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Research article

The Effect of a Mental Task Versus Unilateral Physical Fatigue on Non-Local Muscle Fatigue in Recreationally Active Young Adults

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Abstract

Non-local muscle fatigue (NLMF) has been attributed to both physical and mental fatigue. The purpose of this study was to investigate the effects of mental exertion versus unilateral physical fatigue on NLMF. Sixteen recreationally active participants completed a physical task (2-sets of 100-s unilateral knee extension (KE) maximal voluntary isometric contractions (MVIC) with the dominant leg with 40-s recovery between sets, mental task (4-minute Stroop task), and control condition. Before and after each condition, blood lactate was collected, and contralateral 5-s KE, flexion (KF) and bilateral lateral trunk flexors MVIC (measure of trunk stability strength) was performed. Following the post-test 5-s MVICs, participants performed 12 non-dominant KE MVICs with a work-to-rest ratio of 5/10-s. Electromyography was monitored during the MVICs. Neither the 4-minute Stroop test or the unilateral KE physical fatigue intervention adversely affected the non-dominant KE forces or EMG activity with a single MVIC or 12 repetition MVICs. Although the non-dominant KF fatigue index forces and hamstrings EMG were not impaired by the interventions, there was a significant interaction ($p = 0.001$) small magnitude ($d = 0.42$) decrease in the non-dominant KF single MVIC force following the contralateral fatigue intervention, albeit with no significant change in hamstrings EMG. This MVIC deficit may be related to the significant decrease in dominant ($p = 0.046$, $d = 2.6$) and non-dominant external obliques ($p = 0.048$, $d = 0.57$) activation adversely affecting trunk stability. In conclusion, a 4-minute Stroop test or unilateral KE physical fatigue intervention did not impair non-dominant KE single or repeated 12 repetition MVIC forces or EMG activity. The small magnitude deficit in the non-dominant KF single MVIC force following the contralateral fatigue intervention are in accord with the heterogenous findings common in the literature.

Key words: Crossover fatigue, mental fatigue, unilateral fatigue, maximal voluntary isometric contraction, resistance training.

Introduction

Neuromuscular fatigue has been defined as a progressive reduction in the ability of a muscle to produce power or force (Behm, 2004; Gandevia, 2001). Fatigue is typically attributed to neural and/or muscular origins (Behm, 2004; Gandevia, 2001; MacIntosh and Rassier, 2002). However, Enoka and Duchateau (Enoka and Duchateau, 2016) define fatigue "as a disabling symptom in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability". They argue that the term fatigue should not be preceded by an adjective (e.g., central, mental, muscle, peripheral, and supraspinal) since the locus of fatigue cannot be attributed to a single factor. Behren's et al. (2023) review expanded on the Enoka and Duchateau (2016) review characterizing "fatigue as a psychophysiological condition characterized by a decrease in motor or cognitive performance (i.e., motor or cognitive performance fatigue, respectively) and/or an increased perception of fatigue (i.e., perceived motor or cognitive fatigue)". Motor, cognitive, and perceptual factors are interdependent, and thus no single factor determines performance and perceived fatigue. Hence, factors influencing fatigue can be global.

Unilateral fatigue may not only affect the exercised muscle but also global effects upon homologous contralateral (crossover fatigue) (Behm et al., 2021; Doix et al., 2013; Martin and Rattey, 2007; Post et al., 2008) and heterologous (non-local muscle fatigue: NLMF) non-working muscles (Aboodarda et al., 2015; Aboodarda et al., 2017; Behm et al., 2021; Halperin et al., 2015; Kennedy et al., 2013). There are also a number of studies that have not demonstrated NLMF-induced strength (force) deficits (Aboodarda et al., 2019; Arora et al., 2015; Duffet et al., 2022; Hadjizadeh Anvar et al., 2022; Power et al., 2021; Prieske et al., 2017). Two reviews (Behm et al., 2021; Halperin et al., 2015) have highlighted that crossover fatigue or NLMF is more prevalent with testing involving repeated fatiguing contractions than with single, discrete maximal contractions. Additional research is necessary to clarify the variables affecting NLMF.

The underlying NLMF mechanism are also not consistent. Since there is no direct stress or tension placed on the non-exercised heterologous or homologous muscles, it is generally agreed that NLMF deficits cannot be attributed to morphological mechanisms (Behm et al., 2021; Halperin et al., 2015). Neural deficits affecting the heterologous and homologous muscles have been suggested with evidence of decreased contralateral electromyographic (EMG) activity (Halperin et al., 2014c; Hamilton and Behm, 2017; Li et al., 2019; Post et al., 2008). However, there are also reports of no significant EMG decreases (Arora et al., 2015; Duffet et al., 2022; Hadjizadeh Anvar et al., 2022; Halperin et al., 2014b; Kawamoto et al., 2014; Sambaher et al., 2016). Halperin et al. (Halperin et al., 2014c) reported decreased contralateral knee extensors (homologous) EMG but no change in elbow flexors (heterologous) EMG following a unilateral knee extensors fatiguing protocol. EMG is a non-specific indicator of neuromuscular activation changes (Farina et al., 2004; Konrad, 2005). Other studies have employed more specific neurophysiological measures, finding decreased (Aboodarda et al., 2015;

