European Journal of Applied Physiology (2019) 119:2745–2755
https://doi.org/10.1007/s00421-019-04253-z

ORIGINAL ARTICLE

Transcutaneous electrical nerve stimulation improves fatigue performance of the treated and contralateral knee extensors

D. G. Behm[1] · E. M. Colwell[1] · G. M. J. Power[1] · H. Ahmadi[1] · A. S. M. Behm[1] · A. Bishop[1] · C. Murph[1] · J. Pike[1] · B. McAssey[1] · K. Fraser[1] · S. Kearley[1] · M. Ryan[1]

Received: 19 July 2019 / Accepted: 31 October 2019 / Published online: 6 November 2019

Abstract

Purpose Transcutaneous electrical nerve stimulation (TENS) can reduce acute and chronic pain. Unilateral fatigue can produce discomfort in the affected limb and force and activation deficits in contralateral non-exercised muscles. TENS-induced local pain analgesia effects on non-local fatigue performance are unknown. Hence, the aim of the study was to determine if TENS-induced pain suppression would augment force output during a fatiguing protocol in the treated and contralateral muscles.

Methods Three experiments were integrated for this article. Following pre-tests, each experiment involved 20 min of TENS, sham, or a control condition on the dominant quadriceps. Then either the TENS-treated quadriceps (TENS_Treated) or the contralateral quadriceps (TENS_Contra) was tested. In a third experiment, the TENS and sham conditions involved two\; 100-s isometric maximal voluntary contractions (MVC) (30-s recovery) followed by testing of the contralateral quadriceps (TENS_Contra-Fatigue). Testing involved single knee extensors (KE) MVCs (pre- and post-test) and a post-test 30% MVC to task failure.

Results The TENS-treated study induced greater ($p = 0.03$; 11.0%) time to KE (treated leg) failure versus control. The TENS_Contra-Fatigue induced significant ($p = 0.04$; 11.7%) and near-significant ($p = 0.1$; 7.1%) greater time to contralateral KE failure versus sham and control, respectively. There was a 14.5% ($p = 0.02$) higher fatigue index with the TENS (36.2 ± 10.1%) versus sham (31.6 ± 10.6%) conditions in the second fatigue intervention set (treated leg). There was no significant post-fatigue KE fatigue interaction with the TENS_Contra.

Conclusions Unilateral TENS application to the dominant KE prolonged time to failure in the treated and contralateral KE suggesting a global pain modulatory response.

Keywords Crossover · Endurance · Pain · Strength · Isometric

Abbreviations

DNIC	Diffuse noxious inhibitory control
EMG	Electromyography
KE	Knee extensors
MVC	Maximal voluntary contractions
NLMF	Non-local muscle fatigue
rms	Root mean square of the electromyography signal
TENS	Transcutaneous electrical nerve stimulation
TENS_Treated	TENS-treated dominant quadriceps with testing of treated dominant quadriceps
TENS_Contra	TENS-treated dominant quadriceps with testing of contralateral non-dominant quadriceps
TENS_Contra-Fatigue	TENS-treated dominant quadriceps subjected to a fatigue protocol (2 × 100 s MVCs) with testing of treated dominant and untreated non-dominant quadriceps

Communicated by William J. Kraemer.

✉ D. G. Behm
dbehm@mun.ca

[1] School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NF 1C 5S7, Canada

Introduction

A number of studies have shown crossover or non-local muscle fatigue effects (Halperin et al. 2015), whereby unilateral fatigue of one muscle group may decrease the force output, corticospinal excitability, or fatigue endurance of homologous (Zijdewind et al. 1998; Rattey et al. 2006; Martin and Rattey 2007; Post et al. 2008; Doix et al. 2013; Halperin et al. 2014c; Kawamoto et al. 2014; Aboodarda et al. 2016) and heterologous (Takahashi et al. 2011; Kennedy et al. 2013; Halperin et al. 2014b; Aboodarda et al. 2015a, 2017; Sambaher et al. 2016) muscle groups. In their review, Halperin et al. (2015) highlighted that the non-local deficits appeared more consistently with prolonged fatiguing contractions than with single maximal voluntary contractions (MVC).

This more consistent impairment of fatigue performance (i.e., time to exhaustion, repetitive MVCs) with crossover or non-local muscle fatigue (NLMF) has been attributed to a number of factors including neurological influences, whereby peripheral factors such as the accumulation of metabolites trigger afferent responses leading to an inhibitory effect on the central drive to the affected and non-exercised muscles (Amann 2011; Amann et al. 2013; Sidhu et al. 2014). In addition, reaching an individual's sensory tolerance limit, which could be influenced by metabolites and peripheral fatigue, would influence the desire or decision to desist with fatiguing contractions (Halperin et al. 2015). Behm (2004) summarized fatigue as a transient decrease in working or muscle force-generating capacity (Asmussen and Mazin 1978; Degens and Veerkamp 1994) or loss of force output leading to reduced performance (Fitts and Metzger 1993), but fatigue can also be described as an increase in the perceived effort to exert a desired force (Enoka and Stuart 1992) even when there is no apparent impairment in maintaining the targeted force. Magnusson and colleagues (Magnusson et al. 1996, 1997) indicated that the ability to stretch a muscle to a greater length is highly influenced by the stretch (pain) tolerance. If the discomfort or pain associated with intense stretching can be reduced, then the individual can push themselves to greater levels of musculotendinous elongation. This increased pain or stretch tolerance has been attributed to the increased range of motion of non-stretched, non-local, joints and muscles (Behm et al. 2016; Chaouachi et al. 2017). Analgesic suppression of pain with foam rolling (Aboodarda et al. 2015b), TENS (Ainsworth et al. 2006; Sabino et al. 2008) and improvement of range of motion with topical analgesics (Whalen et al. 2019) can have global or crossover (non-local) effects. Hence, if the sensory or pain tolerance, or perception of fatigue, can be attenuated (i.e., with TENS), then the ability to sustain submaximal forces might be enhanced in both the TENS-treated and -untreated contralateral limbs.

Transcutaneous electrical nerve stimulation (TENS) is a nonpharmacological, non-invasive modality for the treatment of acute and chronic pain (Sluka and Walsh 2003; Vance et al. 2014). Johnson and Martinson (2007) conducted a meta-analysis that concluded that TENS produces analgesic effects reducing pain. If the discomfort and pain associated with fatigue could be ameliorated, then a greater time to task failure or fatigue might be expected. There was one published study examining the effect of TENS on fatigue characteristics prior to 2017. Dailey et al. (2013) found non-local increases in the pain pressure threshold (TENS on spine decreased pain sensitivity at the leg) and fatigue during a 6-min walk test in patients with fibromyalgia, while the TENS unit remained on (30 min with 100 Hz at 200 µs pulse duration). Since then, only Astokorki and Mauger (2017a, b) investigated TENS-induced effects upon fatigue of the treated limbs and found improved cycling endurance performance when TENS was applied 5 min prior to and during the cycling fatigue task with 100 Hz (pulse width 300 µs) bipolar stimulation at an intensity just below muscle contraction detection. However, other than these three fatigue studies, the literature on TENS effects on fatigue performance is scant.

