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Contralateral muscle fatigue from slow, isokinetic contractions is not velocity-specific

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ABSTRACT

Non-local muscle fatigue (NLMF) describes exercise-induced fatigue of non-exercised muscles. An unexplored aspect of NLMF is whether the effects are velocity specific. In a randomized, crossover design, unilateral fatigue (4-sets of 15 maximal repetitions, separated by 15sec) was induced with low velocity ($60^0.s^{-1}$), reciprocating, isokinetic knee extensions (KE) and flexions (KF) or participants rested in the control conditions. Possible NLMF was tested with contralateral KE and KF maximal isokinetic discrete (single contraction) and repeated repetitions force and electromyography (EMG) when measured with low (12 repetitions at $60°.s^{-1}$, slow) or high (48 repetitions at $240°.s^{-1}$, fast) velocity conditions. Sixteen (10 males and 6 females) participants attended the laboratory on four occasions. Participants either rested (control) or were unilaterally fatigued prior to completing either the slow ($60°.s^{-1}$) or fast ($240°.s^{-}1$) testing conditions. The discrete KE and KF forces and EMG were not significantly different from control, with no significant relative force differences at $60°.s^{-1}$ or $240°.s^{-1}$. A significant condition effect revealed that the intervention conditions fatigue index during the KE and KF repeated maximal test significantly decreased 11% (p = .02, Effect Size: ES = 0.34) and 10% (p = .005, ES = 0.41) more respectively than the two control conditions. This study highlights that prior slow maximal isokinetic, unilateral, dominant KE and KF fatigue did not demonstrate decreases or velocity specific testing effects with singular maximal force, with some evidence of NLMF with fatigue endurance in the contralateral muscles.

1. Introduction

Fatigue is a complex, multifactorial phenomenon (Enoka & Stuart, 1992; St. Clair Gibson et al., 2003). Neuromuscular fatigue refers to the decrease in physical performance (e.g., force, torque, power) associated with an increase in the real or perceived difficulty of a task or exercise (Davis & Bailey, 1997; MacIntosh et al., 2006), regardless whether the force can be sustained (Bigland-Ritchie & Woods, 1984), and is present and progressing from the onset of the task (Bigland-Ritchie et al., 1986). Identifying the extent to which central and peripheral fatigue mechanisms interact to affect performance is a major interest in exercise research (Kirkendall, 1990; Behm, 2004). While extensive literature examines muscle fatigue in the exercised muscles (Allen et al., 2008; Gandevia, 2001), effects of fatigue can either be localized or global (Behm et al., 2021; Halperin et al., 2015; Kennedy et al., 2013; Rattey et al., 2006), meaning it can affect the exercised muscles (local) or non-exercised, non-local, muscle groups (non-local muscle fatigue: NLMF) (Behm et al., 2021; Halperin et al., 2015).

NLMF refers to a temporary force, torque, or endurance performance deficit in a contralateral, ipsilateral, inferior or superior, uninvolved, non-exercised or non-local muscle, distant from the fatigued muscle group (Gandevia et al., 1996; Graven-Nielson et al., 2002; Halperin et al., 2015). The most studied version of NLMF might be crossover fatigue, which indicates a temporary deficit in performance of the contralateral, homologous, non-exercised, limb muscles following a fatiguing protocol to the opposite limb (Doix et al., 2013; Martin & Rattey, 2007).

By testing non-local, non-exercised, homologous or heterologous muscles, peripheral fatigue defined as changes at or beyond the neuromuscular junction is primarily eliminated due to the lack of contractions at this muscle. Crossover or NLMF can highlight central fatigue effects, which refers to changes proximal to the neuromuscular junction that can result in a decreased neural drive (e.g., recruitment and discharge rate of motor units) to the

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muscles (Bigland-Ritchie et al., 1978; 1986; Boyas & Guével, 2011; Enoka & Stuart, 1992; Gandevia et al., 1996).

While NLMF research is relatively recent, the research is conflicting. A recently published meta-analysis (52 articles; Behm et al., 2021) found only a trivial NLMF effect when examining unilateral fatigue effects on non-local discrete or single maximal voluntary contractions. An earlier narrative review paper by Halperin et al. (2015) reported that approximately half of NLMF studies reported deleterious effects with single maximal contractions (32 of 58 measures). However, Halperin and colleagues acknowledged that varying methodological considerations such as type and location of muscle (i.e., upper vs. lower body), contraction mode (isometric, cyclic, dynamic, isokinetic), intensity and volume of the fatigue intervention can influence the presence or absence of effects. The review by Halperin et al. (2015) also suggested that fatigue endurance protocols involving repetitive testing measures demonstrated more consistent impairments whereas single, maximal efforts were less consistent (Halperin et al., 2014b). This finding is in accord with the Behm et al. (2021) meta-analysis, which reported moderate magnitude deficits with NLMF endurance outcomes.

Studies using dynamic or stretch-shortening cycle contractions seemed less likely to induce NLMF effects due to recovery periods (usually 1:1 work rest ratio) as well as attenuated NLMF with stretch-shortening cycle versus constant work modes such as isometric or cyclic protocols (Halperin et al., 2015). Only three studies have examined isokinetic exercise, and they demonstrated minimal NLMF effects. Two studies (Grabiner & Owings, 1999; Othman et al., 2017) did not use concentric-concentric contractions or different velocities, while Strang et al. (2009) used concentric-concentric contractions but only at a single velocity. Repetitive, reciprocating, concentric-concentric contractions without rest intervals could exacerbate fatigue while the co-contractions associated with dynamic high-speed contractions (Desmedt & Godaux, 1979; Hallet & Marsden, 1979) may also amplify fatigue effects (Othman et al., 2017; Paillard et al., 2010). Thus, if isokinetic exercise were to be concentric-concentric such as with repetitive, reciprocating, quadriceps and hamstrings concentric contractions, would this increase the incidence of NLMF effects?

Furthermore, might slow or high velocity test contractions demonstrate a velocity specific NLMF effect? Velocity specificity indicates that training adaptations of strength/power are greatest near the training velocity (Behm & Sale, 1993; Coyle et al., 1981; Kanehisa & Miyashita, 1983). Only a single study to date has examined velocity specific effects (Othman et al., 2017) reporting NLMF but a lack of velocity specific effects when comparing isometric ($0°s^{-1}$) and high velocity ($300°s^{-1}$) fatigue protocols with youth. It is unknown if the higher firing frequencies, greater type II motor unit recruitment, altered motor unit recruitment thresholds, as well as the lower force/torque output of high velocity contractions (force-velocity relationship) (Behm & Sale, 1993) would differentially affect NLMF. Thus, the question can be asked if slow velocity fatiguing contractions can differentially affect slow or fast velocity crossover fatigue effects.

