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Effect of prior neuromuscular electrical stimulation of vastus lateralis on the fatigue induced by a sustained voluntary knee extension in men

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ABSTRACT

Purpose: The purpose of this study was to investigate the effect of vastus lateralis (VL) selective fatigue induced by neuromuscular electrical stimulation (NMES) on knee extensor electromyographic (EMG) activity during a sustained submaximal isometric contraction.

Methods: Thirteen healthy men (28 ± 5 years) completed two experimental sessions in which either the VL was pre-fatigued for 17 min (NMES session) or no intervention was performed (control session, CTRL). Subsequently, participants were asked to sustain an isometric knee extension at 20 % of maximal voluntary contraction (MVC) torque until task failure.

Results: VL M-wave amplitude was reduced (−34 ± 26 %, $P = 0.008$) following the NMES intervention, while MVC torque was reduced by 26 ± 10 %. The time to task failure was 23 ± 10 % shorter ($P = 0.002$) in NMES (186 ± 75 s) than in CTRL (251 ± 128 s). EMG activity measured during the sustained contraction was higher for vastus medialis and rectus femoris muscles in NMES compared to CTRL ($P < 0.001$), but was comparable for VL ($P > 0.05$). The extent and origin of neuromuscular fatigue at task failure measured through MVCs combined with electrically-evoked contractions did not differ between NMES and CTRL.

Conclusion: Compensatory activity from synergist muscles occurred in response to a pre-fatigue intervention, which reduced the time to task failure of a sustained submaximal contraction but did not affect the extent and origin of neuromuscular fatigue.

1. Introduction

The concept of musculoskeletal redundancy (Prilutsky and Zatsiorsky 2002) proposes that a wide range of possibilities exist for different synergist muscles to produce a given submaximal torque about a joint. For example, alternating periods of low and high activity between synergist muscles – alternate muscle activity (Tamaki et al. 1998) – have been observed during sustained isometric contractions of the knee extensors at force levels ≤ 5 % maximal voluntary contraction (MVC) (Akima et al. 2012; Kouzaki et al. 2002; Kouzaki and Shinohara 2006; Sjogaard et al. 1986), and particularly between mono- and bi-articular muscles (Akima et al. 2012; Kouzaki et al. 2002; Place et al. 2006b). The occurrence of alternate activity is a strategy used by the central nervous system to attenuate muscle fatigue development (Kouzaki and Shinohara 2006), and adjustments are more likely to occur between mono- vs. bi-articular muscles during exercise (Kouzaki and Shinohara 2006; Place et al. 2006b). With a somewhat different approach, compensatory activity between synergist muscles has been explored by selectively fatiguing one synergist muscle, mostly via neuromuscular electrical stimulation (NMES) (Akima et al. 2002; Bouillard et al. 2014; de Ruiter et al. 2008; Stutzig et al. 2012), but also ice application (Kinugasa et al. 2005), while exploring potential adjustments of the electromyographic (EMG) activity of other synergist muscles. In most cases, compensatory activity was observed during submaximal dynamic

Abbreviations: CTRL, control intervention; EMG, electromyographic; MVC, maximal voluntary contraction; NMES, neuromuscular electrical stimulation; RF, rectus femoris; RMS, root mean square; SD, superimposed doublet; TTF, time to task failure; VL, vastus lateralis ; VM, vastus medialis.

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contractions (Akima et al. 2002; de Ruiter et al. 2008; Kinugasa et al. 2005) and sustained MVC (Stutzig et al. 2012), likely as a reflection of compensatory strategies among synergist muscles. Bouillard et al. (2014) used shear wave elastography to quantify relative changes in force of the superficial quadriceps muscle heads during a sustained isometric contraction performed at 20 % MVC force after NMES-induced fatigue of the *vastus lateralis* (VL) muscle. They showed a reduced time to task failure (TTF) but no changes in force production for the *vastus medialis* (VM) and *rectus femoris* (RF) muscles to compensate for the reduced VL contribution. The discrepancies between these previous studies may result from the different methods used (EMG activity vs. force estimation through elastography). Also, investigation of the neuromuscular function following the pre-fatigue task and the subsequent voluntary contraction was not the main focus of these studies, thereby limiting our understanding of how these factors may affect an eventual compensatory activity. Thus, a complete characterization of the extent and origin of knee extensor neuromuscular fatigue measured through the analysis of MVC force and electrically-evoked contractions after both selective NMES and the fatiguing exercise is needed to better appreciate its relationship with the potential compensatory activity. In addition, we used TTF as a primary index in this study as it has been proposed as a powerful and complementary approach to study the neural determinants of fatigue (Hunter et al., 2004).

Therefore, the aim of this study was to test the following hypotheses: the induction of fatigue in VL by a 17 min NMES protocol aiming at eliciting 20 % MVC torque would (i) increase the contribution of non-fatigued synergist muscles during a sustained isometric contraction, (ii) reduce the TTF of the sustained contraction and (iii) increase the extent of neuromuscular fatigue of the whole knee extensor muscle group.