TENS-induced pain reduction acts through both peripheral and central mechanisms (DeSantana et al. 2008; Vance et al. 2014). Unilateral application of TENS can produce bilateral pain analgesic effects in rats (Somers and Clemente 2006) and humans (Ainsworth et al. 2006; Sabino et al. 2008) and thus might be expected to positively impact fatigue performance by increasing pain tolerance in both the TENS-treated and contralateral, untreated, muscles. Conversely, Pietrosimone et al. (2010) found that contralateral quadriceps central activation ratios were not affected following 4 weeks of a TENS disinhibitory intervention. Thus other than the aforementioned Dailey et al. (2013) human fatigue study, the crossover or non-local effects of TENS on fatigue endurance are not known.

Hence, TENS was applied to the dominant quadriceps in three related studies with the results and interpretations integrated into a single manuscript. The objective of these three studies were to investigate the effects of high intensity TENS versus a sham and control condition on the isometric maximal force output and submaximal isometric fatigue performance of: Study 1: the TENS-treated knee extensors (TENS_Treated); Study 2: contralateral, untreated, non-exercised, knee extensors (TENS_Contra); and Study 3: contralateral, untreated, knee extensors following a unilateral knee extensor fatigue intervention of the treated leg (TENS_Contra-Fatigue). It was hypothesized that TENS would improve time to task failure of the treated (Study 1: TENS_treated) and untreated (Studies 2 and 3:

TENS_Contra and TENS_Contra-Fatigue) contralateral legs. Findings from this research could contribute to the basic science regarding global pain modulatory responses.

Methods

Experimental design

Three experiments were integrated for this article (Table 1). All three experiments involved 20 min of high-intensity TENS, sham TENS, or a control condition. Each experiment was a within-subject, repeated measures design. In all three experimental studies, the dominant quadriceps were subjected to the TENS treatment (high-intensity TENS or sham) or control condition, and then either the TENS-treated quadriceps (Study 1: TENS_Treated) or the contralateral, non-dominant, knee extensors (KE: quadriceps) (Study 2: TENS_Contra) were tested. To examine possible unilateral TENS effects upon crossover or non-local muscle fatigue, a third experiment had the TENS-treated quadriceps fatigued with two 100-s KE isometric maximal voluntary contractions (MVC) with 60-s recovery between repetitions, followed by testing of the contralateral (non-dominant) quadriceps (Study 3: TENS_Contra-Fatigue). The first study (TENS_Treated) examined the effects of TENS on the fatigue tolerance of the treated quadriceps, which has only been documented in two published studies, albeit with a cycling endurance test (Astokorki and Mauger 2017a, b). Since the crossover effects of TENS on performance have not been previously examined, the second and third studies investigated the effects of TENS on the contralateral, homologous quadriceps without (TENS_Contra) and with (TENS_Contra-Fatigue) prior fatigue of the TENS-treated quadriceps. Testing occurred at approximately the same time of day and involved single KE MVCs (pre- and post-test) and a post-test 30% KE MVC to task failure. Hence, the findings from this study could provide both basic (evidence for and the extent of global pain modulation with an exogenous [TENS] non-pharmacological modality) and applied (possible applications for health professional) science.

Participants

Based on measures of force during fatigue protocols from similar studies (Halperin et al. 2014b, c; Kawamoto et al. 2014), an a priori statistical power analysis was conducted with G-Power (University of Dusseldorf), which determined that eight to ten participants were needed per study to achieve an alpha of $p < 0.05$ with a power of 0.8. Hence, 12 (males), 20 (10 males and 10 females) and 12 (6 males and 6 females) participants were recruited for TENS_Treated, TENS_Contra and TENS_Contra-Fatigue studies, respectively (Table 2). Both sexes were recruited when it was possible to recruit an equal number of participants to broaden the application of the findings. However, due to a lack of strong statistical power for a sex difference analysis and the lack of women in study 1 (TENS_Treated), the data for

Table 2 Participant characteristics

	Age (years)	Height (meters)	Mass (kg)
TENS_Treated $n = 12$ males	21.9 ± 2.27	1.77 ± 0.06	85.2 ± 18.0
TENS_Contra $n = 20$	Males 23.3 ± 3.0	Males 177.9 ± 5.9	Males 77.7 ± 13.3
(10 males and 10 females)	Females 20.4 ± 4.1	Females 164.3 ± 4.5	Females 63.0 ± 12.3
TENS_Contra-Fatigue $n = 12$ males	23.4 ± 3.2	1.78 ± 0.05	83.6 ± 14.9

TENS_Treated TENS with testing of the treated leg, *TENS_Contra* TENS with testing of the contralateral leg, *TENS_Contra-Fatigue* TENS with testing of the contralateral leg following a fatigue intervention of the treated leg

Table 1 Experimental design

TENS treatment on dominant leg for all three conditions	TENS_Treated study	TENS_Contra study	TENS_Contra-Fatigue study
Pre-test	TENS-treated leg KE extensor MVC	Contralateral untreated leg KE extensor MVC	Contralateral untreated leg KE extensor MVC
TENS interventions for each study	1. High Intensity TENS 2. Sham TENS 3. Control		
Fatigue intervention	N/A	N/A	2 × 100-s MVC
Post-tests	TENS-treated leg KE extensor MVC 30% MVC fatigue trial	Contralateral leg KE extensor MVC 30% MVC fatigue tria	Contralateral leg KE extensor MVC 30% MVC fatigue trial

TENS_Treated TENS with testing of the treated leg, *TENS_Contra* TENS with testing of the contralateral leg, *TENS_Contra-Fatigue* TENS with testing of the contralateral leg following a fatigue intervention of the treated leg, *KE* knee extensors, *MVC* isometric maximum voluntary contraction, *TENS* transcutaneous electrical nerve stimulation, *Contra* contralateral, *N/A* not applicable both sexes were combined for analysis. All participants were classified as recreationally active, defined as participating in unstructured activity or not highly competitive sport three to four times per week. Exclusion criteria included any participant who reported lower limb musculoskeletal or neural impairments or injuries within the prior 6 months. Participants were asked to avoid ingesting food or caffeine products for at least 3 h prior to testing and abstain from strenuous activity for at least 24 h prior to each testing session. Participants were allowed to consume fluids ad libitum prior to the sessions. Participants did not consume fluids during the experimental sessions. All participants attended a familiarization session prior to the experimental sessions to experience the interventions and practice the testing procedures. Ethical approval for each study was granted by the institution's Interdisciplinary Committee on Ethics in Human Research (TENS_Treated: 20181213-HK, TENS_Contra: 20181244-HK, TENS_Contra-Fatigue: 20180884-HK). All participants were verbally explained the procedures prior to participation and were required to read and sign the consent form and complete a Physical Activity Readiness Questionnaire for Everyone (PAR-Q +) if they agreed to participate.

