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Ipsilateral and Contralateral Torque Responses to Bilateral and Unilateral Maximal, Fatiguing, Isokinetic Leg Extensions

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ABSTRACT

Background: Few studies have compared performance fatigability (PF) for bilateral versus unilateral isokinetic tasks. **Objectives:** The purpose of this study was to examine: Mode-specific testing responses to isokinetic fatigue, differences in PF between bilateral and unilateral leg extensions, and the effects of fatiguing, unilateral, dynamic leg extensions on contralateral isokinetic peak torque (PT) and maximal voluntary isometric contraction (MVIC). **Methods:** Eight men (mean ± SD: age= 22.5 ± 2.5 yr.) completed pre- and post-testing for PT and MVIC following 50 bilateral, unilateral right or left leg maximal, isokinetic leg extensions at 180°·s^{-1}, on three separate days. Fatigue-induced decreases in PT and MVIC were used to quantify PF. The data were analyzed with a 4-way repeated measures ANOVA, follow up, and post-hoc analyses. **Results:** The results indicated that there were no differences ($p > 0.05$) in PF for the bilateral versus unilateral fatiguing tasks, decreases in PT ($p < 0.001$ - 0.016; d = 0.54 - 2.58) and MVIC ($p < 0.001$ - 0.006; η^2_p = 0.682 - 0.962) for the exercised legs during unilateral fatigue, and a contralateral increase ($p = 0.007$) in PT following the right leg fatiguing task. **Conclusion:** The results indicated that PT was more sensitive to fatiguing isokinetic tasks than was MVIC. In addition, there was a facilitation of PT in the contralateral leg following unilateral right leg fatigue. The differences in PT and MVIC testing may be attributable to the timing and/or relative contributions of peripheral and central fatigue.

Key words: Muscle Fatigue, Isometric Contraction, Muscle Strength, Torque, Physical Exertion

INTRODUCTION

Fatigue can be described as "… an exercise-induced decline in maximal voluntary muscle force" (Gandevia, 2001, p. 1725). According to Kluger et al., (2013), however, fatigue includes both performance fatigability (PF) and perceived fatigability. PF involves the decline in an objective measure of performance over a discrete period of time, while perceived fatigability includes changes in sensation that regulate performance (Enoka & Duchateau, 2016; Marrelli et al., 2018). Enoka and Duchateau (2016) recommended that studies of PF focus on outcome variables that "impact real-world performance" (p. 2228) such as the time to task failure and time to task completion, as well as fatigue-induced changes in peak torque (PT), maximal voluntary isometric contraction (MVIC) force, power production, voluntary activation, reaction time, ratings of perceived exertion, heart rate, mean arterial pressure, and core temperature. Recent studies (Anders et al., 2020b; Keller et al., 2020; Neyroud et al., 2016) have used fatigue-induced changes in MVIC to operationally define the global force production aspect of PF, while the contributions of central and peripheral mechanisms to PF have been examined using voluntary activation from the twitch interpolation technique (Ansdell et al., 2019) and involuntary evoked peak twitch amplitude (Thomas et al., 2018), respectively. Although central and peripheral mechanisms of fatigue overlap via the effects of the buildup of metabolic byproducts on processes distal to the neuromuscular junction, as well as type III/IV afferent feedback to reduce cortical drive to the muscle (Enoka & Duchateau, 2016; Weavil & Amann, 2019), decreases in MVIC can reflect either or both mechanisms depending upon the intensity of the contraction (Enoka & Duchateau, 2016, p. 2229). Furthermore, Brownstein et al., (2020) questioned the "ecological validity" (p.2) of the use of evoked isometric measures to quantify PF as the result of fatiguing dynamic tasks, as most all sport and exercise is performed under dynamic conditions, generating different systemic and local responses to fatigue. Recently, Anders et al., (2020) quantified PF from decreases in isokinetic peak torque following fatiguing isokinetic tasks, but differences in the sensitivity of PF from decreases in PT versus MVIC measures following a fatiguing isokinetic task has not been compared.

Previous studies (Anders et al., 2020b; Matkowski et al., 2011; Rossman et al., 2012, 2014) have reported greater

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PF for unilateral than bilateral muscle actions. It has been suggested that the greater PF during unilateral muscle actions is attributable to the smaller amount of engaged muscle mass, less stress on other physiological systems such as the cardiovascular and respiratory systems, and less group III/IV afferent feedback (Hureau et al., 2018; Rossman et al., 2012, 2014; Thomas et al., 2018). Group III afferents are sensitive to a muscle stretching, while group IV afferents are sensitive to intramuscular metabolites and metabolic changes within the muscle, indicative of peripheral fatigue (Hureau et al., 2018). Together, group III/IV afferents work to limit muscle fatigue by modulating peripheral fatigue (Hureau et al., 2018). Typically, when peripheral fatigue becomes intolerable, the task is terminated (open-ended) or force is reduced to continue exercise (closed-ended). While unilateral muscle actions result in a localized source of group III/IV afferent feedback, bilateral muscle actions are associated with a greater magnitude of engaged muscle mass, and therefore, more group III/IV afferent feedback (Hureau et al., 2018; Thomas et al., 2018). Thus, compared to unilateral muscle actions, bilateral muscle actions are characterized by greater threat to overall physiological homeostasis via group III/IV afferents, which typically results in less time to task failure or completion, and PF (Hureau et al., 2018; Thomas et al., 2018).