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Aboodarda et al., 2016; Aboodarda et al., 2017; Sambaher et al., 2016), as well as increased (Aboodarda et al., 2019) corticospinal excitability using transcranial magnetic stimulation. Hadjizedeh Anvar et al. (2022) did not find any NLMF neural or force deficits of the contralateral homologous plantar flexors when monitoring the Hoffman reflex (afferent excitability of the motoneuron (Enoka et al., 1980; Zehr, 2002)) and volitional (V-) wave (level of efferent and descending neural drive (Duclay et al., 2008)). Hence, the underlying NLMF mechanisms lack clarity as well and need further investigation.

Prolonged cognitive tasks can impair subsequent physical performance, especially with endurance activities (Marcora et al., 2009; Pageaux et al., 2014; Pageaux et al., 2013). A number of meta-analyses have reported small to moderate magnitude physical performance deficits in endurance (Van Cutsem et al., 2017), maximal strength, aerobic, and motor control (Brown et al., 2020), and balance (Brahms et al., 2022) with mental fatigue or cognitive exertion. However, while van Cutsem et al. (2017) in their systematic review reported mental fatigue-induced endurance performance deficits, there was no significant evidence for impairments in maximal strength or anaerobic performance. Holgado et al. (2020) in their meta-analysis found mental fatigue-induced small to medium magnitude reductions in endurance performance but also reported evidence of publication bias, which when considered in the analysis reduced the effects to trivial and non-significant. Hence the effect of mental fatigue on performance literature is not fully consensual.

A mental energy deficit or the global perception of fatigue (Behm et al., 2021; Halperin et al., 2015; Herold et al., 2020) could affect the ability to maximally activate motoneuron (decreased corticospinal excitability versus increased inhibition) or execute optimal motor control and coordination (activation or inhibition of agonists, synergists, antagonists and stabilizers) to achieve maximal force outputs or maintain forces (Behm, 1995; 2004). These cognitive tasks can result in a following activity to be perceived as requiring more effort, resulting in an earlier cessation of the activity (Marcora et al., 2009; Pageaux et al., 2014; Pageaux et al., 2013). Harris and Bray (2019; 2021) report that mental fatigue affects exercise decision making with an increased subjective evaluation of exercise cost versus the alternative of being sedentary. Hence, the individual is more likely not to start or continue exercising when mentally fatigued. Given the distinction between the actual fatigue of the exercised muscle and the global perception of fatigue (Steele, 2020), NLMF may be related to fatigue perception. Greenhouse-Tucknott et al. (2020) reported no knee extensor NLMF, however, prior hand-grip exercise increased perception of fatigue suggesting the influence of complex cognitive emotional interactions. As mental fatigue or subjective perception are cognitive responses, their negative effects would not be restricted to a specific muscle but would be expected to exert global (NLMF) effects on performance. Further research is necessary to investigate the effect of prior cognitive and perceptual demands on subsequent NLMF.

Based on these gaps and conflicts in the literature, the objective of the current study was to investigate the force and activation levels of the contralateral knee extensor and flexor muscles before and after physical (unilateral knee extensor fatigue) and mental (Stroop task) effort. Based on prior NLMF reviews (Behm et al., 2021; Halperin et al., 2015), it was hypothesized that NLMF would be evident following unilateral physical fatigue with repeated maximal voluntary isometric contractions (MVIC) but not with single discrete MVICs. Secondly, based on research investigating mental effort and perception (Marcora et al., 2009; Pageaux et al., 2014; Pageaux et al., 2013), NLMF would also be present following the mentally fatiguing task.

Methods

Participants

Based on prior NLMF research (Halperin et al., 2014b; Halperin et al., 2014c; Kawamoto et al., 2014; Sambaher et al., 2016), an “a priori” statistical power analysis was calculated based on force data, determining that 12-21 participants would be needed to achieve a moderate magnitude, effect size of 0.5, alpha of 0.05 and a power of 0.8 for a single, repeated measures study. Six male (181.85 ± 3.6 cm, 84.2 ± 7.4 kg, 24.2 ± 3.6 years of age) and ten female (162.9 ± 7.7 cm, 63.6 ± 8.4 kg, 21.3 ± 2.7 years of age) recreationally active, healthy participants from the university population volunteered for the study. Participants were be asked to avoid the consumption of caffeine and participation in vigorous physical activity at least 1 day before attending each experimental session.