Measurements (all three studies)

KE MVC force

While strapped (minimize extraneous movements) and seated in a custom-made chair (Memorial University Technical Services, St. John's, Newfoundland, Canada), KE MVC forces were assessed with an isometric knee extension (knee angle: 90°) following methods outlined in previous studies from this laboratory (Button and Behm 2008; Kawamoto et al. 2014; Halperin et al. 2014b, c; Aboodarda et al. 2015a, 2017). Arms were placed across their chest to standardize procedures. These studies have reported excellent day-to-day reliability ($r = 0.9$–0.99). Prior to testing, the participants warmed up their knee extensors with five 1–2 s isometric knee extension contractions at a self-perceived 50% of maximum intensity, followed by another five contractions at 75% of perceived maximum. Approximately, 3 s of rest was allocated between each warmup contraction. Pre-intervention (interventions: TENS, sham TENS or control) testing involved at least two 4-s isometric KE MVCs. Participants were instructed and encouraged to contract as hard and as fast as possible. Encouragement was consistently maintained with loud vocalizations of "Go!" provided by all researchers during the 5-s contraction (Jaafar and Lajili 2018; Rendos et al. 2018). Participants could monitor their force output on the computer monitor. A third MVC was performed only if there was a greater than 5% difference in peak force between the first two MVCs. Post-intervention MVC testing involved a single MVC attempt prior to the submaximal (30% MVC) fatigue protocol.

Forces were detected by a strain gauge, amplified (Biopac Systems Inc. DA 150, and analog to digital (A/D) converter MP150WSW; Hilliston, MA), and displayed on a computer monitor. Data were sampled at 2000 Hz and analyzed using a software program (AcqKnowledge 4.1, BioPac Systems Inc. Hilliston, MA). Peak force and the peak force produced in the first 100 ms of the contraction (F100) were analyzed from the TENS-treated dominant leg (TENS_Treated), contralateral non-dominant leg (TENS_Contra) or both legs (TENS_Contra-Fatigue).

Quadriceps and hamstrings electromyographic (EMG) activity

EMG activity was used as a measure of peripheral muscle activation during the single MVCs and the post-test submaximal fatigue protocol. Surface EMG decomposition measures are affected by a wide variety of factors including strong associations with force output, motor unit conduction velocity and recruitment thresholds, but weaker correlations with motor unit recruitment (Del Vecchio et al. 2017). The skin electrode placement was performed after shaving the hair of the skin and using isopropyl alcohol swabs to reduce the resistance. Surface EMG recording electrodes (Tyco Healthcare Group LP, Meditrace 133, ECG Conductive Adhesive Electrodes, Mansfield, MA) were placed on the dominant (TENS_Treated and TENS_Contra-Fatigue studies) or non-dominant (TENS_Contra and TENS_Contra-Fatigue studies) leg, over the muscle bellies of the rectus femoris and biceps femoris. Rectus femoris electrodes were placed at half the distance between the pelvic anterior superior iliac spine and the patella, while biceps femoris electrodes were placed halfway between the gluteal fold and the popliteal space. A ground electrode was secured on the fibular head. Thorough skin preparation for all electrodes was administered. EMG activity was sampled at 2000 Hz, with a Blackman − 92 dB band pass filter between 10–500 Hz, amplified (bi-polar differential amplifier, input impedance = 2 MΩ, common mode ejection ratio > 110 dB min (50/60 Hz), gain × 1000, noise > 5 µV) and was analog-to-digitally converted and stored on a personal computer for analysis. The mean amplitude of the root mean square (rms) of the EMG signal was measured for a 1-s period during participant's peak MVC force (0.5 s pre- and post-maximum force output) (Button and Behm 2008; Halperin et al. 2014a, b, c). Prior research from this laboratory has demonstrated excellent EMG measure reliability ($r = 0.91$–0.96) (Button and Behm 2008; Halperin et al. 2014b, c).

Submaximal (30%) MVC protocol

One minute following the post-test MVC (approximately 1.5 min after the intervention), participants performed the submaximal isometric fatigue trial. Participants viewed the computer monitor to maintain a force level equal to 30% of their pre-test MVC. This task was maintained until task failure, which was defined as failing to maintain the force level after being warned by researchers for the third time. The duration of the fatigue task was kept hidden from the participants. Participants were encouraged to maintain the force by a consistent verbalization by the researchers of "keep it up" every 15 s until task failure. Time to task failure was monitored. Further analysis involved dividing the duration of the fatigue protocol into quartiles and analyzing the variance in the ability (force variability) to maintain the 30% MVC force target as well as the quadriceps and hamstrings EMG activity.

TENS intervention: dominant quadriceps TENS protocols (all three studies)

With a random allocation, the three interventions involved 20 min of either a high-intensity TENS, sham, or a control condition. The high-intensity TENS (NeuroTrac MultiTENS: VMVerity; Romsey, Hampshire, UK) was set at a constant frequency of 150 Hz with the current increased for each participant until the first signs of visible muscle contractions appeared. High-frequency TENS (≥ 100 Hz) (DeSantana et al. 2008; Dailey et al. 2013; Astokorki and Mauger 2017b, a) with relatively strong intensity (≥ perception of muscle contractions) (Denegar and Perrin 1992; Astokorki and Mauger 2017b, a) have been shown to provide effective pain analgesia of the treated limb. The sham intervention had the electrodes placed on the quadriceps, but the TENS device was not activated. The participants were informed that the objective was to compare high- and low-intensity TENS treatments and that they would not feel any sensations with the low-intensity TENS. The researcher pretended to activate and manipulate the device controls with the sham condition. The four TENS electrodes were placed over the heads and the mid-bellies of the dominant vastus lateralis and medialis. The control condition involved a 20-min rest period. Post-tests began 1 min following completion of the 20-min intervention.

Fatigue intervention: TENS treated, quadriceps fatigue (Study 3: TENS_Contra-Fatigue)

Only the TENS_Contra-Fatigue condition involved a fatigue intervention of the TENS treated, dominant quadriceps to examine non-local (contralateral) muscle fatigue responses with unilateral TENS application. The fatigue intervention had the participants perform two 100-s MVCs with 60-s recovery between the repetitions, which was performed during the last 5 min of the TENS and sham interventions. The force output was monitored during the fatigue intervention and a fatigue index was calculated (Fatigue index = (mean force of the last 5 s/mean force of the first 5 s) × 100).

