of the FDI and the BB over post-tests for two conditions. † indicates significant differences between conditions and ‡ indicates significant differences between muscles ($p < 0.05$).

Figure 9a

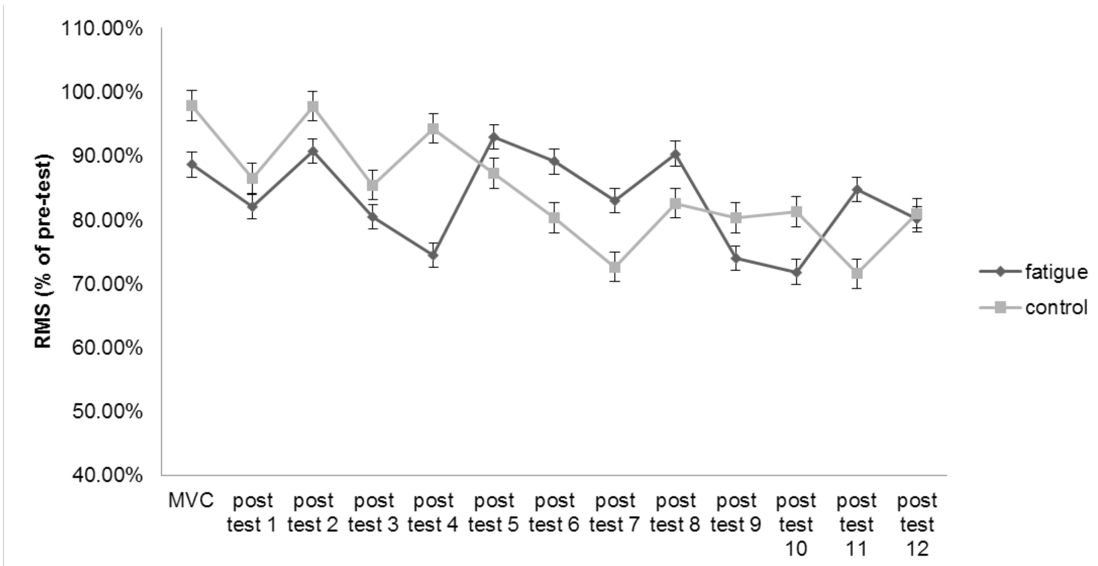

Figure 9b

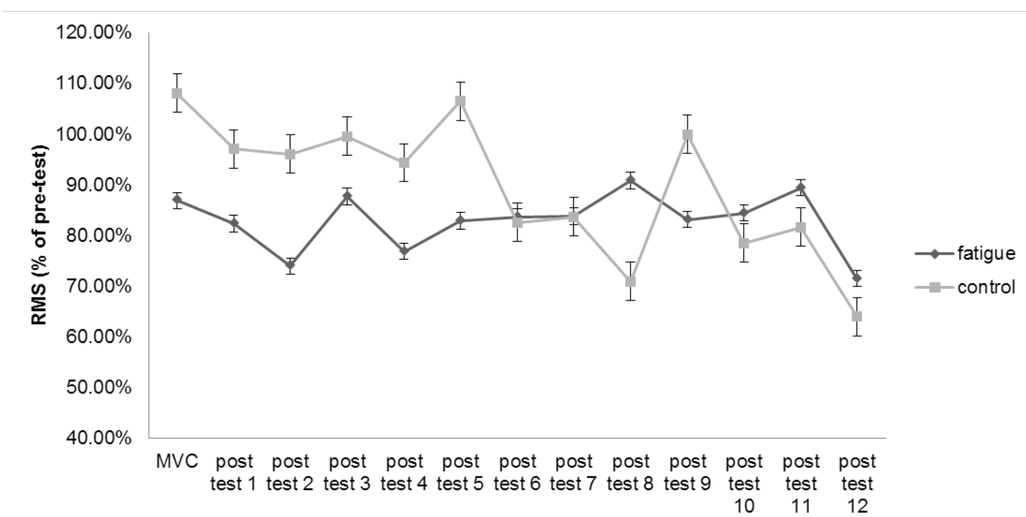

FIGURE 9 EMG RMS of FDI and BB over post-tests for two conditions. Data is presented in percentage relative to the highest activation recorded during the pre-test for each condition. 9a: FDI RMS. 9b: BB RMS.