Experimental design

Participants visited the laboratory on three occasions separated by at least 48h. During the first testing session, the research procedures were explained, participants signed the consent form, they were asked which leg was used to kick a ball to determine leg dominance and they were also familiarized with the equipment and testing procedures. When participants arrived at the laboratory, they were seated for 5-minutes, after which blood lactate was measured in the non-dominant index finger (based on leg dominance). Subsequently, warm-up activities including isometric unilateral knee extension and flexion as well as bilateral trunk flexion contractions were performed at 50% of perceived MVIC. During each session, participants randomly performed one of three experimental conditions: (i) two sets of 100-s unilateral knee extension MVIC with the dominant leg (fatigue) with 40-s recovery between sets (4-minute intervention duration), (ii) a 4-minute Stroop task (mental fatigue) or (iii) 4-minute rest (control). Before each experimental condition, 2-3, 5-s knee extension and flexion MVIC were performed with the contralateral, non-exercised, non-dominant leg. Two or three bilateral trunk lateral flexion MVICs were also performed. A third pre-test MVIC was only performed if there was more than a 5% difference between the first two contractions. Following the intervention, blood lactate was again monitored followed by single 5-s knee extension and flexion MVICs, followed by 12 knee extension MVICs with a work-to-rest ratio of 5/10 s with the non-dominant leg (Duffet, 2022; Halperin et al., 2014b; Halperin et al., 2014c; Hamilton and

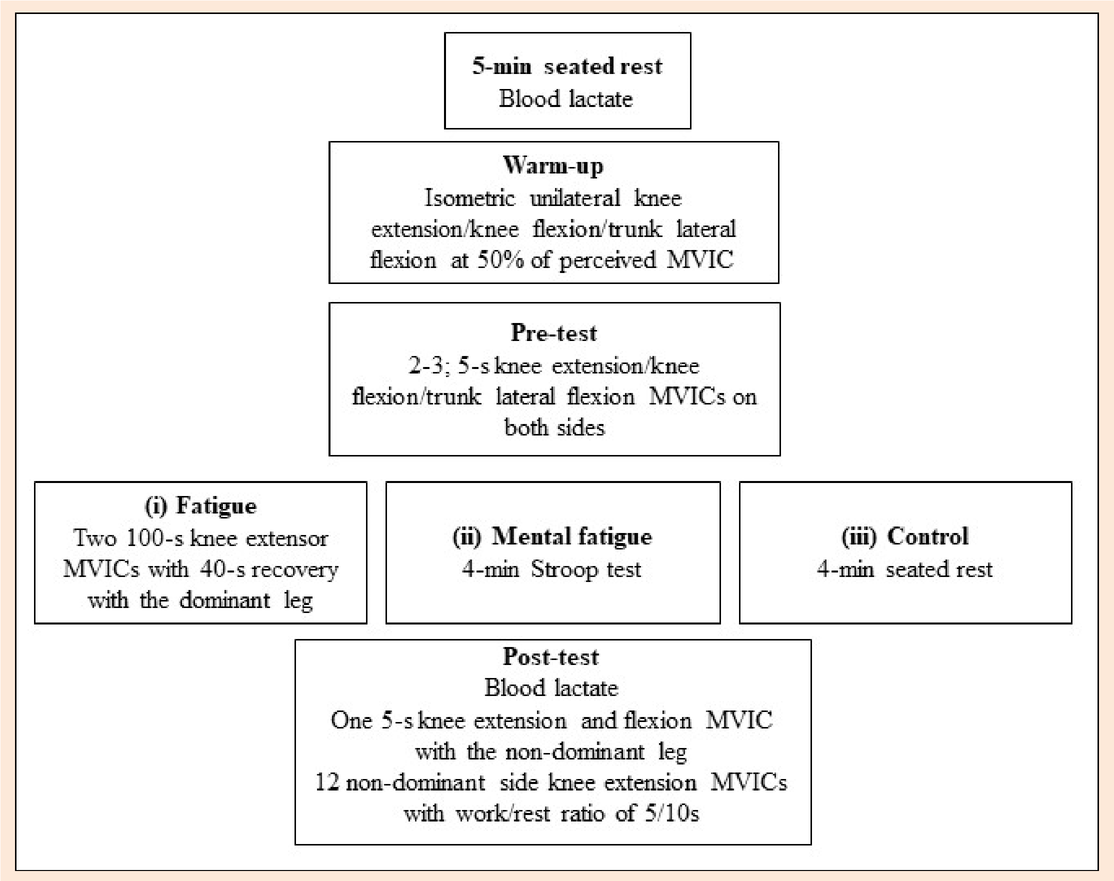

Figure 1. **Schematic diagram of the experimental design.**

Behm, 2017; Sambaher et al., 2016). The intervention protocol is outlined in Figure 1.

Dependent variables (Measures)

Maximal Voluntary Isometric Contraction (MVIC) Force

Participants were seated in a custom designed seat/apparatus, which allows the execution and monitoring of the force of the knee extensor and knee flexor MVICs (constructed by Memorial University of Newfoundland Technical Services). To eliminate upper body movement, a strap was placed around the waist and the participants were instructed to cross their arms across their chest with the hip flexed at 90°. The dominant and non-dominant ankles were inserted into padded ankle cuffs that were attached to strain gauges (Omega Engineering Inc., LCCA 250, sensitivity = 3 mV/V, Don Mills, Ontario) via taut non-extensible straps. The strain gauge and straps were secured to the isometric leg extension machine and adjusted to form a 90° and 120° angle with the participant's lower shin, for knee extension and knee flexion, respectively. Differential voltage from the strain gauge was sampled at a rate of 2,000-Hz, amplified (1000x), band pass filter of 10-500 Hz, digitally converted (Biopac Systems Inc. DA and analog to digital converter MP100WSW; Holliston, MA) and monitored on a computer. A commercial software program (AcqKnowledge III, Biopac Systems Inc., Holliston, MA) was used to analyze the digitally converted analog data.