Most studies that have examined the effects of unilateral fatigue on the contralateral, non-exercised limb have utilized isometric tasks and reported decreases or no changes in contralateral MVIC. In contrast, Strang et al., (2009) and Kawamoto et al., (2014) utilized fatiguing, dynamic, unilateral leg extension tasks and reported increases and decreases in contralateral MVIC, respectively. Thus, previous studies of isometric and dynamic tasks have reported mixed findings for contralateral MVIC, and no previous studies have examined the effects of unilateral dynamic fatigue of the leg extensors on dynamic contralateral force production. Therefore, the purpose of this study was to examine: 1) Mode-specific testing responses to isokinetic fatigue; 2) differences in PF between bilateral and unilateral leg extensions; and 3) the effects of fatiguing, unilateral, dynamic leg extensions on contralateral leg extension isokinetic PT and MVIC. Based on previous findings, it was hypothesized that there would be similar decreases in PT and MVIC following bilateral, as well as, unilateral muscle actions (Byrne et al., 2001; Camic, 2011; Hill et al., 2016), that unilateral muscle actions would result in greater decreases in PT and MVIC than bilateral muscle actions (Anders et al., 2020b; Matkowski et al., 2011; Rossman et al., 2012, 2014) and that fatiguing, maximal, unilateral leg extensions would decrease contralateral PT and MVIC.

MATERIALS AND METHODS

Participants and Design of Study

Eight men (mean ± SD: age = 22.5 ± 2.5 years; body mass = 86.6 ± 6.1 kg; height = 186.1 ± 4.8 cm) volunteered to participate in this study utilizing a Quasi-Experimental design. A priori power analysis was conducted using G*Power3 (Faul et al., 2007) and determined a minimum of 6 subjects were required to demonstrate mean differences between two dependent groups using repeated measures ANOVAs, an effect size of $\eta^2_p = 0.594$ (Anders et al., 2020a), a power of 0.95, and an alpha of 0.05. To be included in this study, all subjects were required to be recreationally trained and participated in resistance and/or aerobic training at least three days per week (Riebe et al., 2018). Subjects were excluded from the study if they had a previous knee or ankle pathologies within the last six months that would potentially affect their performance. The dependent variables measured in this study are PT and MVIC. The study was approved by the University Institutional Review Board for Human Subjects (#20191019755FB), and all subjects signed a written Informed Consent document and completed a Health History Questionnaire prior to participation in the study.

Protocol

The subjects visited the laboratory on four separate occasions. The first visit was an orientation to become familiar with the equipment and testing procedures. For the orientation and testing sessions, the subjects were positioned according to the Cybex 6000 owner's manual (Cybex, Division of Lumex, Inc., Ronkonkoma, NY, USA) with a strap over the shoulder and across the chest for stability. The lever arm of the dynamometer was aligned with the axis of rotation of the knee joint (Figure 1). The dynamometer orientation was fixed at 90° with a tilt of 0° and a seatback tilt of 85°. During the orientation session, subjects practiced submaximal and maximal, bilateral, and unilateral, isometric, and isokinetic leg extensions. During each of the three testing visits, the subjects warmed up by performing 5 submaximal (approximately 50% of maximum) isokinetic leg extensions at $180°s^{-1}$ on a calibrated Cybex 6000 dynamometer. Subjects then performed pre-testing that included two maximal bilateral, unilateral right leg, and unilateral left leg isokinetic leg extensions at $180°s^{-1}$ to determine PT values, as well as two, 6 s bilateral, unilateral right leg, and unilateral left leg maximum voluntary isometric contractions at a knee joint angle of 135° (180° corresponding to full extension). The

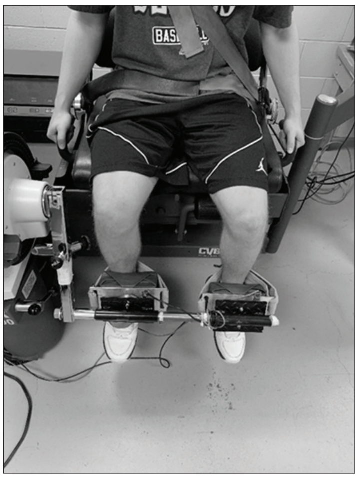

Figure 1. Subject setup on the Cybex 6000 isokinetic dynamometer

isometric angle was chosen to be consistent with previous studies (Anders et al., 2019, 2020b) and corresponds to the middle of the range of motion (Babault et al., 2006). The entire testing order was randomized for every subject for each test visit. The subjects were given 5 seconds rest between repetitions of the same test, and the next test was started as quickly as possible upon completion of the prior test. The subjects were given at least 48 hours between each visit. After pre-testing, subjects performed 50 consecutive maximal, bilateral, unilateral right leg, or unilateral left leg (randomly ordered) isokinetic leg extensions at $180°s^{-1}$ on separate days. The selected speed of $180°\cdot s^{-1}$ was utilized to assess strength at a moderate velocity, as the effects of fatigue have been previously examined using a slow velocity ($60°\cdot s^{-1}$) protocol (Anders et al., 2020a). Subjects received strong verbal encouragement throughout all testing and fatiguing workbouts. Immediately following the 50 repetitions on each testing visit, subjects completed post-testing for bilateral and unilateral PT and MVIC that was identical to the pre-testing protocol. PT and MVIC were determined using the highest value from the two repetitions of each test.