Statistical analysis

All data are expressed as mean and standard deviation (SD), and analyses were performed with SPSS 24.0 software (Chicago, IL, USA). An alpha level of 0.05 was used to determine statistical significance. The normality of all values was verified using the Shapiro–Wilk test. Levene's test was used to check the homogeneity of variance for all tests. The contralateral single MVC responses (peak torque, F100, rmsEMG) of all three studies were analyzed with a two-way, repeated measures analysis of variance (ANOVA) with three conditions (TENS, sham TENS, and control), and two times (pre- and post-intervention). The post-test submaximal fatigue protocol was analyzed with a one-way ANOVA (three conditions) for all three studies. The TENS_Treated and TENS_Contra conditions did not involve a fatiguing intervention of the TENS-treated quadriceps. Since the fatigue intervention of the TENS-treated quadriceps only occurred with the TENS_Contra-Fatigue condition, the TENS-treated leg fatigue intervention was analyzed with a two-way ANOVA with two interventions (TENS and sham) and two fatigue repetitions (2 × 100 s MVCs). Effect sizes (eta^2) for main effects and interactions were calculated by SPSS. Reliability was assessed using intraclass correlation coefficients (Cohen 1988).

Results

Reliability

Table 3 illustrates the good to excellent reliability from the three studies.

TENS_Treated study

MVC force and EMG

A significant main effect for time demonstrated 4.8% ($p = 0.037$; eta^2: 0.34) and 11.6% ($p = 0.003$; eta^2: 0.57) pre- to post-TENS decreases in quadriceps (TENS-treated limb) MVC force and F100, respectively (Table 4). There were no significant main effects or interactions for MVC rectus femoris or biceps femoris EMG activity.

Table 3 Reliability and coefficient of variation (CV%) from intraclass correlation coefficients

	TENS_Treated	TENS_Contra	TENS_Contra_Fatigue
MVC force	0.94	0.96	0.97
F100	0.83	0.79	0.78
Rectus femoris rmsEMG	0.86	0.90	0.92
Biceps femoris rmsEMG	0.78	0.77	0.70

TENS_Treated TENS with testing of the treated leg, *TENS_Contra* TENS with testing of the contralateral leg, *TENS_Contra-Fatigue* TENS with testing of the contralateral leg following a fatigue intervention of the treated leg, *F100* force produced in the first 100 ms of the MVC, *rmsEMG* root mean square of the electromyographic signal

Table 4 MVC force and EMG analysis of main effects for time

	Main effect for time
TENS_Treated	
MVC force pre-test: 728.3 ± 182.1	
$p=0.037$ post-test: 692.8 ± 173.2	
F100 pre-test: 353.4 ± 88.3	
$p=0.003$ post-test: 312.4 ± 78.1	
Rectus femoris rmsEMG	NS
Biceps femoris rmsEMG	NS
TENS_Contra	
MVC force pre-test: 677.6 ± 169.4	
$p=0.02$ post-test: 640.3 ± 160.1	
F100 pre-test: 229.5 ± 57.3	
$p=0.014$ post-test: 196.7 ± 49	
Rectus femoris rmsEMG	NS
Biceps femoris rmsEMG	NS
TENS_Contra-Fatigue	
MVC force pre-test: 591.9 ± 186.7	
$p=0.007$ post-test: 551.1 ± 176.6	
F100 pre-test: 290.6 ± 108.9	
$p=0.08$ post-test: 258.7 ± 106.1	
Rectus femoris rmsEMG	NS
Biceps femoris rmsEMG	NS

Post-test 30% submaximal fatigue protocol

The TENS condition induced a significant ($p=0.03$; eta^2: 0.44; 11.0%) greater time to failure versus the control condition with the TENS-treated limb (Fig. 1). A significant force variability main effect ($p<0.0001$; eta^2: 0.43) for the post-TENS fatigue quartiles indicated that overall, quadriceps force variability in the first, second and third quartiles were 28.0% ($p=0.02$), 24.0% ($p=0.004$), and 52% ($p=0.005$) less than the fourth quartile, respectively. Near significant and significant main effects for quartiles were evident for the post-test knee extensor and flexor EMG quartiles. Overall, rectus femoris ($p=0.06$; eta^2: 0.21) and biceps femoris ($p=0.03$; eta^2: 0.32) EMG activity in the fourth quartile were 18.6%, 14.8%, and 6.7% greater than in the first, second and third quartiles, respectively. A main effect for conditions ($p=0.034$; eta^2: 0.35) indicated that biceps femoris EMG was 70.0% and 66.6% significantly lower with the TENS (0.06 ± 0.015 mV) condition compared to the sham (0.2 ± 0.05 mV) and control (0.18 ± 0.04 mV) conditions, respectively.

TENS_Contra study

MVC force and EMG

Significant main effects for time ($p=0.026$; eta^2: 0.44) displayed pre- to post-TENS MVC force decrements of −6.9% (Table 4). Significant condition effects ($p=0.05$; eta^2: 0.27) showed that TENS (605.3 ± 151.3 N) produced 10.4% and 12.9% less MVC force than sham (695.3 ± 173.8) and control (676.3 ± 169.1) respectively.

Post-test 30% submaximal fatigue protocol

There were no significant differences between conditions in the time to failure of the contralateral limb (Fig. 1). A significant main effect ($p<0.0001$; eta^2: 0.43) for the post-test fatigue quartiles indicated that overall, quadriceps force variability in the fourth quartile was 31.9% ($p<0.0001$), 46.5% ($p=0.011$), and 23.8% ($p=0.005$) greater than in the first, second, and third quartiles, respectively. In addition, a significant main effect ($p=0.0008$; eta^2: 0.28) for post-fatigue quartiles displayed that the rectus femoris fourth quartile rmsEMG was 21.2% ($p=0.048$) and 8.1% ($p=0.024$) higher than the first and third quartiles, respectively. Similarly, a significant quartiles main effect ($p<0.0001$; eta^2: 0.81) showed that the fourth quartile hamstrings rmsEMG was 64.7% ($p<0.0001$), 61.2% ($p<0.0001$) and 59.8% ($p<0.0001$) greater than the first to third quartiles, respectively (Fig. 1).

TENS_Contra-Fatigue study

MVC force and EMG

There were no significant interactions for MVC force or F100, but there was a significant ($p=0.007$; eta^2: 0.50) main effect for time with a 6.6% decrease in MVC force from pre- to post-test (TENS and fatigue interventions). The MVC F100 presented a near significant ($p=0.08$; eta^2: 0.30) main effect for time with a 8.1% decrease from pre- to post-test (Table 4). There were no significant interactions

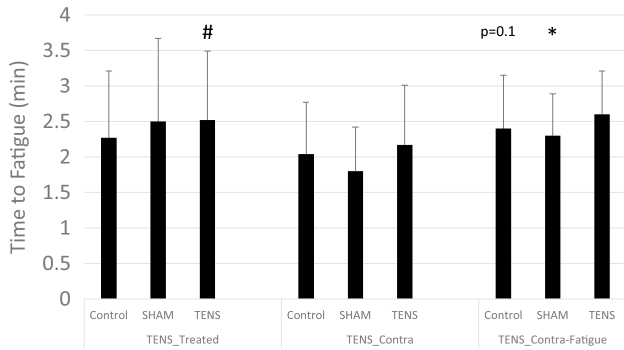

Fig. 1 Time to fatigue for the 30% of MVC test. Hashtag (#) symbol represents that TENS was significantly longer than control. Asterisk (*) symbol represents that sham TENS was of significantly shorter duration than TENS in the TENS_Contra-Fatigue study. $p=0.1$ indicates that the control exhibited a near significantly shorter fatigue duration than TENS in the TENS_Contra-Fatigue study

or main effects for MVC rectus femoris or biceps femoris EMG activity.