A benefit of using an isokinetic dynamometer is the control of the volume and velocity, allowing consistency in the contraction time, work/rest ratio and exercise durations. Equalization of contraction times using different velocities can be completed by increasing the number of repetitions over the same range of motion, since velocity will remain constant, may help determine whether NLMF may be velocity specific. Hence, the aim of this study was to determine if the existence or extent of lower limb NLMF or crossover (homologous muscles) fatigue is apparent with concentric-concentric isokinetic contractions and velocity dependent. More specifically, does constant, maximal intent, slow ($60°.s^{-1}$) isokinetic knee extension and flexion concentric contractions influence maximal contralateral knee extensions and flexions at slow ($60°s^{-1}$) and fast ($240°s^{-1}$) velocities (single contraction maximal torque, fatigue endurance, and electromyographic [EMG] parameters)? Based on the scant isokinetic NLMF literature (Grabiner & Owings, 1999; Othman et al., 2017; Strang et al., 2009), it was hypothesized that NLMF would be observed with repeated but not discrete (single) maximal contractions. With only one NLMF velocity specific investigation using youth as the recruited population (Othman et al., 2017), it is difficult to hypothesize based on the literature and hence this research question was considered an exploratory question. The research outcomes may provide practical insights into the order of exercises used in training or rehabilitation programs. Differential velocity effects may provide some insights into the mechanisms of NLMF.

2. Methods

2.1. Participants

Based on prior repeated measures (within subjects) using NLMF isometric maximal voluntary contraction (MVC) force data (Bogdanis et al., 1994; Halperin et al., 2014a,b), an "a priori" statistical power analysis (G*Power, Dusseldorf Germany) with an effect size of 0.5 (test family: F-tests), indicated that a minimum of 12 participants would be needed to achieve an alpha of 0.05 with a statistical power of 80%. Hence, a convenience sample of 16 healthy (absence of knee pain within the last six months), resistance trained (resistance trained at least three times a week for over two years [Halperin et al., 2014a]) participants (10 males: 172.2 ± 6.8cm, 82.1 ± 8.1kg, 24.2 ± 2.5 years; 6 females: 169.3 ± 4.6cm, 70.4 ± 11.3kg, 22.8 ± 1.8 years) were verbally explained the experimental procedures, completed the Physical Activity Readiness Questionnaire, (CSEP Path: Canadian Society for Exercise Physiology, 2011) and read and signed a letter of informed consent. Thirteen participants were determined to be right-leg dominant, while three participants were left-leg dominant (Oldfield, 1971). Resistance trained individuals were recruited as they would be familiar with producing maximal efforts against resistance reducing the force variability typically found with untrained individuals. Ethical approval for the study was granted by the Institutional Health Research Ethics Board (ICEHR: # 20200137) and conducted according to the latest version of the Declaration of Helsinki. To minimize confounding variables, subjects were requested to avoid intense exercise training a day before the testing days and avoid caffeine or other drugs within eight hours (Canadian Society for Exercise Physiology, 2011). In addition, testing was attempted to be completed at the same time on each day, and participants had a minimum rest interval between test days of 48 hours in accordance with American College of Sports Medicine recommendations for exercise recovery (ACSM, 2009).

2.2. Experimental Design

A fully randomized, repeated measure crossover design was used to examine the acute effects of unilateral, dominant, knee extensors and flexors isokinetic muscle fatigue on the performance of the contralateral (non-dominant) homologous muscles (Table 1). Participants visited the laboratory for four sessions (2 control and 2 experimental) and completed them in a random order separated by a minimum of 48 hours. The sessions consisted of (i) control-slow (no prior dominant leg fatigue: slow-isokinetic test of contralateral leg, 60°s^{-1}), (ii) control-fast (no prior dominant leg fatigue: fast isokinetic test of contralateral leg, 240°s^{-1}), (iii) slow-slow (prior slow isokinetic fatigue of dominant leg at 60°s^{-1}: slow isokinetic test of contralateral leg, 60°s^{-1}), (iv) slow-fast (prior slow isokinetic fatigue of dominant leg at 60°s^{-1}: fast isokinetic test of contralateral leg, 240°s^{-1}).

The intervention fatigue protocol of the dominant leg involved maximal force contractions completed at 60°s^{-1} and consisted of 4 sets of 15 consecutive 90° range of motion knee extension / flexion repetitions, separated by 15sec, totaling 3min of contraction time. For the testing protocols of the contralateral non-dominant leg, initially a single maximal intent effort (discrete contraction) at the prescribed angular speed (60°s^{-1} or 240°s^{-1}) for that session's condition (i.e., control-slow, control-fast, slow-slow or slow-fast) was used. To determine post-intervention fatigue resistance (endurance), the slow testing fatigue protocol of the non-dominant, non-exercised leg consisted of 12 consecutive, reciprocating, repetitions at 60°s^{-1}, ([90° range of motion / 60°s^{-1}] x 12 repetitions = 18sec) with a similar duration achieved with the high-speed protocol by using 48 consecutive, reciprocating, repetitions at 240°s^{-1} ([90° range of motion / 240°s^{-1}] x 48 repetitions = 18sec). During the experiment, isokinetic muscle torque was measured in both the dominant and non-dominant knee extensors (quadriceps) and flexors (hamstrings) muscles, muscle electrical activity by EMG in the non-dominant knee extensors (vastus lateralis: VL) and flexors (biceps femoris: BF) was recorded.

2.3. Experimental Procedures

Participants first performed a general warm up on a stationary cycle ergometer (Monark, WA, U.S.A) for 5min at 70 repetitions per min at 0.5kp resistance. They were then prepared for EMG electrode placement.