Statistical Analysis

Reliability analyses for the bilateral, unilateral right leg, and unilateral left leg, PT and MVIC values were performed using the pre-testing values from the three testing visits, regardless of the order the fatiguing tasks were performed (Visit 1 vs Visit 2 vs Visit 3). The reliability analyses included repeated measures ANOVAs to assess systematic error, as well as calculation of intraclass correlations (ICCs), 95% confidence intervals ($ICC_{95\%}$), and standard error of measurement (SEMs) using the 2,k model (Weir, 2005). A 2 (Mode: PT, MVIC) x 2 (Time: pre-testing, post-testing) x 3 (Fatiguing Task: bilateral, unilateral right leg, unilateral left leg) x 3 (Testing Condition: bilateral, unilateral right leg, unilateral left leg) repeated measures ANOVA was used to analyze the torque values. Two separate (one each for PT and MVIC) follow-up 2 (Time: pre-testing, post-testing) x 3 (Fatiguing Task: bilateral, unilateral right leg, unilateral left leg) x 3 (Testing Condition: bilateral, unilateral right leg, unilateral left leg) ANOVAs were planned to be used pending a significant interaction. Further follow-up repeated measures ANOVAs and post-hoc comparisons were performed, as necessary. Measures of effect size for ANOVAs and pairwise comparisons were assessed with partial eta squared and Cohen's *d*, respectively. All statistical analyses were performed using IBM SPSS v. 25 (Armonk, NY, USA). An alpha of $p < 0.05$ was considered statistically significant for all comparisons.

Table 1. Subject characteristics

Subject	Age	Height (cm)	Weight (kg)	BMI
1	25	177.8	78.0	24.7
2	25	188.0	96.2	27.2
3	23	188.0	93.0	26.3
4	22	182.9	79.4	23.7
5	19	190.5	87.5	24.1
6	22	182.9	86.2	25.8
7	19	193.0	86.2	23.1
8	25	185.4	86.2	25.1
Avg	22.5	186.1	86.6	25.0
SD	2.51	4.85	6.09	1.38

RESULTS

The results of the reliability analyses are presented in Table 2. Tables 3-8 present the bilateral, unilateral right leg, and unilateral left leg, PT and MVIC values for each subject for each fatiguing task. Pre-testing trials were pooled together for calculation of ICC and SEM.

The repeated measures ANOVA indicated a significant four-way interaction (Mode x Time x Fatiguing Task x Testing Condition; $p < 0.05$, $\eta^2_p = 0.373 - 0.613$) that was decomposed by Mode using separate three-way repeated measures ANOVAs (Time x Fatiguing Task x Testing Condition) for the PT and MVIC values. For PT, there was a significant three-way interaction ($p = 0.014$, $\eta^2_p = 0.403$) that was decomposed by Fatiguing Task using separate two-way repeated measures ANOVAs (Time x Testing Condition) for the bilateral, unilateral right leg, and unilateral left leg fatiguing tasks. For the bilateral fatiguing task, there was no significant two-way interaction, but significant main effects for Time ($p = 0.003$, $\eta^2_p = 0.745$) and Testing Condition ($p < 0.001$, $\eta^2_p = 0.923$). For Time, the Bonferroni corrected pairwise

Table 2. Reliability data for PT and MVIC values for the three testing visits

	p	ICC	ICC 95 %	MSE	SEM	Grand mean
Peak Torque						
Bilateral	0.125	0.823	.543-.957	610.881	24.716	317.21
Right	0.061	0.853	.588-.966	157.792	12.562	188.29
Left	0.387	0.586	.174-.884	644.97	25.396	177.5
MVIC						
Bilateral	0.183	0.486	.079-.843	2674.875	51.719	406.54
Right	0.972	0.739	.364-935	837.268	28.936	244.88
Left	0.578	0.704	.327-.824	897.97	29.966	221.58

PT = peak torque, MVIC = maximum voluntary isometric contraction, *p* value = significance for ANOVA that examined systematic error, ICC = Intraclass correlation coefficient, ICC95% = 95% confidence interval for ICC, MSE = Mean square error, SEM = Standard error of measurement

Table 3: Isokinetic PT values for the bilateral fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	291	285	172	170	161	182
2	416	370	232	170	222	218
3	257	206	167	160	159	126
4	362	274	231	206	189	185
5	438	363	245	221	213	225
6	304	313	205	195	230	196
7	280	266	161	119	120	113
8	285	247	163	143	159	158
Mean	329	291	197	173	182	175
SD	68	56	35	34	38	40

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

Table 4: Isokinetic PT for the unilateral right leg fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	291	284	156	127	176	182
2	408	395	233	211	209	214
3	302	212	181	131	153	160
4	353	334	234	197	177	175
5	398	265	232	212	219	222
6	257	199	152	114	131	144
7	287	133	151	133	126	131
8	265	231	159	149	146	154
Mean	320	257	187	159	167	173
SD	59	82	39	41	34	32

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

Table 5: Isokinetic PT values for the unilateral left leg fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	301	300	151	156	165	166
2	386	402	220	230	232	176
3	234	193	172	182	127	124
4	384	386	215	219	257	179
5	341	393	229	228	214	228
6	270	230	146	174	167	121
7	230	223	138	144	150	124
8	273	242	174	181	158	143
Mean	302	296	181	189	184	158
SD	62	86	36	33	45	37

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

comparisons indicated pre-testing (236 ± 44 N·m) was greater than post-testing (213 ± 39 N·m; p = 0.003, *d* = 0.54; collapsed across Testing Condition). There was no difference ($p > 0.05$) between unilateral right leg and unilateral left leg torque for the bilateral fatiguing task collapsed across time. For the unilateral right leg fatiguing task, there was a significant two-way interaction (Time x Testing Condition; p = 0.21, η^2_p = 0.542), which was followed up with separate paired t-tests by Testing Condition. The paired t-tests for the bilateral test indicated pre-testing (320 ± 59 N·m) was greater than post-testing (257 ± 82 N·m; p = 0.016, *d* = 0.87). For the unilateral right leg test, pre-testing (187 ± 39 N·m) was greater (p = 0.001, *d* = *0.70*) than post-testing (159 ± 41 N·m). For the unilateral left leg test, post-testing (173 ± 32 N·m)