After positioning on the knee extensor machine, participants performed 2 - 3, 5-s isometric MVICs of the dominant and non-dominant knee extensors, knee flexors, and external obliques in a randomized order (pre-test). For the external obliques MVIC testing, participants attempted to flex and rotate the trunk against an inextensible strap. Prior to performing the MVICs, a warm-up that included 2 - 3, 5-s isometric contractions at an intensity of approximately 50% of their perceived MVIC was performed. If the second MVIC was 5% or greater than the highest force output of the first MVIC then a third MVIC was performed. The MVIC with the greatest force output (peak of the force-time curve) was used for analysis. Participants were instructed to initiate the MVIC by contracting their muscles as hard and as fast as possible.

Electromyography (EMG)

Prior to electrode placement, the skin was shaved and abraded to remove dead skin with abrasive paper and cleansed with an isopropyl alcohol swab to decrease skin resistance. Self-adhesive Ag/AgCl electrodes (MediTraceTM 130 ECG conductive adhesive electrodes) were placed parallel to the direction of the vastus lateralis (VL) and biceps femoris (BF) muscle fibers according to SENIAM recommendations (Hermens et al., 1999). The electrodes were placed at the mid-point of the anterior superior iliac spine to the patella for the VL and the gluteal fold and popliteal space for the BF (Hermens et al., 1999). EMG was also recorded from the external oblique muscles to account for any stabilizing movements during the knee extensors MVICs. These electrodes were placed approximately 3 cm anterior to and mid-way along a line drawn from the lateral pelvic crest to the lateral lower ribcage (Workman et al. 2008; Behm et al. 2009). The inter-electrode distance was 2 cm (center to center) and electrode locations were recorded to ensure consistent placement for all sessions. The ground electrode was placed on the lateral femoral epicondyle. An inter-electrode impedance of <5 kOhms was obtained prior to recording to ensure an adequate signal-to-noise ratio. EMG activity was digitally filtered with a linear phase Blackman -61 dB band-pass filter between 10 - 500 Hz, amplified (bi-polar differential amplifier, input impedance = 2 MΩ, common mode rejection ratio > 110 dB min (50/60 Hz), gain x 1000, noise > 5 µV), and analog-to-digitally converted (12 bit). All EMG signals were recorded (Biopac System Inc., DA 100: analog-digital converter MP150WSW; Holliston, Massachusetts) with sampling rate of 2000 Hz using a commercially designed software program (AcqKnowledge III, Biopac System Inc.). Over a one second period around the MVIC peak force output (500ms before and 500ms after), the mean amplitude of the EMG root mean square (RMS) was recorded.

Blood lactate

After being seated for 5 minutes, pre-test blood lactate concentrations (Lactate Pro, Arkray, Kyoto, Japan) were collected and measured in the non-dominant index finger. This procedure was repeated immediately after (within 10 s) the intervention protocol.

Post-intervention testing

Immediately following post-intervention (within 10 s) blood lactate concentrations measurements, the peak force of a single discrete MVIC was recorded with participants asked to perform a single 5-s knee extension and flexion MVIC with their non-dominant leg followed by the 12-repetition fatigue protocol with the non-dominant knee extensors, which consisted of twelve 5-s MVICs with 10 s rest between contractions (Duffet et al., 2022; Halperin et al., 2014b; Halperin et al., 2014c; Hamilton and Behm, 2017; Sambaher et al., 2016). A fatigue index was also calculated for the post-test repeated MVICs by dividing the mean force and EMG of the last two contractions into the mean force of the first two contractions. An EMG fatigue index was also monitored for the external obliques in order to monitor trunk or core fatigue during the 12 repetitions.

Independent variables (Intervention)

The intervention protocols involved either a physical fatigue task of 2x100-s dominant knee extension MVICs with 40-s recovery between repetitions: 4-minute duration (Hadjizadeh Anvar et al., 2022; Halperin et al., 2014c; Hamilton and Behm, 2017; Li et al., 2019), a 4-minute Stroop task for the mental task condition (Hakim et al., 2022; Smith et al., 2016a; Smith et al., 2016b; Stroop, 1935), or 4-minutes of rest for the control condition. To determine the extent of physical fatigue during the intervention, a fatigue index was calculated for the physical fatigue condition by dividing the mean force of the last 10-seconds into the mean force of the first 10-seconds.