Fatigue intervention with TENS-treated leg

While there was a numerically higher fatigue index associated with TENS (42.3 ± 18.8%) versus Sham (38.4 ± 15.1%) in the first set, it failed to reach significance ($p=0.22$). However, there was a 14.5% significantly ($p=0.02$) higher fatigue index with the high (36.2 ± 10.1%) versus Sham (31.6 ± 10.6%) conditions in the second fatigue intervention set.

Post-test 30% submaximal fatigue protocol

The TENS condition induced a significant ($p=0.04$; eta^2: 0.53; 11.7%) and near significant ($p=0.1$; eta^2: 0.25; 7.1%) greater time to failure versus the sham and control conditions, respectively (Fig. 1). A significant main effect ($p<0.0001$; eta^2: 0.73) for the post-test fatigue quartiles indicated that quadriceps force variability in the fourth quartile was 65.8% ($p=0.001$), 62.3% ($p=0.001$), and 29.1% ($p=0.001$) greater than in the first, second, and third quartiles, respectively. The third quartile force variability also exceeded the first ($p=0.002$; 28.4%) and second ($p=0.12$; 25.0%) quartiles. A significant main effect ($p<0.001$; eta^2: 0.32) for post-fatigue quartiles displayed that the rectus femoris fourth quartile rmsEMG was 19.2% ($p=0.03$) and 7.6% ($p=0.03$) higher than the first and third quartiles, respectively. Similarly, a significant quartiles main effect ($p=0.01$; eta^2: 0.89) showed that the fourth quartile hamstrings rmsEMG was 56.7% ($p=0.01$), 63.1% ($p<0.01$) and 54.1% ($p=0.01$) greater than the first to third quartiles, respectively.

Discussion

Prior crossover and non-local muscle fatigue (NLMF) studies have demonstrated muscle endurance impairments of contralateral homologous and heterologous muscle groups (see review: Halperin et al. 2015). This is the first study to demonstrate that local, unilateral, and TENS-induced analgesic effects can counteract NLMF effects and positively impact the time to fatigue of both the TENS-treated (Study 1: TENS_Treated) and contralateral, homologous, untreated (no TENS) quadriceps (Studies 2 and 3: TENS_Contra and TENS_Contra-Fatigue). The findings emphasize the global (non-local or crossover) effect of treating a single limb with TENS, with possible implications for training and rehabilitation outcomes.

TENS_Treated and contralateral leg fatigue responses

Specifically, the most important findings in this study were the increased knee extensors time to failure in the TENS_Treated and TENS_Contra-Fatigue studies and the greater fatigue index (lower rate of fatigue) with the TENS-treated leg fatigue intervention in the TENS_Contra-Fatigue study. Both findings provided evidence that TENS can either prolong submaximal (30% MVC) isometric force output of the treated (TENS_Treated) or contralateral leg (TENS_Contra-Fatigue) or decrease the extent of force loss (fatigue index) with a prolonged, maximal intensity, fatigue protocol of the TENS-treated leg (TENS_Contra-Fatigue). There were no effects of TENS in any of the three studies on the single, discrete MVC force, F100 or EMG activity.

Single MVC responses

The performance of single, 5-s, maximal intent, isometric, voluntary contractions can induce fatigue effects (main effects for time showed consistent pre- to post-test decreases: Table 4) and an uncomfortable sensation (i.e., high muscle tension, occluded blood flow to the contracting muscle, elevated whole body blood pressure, facial vasodilation). While TENS is used as a nonpharmacological, non-invasive analgesic for the treatment of pain (Sluka and Walsh 2003; Johnson and Martinson 2007; Vance et al. 2014), there was no effect on the force or activation of single MVCs with the treated or contralateral knee extensors. The short duration of this contraction may permit the individual to overcome any detriments or distractions from the discomfort of the MVC and thus without an impairment or deficit, the TENS treatment could not augment the force of a maximally or near maximally activated muscle. However, prolonged isometric contractions can exacerbate the intensity of the uncomfortable or painful sensations and, hence, TENS benefits were accrued with the fatiguing contractions.

Mechanisms contributing to improved TENS_Treated leg fatigue

If the greater fatigue performance only occurred with the TENS-treated leg, it might be speculated that there was a direct effect of TENS upon the affected muscle such as TENS contraction-induced vasodilation providing a more efficient supply of oxygen, substrates or removal of metabolites (Naik et al. 1999). Secondly, the TENS-induced contractions could have increased muscle temperature improving enzymatic cycling and muscle strength output (Clarke et al. 1958; Bergh and Ekblom 1979; Drinkwater and Behm 2007). Thirdly, post-activation potentiation effects might have been induced by the prior TENS contractions with the regulatory myosin light chain phosphorylation augmenting the cross-bridge kinetics (Houston et al. 1985; Houston and Grange 1990; Behm 2004). While these mechanisms might indeed have contributed to the extended force maintenance of the treated leg (TENS_Treated group) and the improved fatigue index with the fatigue intervention of the TENS-treated leg (TENS_Contra-Fatigue), these mechanisms could not have contributed to the prolongation of submaximal forces with the contralateral knee extensors (TENS_Contra-Fatigue).

Mechanisms contributing to improved contralateral, untreated, leg fatigue

The improved maintenance of the 30% MVC load with the contralateral knee extensors would have to be attributed to a crossover or global response. As a primary function of the TENS protocol is to suppress pain and the prolonged maintenance of isometric submaximal forces can be quite uncomfortable, it is quite likely that there may have been a global pain-modulatory response (Aboodarda et al. 2015b; Cavanaugh et al. 2017). If the pain or discomfort of the submaximal fatiguing contractions can be reduced, then it would be expected that the individual could continue for longer durations. Two possible pain-modulatory systems could be the gate control theory of pain (Melzack and Wall 1965; Moayedi and Davis 2013) and diffuse noxious inhibitory control (DNIC) of pain (Le Bars et al. 1992). Gate control theory indicates that thick myelinated ergoreceptor nerve fibers (via activation of percutaneous mechanoreceptors and proprioceptors) activation can affect ascending nociceptive transmission through small diameter Aδ fibers, resulting in a descending inhibitory effect that permits pain perception modulation. A second or contributing pain suppression mechanism is DNIC, which is described as an anti-nociceptive pathway or counter-irritation (Le Bars et al. 1992; Mense 2000). DNIC can be activated by nociceptive stimuli that inhibit ascending nociceptive transmission to the central nervous system, especially inhibition by the brain's periaqueductal gray matter and rostral ventromedial medulla. Descending pathways from these areas transmit high levels of opioid receptors, to the spinal dorsal horn and inhibit pain transmission monoaminergically (i.e., norepinephrine and serotonin) (Sigurdsson and Maixner 1994). Thus, DNIC would suppress pain perception not only with the treated limb, but also in non-local (contralateral) muscles as well.