Table 6: MVIC values for the bilateral fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	387	293	214	207	174	175
2	510	405	293	257	277	253
3	443	384	229	201	230	186
4	569	488	291	277	301	273
5	432	392	283	254	221	213
6	373	342	232	203	264	226
7	367	384	171	162	141	114
8	395	310	262	200	207	163
Mean	435	375	247	220	227	200
SD	72	61	43	38	53	52

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

Table 7: MVIC values for the unilateral right leg fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	390	366	204	185	213	106
2	451	407	338	298	270	283
3	390	399	174	224	216	232
4	412	410	314	256	219	227
5	487	467	323	318	281	235
6	319	258	210	126	174	180
7	321	291	156	164	132	150
8	430	247	231	188	194	180
Mean	400	356	244	220	212	199
SD	59	81	71	67	48	56

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

Table 8: MVIC values for the unilateral left leg fatiguing task (N·m).

Testing Condition	pre both	post both	pre right	post right	pre left	post left
Subject 1	394	396	237	236	219	169
2	412	434	251	244	305	273
3	274	380	258	228	238	205
4	574	522	284	309	301	260
5	391	461	302	299	218	180
6	367	273	248	249	212	121
7	315	277	167	178	119	114
8	354	307	205	196	192	159
Mean	385	381	244	242	226	185
SD	89	90	43	45	60	58

PT = peak torque, MVIC = maximum voluntary isometric contraction, Pre = pre-testing, post = post-testing, both = bilateral, right = unilateral right leg, left = unilateral left leg.

was greater than pre-testing (167 ± 34 N·m; $p = 0.007$, *d =0.17*). For the unilateral left leg fatiguing task, there was no significant two-way interaction ($p = 0.068$), but a significant main effect for Testing Condition ($p < 0.001$, $\eta^2_p = 0.893$), collapsed across Time. There was no difference ($p > 0.05$) between unilateral right leg and unilateral left leg torque collapsed across time for the unilateral left leg fatiguing task.

For the MVIC values, there were no significant three-way ($p = .160$, $\eta^2_p = 0.222$) or two way ($p > 0.05$) interactions, but there were significant main effects for Time ($p = 0.006$, $\eta^2_p = 0.682$) and Testing Condition ($p < 0.001$, $\eta^2_p = 0.962$). Follow-up Bonferroni corrected pairwise comparisons indicated pre-testing (291 ± 50 N·m) was greater than post-testing (264 ± 52 N·m; $p = 0.006$, $d = 0.52$), collapsed across Fatiguing Task and Testing Condition.

DISCUSSION

The results of the test-retest reliability analyses indicated moderate/fair to good/excellent reliability for five of the six PT and MVIC testing conditions (Cicchetti & Sparrow, 1981; Koo & Li, 2016). The bilateral MVIC measures exhibited an ICC of 0.486 which is considered fair or poor based on the classification descriptors of Cicchetti and Sparrow, (1981) and Koo and Li, (2016), respectively (Table 2). The ICCs ranged from 0.486 to 0.853 with no systematic error for any of the testing conditions ($p > 0.05$). These findings were consistent with previous studies (Jenkins et al., 2014; Ruschel et al., 2015; Sleivert & Wenger, 1994) that have reported test-retest ICCs for isometric and isokinetic leg extensions that ranged from 0.64 to 0.94.

The current findings indicated that PT was more sensitive to decreases in torque as a result of the fatiguing isokinetic tasks than was MVIC. Specifically, PT assessments identified differences in the fatigue-induced decreases in unilateral and bilateral torque among the three modes of fatiguing tasks, as well as the contralateral facilitation in torque following the unilateral right leg fatiguing task, while MVIC assessments did not. For PT, the bilateral and unilateral right leg fatiguing tasks resulted in significant PF of the exercising leg (decreases of approximately 12 and 15%, respectively), while the unilateral left leg PF was non-significant (decrease of approximately 14%). For MVIC, however, the bilateral, unilateral right leg, and unilateral left leg fatiguing tasks resulted in non-significant PF in the exercising legs (decreases of approximately 14, 10, and 18%, respectively.) Previous studies (Byrne et al., 2001; Camic, 2011; Hill et al., 2016; Thompson et al., 2015) have reported conflicting evidence for quantifying PF from the PT and MVIC responses to various modes of fatiguing tasks. For example, Thompson et al., (2015) found that following a fatiguing, intermittent, isometric task, concentric PT recovered to the pre-fatigued level more quickly than did MVIC. Previous investigations, however, reported similar magnitudes of PF as assessed by decreases in PT and MVIC following fatiguing maximal and submaximal isometric (Camic, 2011), concentric isokinetic (Camic, 2011; Hill et al., 2016), and eccentric isokinetic (Byrne et al., 2001) fatiguing tasks. Perhaps, the mode-specific differences for testing in the present study were due to the timing and/or relative contributions of peripheral and central fatigue to the decreases in torque as assessed by PT versus MVIC (Babault et al., 2006). For example, Babault et al., (2006) reported that the early phase of a fatiguing isokinetic task was characterized primarily by peripheral fatigue, while central fatigue increased in prominence later in the task, and the opposite pattern was true for a fatiguing isometric task.