The Stroop color-word test, a widely used neuropsychological test, measures a subject's capacity to suppress cognitive interference, which happens when the processing of one stimulus attribute interferes with the concurrent processing of another (Stroop, 1935). It has been demonstrated that the Stroop task, which demands prolonged attention and response inhibition, induces a state of mental fatigue (Smith et al., 2016a, 2016b). The participant was asked to identify the colour of the word without regard for its actual meaning. Fifty percent (50%) of the trials were congruent (matched word and color), whereas 50% were incongruent, according to a pseudo-random sequence that was used to govern the trials (with all incongruent word-color combinations). The participants were then instructed to push the key on the keyboard that matches the color of the text that is displayed on the screen. For 1000 ms, each word appeared on the screen in font size 34, and then the screen remained blank before the next word appeared (Barzegarpoor et al., 2020).

Statistical analysis

Statistical analyses were completed using SPSS software (Version 16.0, SPSS, Inc, Chicago, IL, USA). Assumption of normality (Kolmogorov-Smirnov) and homogeneity of variances (Levene) tests were conducted for all dependent variables. If the assumption of sphericity was violated, the corrected value for non-sphericity with Greenhouse-Geisser epsilon was reported. Intraclass coefficients (ICC) were measured for mean force and EMG for the pre-test of all three conditions to assess consistency of the data. A 2x2 repeated measures two-way ANOVA (2 sets of 100s MVICs x 2 times (first and last 10s of 100s MVIC)) was used to analyze the changes in force and EMG of the two sets of the fatiguing intervention. A two-way repeated measure analysis of variance (ANOVA) test was used to compare the single knee extensor MVIC forces (3 intervention conditions [physical fatigue, mental fatigue, control] × 2 MVICs [pre- vs. post-test]). Furthermore, a two-way repeated measures ANOVA tests (3 interventions × 12 MVICs) were conducted to determine potential differences between conditions with the fatigue test for the following variables: normalized mean force and EMG of vastus lateralis, biceps femoris, and external oblique muscles. A repeated measures 2-way ANOVA was used to compare the peak forces of the single discrete MVICs versus the first repetition of the 12-repetition fatigue test to identify if pacing occurred in anticipation of the fatigue protocol. Lastly, a three-way repeated measures ANOVA test was used to compare blood lactate levels (2 groups × 3 conditions × 2 time periods). Paired t-tests with Holm-Bonferroni corrections were used to decompose significant interactions, and Bonferroni post hoc tests were used if main effects were found. Significance was set at 0.05. Cohen's *d* effects sizes (ES, Cohen, 1988) were also calculated to compare mean force and EMG between conditions with >0.2 representing trivial magnitude effects, 0.2 - >0.5: small, 0.5 - >0.8: moderate and ≥0.8 representing large magnitude effect sizes. Reliability was tested with a Cronbach alpha intraclass correlation coefficient (ICC) with 0.9 indicating excellent reliability, 0.75 - 0.9: good reliability, 0.5 - 0.75: moderate reliability and <0.5: poor reliability (Cohen, 1988).

Results

Reliability

ICC reliability coefficients indicated excellent intra-day reliability for the non-dominant knee extensors (r = 0.965), flexors (r = 0.937) and trunk rotation (r = 0.912) MVIC forces and good reliability for quadriceps (r = 0.878), hamstrings (r = 0.841) and external oblique (r = 0.827) MVIC EMG activity.

Post-test fatigue index

There was no significant main effect for condition, or interactions for the force or EMG fatigue indexes of the non-dominant quadriceps, hamstrings, nor the dominant and non-dominant external obliques.

Single discrete MVIC

Non-dominant knee extensor forces and quadriceps EMG:

A significant main effect for conditions (F(2,28) = 3.114, p = 0.05) revealed that the control condition (413 ± 174.12 N) exhibited trivial and small magnitude higher knee extensor forces than the mental (p = 0.08, d = 0.11, 392.72 ± 169.12 N) and physical (p = 0.001, d = 0.26, 369.24 ± 157.96 N), conditions, while the physical condition also had significant but trivial magnitude (p = 0.05, d = 0.14) lower MVIC forces than the mental conditions respectively. A significant main effect for time demonstrated that pre-test (402.14 ± 162.8 N) exceeded post-test (381.19 ± 171.23 N) forces by a trivial magnitude (d = 0.12). There were no significant force interactions, nor any significant main effects or interactions for EMG activity.

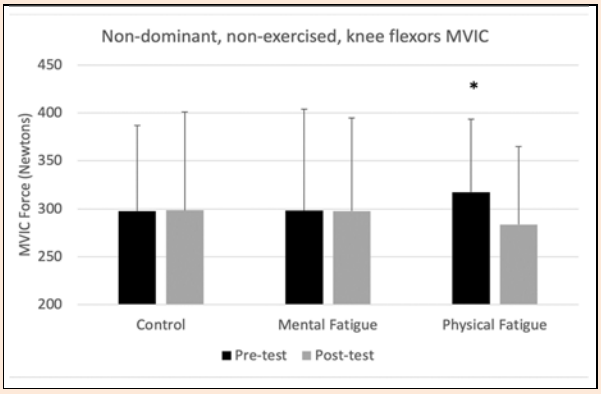

Figure 2. Condition x Time interaction effect for non-dominant, non-exercised knee flexors maximal voluntary isometric contraction (MVIC) force (Newtons).