Table 1: Experimental Design

Aerobic warm-up: 5min on a stationary cycle ergometer at 70 rpm and 1 kilopond			
Conditions			
Control-Slow test	Control- Fast test	Slow Fatigue-Slow Test	Slow Fatigue- Fast test
Familiarization and test specific warm-up:			
12 KE and KF repetitions at 60°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 240°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 60°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM	12 KE and KF repetitions at 240°/s at 50% of self-perceived maximal intensity of DOM and Non-DOM
Pre-tests			
3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg
Interventions			
5min seated rest	5min seated rest	4x15; 60°/s with 15sec rest between sets with DOM leg	4x15; 60°/s with 15sec rest between sets with DOM leg
Post-tests			
3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 60°/s of DOM and Non-DOM leg	3 KE and KF maximal isokinetic contractions @ 240°/s of DOM and Non-DOM leg
Post-intervention fatigue tests			
12 maximal contractions at 60°/s with Non-DOM knee	48 maximal contractions at 240°/s with Non-DOM knee	12 maximal contractions at 60°/s with Non-DOM knee	48 maximal contractions at 240°/s with Non-DOM knee

Note: DOM: dominant leg, Non-DOM: non-dominant leg, KE: knee extensions, KF: knee flexions

2.4. Electromyography (EMG)

EMG of the non-dominant VL and BF were monitored using self-adhesive Ag/AgCl bipolar electrodes (MeditraceTM 130 ECG conductive adhesive electrodes, Syracuse, USA) placed parallel to the muscle fibers according to the area specifications of Hermens et al. (2000) after area shaving, abrading, cleaning with isopropyl alcohol swabs, and left to dry. A ground electrode was placed on the femoral lateral epicondyle. EMG activity was collected from the mid-belly (midway between the anterior superior iliac spine to the superior edge of the patella) of the VL and BF (midway between the gluteal fold and the popliteal space) at 2cm apart (Hermens et al., 2000). Following electrode placement, electrodes were taped to minimize movement and tested for inter-electrode impedance noise (< 5kOhms).

All EMG signals were amplified (×1000) (CED 1902 Cambridge Electronic Design Ltd., Cambridge, UK) and filtered using a 3-pole Butterworth filter with cut-off frequencies of 10–1000 Hz. All signals were analog digitally converted at a sampling rate of 5kHz using a CED 1401 (Cambridge Electronic Design Ltd., Cambridge, UK) interface and recorded with sampling rate of 2000Hz using a commercially designed software program Signal 4.0 (Cambridge Electronic Design Ltd., Cambridge, UK) and stored on personal computer for further analysis. Post-test EMG were normalized to the pre-test values. Only the non-dominant (contralateral to the exercised leg) limb was monitored for EMG as the focus of the study was on velocity specific, non-local effects and the decline in dominant limb force was sufficient to document fatigue of the exercised limb.

2.5. Isokinetic Dynamometry

Following placement of EMG electrodes, participants were instructed to sit comfortably on the dynamometer seat according to manufacturer's specifications for seated knee extension/flexion (NORM; CSMI, Inc., Stoughton, MA). One manufacturer procedure that was changed for our protocol was the switch from using hand grips to placing the hands-on shoulder without use of shoulder straps. This change was made due to the possibility of NLMF effects due to upper body and arm fatigue from bracing (stabilizing). A dual crossover strap was used to secure the torso, a waist strap for the hips, and individual thigh straps for the legs. Special care was taken to minimize extraneous movement as movement could affect the force values and biomechanical moments (Weir et al., 1996). The lever arm attachment was placed just proximal to the medial malleolus and stabilized tightly against the limb with Velcro straps. The isokinetic device lever axis was positioned in line with the axis of the knee. All isokinetic chair and apparatus settings were recorded for each participant to ensure an identical setup for each session.

2.6. Specific Warm-Up

Following the dynamometer physical setup, participants completed an isokinetic specific warm-up involving full explanations in addition to familiarization repetitions. The specific warm-up performed at every session consisted of 12 unilateral knee extension and flexions contractions at $60°s^{-1}$ and $240°s^{-1}$ over 90° range of motion (ROM) (90°-0° with knee flexed at 90° as start) at 50% of self-perceived maximal contractions with the dominant leg, then repeated with the non-dominant leg. Prior to contractions at each speed, participants were informed that with isokinetic actions, the lever arm will have zero resistance until the setting velocity is reached ($60°s^{-1}$ or $240°s^{-1}$) at which point it will maintain that velocity, and torque will be measured as force exerted against the arm at that speed. This meant participants must kick (contract) at the set velocity in order to register torque. In addition, because momentum cannot be used, participants were instructed to maintain effort throughout the ROM set in order to complete 'work' during the entire protocol. Computer settings for ROM prevented hyperextension/flexion to reduce risk of injury, and rubber stoppers were placed as an extra precaution. To better understand the isokinetic principles, the computer screen, displaying torque, position, and velocity was visible for the participant. Finally, the isokinetic action was reciprocating concentric knee extension and concentric knee flexion with no eccentric phase and no rest between contractions. Participants were instructed to 'push' to extend their leg and activate their knee extensors, and 'pull' to activate their knee flexors to return the lever arm to the start position as verbal encouragement has been shown to improve performance (Lauber & Keller, 2014).

2.7. Pre-Test (Peak Isokinetic Torque)

To minimize the possibility of fatigue, five minutes following familiarization, three pre-test maximal isokinetic contractions were completed with the dominant and non-dominant leg with 30-seconds recovery between repetitions in order to measure peak torque. Participants were instructed and encouraged to exert maximally as hard and as fast as possible over the full range of motion for both the knee extensors and flexors. Participants were able to see the computer monitor to compare trials to encourage them to outperform previous trials. EMG was recorded from the non-dominant leg during non-dominant trials.

2.8. Fatigue Protocol

Five minutes following the pre-tests, with the intervention protocols (sessions: slow-slow and slow-fast) the dominant leg was initially fatigued, as cross education (unilateral training induces training effects in contralateral, untrained limb) studies have demonstrated greater effects from dominant to non-dominant limbs (Carroll et al., 2006). Prior NLMF studies using isokinetic contractions have imposed 60-175sec (< 3min) of repeated maximal contractions (Grabiner & Owings, 1999; Othman et al., 2017; Strang et al., 2009), while a number of isometric NLMF studies from this lab have utilized two repetitions of 100sec MVCs (3min 20sec) (Aboodarda et al., 2016; Halperin et al., 2014a,b; Sambaher et al., 2016). To meet or exceed both the prior isokinetic and isometric NLMF durations and ensure the development of significant fatigue, the intervention fatigue protocol in this study consisted of four sets of 15 knee extension and flexion repetitions each with no rest between repetitions. Repetitions were performed through 90° ROM at $60°s^{-1}$, with sets separated by 15sec (3min of extension and 3min of flexion), with one minute of rest total (4x15sec), totalling seven minutes for the protocol). The slow angular velocity ($60°s^{-1}$) was chosen for the fatigue intervention since higher contractile forces would be sustained by the muscle over longer duration repetitions, inducing greater physical and metabolic stress on the muscle (Allen et al., 2008; Allen, 2009; Asmussen, 1979). Higher relative contractile forces have demonstrated greater NLMF effects (Kawamoto et al., 2015; Kennedy et al., 2014). The control sessions (control-slow and control-fast) consisted of 5min of seated rest before post-tests. EMG of the non-dominant leg was monitored throughout the protocol and at any sign of activity, participants were reminded to relax that leg. Participants were verbally encouraged and able to view the computer screen demonstrating torque values to encourage them to outperform previous repetitions in order to promote maximal contractions.