The bilateral fatiguing task resulted in 3-12% decreases in bilateral, unilateral right leg, and unilateral left leg torque (Table 3). Furthermore, the unilateral right and left leg fatiguing tasks resulted in a 3% to 20% decrease in bilateral torque, 15% decrease in unilateral right leg torque, and 13% decrease in unilateral left leg torque, respectively (Table 4 & 5). These findings were consistent with previous studies (Anders et al., 2020b; Keller et al., 2020; Matkowski et al., 2011) that have reported approximately 20 to 42% decreases in PT and/or MVIC following unilateral, isokinetic and isometric fatiguing tasks. The unilateral right and left leg fatiguing tasks, however, resulted in 4% and 5% increases in torque for the contralateral, non-exercised leg, respectively. These findings were not consistent with studies that reported decreases (Martin & Rattey, 2007; Rattey et al., 2006) or no change (Regueme et al., 2007; Todd et al., 2003) in torque in the non-exercised leg following sustained unilateral isometric leg extensions. The decrease in torque in the contralateral, non-exercised leg following fatiguing, isometric muscle actions has been attributed to a "cross-over" inhibitory phenomenon (Aboodarda et al., 2015). Theoretically, group III/IV afferent fibers sense fatigue-induced metabolic perturbations within the working muscles which leads to central fatigue, limited cortical drive to the contralateral leg, and decreased torque without peripheral fatigue (Amann et al., 2013). In the present study, however, torque production in the contralateral, non-exercised leg was facilitated, not compromised, following dynamic fatigue. The limited studies that have examined the effects of unilateral, dynamic fatigue on muscle strength in the contralateral limb have reported mixed findings. Kawamoto et al., (2014) reported approximately 4-7% decreases in MVIC force following 4 sets of dynamic constant external resistance leg extensions to task failure at loads equal to 40% and 70% of max. Strang et al., (2009, p. 249), however, reported a 13.4% increase in the "total work" performed during a 5s MVIC for the contralateral leg extensors following 7 sets of 20 repetitions of leg extensions on an isokinetic dynamometer at a speed of 110 d/s. Studies (Hess et al., 1986; Hortobágyi et al., 2011; Muellbacher et al., 2000; Stedman et al., 1998) of motor evoked potentials (MEP) have suggested that fatiguing, high intensity, unilateral muscle actions may be associated with "cross facilitation" (Aboodarda et al., 2015, p. 2) which leads to increases in cortical drive to the contralateral, non-exercised limb. The mechanism underlying cross facilitation may originate upstream from the motor cortex or include interhemispheric facilitation and/or reductions in interhemispheric inhibition at the level of the motor cortex (Aboodarda et al., 2015). It has been hypothesized that the enhanced cortical drive from cross facilitation may act to compensate for decreased spinal motor neuron excitability assessed via cervicomedullary motor evoked potentials (CMEP). Aboodarda et al., (2015) reported an increase in the MEP/CMEP ratio in the contralateral, non-exercised limb following a fatiguing, unilateral task at 100% MVIC which may have been responsible for the lack of post-intervention change in MVIC in the non-exercised limb. In addition, Takahashi et al., (2011) reported a facilitation of MEPs in the contralateral limb immediately following unilateral fatigue. Thus, contralateral fatigue is likely mediated, in part, by the relationship between the magnitude of enhanced cortical drive due to cross-over facilitation versus the reduction in spinal motor neuron excitability. It is possible that the contralateral facilitation in PT following the isokinetic fatiguing task in the present study was due to enhancement of cortical drive and/or limited reduction in spinal motor neuron excitability. Future studies are needed to examine the contralateral MEP/CMEP ratio following unilateral, dynamic fatiguing tasks.

An alternate hypothesis to explain the cross-over facilitation in torque in the non-exercised leg in the present study is that of a post-activation potentiation (PAP) effect in the contralateral muscles caused by the approximately 10% of descending anterolateral corticospinal neurons that fail to decussate, but rather cause activation of the ipsilateral muscles (Phillips & Porter, 1964; Purves et al., 2011). It has been suggested that post-activation potentiation occurs due to both, peripheral and central mechanisms (Andrews et al., 2016). Reportedly, the peripheral mechanisms of post-activation potentiation suggests that the contraction of a muscle induces myosin regulatory light chain phosphorylation via an increase in calcium concentration and subsequent binding of the calcium-calmodulin complex to myosin light chain kinase, which increases the rate of cross-bridge attachment (Rassier & MacIntosh, 2000). Furthermore, previous studies have reported contralateral muscle activity during unilateral exercise (Di Lazzaro et al., 1999; Farthing et al., 2005; Houston et al., 1983; Zijdewind & Kernell, 2001). Therefore, it is possible that the activation of the contralateral, homologous muscles during unilateral muscle actions, could have resulted in enough calcium release to stimulate myosin light chain phosphorylation, subsequently increasing torque production. Future research should include testing the contralateral limb using the potentiated twitch amplitude technique to examine the peripheral aspects of post-activation potentiation. Additionally, the central mechanisms involve reduced monosynaptic transmission failure via enhanced efficacy of the neurotransmitter, an increase in quantity of the neurotransmitter, or a reduction in axonal branch-point failure along the afferent neural fibers, leading to an increase in force production (Tillin & Bishop, 2009). In the present study, it is possible that the torque increases in the contralateral, non-exercised limb resulted from one, or a combination of, these central mechanisms leading to reduced monosynaptic transmission failure. Testing this hypothesis requires additional research, perhaps involving the use of the interpolated twitch technique on the contralateral, non-exercised limb to quantify cortical drive. Thus, it is possible that repeated unilateral muscle actions in the present study caused a post-activation potentiation effect in the contralateral limb due to peripheral and/or central mechanisms that resulted in the increase in torque.