Non-dominant knee flexor forces and hamstrings EMG:

A significant (F(1,14) = 4.805, p = 0.046) main effect for time showed that pre-test (304.35 ± 90.37 N) knee flexors forces had trivial magnitude (d = 0.11) higher forces than post-test (293.43 ± 93.32 N). There were no significant main effect for condition but there was a significant condition x time interaction (F(2,28) = 2.79, p = 0.04) indicating a small magnitude (d = 0.42) decrease from pre-test (316.92 ± 76.5 N) to post-test (283.77 ± 81.04 N) with the physical fatigue condition (p = 0.001)(Figure 2). There were no other significant interactions for MVIC knee flexor force as well as no significant main effects or interactions for hamstrings EMG.

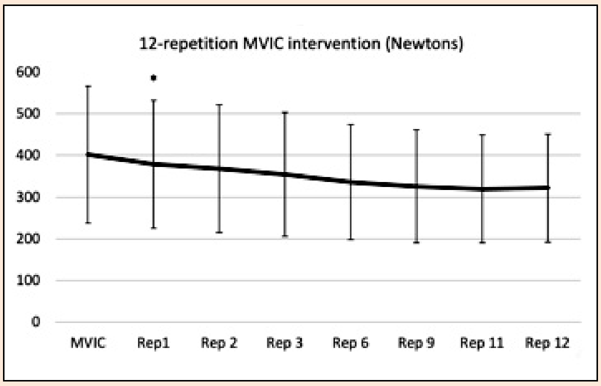

Figure 3. Force means and standard deviations from the post-test, single knee extension MVIC and the following 12-repetition MVIC intervention. Asterisk (*) represents a significant difference between the single MVIC force (Newtons) and the first repetition of the 12-repetition MVIC intervention.

Pacing

Evidence of pacing (decreased force output at start of fatigue protocol) was evident overall with a significant main effect (F(1,15) = 5.69, p = 0.031) with the first repetition of the "intended" MVIC fatigue protocol (379.1 ± 107.0 N) exhibiting a small magnitude (d = 0.21) decrease compared to the single discrete MVIC (402.1 ± 109.1 N) peak force. There were no other significant main effects or interactions (Figure 3).

Blood lactate

A significant (F(1,14) = 23.96, p < 0.0001) main effect for time revealed a moderate magnitude (d = 0.69) bloods lactate increase from pre-test (2.94 ± 2.1mmol/L) to post-test (5.57 ± 5.5 mmol/L). There was also a significant condition x time interaction (F(2,28) = 4.16, p = 0.026) showing that the physical condition post-test (7.43 ± 3.07 mmol/L) exhibited a large magnitude (d = 1.56) increase over the pre-test (3.22 ± 2.44 mmol/L) values.

Fatigue intervention of dominant quadriceps

Force:

Significant set x time interactions ($F_{(1,14)}$ = 8.42, p = 0.001) demonstrated force reductions of 58.9 ± 15.0% and 47.6 ± 20.1% in the first and second fatigue intervention sets respectively. There was no significant main effect for sets ($F_{(1,14)}$ = 1.87, p = 0.192) with similar decreases in fatigue indexes for set #1 and #2.

EMG:

Significant set x time interactions ($F_{(1,14)}$ = 6.34, p = 0.003) demonstrated quadriceps EMG decreases of 31.4 ± 23.4% and 43.4 ± 23.7% in the first and second fatigue intervention sets respectively. There was a non-significant, moderate magnitude (d = 0.51) main effect for sets ($F_{(1,14)}$ = 3.61, p = 0.078) with a greater decreased EMG fatigue index for set #2 over set #1.

Fatigue intervention effects on EMG Fatigue Index (FI) of dominant hamstrings

Significant set x time interactions ($F_{(1,14)}$ = 4.03, p = 0.02) demonstrated hamstrings EMG decreases of 31.5 ± 31.0% and 21.2 ± 41.0% in the first and second fatigue intervention sets respectively. There were no significant differences between the sets.

Fatigue intervention effects on EMG Fatigue Index (FI) of external obliques

Dominant external obliques

Significant set x time interactions ($F_{(1,14)}$ = 3.92, p = 0.04) demonstrated dominant external oblique EMG decreases of 16.0 ± 5.5% and 2.6 ± 4.6% in the first and second fatigue intervention sets respectively. There was a significant, ($F_{(1,14)}$ = 4.76, p = 0.046) large magnitude (d = 2.6) main effect for sets with a greater decreased dominant external obliques EMG fatigue index for set #1 over set #2.

Non-dominant external obliques

Significant set x time interactions ($F_{(1,14)}$ = 3.65, p = 0.048) demonstrated moderate magnitude (d = 0.57), non-dominant external oblique EMG decreases of 14.6 ± 4.6% and 2.5 ± 5.6% in the first and second fatigue intervention sets respectively. There was no significant main effect for sets.

Discussion

The major findings of the present study were that a 4-minute Stroop test or the unilateral knee extensors physical fatigue intervention did not adversely affect the non-dominant knee extensors single discrete MVIC forces or EMG activity, or the force and EMG activity fatigue indexes of a repeated 12 repetition MVIC task. There was a small magnitude decrease in the non-dominant knee flexors single discrete MVIC force following the contralateral fatigue intervention, albeit with no significant change in hamstrings EMG activity.