2.9. Post-Test & Endurance Test

Participants were allocated 15sec between the intervention fatigue protocol of the dominant leg or 5min of seated rest for the control sessions and the post-test to refocus on the next task (post-tests). The initial post-test measure involved one maximal isokinetic contraction with the dominant leg at either 60°s^{-1} (slow-slow and control-slow conditions) or 240°s^{-1} (slow-fast and control-fast conditions) to determine the extent of fatigue intervention of the exercised leg. Then the non-dominant leg was tested similarly at 60°s^{-1} or 240°s^{-1} dependent on the testing condition to assess differences in contralateral (non-exercised) single, discrete maximal torque. Switching the dynamometer arm from one leg to the other leg took 30sec. Similarly, 15sec following the non-dominant single maximal contraction (1min post-intervention), participants completed a maximal endurance test of 12 maximal contractions at 60°s^{-1} for sessions control-slow and slow-slow, and 48 contractions at 240°s^{-1} for sessions control-fast and slow-fast with the non-dominant leg. The 240°s^{-1} protocol consists of four-fold greater repetitions to equalize total contraction time or volume of work.

2.10. Measurements and Data Analysis

Changes in isokinetic peak torque pre- and post-fatigue (or rest) with the dominant and non-dominant knee extensors and flexors were recorded, with the highest peak torque (baseline to highest force amplitude) measurement recorded. During the endurance test, changes in peak torque for the first and average of the final two contractions were used to calculate a fatigue index ([average of final two contractions peak torque / first contraction peak torque] x 100).

EMG activity of the VL and BF were also investigated pre- and post-fatigue (or rest) with post-fatigue values normalized to the pre-test MVC. A finite response high pass filter with a frequency cut-off of 20Hz was used. The data was then rectified and the root mean square (with an average of 20 data points) was calculated across 1-sec windows that included the peak force output from 0.5sec before and 0.5sec after the peak force in both muscles. A power spectral analysis was also completed to examine the median frequency (Hz) with a 3-sec window epoch that included the peak force output.

For the maximal endurance test, the EMG root mean square was measured during the first contraction and last contraction to determine the EMG output before a power spectrum analysis was conducted to determine the median frequency.

2.11. Statistical Analysis

Statistical analyses were calculated using SPSS software (Version 16.0, SPSS, Inc, Chicago, IL). This study employed a repeated measure, within subjects, cross-over design. Kolmogorov–Smirnov tests of normality were conducted for all dependent variables. Significance was defined as $p < .05$. If the assumption of sphericity was violated, the Greenhouse−Geiser correction was employed. Modified Bonferroni post-hoc tests were conducted to detect significant main effect differences whereas for significant interactions, post-hoc t-tests corrected for multiple comparisons were conducted to determine differences between values. Cronbach alpha intraclass correlation coefficients (ICCs) were measured for the pre-test trials of the Control-slow test and slow fatigue-slow tests to assess consistency of these data (Table 2). Based on Koo and Li (2016), ICC between 0.75 – 0.9 were classified as good, and over 0.9 was considered excellent. We also report the coefficient of variation (CV = [Standard Deviation / Mean] * 100) and standard error of the mean (SEM = standard deviation / square root of the sample size). Standards for CV are as follows: CV < 10% is considered very good, 10-20% is good, 20-30% is acceptable, and CV > 30% is not acceptable (Campbell et al., 2010). Cohen's "d" effect size (ES) statistics were conducted to evaluate the magnitude of the changes following various exercise protocols to the criterion of ≥ 0.80 for large; 0.50-0.79 for moderate, 0.20-0.49 for small and < 0.20 for trivial (Cohen, 1988).

To examine a single maximal contraction peak torque and EMG with slow angular velocity testing, a three-way repeated measures ANOVA comparing 2 conditions (control-slow vs. slow-slow) x 2 limbs (dominant vs. non-dominant) x 2 times (pre- vs. post-test) was used for both quadriceps and hamstrings. Similarly, a single maximal contraction peak torque with fast angular velocity testing was examined using a three-way repeated measures ANOVA comparing 2 conditions (control-fast vs. slow-fast) x 2 limbs (dominant vs. non-dominant) x 2 times (pre- vs. post-test) for both quadriceps and hamstrings. Separate ANOVAs were used for single absolute maximal peak torques with slow and fast isokinetic testing due to the inherent torque differences associated with the force-velocity muscle characteristics.

When examining the slow fatigue (endurance) test, a two-way repeated measures ANOVA comparing 2 conditions (control-slow vs. slow-slow) x 4 tests (pre-test, post-test, first and last fatigue repetitions) was used. Likewise, the same setup was used for examining the fast fatigue test. To compare the slow versus fast peak torque and EMG (normalized to the pre-test single maximal contraction peak torque or EMG) testing, a two-way repeated measures ANOVA with 2 limbs (dominant vs. non-dominant) x 4 conditions (control-slow, slow-slow, control-fast, slow-fast) was conducted for the quadriceps and hamstrings. To compare slow versus fast testing for fatigue, a fatigue index was used, analyzed with a two-way repeated measures ANOVA with 2 conditions (control and fatigue intervention) x 2 tests (slow and fast isokinetic velocity).

3. Results

The excellent intraclass correlation coefficient torque measures (r = .87-.91) are presented in Table 2.

Table 2: Cronbach alpha Intraclass Correlation Coefficients (ICC), coefficient of variation (CV) and standard error of the means (SEM).

Leg	Muscle	Peak Torque (Nm) Pre-tests	Cronbach's Alpha ICC	CV	SEM (Nm)
Dominant	Hamstrings	133.7±27.1 132.9±26.7	0.87	28.6%	7.1
Non-Dominant	Hamstrings	127.8±26.2 132.9±26.7	0.90	30.4%	7.2
Dominant	Quadriceps	189.4±36.1 193.5±46.1	0.91	28.9%	9.3
Non-Dominant	Quadriceps	189.1±37.8 185.3±46.1	0.89	26.7%	9.1

3.1. Slow Test Condition

3.1.1. Quadriceps Single MVC Peak Torque - Slow Test Condition (Table 3)

A significant interaction was seen for intervention x time (F(1,15) = 17.44, *p* = .001), revealing a significant peak torque decrease of the dominant quadriceps from pre- vs. post-test for control-slow (*p* = .001, ES = 0.27) and slow-slow test (*p* < .001, ES = 0.57) of 6% and 14% respectively.