The results of this study suggest that the fatigue-response to isokinetic muscle actions is specific to the conditions under which one is being tested (isokinetic versus isometric), therefore indicating a need to train in the same conditions in which you perform in order to improve upon fatigue resistance. In addition, unilateral muscle actions can be used in the absence of bilateral muscle actions to achieve a similar degree of PF. The results of this study suggest that unilateral muscle actions may result in a PAP in the contralateral limb. Subsequently, one could attempt to increase unilateral strength acutely by performing contralateral muscle actions of the same motion.

Limitations of the present study included the assessment of male subjects only which did not allow for sex comparisons of the effects of the fatiguing tasks. In the present study, the torque values for the right and left leg during bilateral testing were measured simultaneously, rather than assessing the individual contributions of each leg during the bilateral task. Furthermore, the isokinetic testing was performed at only one velocity, therefore, it remains unclear whether similar responses would be found at slower or faster velocities.

CONCLUSION

The present study aimed to investigate the differences between bilateral and unilateral fatiguing tasks on post-exercise torque production. The results of this study indicated mode-specific testing responses to fatiguing isokinetic tasks. Decreases in PT were more sensitive to fatiguing isokinetic tasks than was MVIC. Another mode-specific response in this study was the facilitation of PT, but not MVIC, in the contralateral non-exercised leg following unilateral muscle actions. The differences in PT and MVIC testing may be attributable to the timing and/or relative contributions of peripheral and central fatigue. In the current study there were no differences in performance fatigability between bilateral and unilateral muscle actions. Future research is needed to compare the contributions of central and peripheral fatigue during PT and MVIC testing.

REFERENCES

Aboodarda, S. J., Šambaher, N., & Behm, D. G. (2015). Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. *Scandinavian Journal of Medicine & Science in Sports*, *26*(11), 1301–1312. https://doi.org/10.1111/sms.12596

Amann, M., Venturelli, M., Ives, S. J., McDaniel, J., Layec, G., Rossman, M. J., & Richardson, R. S. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *Journal of Applied Physiology*, *115*(3), 355–364. https://doi.org/10.1152/japplphysiol.00049.2013

Anders, J. P. V., Keller, J. L., Smith, C. M., Hill, E. C., Neltner, T. J., Housh, T. J., Schmidt, R. J., & Johnson, G. O. (2020a). Performance fatigability and neuromuscular responses for bilateral and unilateral leg extensions in men. *Journal of Musculoskeletal & Neuronal Interactions*, *20*(3), 325–331.

Anders, J. P. V., Keller, J. L., Smith, C. M., Hill, E. C., Neltner, T. J., Housh, T. J., Schmidt, R. J., & Johnson, G. O. (2020b). Performance fatigability and neuromuscular responses for bilateral versus unilateral leg extensions in women. *Journal of Electromyography and Kinesiology*, *50*, 102367. https://doi.org/10.1016/j.jelekin.2019.102367

Anders, J. P. V., Smith, C. M., Keller, J. L., Hill, E. C., Housh, T. J., Schmidt, R. J., & Johnson, G. O. (2019). Inter- and Intra-Individual Differences in EMG and MMG during Maximal, Bilateral, Dynamic Leg Extensions. *Sports*, *7*(7), 175. https://doi.org/10.3390/sports7070175

Andrews, S. K., Horodyski, J. M., MacLeod, D. A., Whitten, J., & Behm, D. G. (2016). The Interaction of Fatigue and Potentiation Following an Acute Bout of Unilateral Squats. *Journal of Sports Science & Medicine*, *15*(4), 625–632.

Ansdell, P., Brownstein, C. G., Škarabot, J., Hicks, K. M., Howatson, G., Thomas, K., Hunter, S. K., & Goodall, S. (2019). Sex differences in fatigability and recovery relative to the intensity–duration relationship. *The Journal of Physiology*, *597*(23), 5577–5595. https://doi.org/10.1113/JP278699

Babault, N., Desbrosses, K., Fabre, M.-S., Michaut, A., & Pousson, M. (2006). Neuromuscular fatigue development during maximal concentric and isometric knee extensions. *Journal of Applied Physiology*, *100*(3), 780–785. https://doi.org/10.1152/japplphysiol.00737.2005

Brownstein, C. G., Millet, G. Y., & Thomas, K. (2020). Neuromuscular responses to fatiguing locomotor exercise. *Acta Physiologica*. https://doi.org/10.1111/apha.13533

Byrne, C., Eston, R. G., & Edwards, R. H. T. (2001). Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage. *Scandinavian Journal of Medicine & Science in Sports*, *11*(3), 134–140. https://doi.org/10.1046/j.1524-4725.2001.110302.x

Camic, C. L. (2011). *An assessment of the motor control strategies and effects of fatigue specific to isometric, concentric, and eccentric muscle actions* [Ph.D., The University of Nebraska - Lincoln]. https://search.proquest.com/docview/862368443/abstract/680283F6236340FCPQ/1

Cicchetti, D., & Sparrow, S. A. (1981). Developing Criteria for Establishing Interrater Reliability of Specific Items: Applications to Assessment of Adaptive Behavior. *American Journal of Mental Deficiency*, *86*, 127–137.