The lack of NLMF with single discrete knee extensors MVIC and quadriceps EMG are in accord with the Behm et al. (2021) meta-analysis and the earlier Halperin et al. (2015) narrative review. Halperin indicated that single contractions were less likely to demonstrate NLMF effects, whereas the more recent Behm meta-analysis reported no statistically significant evidence of NLMF with single MVIC contractions. Between-study heterogeneity in the meta-analysis was high (I^2 = 94.5%), contributing to the lack of significant findings (Behm et al., 2021). The lack of an overall significant effect does not mean that NLMF has not been identified in specific studies. NLMF with single discrete MVIC have been reported with contralateral homologous (Doix et al., 2013; 2018; Halperin et al., 2015; Kawamoto et al., 2014; Li et al., 2019; Martin and Rattey, 2007; Post et al., 2008) and heterologous non-working muscles (Aboodarda et al., 2015; 2017; Behm et al., 2021; Halperin et al., 2015; Johnson et al., 2015; Kennedy et al., 2013; Li et al., 2019), while no significant NLMF changes have also been published (Aboodarda et al., 2019; Arora et al., 2015; Duffet et al., 2022; Hadjizadeh Anvar et al., 2022; Power et al., 2021; Prieske et al., 2017). The Behm et al. (2021) meta-analysis may have been influenced by the reported publication bias against non-significant results (Boning, 2016), which may also have affected the variety of articles located for the meta-analysis. Within this present study, there were also contradictory findings between individuals with 10/16 and 6/16 individuals presenting some degree of NLMF following the physical and mental fatigue conditions respectively. Hence, the present study continues this heterogenous results trend with a lack of statistically significant knee extensor MVIC force and quadriceps EMG deficits but evidence of contralateral knee flexor MVIC impairments.

Proposed mechanisms underlying the NLMF contralateral knee flexor MVIC impairments found in the present study have previously been attributed to accumulation of metabolites (e.g., H+ ions), increased perception of fatigue and effort (mental energy deficit), neuromuscular activation deficits or decreased biomechanical stabilization of core muscles (Behm et al., 2021; Halperin et al., 2015). There was an increased accumulation of metabolites as the physical condition post-test (7.43 ± 3.07 mmol/L) exhibited a greater blood lactate (buffer for H+ ions) accumulation than the pre-test (3.22 ± 2.44 mmol/L). However, it would be difficult to explain why the increased blood lactate accumulation would only significantly affect the knee flexors MVIC and not the knee extensors MVIC. Furthermore, as blood lactate with high intensity exercise can reach 20 mmol/L, an increase from approximately 3 to 7 mmol/L would not be considered to be a high level (Hermansen and Stensvold, 1972). Hence, it is unlikely that metabolite (lactate, H+ion) accumulation would be a major contributing factor to the decline observed with knee flexors MVIC force.

The perception of fatigue and effort or the mental energy deficit (Noakes, 2009; Steele, 2020) have been suggested as possible mechanisms. The mental energy deficit suggests that the mental energy used to focus and concentrate during the fatiguing intervention may diminish the mental energy needed to fully activate the muscles during the subsequent MVIC (Halperin et al., 2015). Alternatively, Steele (2020) proposed that the actual effort from an activity can influence the perception of effort in another or subsequent task impacting that performance. Once again, it is difficult to explicate how deficits in mental energy or increased perception of effort would delineate between knee extension and knee flexion MVICs.

During the knee extension MVIC fatiguing intervention (2x100-s) hamstrings EMG activity was monitored and decreases of approximately 31% and 21% were observed in the first and second knee extension fatigue intervention sets respectively. This is not unusual as co-contractions (antagonist) occur during agonist contractions due to a common neural drive and antagonist functions such as joint stabilization (Behm, 2004; Gordon and Ghez, 1984; Smith, 1981; Wierzbicka et al., 1986). While it might be postulated that the decrease in dominant hamstrings EMG might have induced neural crossover effects in the contralateral hamstrings, there was no significant changes in post-test knee flexor MVIC EMG activity. The literature showing no consensus on impairments to corticospinal excitability (Aboodarda et al., 2015; 2017; 2019) or afferent excitability of the motoneurons (Hadjizadeh Anvar et al., 2022), the possibility of neuromuscular activation deficits also would not be considered as plausible mechanisms for knee flexors MVIC force impairments.

Regarding biomechanical stabilization, there were significant decreases in dominant (16% and further 2.6%) and non-dominant (14.6% and further 2.5%) external obliques EMG activity following the first and second sets of the 100-s MVIC fatiguing interventions respectively. The question must again be posed how biomechanical stabilization could be a factor for knee flexors but not knee extensors MVIC. When performing knee extensions in the present study, the reaction force of the lower limb against the inextensible strap tended to push the trunk back into the seat and backrest, whereas the knee flexion MVIC pulled the body away from the backrest. Hence, it is possible that the effect of the knee extension MVIC pushing the trunk into the seat contributed to trunk stability whereas the knee flexion MVIC pulling the trunk away from the seat necessitated more trunk stability from the external obliques, which was diminished by the fatiguing protocol. It is well documented that increased instability can contribute to decreased limb force output (Anderson and Behm, 2004; Behm and Colado, 2012; Behm and Anderson, 2006; Behm et al., 2010).