A significant dominance x time (F(1,15) = 23.49, *p* < .001) interaction found decreases of 16% (*p* < .001, ES = 0.70) and 4% (*p* < .01, ES = .17) for pre- to post-test for dominant and non-dominant limbs, respectively (combined data from both the fatigue intervention and control conditions). A significant intervention x dominance x time interaction (F(1,15) = 9.21, *p* = .008) showed a significant 25% decrease (*p* < .001, ES = 1.04) from pre- vs. post-test for dominant quadriceps with the intervention slow test condition. Post-test dominant quadriceps MVC during the intervention condition was significantly (*p* = .008, ES = 0.53) lower than control by 13%.

3.1.2. Hamstrings Single MVC Peak Torque - Slow Test Condition (Table 3)

A significant dominance x time interaction (F(1,15) = 8.42, *p* = .011) indicated that peak torque of the dominant (exercised) and non-dominant (non-exercised) hamstrings decreased significantly 9.1% (*p* < .001, ES = .44) and 4.7% (*p* = .001, ES = 0.23) pre- vs. post-test respectively (combined data from both the fatigue intervention and control conditions). A significant intervention x dominance x time (F(1,15) = 10.57, *p* = .005) interaction illustrated pre- to post-test decreases for slow-dominant hamstrings of 14.6% (*p* < .001, ES = 0.65). When comparing post-test conditions, the dominant hamstrings peak torque post-test in the fatigue condition was 11% (*p* = .03, ES = 0.49) lower than control.

3.2. Fast Test Condition

3.2.1. Quadriceps Single MVC Peak Torque - Fast Test Condition (Table 3)

An intervention x time interaction (F(1,15) = 5.94, *p* = .03) demonstrated a significant (*p* = .005, ES = 0.30) 11% pre- to post-test decrease of the dominant quadriceps for the slow-fast intervention fatigue protocol. In addition, the dominant quadriceps post-test for the slow-fast intervention was significantly (*p* = .02, ES = 0.26) lower than control-fast post-test by 9%. An intervention x dominance x time interaction (F(1,15) = 12.77, *p* = .003) found a significant (*p* = .006, ES = 0.57) decrease of 20% for pre- vs. post-test for the dominant leg intervention.

3.2.2. Hamstrings Single MVC Peak Torque - Fast test condition (Table 3)

A significant intervention x dominance interaction (F(1,15) = 5.77, *p* = .03) exhibited a significant (*p* = .02, ES = 0.25) decrease of 8% for dominant hamstrings post-test in the intervention test vs. control. A significant interaction effect for intervention x dominance x time (F(1,15) = 9.35, *p* = .008) disclosed a significant (*p* = .001, ES = 0.55) 17% decrease in pre- to post-test dominant leg hamstrings in the intervention protocol.

3.3. Slow versus Fast Testing Conditions

3.3.1. Quadriceps Torque and EMG

There was no significant main effects or interactions for quadriceps peak torque when comparing slow vs. fast contraction effects. Furthermore, there was no significant interaction for quadriceps EMG but there was a significant main effect for time (F(2,10) = 4.45, *p* = .04). Although the main effect was significant, post-hoc analysis indicated that there was a non-significant (*p* = .20), small magnitude (14.3%, ES = 0.27) lower EMG with the pre-test versus the post-slow test (Table 4).

3.3.2. Hamstrings Torque and EMG

A significant interaction between conditions x dominance (F(1,15) = 9.54, *p* = .007) indicated a significant (*p* = .002, ES = 0.94) fatigue intervention-induced torque decrease of 11.7% in dominant hamstrings (knee flexion) performance with the interventions (slow-slow and slow-fast) vs. control (control-slow and control-fast) conditions. There was no significant interaction for hamstrings EMG but there was a significant main effect for time (F(2,10) = 7.78, *p* = .009). Post-hoc analysis revealed that there was a significant (*p* = .01), small magnitude (8.3%, ES = 0.22) lower EMG with the post-test versus the pre-test (Table 4).

Table 3: Discrete (single) maximal mean peak torque (N x m) and standard deviation (SD) of quadriceps and hamstrings during slow (60°s-1) and fast (240°s-1) tests. Percentage changes represent pre- to post-test or first to last repetition relative different.

	Peak Torque – $60°s^{-1}$ Test				Peak Torque – $240°s^{-1}$ Test			
	Quadriceps		Hamstrings		Quadriceps		Hamstrings	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control – Single Contraction Pre-Test – Dom	189.3	37.2	133.6	27.9	98.3	37.7	81.5	29.7
Control – Single Contraction Post-Test – Dom	175.2	47.2	127.9	25.6	98.1	36.8	79.6	30.1
% Δ Pre to Post	-7.4%		-4.3%		-0.2%		-2.3%	
Control – Single Contraction Pre-Test – Non-Dom	189.1	39.1	127.7	27.1	102.3	33.6	79.0	31.3
Control – Single Contraction Post-Test – Non-Dom	181.1	42.0	119.6	25.6	99.6	38.1	73.5	30.5
% Δ Pre to Post	-4.2%		-6.3%		-2.6%		-6.9%	
Control – Fatigue Post-Test – Non-Dom Repetition #1	177.7	45.4	132.9	27.5	90.6	32.8	73.2	23.8
Control – Fatigue Post-Test – Non-Dom Last Repetition	154.2	43.1	118.2	25.1	46.2	15.4	45.3	12.7
% Δ first to last repetition	-13.2%		-11.1%		-49.0%		-38.1%	
Fatigue Intervention – Single Contraction Pre-Test - Dom	198.5	47.3	97.6	21.3	102.7	41.7	80.5	29.7
Fatigue Intervention– Single Contraction Post-Test - Dom	151.1	46.2	113.6	33.3	82.7	28.9	66.9	21.4
% Δ Pre to Post	-23.8%		16.4%		-19.4%		-16.9%	
Fatigue Intervention – Single Contraction Pre-Test – Non-Dom	185.2	47.6	129.3	25.6	99.1	37.6	79.0	26.0
Fatigue Intervention – Single Contraction Post-Test - Non-Dom	177.4	55.6	125.3	28.8	96.6	37.1	74.6	28.1
% Δ Pre to Post	-4.2%		-3.1%		-2.5%		-5.6%	
Fatigue Intervention– Post-Test – Non-Dom Repetition #1	175.5	51.6	117.2	26.1	93.6	32.6	76.5	22.8
Fatigue Intervention– Post-Test – Non-Dom Last Repetition	136.9	50.1	92.1	23.4	41.1	13.6	39.6	12.4
% Δ first to last repetition	-21.9%		-21.4%		-56.1%		-48.2%	

Note: Dom: dominant leg; Non-Dom: non-dominant leg

Table 4: Pre- and post-test EMG measures. Significant difference between control and fatigue, and between fast and slow intervention groups (p = .0009, ES = 0.63).