Di Lazzaro, V., Oliviero, A., Profice, P., Insola, A., Mazzone, P., Tonali, P., & Rothwell, J. C. (1999). Direct demonstration of interhemispheric inhibition of the human motor cortex produced by transcranial magnetic stimulation. *Experimental Brain Research*, *124*(4), 520–524. https://doi.org/10.1007/s002210050648

Enoka, R. M., & Duchateau, J. (2016). Translating Fatigue to Human Performance. *Medicine and Science in Sports and Exercise*, *48*(11), 2228–2238. https://doi.org/10.1249/MSS.0000000000000929

Farthing, J. P., Chilibeck, P. D., & Binsted, G. (2005). Cross-Education of Arm Muscular Strength Is Unidirectional in Right-Handed Individuals. *Medicine & Science in Sports & Exercise*, *37*(9), 1594–1600. https://doi.org/10.1249/01.mss.0000177588.74448.75

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Gandevia, S. C. (2001). Spinal and Supraspinal Factors in Human Muscle Fatigue. *Physiological Reviews*, *81*(4), 1725–1789. https://doi.org/10.1152/physrev.2001.81.4.1725

Hess, C. W., Mills, K. R., & Murray, N. M. F. (1986). Magnetic stimulation of the human brain: Facilitation of motor responses by voluntary contraction of ipsilateral and contralateral muscles with additional observations on an amputee. *Neuroscience Letters*, *71*(2), 235–240. https://doi.org/10.1016/0304-3940(86)90565-3

Hill, E., Housh, T., Smith, C., Schmidt, R., & Johnson, G. (2016). Muscle- and Mode-Specific Responses of the Forearm Flexors to Fatiguing, Concentric Muscle Actions. *Sports (Basel, Switzerland)*, *4*(4). https://doi.org/10.3390/sports4040047

Hortobágyi, T., Richardson, S. P., Lomarev, M., Shamim, E., Meunier, S., Russman, H., Dang, N., & Hallett, M. (2011). Interhemispheric Plasticity in Humans. *Medicine and Science in Sports and Exercise*, *43*(7), 1188–1199. https://doi.org/10.1249/MSS.0b013e31820a94b8

Houston, M. E., Froese, E. A., Valeriote, St. P., Green, H. J., & Ranney, D. A. (1983). Muscle performance, morphology and metabolic capacity during strength training and detraining: A one leg model. *European Journal of Applied Physiology and Occupational Physiology*, *51*(1), 25–35. https://doi.org/10.1007/BF00952534

Hureau, T. J., Romer, L. M., & Amann, M. (2018). The "sensory tolerance limit": A hypothetical construct determining exercise performance? *European Journal of Sport Science*, *18*(1), 13–24. https://doi.org/10.1080/17461391.2016.1252428

Jenkins, N. D. M., Buckner, S. L., Bergstrom, H. C., Cochrane, K. C., Goldsmith, J. A., Housh, T. J., Johnson, G. O., Schmidt, R. J., & Cramer, J. T. (2014). Reliability and relationships among handgrip strength, leg extensor strength and power, and balance in older men. *Experimental Gerontology*, *58*, 47–50. https://doi.org/10.1016/j.exger.2014.07.007

Kawamoto, J.-E., Aboodarda, S. J., & Behm, D. G. (2014). Effect of Differing Intensities of Fatiguing Dynamic Contractions on Contralateral Homologous Muscle Performance. *Journal of Sports Science & Medicine*, *13*(4), 836–845.

Keller, J. L., Housh, T. J., Hill, E. C., Smith, C. M., Schmidt, R. J., & Johnson, G. O. (2020). Are There Sex-Specific Neuromuscular or Force Responses to Fatiguing Isometric Muscle Actions Anchored to a High Perceptual Intensity? *The Journal of Strength & Conditioning Research*, *Publish Ahead of Print*. https://doi.org/10.1519/JSC.0000000000003394

Kluger, B. M., Krupp, L. B., & Enoka, R. M. (2013). Fatigue and fatigability in neurologic illnesses: Proposal for a unified taxonomy. *Neurology*, *80*(4), 409–416. https://doi.org/10.1212/WNL.0b013e31827f07be

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Marrelli, K., Cheng, A. J., Brophy, J. D., & Power, G. A. (2018). Perceived Versus Performance Fatigability in Patients With Rheumatoid Arthritis. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.01395

Martin, P. G., & Rattey, J. (2007). Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. *Pflügers Archiv - European Journal of Physiology*, *454*(6), 957–969. https://doi.org/10.1007/s00424-007-0243-1

Matkowski, B., Place, N., Martin, A., & Lepers, R. (2011). Neuromuscular fatigue differs following unilateral vs bilateral sustained submaximal contractions. *Scandinavian Journal of Medicine & Science in Sports*, *21*(2), 268–276. https://doi.org/10.1111/j.1600-0838.2009.01040.x

Muellbacher, W., Facchini, S., Boroojerdi, B., & Hallett, M. (2000). Changes in motor cortex excitability during ipsilateral hand muscle activation in humans. *Clinical Neurophysiology*, *111*(2), 344–349. https://doi.org/10.1016/S1388-2457(99)00243-6

Neyroud, D., Kayser, B., & Place, N. (2016). Are There Critical Fatigue Thresholds? Aggregated vs. Individual Data. *Frontiers in Physiology*, *7*(376). https://doi.org/10.3389/fphys.2016.00376

Phillips, C. G., & Porter, R. (1964). The Pyramidal Projection to Motoneurones of Some Muscle Groups of the Baboon's Forelimb. In J. C. Eccles & J. P. Schadé (Eds.), *Progress in Brain Research* (Vol. 12, pp. 222–245). Elsevier. https://doi.org/10.1016/S0079-6123(08)60625-1

Purves, D., Augustine, G. J., Fitzpatrick, D., Hall, W. C., LaMantia, A.-S., McNamara, J. O., & Williams, S. M. (2011). *Neuroscience* (3rd Edition). Sinauer Associates is an imprint of Oxford University Press.