An exception to the improved fatigue performance with the TENS_Treated and TENS_Contra-Fatigue groups was the lack of improvement in contralateral submaximal force maintenance with the TENS_Contra group. Whereas the TENS_Contra-Fatigue group was subjected to a fatigue intervention of the TENS-treated leg, the TENS_Contra group had no fatigue intervention of the TENS-treated leg. Without a fatiguing intervention, there would not be a unilateral stressor that could induce crossover or non-local muscle fatigue (NLMF). Crossover or NLMF has been attributed to group III and IV muscle afferents exerting inhibition on the corticospinal motor pathways (Halperin et al. 2015; Amann et al. 2013). NLMF inhibition has been shown to decrease corticospinal excitability (Sambaher et al. 2016), motor evoked potentials (Takahashi et al. 2011), short interval intracortical inhibition (SICI: excitability of intracortical inhibitory circuits) (Takahashi et al. 2009) as well as increase interhemispheric or transcallosal inhibition (Takahashi et al. 2009; 2011). Furthermore, the two sets of 100 s MVCs of this study's fatigue intervention (TENS_Contra-Fatigue) could be mentally challenging as motivation, focus, and continued attention are needed to maintain prolonged MVCs (Halperin et al. 2014a; Hamilton and Behm 2017). Prior mentally fatiguing tasks can cause individuals to perceive activity as more strenuous, and thus stop earlier (Pageaux et al. 2013, 2014). Fatigue-induced afferent feedback could contribute to an earlier attainment of the sensory tolerance limit due to a more rapid central drive inhibition (Amann et al. 2013). However, in the TENS_Contra experiment, there was no prior unilateral fatiguing intervention that would have inhibited the ability to maintain the 30% load of the contralateral knee extensors. In the TENS_Contra-Fatigue experiment, crossover fatigue or NLMF would have impaired performance, while the TENS intervention could have altered the contralateral perception of discomfort or difficulty allowing the individual to overcome inhibitory influences and achieve more near-optimal performance. Since the TENS_Contra experiment did not have a prior unilateral fatiguing contraction, the contralateral fatigue test would not have been compromised and thus the TENS treatment would have had less impact on a more fully functioning knee extensors muscle group. In summary, rather than TENS facilitating fatigue endurance performance, the TENS treatment contributed to a disinhibition of the crossover or NLMF effects on contralateral fatigue endurance. When there was no crossover or NLMF, then the TENS treatment had trivial effects.

TENS effects upon fatigue-induced force jitter

A common observation with fatigue is the increased force jitter (tremor) or force variability due to the fatigue-induced synchronization of motor unit firing (Behm 2004). We initially speculated whether the TENS treatment would have any neurophysiological consequences upon motor unit synchronization, perhaps associated with a lower perception of effort or discomfort. In each study, the force variability or jitter significantly increased over the duration of the submaximal fatigue protocol, but there were no interactions showing any significant TENS benefit (i.e., decreased jitter or tremor).

Fatigue-induced changes in EMG activity

Similarly, it is well documented that EMG activity tends to increase with prolonged submaximal force maintenance, as there is an increased motor unit recruitment and firing frequency to compensate for the fatigue of the initially activated motor units (Behm 2004). As expected, EMG activity of both the rectus femoris and biceps femoris increased over the duration of the submaximal fatigue test for the TENS_Contra and TENS_Contra-Fatigue studies. However, there were no interactions to demonstrate an effect of TENS treatment on agonist or antagonist EMG activity. However, the TENS_Treated study did find a main effect for conditions with biceps femoris EMG significantly lower with the TENS condition compared to the sham and control conditions. While this was not a pre- to post-test interaction with the three conditions, it still provides a suggestion that at least in the TENS_Treated study that the prolonged time to failure might have benefitted from decreased antagonist (hamstrings) contractions and thus less resistance to the intended movement. Since it was a significant main effect (combines the pre- and post-TENS test values) rather than an interaction (analyzes pre- and post-test values independently for each condition) and the lower co-activation occurred in only one of the three studies, the evidence that diminished co-activation is a major contributor to TENS-induced improved fatigue endurance might not be considered strong.

Limitations

While including both sexes in two of the three studies can be considered a methodological strength, a limitation of the analysis is that with only six males and females, the possibility of finding significant differences with this statistical power would be difficult contributing to a possible type II error. Hence, we combined the male and female data and did not analyze sex differences to observe overall physiological responses and ensure greater statistical power. A second possible limitation might be the use of isometric testing and fatigue interventions. Whereas dynamic contractions may be used more predominately with training and rehabilitation, isometric contractions are still used in the earlier stages of rehabilitation especially with joint injuries that are not recommended to experience dynamic resisted movements for fear of further joint damage to ligaments and other connective tissue (Behm 1993). Isometric contractions would also not induce the extent of delayed onset muscle soreness as dynamic contractions with an eccentric component and thus would ensure that exercise-induced muscle damage would not impact subsequent testing sessions. Furthermore, the analysis of isometric EMG activity does not have to take into consideration muscle activation changes induced by alterations in muscle length.

Conclusions

In conclusion, the lack of neurophysiological effects such as a lack of decrease in jitter or consistent decrease in EMG activity from TENS (only 1/3 studies) would suggest that the unilateral application of TENS can have crossover or global effects upon the perception of pain or discomfort during a contralateral, isometric, submaximal intensity, fatigue protocol. The TENS treatment can also positively impact the fatigue index of maximal intensity fatiguing contractions with the TENS-treated leg. However, with the short duration of discrete MVCs, the level of discomfort or pain may not be sufficient for TENS to play a significant role.

Perspectives

While TENS is used to alleviate pain in a targeted muscle, the presented studies highlight that TENS can have more global or contralateral (crossover) consequences. Hence, the TENS-induced prolongation of a submaximal fatiguing task with both the treated and contralateral limbs suggests that TENS can enhance muscle endurance when prescribing physical activity for rehabilitation or training. A prolongation of submaximal forces with rehabilitation or exercise training could increase the training stimulus and accelerate or augment the training adaptations (Behm 1993). Secondly, this evidence for crossover effects of TENS suggests that users do not need to purchase two units to achieve simultaneous effects in both limbs. Decreasing rehabilitation-related costs might positively impact patient adherence.

Acknowledgements The study was funded by Natural Sciences and Engineering Research Council of Canada (Grant number 2017-03728).

Authors contributions BDG: data interpretation and writing of manuscript. CEM, PGMJ, AH, BASM, BA, MC, PJ, MB, FK, KS, RM: data collection, analysis, and review of manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest with the contents of this manuscript.