	EMG Median Frequency (Hz) - Quadriceps											
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	73.9	76.9	62.7	81.6	75.9	55.6	72.3	70.2	66.3	77.1	80.2	56.2
SD	18.4	17.8	18.2	18.2	14.9	15	17.2	13.7	15.1	18.2	13.4	14.9
	EMG Median Frequency (Hz) - Hamstrings											
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	78.4	73.9	132.4	73.6	76.3	57.6	153.1	78.8	125.7	78.4	75.6	54.9
SD	15.7	14.8	250.6	22.8	17.7	12.9	245.5	19.6	233.9	18.4	15.1	12.2
	EMG Peak – Quadriceps (RMS: mV)											
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	0.7	0.6	0.7	0.4	0.4	0.5	0.6	0.5	0.7	0.4	0.3	0.4
SD	0.5	0.4	0.5	0.2	0.3	0.6	0.5	0.4	0.6	0.2	0.1	0.2
	EMG Peak – Hamstrings (RMS: mV)											
	Control - Slow Test			Control - Fast Test			Slow Fatigue - Slow Test			Slow Fatigue - Fast Test		
	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last	Pre-test	Post First	Post Last
Mean	0.3	0.4	0.5	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.4
SD	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2

Note: Pre-test: single maximum contraction. Post First: post-test first repetition of fatigue protocol, Post Last: post-test 12th repetition of fatigue protocol, RMS: root mean square

3.4. Unilateral Fatigue Intervention Effects on Contralateral, Non-dominant, Leg Fatigue Tests

3.4.1. Contralateral (Non-dominant) Quadriceps Fatigue Index (Figure 1)

Significant main effects for time with the slow ($F(1,15) = 46.88$, $p < .001$) and fast fatigue ($F(3,45) = 43.78$, $p < .001$) tests displayed significant decreases of 18% ($p < .001$, ES = 0.67) and 53% ($p < .001$, ES = 2.1) between the first and last repetition of the contralateral, non-dominant, quadriceps fatigue tests.

A significant main effect for conditions ($F(1,15) = 6.27$, $p = .02$) revealed that the intervention conditions (slow-slow and slow-fast) peak torque during the repeated maximal test significantly decreased 11% ($p = .02$, ES = 0.34) more than control (control-slow and control-fast) (Figure 1). In addition, a significant main effect for tests ($F(1,15) = 31.26$, $p < .001$) indicated that high velocity, contralateral, non-dominant, quadriceps peak torque fatigue index decreased 37% ($p < .001$, ES = 1.77) more than slow test.

The ANOVA revealed a significant condition x time interaction ($F(9,27) = 2.77$, $p = .019$). with every condition. The pre-test quadriceps EMG median frequency either significantly ($p < .001 – p = .02$) or nearly significantly (slow-fast condition; $p = .10$) was greater than the last repetition of the fatigue protocol. A main effect for time ($F(3,9) = 16.02$, $p = .026$) for the contralateral quadriceps EMG median frequency revealed that the post-test frequency was 6.2% ($p = .01$, ES = 0.21) and 35.1% ($p = .05$, ES = 0.73) higher than first and last repetitions of the fatigue test.

3.4.2. Contralateral (Non-dominant) Hamstrings Fatigue Test (Figure 1)

Significant main effect for times for the slow ($F(3,45) = 63.29$, $p < .001$) and fast ($F(3,45) = 41.32$, $p < .001$) fatigue tests revealed significant decreases of 19% ($p < .001$, ES = 0.98) and 5% ($p = .03$, ES = 0.16) between the first and last repetition of the repetitive fatigue endurance test respectively.

A significant main effect for conditions ($F(1,15) = 8.32$, $p = .011$) displayed that the intervention conditions (slow-slow and slow-fast) peak torque during repeated maximal test decreased 10% significantly ($p = .005$, ES = 0.41) more than control (control-slow and control-fast) (Figure 1). Furthermore, analysis revealed a significant effect for tests ($F(1,15) = 14.94$, $p = .002$) revealing that high velocity peak torque endurance decreased 30% significantly ($p = .003$, ES = 1.54) more than slow test.

A main effect for time ($F(3,9) = 27.10$, $p < .0001$) for the hamstrings EMG median frequency revealed that the post-test frequency was 40.7% ($p = .01$, ES = 0.91) greater than last repetition of the fatigue protocol, while first repetition of the fatigue protocol was 34.0% ($p = .002$, ES = 1.1) higher than the last repetition. There were no significant interactions for hamstrings EMG median frequency.

4. Discussion

The most important finding in this study was that velocity specific effects were not demonstrated with relative peak torque or relative fatigue endurance changes between slow (60°s^{-1}) or fast (240°s^{-1}) testing. In accord with the hypothesis, prior unilateral fatigue of the dominant quadriceps and hamstrings by repetitive slow (60°s^{-1}) maximal isokinetic actions did not demonstrate decreases in singular (discrete) maximal peak torque in the contralateral, homologous muscles. However, there was some evidence (main effect for conditions) of NLMF with repetitive fatigue endurance (fatigue index). These findings are in agreement with a recent meta-analysis that determined that an analysis of the NLMF literature generated only trivial NLMF discrete maximal contraction differences but moderate effects with endurance testing (Behm et al., 2021).