The lack of NLMF with either the knee extensors repetitive contractions contradicts the Halperin et al. (2015) reviews who suggested that tests involving repetitive contractions provide clearer NLMF evidence than single MVICs and NLMF can induce moderate magnitude endurance (fatigue tolerance) deficits of the another non-exercised muscle (Behm et al., 2021) respectively. However, the Behm et al. (2021) systematic review also indicated that the interval estimate analysis was relatively imprecise with the study results ranging from trivial to large effects with considerable between-study heterogeneity. A possible mitigating factor in this study and possibly others is the tendency to pace when confronted with a prolonged task (Halperin et al., 2014a; Hamilton and Behm, 2017; Noakes et al., 2004; 2005). The participants in this study seemed to anticipate the effort involved when attempting to perform 12 MVICs and although their intention was to produce a maximal effort, they may have subconsciously paced by decreasing the force of the initial repetition of the 12-repetition fatigue protocol by 5.7% (Figure 2). Hence, by not actually producing the intended MVICs, they may have attenuated the extent of fatigue.

The mental task (4-minute Stroop test) did not induce NLMF with either the knee extensors or flexors. While similar arguments can be postulated about the high heterogeneity found when comparing prior crossover or NLMF studies (Behm et al., 2021) or the pacing effect seen with this study's sample of subjects, an additional explanation may be that the duration of the Stroop test was insufficient to induce adequate mental exertion or fatigue to compromise a subsequent non-exercised muscle group. The duration of 4-minutes was chosen to ensure a comparable duration of tasks as the physical fatigue (2 x100s with 40s recovery between repetitions) and control conditions were also 4-minute durations. However, the Stroop task has been implemented in other studies for 30 - 90 minutes (Skala and Zemkova, 2022; Slimani et al., 2018; Vrijkotte et al., 2018) to induce mental fatigue. It seems the duration implemented in this study did not induce adequate mental or cognitive stress.

Limitations

All studies can benefit from larger sample sizes. A contributing factor to the literature heterogeneity conundrum is the typical sample population of the studies. Almost all the cited studies recruited between 12-20 participants. According to Hackshaw (2008) although low participant numbers studies can yield quicker results, they may not generally provide as reliable or precise estimates as larger samples. Lower sample populations are more liable to produce positive results or false positive results (Hackshaw, 2008) based on the chance recruitment of susceptible or responder participants. Smaller samples have difficulty in providing a representative sample of the target or general population (Graham et al., 2012). Thus, while the sample population used in this study adhered to the range suggested by the statistical power analysis, greater number of subjects may have provided more clarity.

Placebo or nocebo effects are also a distinct factor if the objective of the investigation is consciously or subconsciously revealed to the participant (Beedie and Foad, 2009; Janes et al., 2016; Rosenzweig et al., 1993). Participants when reading the consent form and informed verbally of the procedures knew beforehand that there would be a unilateral physically taxing intervention followed by contralateral testing, which would also include a maximum exertion 12-repetition task. This may have contributed to the pacing effects observed.

Conclusion

In conclusion, the present findings tend to resemble the literature as a whole, with heterogenous results. A 4-minute Stroop test or the unilateral knee extensors physical fatigue intervention did not impair the forces or EMG activity of non-dominant knee extensors single discrete MVICs or repeated 12 repetition MVIC task (post-test comparisons between the three conditions). While the heterologous non-dominant hamstrings EMG were not impaired by the mental or physical fatigue interventions, there was a significant, small magnitude deficit in the non-dominant knee flexors single MVIC force following the fatigue intervention. This deficit may be related to the decreased activation of the external obliques (core muscles) adversely affecting the ability to stabilize the trunk when contracting.

However, attributing fatigue mechanisms to a reductionist approach (mental vs. physical) may not be entirely appropriate since fatigue cannot be attributed to a single factor (Enoka and Duchateau, 2016) and is rather a psychophysiological condition (Behrens et al., 2023) with interdependent motor, cognitive, and perceptual factors. Future research should implement much large sample populations and longer duration mental exertion tasks. As most prior research examines isometric contractions, future research should focus more on dynamic activities as well.

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study complies with the current laws of the country in which it was performed. The datasets analysed in this research are available from the corresponding author upon reasonable request.

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Key points

- Non-local muscle fatigue (NLMF) was not evident when testing the force output or EMG activity of knee extension single or repeated (12) maximal voluntary isometric contractions following a mental task (Stroop test) or unilateral knee extensors physical fatigue.
- A small magnitude decrease in the non-dominant knee flexors single discrete MVIC force following the contralateral fatigue intervention was observed, but with no significant change in hamstrings EMG activity.
- The knee flexors NLMF might be attributed to decreased EMG activity of the external oblique muscles which contribute to core stability.

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