References

Aboodarda SJ, Copithorne DB, Power KE, Drinkwater E, Behm DG (2015a) Elbow flexor fatigue modulates central excitability of the knee extensors. Appl Physiol Nutr Metab 40(9):924–930. https://doi.org/10.1139/apnm-2015-0088

Aboodarda SJ, Spence AJ, Button DC (2015b) Pain pressure threshold of a muscle tender spot increases following local and non-local rolling massage. BMC Musculoskelet Disord 16:265. https://doi.org/10.1186/s12891-015-0729-5

Aboodarda SJ, Sambaher N, Behm DG (2016) Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. Scand J Med Sci Sports 26(11):1301–1312. https://doi.org/10.1111/sms.12596

Aboodarda SJ, Sambaher N, Millet GY, Behm DG (2017) Knee extensors neuromuscular fatigue changes the corticospinal pathway excitability in biceps brachii muscle. Neurosci 340:477–486. https://doi.org/10.1016/j.neuroscience.2016.10.065

Ainsworth L, Budelier K, Clinesmith M, Fiedler A, Landstrom R, Leeper BJ, Moeller L, Mutch S, O'Dell K, Ross J, Radhakrishnan R, Sluka KA (2006) Transcutaneous electrical nerve stimulation (TENS) reduces chronic hyperalgesia induced by muscle inflammation. Pain 120(1–2):182–187. https://doi.org/10.1016/j.pain.2005.10.030

Amann M (2011) Central and peripheral fatigue: interaction during cycling exercise in humans. Med Sci Sports Exerc 43(11):2039–2045. https://doi.org/10.1249/MSS.0b013e31821f59ab

Amann M, Venturelli M, Ives SJ, McDaniel J, Layec G, Rossman MJ, Richardson RS (2013) Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. J Appl Physiol (1985) 115(3):355–364. https://doi.org/10.1152/japplphysiol.00049.2013

Asmussen E, Mazin B (1978) A central nervous component in local muscular fatigue. Eur J Appl Physiol 38:9–15

Astokorki AH, Mauger AR (2017) Tolerance of exercise-induced pain at a fixed rating of perceived exertion predicts time trial cycling performance. Scand J Med Sci Sports 27(3):309–317. https://doi.org/10.1111/sms.12659

Astokorki AHY, Mauger AR (2017) Transcutaneous electrical nerve stimulation reduces exercise-induced perceived pain and improves endurance exercise performance. Eur J Appl Physiol 117(3):483–492. https://doi.org/10.1007/s00421-016-3532-6

Behm DG (1993) Debilitation to adaptation. J Strength Cond Res 7(2):65–75

Behm DG (2004) Force maintenance with submaximal fatiguing contractions. Can J Appl Physiol 29(3):274–290

Behm DG, Cavanaugh T, Quigley P, Reid JC, Nardi PS, Marchetti PH (2016) Acute bouts of upper and lower body static and dynamic stretching increase non-local joint range of motion. Eur J Appl Physiol 116(1):241–249. https://doi.org/10.1007/s00421-015-3270-1

Bergh U, Ekblom A (1979) Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. Acta Physiol Scand 107(1):33–37

Button DC, Behm DG (2008) The effect of stimulus anticipation on the interpolated twitch technique. J Sports Sci Med 7(520):524

Cavanaugh MT, Doweling A, Young JD, Quigley PJ, Hodgson DD, Whitten JH, Reid JC, Aboodarda SJ, Behm DG (2017) An acute session of roller massage prolongs voluntary torque development and diminishes evoked pain. Eur J Appl Physiol 117(1):109–117. https://doi.org/10.1007/s00421-016-3503-y

Chaouachi A, Padulo J, Kasmi S, Othmen AB, Chatra M, Behm DG (2017) Unilateral static and dynamic hamstrings stretching increases contralateral hip flexion range of motion. Clin Physiol Funct Imaging 37(1):23–29. https://doi.org/10.1111/cpf.12263

Clarke SJ, Hellon RF, Lind AR (1958) The duration of sustained contractions of the human forearm at different muscle temperatures. J Physiol (London) 143:454–473

Cohen J (1988) Statistical power analysis for the behavioural sciences. L. Erbraum Associates, Hillside, pp 12–82

Dailey DL, Rakel BA, Vance CGT, Liebano RE, Anand AS, Bush HM, Lee KS, Lee JE, Sluka KA (2013) Transcutaneous electrical nerve stimulation (TENS) reduces pain, fatigue, and hyperalgesia while restoring central inhibition in primary fibromyalgia. Pain 154(11):2554–2562

Degens H, Veerkamp JH (1994) Changes in oxidative capacity and fatigue resistance in skeletal muscle. Int J Biochem 26(7):871–878

Del Vecchio A, Negro F, Felici F, Farina D (2017) Associations between motor unit action potential parameters and surface EMG features. J Appl Physiol 123:835–843

Denegar CR, Perrin DH (1992) Effect of transcutaneous Eeectrical nerve stimulation, cold, and a combination treatment on pain, decreased range of motion, and strength loss associated with delayed onset muscle soreness. J Athletic Train 27(3):20–206

DeSantana JM, Walsh DM, Vance C, Rakel BA, Sluka KA et al (2008) Effectiveness of transcutaneous electrical nerve stimulation for treatment of hyperalgesia and pain. Curr Rheumatol Rep 10(6):492–499

Doix AC, Lefevre F, Colson SS (2013) Time course of the cross-over effect of fatigue on the contralateral muscle after unilateral exercise. PLoS ONE ONE 8(5):e64910. https://doi.org/10.1371/journal.pone.0064910

Drinkwater EJ, Behm DG (2007) Effects of 22 degrees C muscle temperature on voluntary and evoked muscle properties during and after high-intensity exercise. Appl Physiol Nutr Metab 32(6):1043–1051. https://doi.org/10.1139/H07-069

Enoka RM, Stuart DG (1992) Neurobiology of muscle fatigue. J Appl Physiol 72(5):1631–1648

Fitts RH, Metzger JM (1993) Mechanisms of muscular fatigue. Med Sport Sci 38:248–268

Halperin I, Aboodarda SJ, Basset FA, Byrne JM, Behm DG (2014) Pacing strategies during repeated maximal voluntary contractions. Eur J Appl Physiol 114(7):1413–1420. https://doi.org/10.1007/s00421-014-2872-3

Halperin I, Aboodarda SJ, Behm DG (2014) Knee extension fatigue attenuates repeated force production of the elbow flexors. Eur J Sport Sci 14(8):823–829. https://doi.org/10.1080/17461391.2014.911355

Halperin I, Copithorne D, Behm DG (2014) Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. Appl