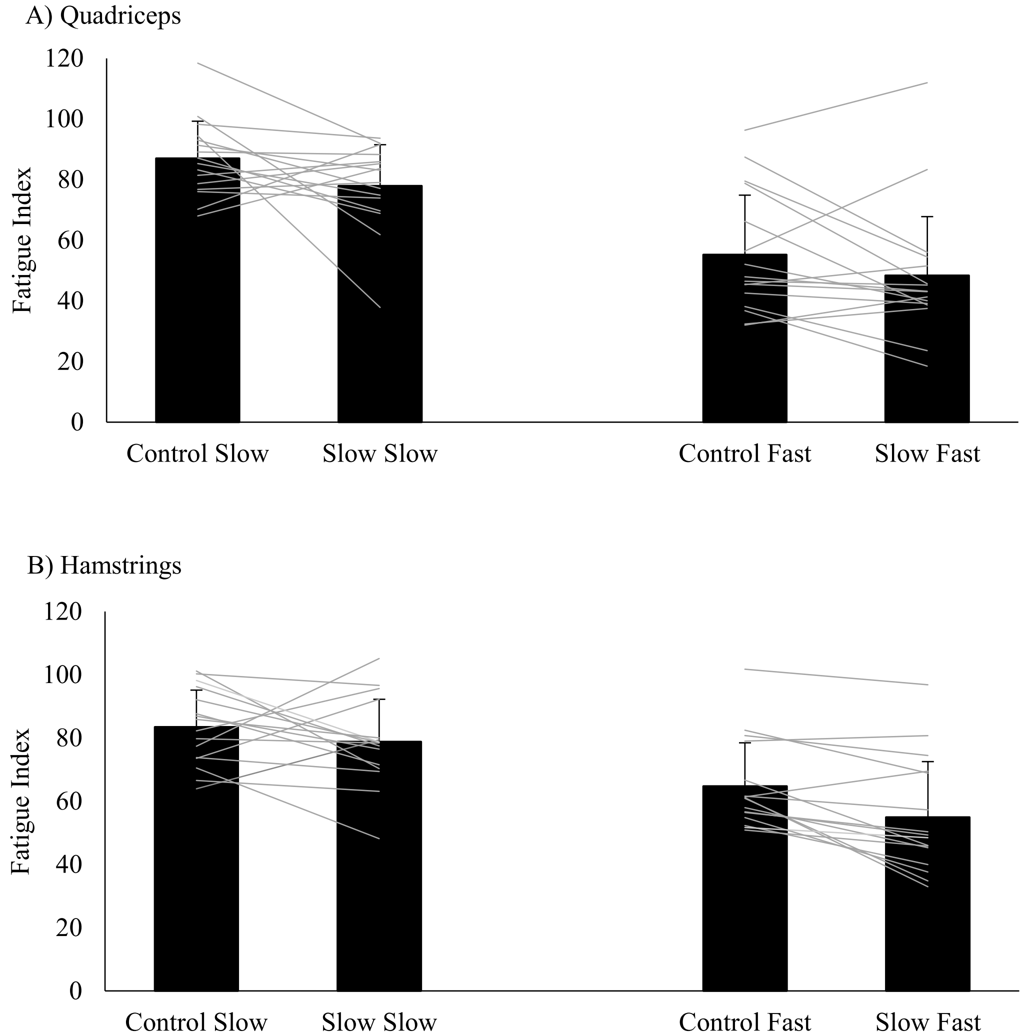
4.1. Velocity Specificity

A relatively unexplored aspect of NLMF is whether effects are velocity specific. The majority of prior NLMF or crossover literature intervened and tested with maximal voluntary isometric contractions and hence did not compare varying contraction velocities. No velocity specific effects (60°s^{-1} vs. 240°s^{-1}) were demonstrated in peak torque. Velocity specific differences were observed for the non-dominant, contralateral, repetitive fatigue endurance test, with the high velocity test demonstrating a 30% (ES = 1.5) greater decrease in the fatigue index compared to the slow velocity test. This difference however was not deemed NLMF as it was not significantly different from control. It is likely the greater decrease in repetitive fatigue endurance in the high velocity protocol is due to the greater fatiguability of fast (type 2) muscle fibers at higher velocities. The only study that also compared velocity specific effects was Othman et al. (2017) who compared isometric (0°s^{-1}) and high velocity (300°s^{-1}) fatigue protocol on isometric and high velocity peak torque. In contrast to the current study, they found evidence of NLMF for both isometric and isokinetic protocols, however there was no difference between protocols, also demonstrating a lack of velocity specific NLMF effects.

4.2. Fatigue Intervention

In the present study, the intervention fatigue protocol consisting of four sets of 15 unilateral isokinetic knee extensions and flexions utilized maximal intent contractions, delivering similar dominant (exercised) quadriceps and hamstrings torque deficits of 24% (ES = 1.01) and 15% (ES = 0.65) when tested at 60°.s^{-1}, with 20% (ES = 0.57) and 17% (ES = 0.55) quadriceps and hamstrings deficits when tested at 240°.s^{-1}. These fatigue-induced deficits of the exercised leg were similar to Kawamoto et al. (2014) (↓32%), Doix et al. (2013) (↓17%), Martin and Rattey (2007) (↓16%) and Othman et al. (2017) with 12.6% and 11.3% decrements at 90° and 120° respectively. In contrast, Grabiner and Owings (1999) and Strang et al. (2009) exhibited greater fatigue impairments of the exercised muscle of 39% and 19% respectively.

It has been demonstrated that higher or maximal intensity exercise (Kawamoto et al., 2015; Kennedy et al., 2014) has demonstrated greater NLMF effects than lower intensity exercise (Arora et al., 2015; Paillard et al., 2010). In addition, the amount of contraction time might play a role as fatigue accumulates over time (Bigland-Ritchie et al., 1986). When shorter and longer



Conditions		Peak Torque Fatigue Index			
		Quadriceps		Hamstrings	
		Mean	SD	Mean	SD
Control – Slow	(Rest - 60°.s^{-1})	87.01	12.6	83.5	12.01
Control – Fast	(Rest - 240°.s^{-1})	55.2	20.3	64.8	14.1
Slow – Slow	(60°.s^{-1} - 60°.s^{-1})	77.9	14.1	78.8	13.8
Slow – Fast	(60°.s^{-1} - 240°.s^{-1})	48.3	22.2	54.9	18.2

Figure 1: Fatigue Index (mean and standard deviation (SD) % decrease) for quadriceps (Figure 1A) and hamstrings (Figure 1B) peak torque between 1st and last repetition of fatigue endurance tests.

isometric durations were compared, the longer protocol induced greater decrements (Doix et al., 2013). However, for isokinetic protocols, the data is mixed even though all protocols used maximal intent contractions. With isokinetic studies, Grabiner and Owings (1999) contracted for 3min, Strang et al. (2009) used 3.8min, and the current study used 3min and did not demonstrate NLMF strength effects, whereas Othman et al. (2017) used 60sec and demonstrated effects. The present study results again call into question further methodological considerations. For example, Grabiner and Owings (1999) suggested the allowance of a passive return of the dynamometer giving the protocol a 1:1 work/rest ratio, which might have allowed a recovery effect. However, the present study and Strang et al. (2009) used concentric-concentric actions of the quadriceps and hamstrings, not allowing a full recovery of either muscle (i.e., co-contractions) and did not demonstrate deficits, while Othman et al. (2017) utilized concentric only actions of the quadriceps and demonstrated NLMF effects. It might then be possible that the velocity being used to fatigue might play a role, as isokinetic actions allow control over movement velocity. While Grabiner and Owings (1999) used slower velocity (30°s^{-1}), the current study used 60°s^{-1}, and Strang et al. (2009) used 110°s^{-1} and did not demonstrate effects, Othman et al. used a much faster 300°s^{-1} protocol and reported impairments. As mentioned earlier, the other three studies used adults, Othman et al. (2017) used children, which might be a contributor to the NLMF effects.