Rassier, D. E., & MacIntosh, B. R. (2000). Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research*, *33*(5), 499–508. https://doi.org/10.1590/S0100-879X2000000500003

Rattey, J., Martin, P. G., Kay, D., Cannon, J., & Marino, F. E. (2006). Contralateral muscle fatigue in human quadriceps muscle: Evidence for a centrally mediated fatigue response and cross-over effect. *Pflügers Archiv - European Journal of Physiology*, *452*(2), 199–207. https://doi.org/10.1007/s00424-005-0027-4

Regueme, S. C., Barthèlemy, J., & Nicol, C. (2007). Exhaustive stretch-shortening cycle exercise: No contralateral effects on muscle activity in maximal motor performances. *Scandinavian Journal of Medicine & Science in Sports*, *17*(5), 547–555. https://doi.org/10.1111/j.1600-0838.2006.00614.x

Riebe, D., Ehrman, J., Liguori, G., & Magal, M. (2018). *ACSM's Guidelines for Exercise Testing and Prescription* (10th ed.). Wolters Kluwer.

Rossman, M., Garten, R., Venturelli, M., Amann, M., & Richardson, R. (2014). The role of active muscle mass in determining the magnitude of peripheral fatigue during dynamic exercise. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, *306*(12), R934-940. https://doi.org/10.1152/ajpregu.00043.2014

Rossman, M., Venturelli, M., McDaniel, J., Amann, M., & Richardson, R. (2012). Muscle mass and peripheral fatigue: A potential role for afferent feedback? *Acta Physiologica (Oxford, England)*, *206*(4), 242–250. https://doi.org/10.1111/j.1748-1716.2012.02471.x

Ruschel, C., Haupenthal, A., Jacomel, G. F., Fontana, H. de B., Santos, D. P. dos, Scoz, R. D., & Roesler, H. (2015). Validity and Reliability of an Instrumented Leg-Extension Machine for Measuring Isometric Muscle Strength of the Knee Extensors. *Journal of Sport Rehabilitation*, *24*(2). https://doi.org/10.1123/jsr.2013-0122

Sleivert, G. G., & Wenger, H. A. (1994). Reliability of measuring isometric and isokinetic peak torque, rate of torque development, integrated electromyography, and tibial nerve conduction velocity. *Archives of Physical Medicine and Rehabilitation*, *75*(12), 1315–1321. https://doi.org/10.1016/0003-9993(94)90279-8

Stedman, A., Davey, N. J., & Ellaway, P. H. (1998). Facilitation of human first dorsal interosseous muscle responses to transcranial magnetic stimulation during voluntary contraction of the contralateral homonymous muscle. *Muscle & Nerve*, *21*(8), 1033–1039. https://doi.org/10.1002/(SICI)1097-4598(199808)21:8<1033::AID-MUS7>3.0.CO;2-9

Strang, A. J., Berg, W. P., & Hieronymus, M. (2009). Fatigue-induced early onset of anticipatory postural adjustments in non-fatigued muscles: Support for a centrally mediated adaptation. *Experimental Brain Research*, *197*(3), 245–254. https://doi.org/10.1007/s00221-009-1908-0

Takahashi, K., Maruyama, A., Hirakoba, K., Maeda, M., Etoh, S., Kawahira, K., & Rothwell, J. C. (2011). Fatiguing intermittent lower limb exercise influences corticospinal and corticocortical excitability in the non-exercised upper limb. *Brain Stimulation*, *4*(2), 90–96. https://doi.org/10.1016/j.brs.2010.07.001

Thomas, K., Goodall, S., & Howatson, G. (2018). Performance Fatigability Is Not Regulated to A Peripheral Critical Threshold. *Exercise and Sport Sciences Reviews*, *46*(4), 240–246. https://doi.org/10.1249/JES.0000000000000162

Thompson, B. J., Conchola, E. C., & Stock, M. S. (2015). Effects of age and muscle action type on acute strength and power recovery following fatigue of the leg flexors. *Age*, *37*(6). https://doi.org/10.1007/s11357-015-9845-2

Tillin, N. A., & Bishop, D. (2009). Factors Modulating Post-Activation Potentiation and its Effect on Performance of Subsequent Explosive Activities. *Sports Medicine*, *39*(2), 147–166. https://doi.org/10.2165/00007256-200939020-00004

Todd, G., Petersen, N. T., Taylor, J. L., & Gandevia, S. C. (2003). The effect of a contralateral contraction on maximal voluntary activation and central fatigue in elbow flexor muscles. *Experimental Brain Research*, *150*(3), 308–313. https://doi.org/10.1007/s00221-003-1379-7

Weavil, J. C., & Amann, M. (2019). Neuromuscular fatigue during whole body exercise. *Current Opinion in Physiology*, *10*, 128–136. https://doi.org/10.1016/j.cophys.2019.05.008

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*. https://doi.org/10.1519/15184.1

Zijdewind, I., & Kernell, D. (2001). Bilateral interactions during contractions of intrinsic hand muscles. *Journal of Neurophysiology*, *85*(5), 1907–1913. https://doi.org/10.1152/jn.2001.85.5.1907