Physiol Nutr Metab 39(12):1338–1344. https://doi.org/10.1139/apnm-2014-0109
Halperin I, Chapman DW, Behm DG (2015) Non-local muscle fatigue: effects and possible mechanisms. Eur J Appl Physiol 115(10):2031–2048. https://doi.org/10.1007/s00421-015-3249-y
Hamilton AR, Behm DG (2017) The effect of prior knowledge of test endpoint on non-local muscle fatigue. Eur J Appl Physiol 117(4):651–663. https://doi.org/10.1007/s00421-016-3526-4
Houston ME, Grange RW (1990) Myosin phosphorylation, twitch potentiation, and fatigue in human skeletal muscle. Can J Physiol Pharmacol 68:908–913
Houston ME, Green HJ, Stull JT (1985) Myosin light chain phosphorylation and isometric twitch potentiation in intact human muscle. PflÅgers Arch Eur J Physiol 403:348–352
Jaafar H, Lajili H (2018) The influence of verbal instruction on measurement reliability and explosive neuromuscular performance of the knee extensors. J Hum Kinet 65:21–34. https://doi.org/10.2478/hukin-2018-0031
Johnson M, Martinson M (2007) Efficacy of electrical nerve stimulation for chronic musculoskeletal pain: a meta-analysis of randomized controlled trials. Pain 130(1–2):157–165. https://doi.org/10.1016/j.pain.2007.02.007
Kawamoto JE, Aboodarda SJ, Behm DG (2014) Effect of differing intensities of fatiguing dynamic contractions on contralateral homologous muscle performance. J Sports Sci Med 13(4):836–845
Kennedy A, Hug F, Sveistrup H, Guevel A (2013) Fatiguing handgrip exercise alters maximal force-generating capacity of plantar-flexors. Eur J Appl Physiol 113:559–566. https://doi.org/10.1007/s00421-012-2462-1
Le Bars D, Villanueva L, Bouhassira D, Willer JC (1992) Diffuse noxious inhibitory controls (DNIC) in animals and in man. Patol Fiziol Eksp Ter 4:55–65
Magnusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M (1996) A mechanism for altered flexibility in human skeletal muscle. J Physiol 497(1):291–298
Magnusson SP, Simonsen EB, Aagaard P, Boesen J, Johannsen F, Kjaer M (1997) Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. Scand J Med Sci Sports 7(4):195–202
Martin PG, Rattey J (2007) Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. Pflug Archiv Eur J Physiol 454(6):957–969. https://doi.org/10.1007/s00424-007-0243-1
Melzack R, Wall PD (1965) Pain mechanisms: a new theory. Science 150(3699):971–979
Mense S (2000) Neurobiological concepts of fibromyalgia–the possible role of descending spinal tracts. Scand J Rheumatol Suppl 113:24–29
Moayedi M, Davis KD (2013) Theories of pain: from specificity to gate control. J Neurophysiol 109(1):5–12. https://doi.org/10.1152/jn.00457.2012
Naik JS, Valic Z, Buckwalter JB, Clifford PS (1999) Rapid vasodilation in response to abrief tetanic muscle contraction. J Appl Physiol 87(5):1741–1746
Pageaux B, Marcora SM, Lepers R (2013) Prolonged mental exertion does not alter neuromuscular function of the knee extensors. Med Sci Sports Exerc 45(12):2254–2264. https://doi.org/10.1249/MSS.0b013e31829b504a
Pageaux B, Lepers R, Dietz KC, Marcora SM (2014) Response inhibition impairs subsequent self-paced endurance performance. Eur J Appl Physiol 114(5):1095–1105. https://doi.org/10.1007/s00421-014-2838-5
Pietrosimone BG, Saliba SA, Hart JM, Hertel J, Ingersoll CD (2010) Contralateral effects of disinhibitory tens on quadriceps function in people with knee osteoarthritis following unilateral treatment. N Am J Sports Phy Ther 5(3):111–121
Post M, Bayrak S, Kernell D, Zijdewind I (2008) Contralateral muscle activity and fatigue in the human first dorsal interosseous muscle. J Appl Physiol 105(1):70–82. https://doi.org/10.1152/japplphysiol.01298.2007
Rattey J, Martin PG, Kay D, Cannon J, Marino FE (2006) Contralateral muscle fatigue in human quadriceps muscle: evidence for a centrally mediated fatigue response and cross-over effect. Pflugers Archiv Eur J Physiol 452(2):199–207. https://doi.org/10.1007/s00424-005-0027-4
Rendos NK, Harriell K, Qazi S, Regis RC, Alipio TC, Signorile JF (2018) Variations in verbal encouragement modify isokinetic performance. J Hum Kinet 65:21–34. https://doi.org/10.2478/hukin-2018-0031
Sabino GS, Santos CM, Francischi JN et al (2008) Release of endogenous opioids following transcutaneous electric nerve stimulation in an experimental model of acute inflammatory pain. J Pain 9:157–163
Sambaher N, Aboodarda SJ, Behm DG (2016) Bilateral knee extensor fatigue modulates force and responsiveness of the corticospinal pathway in the non-fatigued, dominant elbow flexors. Front Hum Neurosci 10:18. https://doi.org/10.3389/fnhum.2016.00018
Sidhu SK, Weavil JC, Venturelli M, Garten RS, Rossman MJ, Richardson RS, Gmelch BS, Morgan DE, Amann M (2014) Spinal mu-opioid receptor-sensitive lower limb muscle afferents determine corticospinal responsiveness and promote central fatigue in upper limb muscle. J Physiol 592(22):5011–5024. https://doi.org/10.1113/jphysiol.2014.275438
Sigurdsson A, Maixner W (1994) Effects of experimental and clinical noxious counterirritants on pain perception. Pain 57(3):265–275
Sluka KA, Walsh D (2003) Transcutaneous electrical nerve stimulation: basic science mechanisms and clinical effectiveness. J Pain 4(3):109–121
Somers DL, Clemente FR (2006) Transcutaneous electrical nerve stimulation for the management of neuropathic pain: the effects of frequency and electrode position on prevention of allodynia in a rat model of complex regional pain syndrome type II. Phys Ther 86(5):698–709
Takahashi K, Maruyama A, Maeda M, Etoh S, Hirakoba K, Kawahira K, Rothwell JC (2009) Unilateral grip fatigue reduces short interval intracortical inhibition in ipsilateral primary motor cortex. Clin Neurophysiol 120(1):198–203. https://doi.org/10.1016/j.clinph.2008.10.003
Takahashi K, Maruyama A, Hirakoba K, Maeda M, Etoh S, Kawahira K, Rothwell JC (2011) Fatiguing intermittent lower limb exercise influences corticospinal and corticocortical excitability in the nonexercised upper limb. Brain Stimulation 4(2):90–96. https://doi.org/10.1016/j.brs.2010.07.001
Vance CG, Dailey DL, Rakel BA, Sluka KA (2014) Using TENS for pain control: the state of the evidence. Pain Manag 4(3):197–209. https://doi.org/10.2217/pmt.14.13
Whalen A, Farrell K, Roberts S, Smith H, Behm DG (2019) Topical analgesic improved or maintained ballistic hip flexion range of motion with treated and untreated legs. J Sport Sci Med 18:552–558
Zijdewind I, Zwarts MJ, Kernell D (1998) Influence of a voluntary fatigue test on the contralateral homologous muscle in humans? Neurosci Lett 253(1):41–44