4.3. Fatigue Measures

The most commonly used NLMF detection method has been peak force during a singular, maximal contraction, (Halperin et al., 2015). Several studies have (Aboodarda et al., 2015; Doix et al., 2013; Martin & Rattey, 2007; Othman et al., 2017) and have not (Arora et al., 2015; Decorte et al., 2012; Elmer et al., 2013; Grabiner & Owings, 1999; Halperin et al., 2014; Halperin et al., 2014; Kennedy et al., 2015; Paillard et al., 2010; Regueme et al., 2007; Strang et al., 2009; Triscott et al., 2008; Zijdewind et al., 1998) demonstrated deficits in singular maximal contractions. A NLMF meta-analytical review (Behm et al., 2021) illustrated that studies that demonstrated NLMF of single maximal contractions generally counterbalanced those that did not, resulting in an overall trivial magnitude effect.

Although there is evidence for NLMF effects with repeated maximal contractions (Amann et al., 2013; Behm et al., 2021; Halperin et al., 2014a; Rasmussen et al., 2010; Triscott et al., 2008), the evidence for NLMF of repetitive contractions was not comprehensive in the present study as there were no significant interactions. But there were main effects for conditions with greater decreases in quadriceps and hamstrings peak torque fatigue indexes following the fatiguing intervention (slow-slow and slow-fast) compared to control conditions (control-slow and control-fast). It can then be suggested that the fatigue induced with most NLMF studies might not be sufficient to elicit a deficit in a singular maximal contraction, however prolonged or repetitive testing demands, may require more persistent neural input (e.g., inter-hemispheric and/or corticospinal inhibition: Takahashi et al., 2011) that could exacerbate global neural failure and afferent inhibition of spinal and cortical motoneurons (Behm, 2004). Furthermore, according to the mental energy deficit theory, mentally fatiguing tasks (e.g., concentration and focus necessary to maintain high contractile forces for a prolonged period) can impair subsequent physical performance, especially with repeated and/or prolonged exertion (Marcora et al., 2009; Pageaux et al., 2013, 2014). Mentally fatiguing tasks influence participants perception of the activity as more strenuous or uncomfortable (Steele, 2020), and hence, disengage sooner from the activity (Marcora et al., 2009; Pageaux et al., 2013, 2014). As persistent focus and concentration are also a requisite for performing repetitive MVCs, the mental energy involved with the fatigue intervention may have negatively impacted the repetitive, contralateral, fatigue test. Similar to the general findings of the Behm et al. (2021) meta-analysis, the present study failed to demonstrate impairments in single maximal peak torque contractions, but did provide some evidence of deficits with the peak torque fatigue index.

Neuromuscular activation as monitored by EMG activity did not demonstrate a NLMF effect but the power density spectrum median frequency did decrease in response to the fatigue test protocol (irrespective of the condition) as has been frequently reported in the literature (Ament et al., 1996; Krogh-Lund & Jorgensen, 1991; Warren et al., 2000). Reduced EMG median frequency represents decreases in action potential conduction velocities and motoneuronal rate coding associated with fatigue. (Ament et al., 1996; Krogh-Lund & Jorgensen ,1991; Warren et al., 2000).

4.4. Contraction Mode

The contraction mode has been suggested to play a role in NLMF (Halperin et al., 2015), with constant action fatiguing protocols such as isometric (Aboodarda et al., 2015; Doix et al., 2013; Halperin et al., 2014a,b; Kennedy et al., 2013. 2015; Martin & Rattey, 2007; Post et al., 2008; Todd et al., 2003), and cycling (Bangsbo et al., 1996; Bogdanis et al., 1994; Bouhlel et al., 2010; Johnson et al., 2014; Nordsborg et al., 2003; Rasmussen et al., 2010; Sidhu et al., 2014) more likely to demonstrate NLMF effects than dynamic. However, significant impairments have been demonstrated in a few dynamic studies with isoinertial and isokinetic fatigue interventions (Amann et al., 2013; Ciccone et al., 2014; Kawamoto et al., 2014; Othman et al., 2017; Šambaher et al., 2016). Of three studies examining isokinetic contractions, Strang et al. (2009) used concentric unilateral knee extensions and flexions, but at 110°.s^{-1}, and tested isometrically whereas the current study tested at slow (60°.s^{-1}) and high velocities (240°.s^{-1}). In contrast to the current study, Grabiner and Owings (1999) used slower (30°.s^{-1}) unilateral knee extensions or flexions, and Othman et al. (2017) used faster (300°.s^{-1}) unilateral knee extensions and isometric contractions. Within these three isokinetic studies, only one demonstrated NLMF effects (Othman et al., 2017). In addition, to employing higher velocity fatiguing contractions, Othman et al. (2017) reported global NLMF (i.e., knee extensors, elbow flexors, handgrip, and balance test), suggesting that NLMF may be more susceptible with youth.

A limitation was the time required to switch the isokinetic device from the dominant exercised to non-dominant non-exercised testing legs (approximately 30sec). NLMF effects seem to diminish quickly following recovery of the exercised limb, and therefore a quick transition to the non-exercised leg may be critical to monitor immediate responses. However, it can also be argued that an effect that persists for less than 1min has little practical significance. However, significant NLMF effects have been observed at 30sec (Prieske et al., 2017), 1-min (Halperin et al., 2014a) and 3min (Halperin et al., 2014b; Prieske et al., 2017) post-fatigue protocol. Furthermore, while a sample size of 16 participants was calculated from an “a priori” statistical power analysis and is a typical population number in these types of studies, the ability to detect significant differences may have been strengthened but a greater number of participants.

A major strength of this study was the inclusion of both sexes and the scope of measurements that highlighted both physical performance (i.e., maximal torque, fatigue endurance), and neural mechanisms (EMG RMS, EMG median frequency). However, the inclusion of both males and females could also be perceived as a disadvantage due to sex differences in fatigability. Females are reported to be less fatigable during low velocity contractions (Yoon et al., 2007) and this could have skewed the results.

In conclusion, this study highlighted that prior unilateral fatigue of the dominant quadriceps and hamstrings by repetitive slow ($60°s^{-1}$) maximal isokinetic actions did not demonstrate decreases in singular maximal peak torque but some NLMF evidence with repetitive fatigue endurance in the contralateral homologous muscles. In addition, velocity specific effects were not demonstrated in relative peak torque or relative fatigue endurance changes. The present findings suggest that individuals can still expect to produce a maximal contraction force of a contralateral leg following unilateral knee extensor and flexor fatiguing activities at slow or faster angular velocities. However, subsequent contralateral exercise that involves muscular endurance could be negatively impacted by prior unilateral fatiguing contractions.

Conflict of Interest

The authors declare no conflict of interests.

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