2. Materials and methods

2.1. Participants

Thirteen physically active men (age: 28 ± 5 years, height: 178 ± 6 cm, body mass: 70 ± 10 kg) volunteered to participate in this study after having been informed of potential risks and discomfort linked to the different experimental procedures. Each participant gave written consent before the start of experimentations and the University of Burgundy Committee on Human Research approved the study protocol. The study was conducted according to the Declaration of Helsinki.

2.2. Experimental protocol

The participants completed two randomly-presented experimental sessions separated by 8 ± 6 days with their right knee extensor muscles (dominant side). The two sessions were identical, except for the application of NMES, and basically consisted of three phases: a standardized warm-up entailing several submaximal contractions (from 20 to 80 % of the maximal estimated strength) lasting approximatively 2 min, an intervention phase of 17 min (NMES or passive rest, CTRL) and a sustained submaximal isometric contraction of the knee extensors until failure. Neuromuscular fatigue was evaluated with a battery of maximal voluntary and electrically-evoked contractions that were completed before and immediately after the intervention phase (Pre and Mid, respectively) as well as immediately after the sustained contraction (Post) (see Fig. 1). Knee extension torque and surface EMG activity of the VL, VM and RF muscles were recorded during the sustained contraction and during the test battery to quantify the following main outcomes: submaximal EMG activity (to verify eventual compensatory strategies), TTF (endurance time), knee extensor MVC torque, to verify the extent of neuromuscular fatigue, and various markers of central (voluntary activation level) and peripheral fatigue (M-wave amplitude, twitch and doublet peak torque), to assess the mechanisms underlying the reduced MVC torque. As all participants were already accustomed to all the procedures employed in the experiments, no familiarization session was needed.

2.3. Torque and EMG recordings

Voluntary and evoked knee extension torque was recorded with an isokinetic dynamometer (Biodex, Shirley, New York). The knee joint was positioned at an angle of 75° and the hips at an angle of 100° (180° corresponding to full extension) throughout the session. The torque signal was recorded at a sampling rate of 2 kHz and stored for off-line analysis with a commercially-available software (Tida, Heka elektronik, Lambrecht/Pfalz, Germany). The axis of the dynamometer was consistently aligned with the knee extension axis, and the lever arm was firmly attached to the shank with a strap. The upper body was strapped to the dynamometer chair with a belt across the abdomen and two crossover shoulder harnesses to limit compensatory movements. Participants were asked to keep their arms crossed on the chest during the session.

The EMG activity of the VL, VM and RF muscles was recorded with

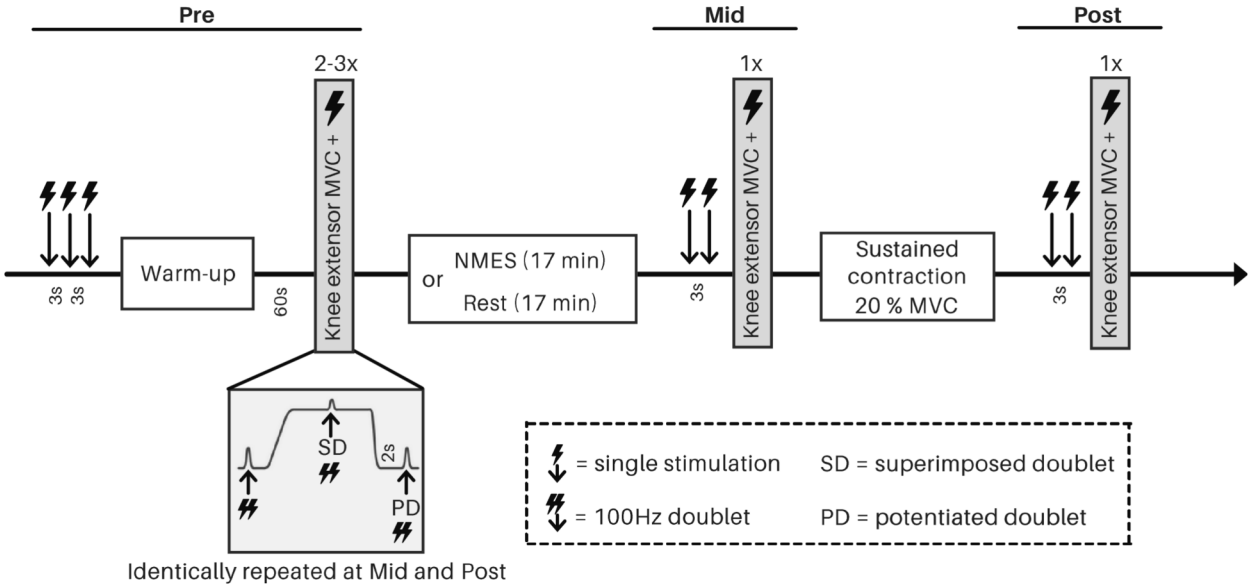

Fig. 1. Graphical representation of the experimental protocol. MVC maximal voluntary contraction, NMES neuromuscular electrical stimulation.

pairs of silver-chloride circular electrodes (recording diameter: 10 mm, inter-electrode distance: 20 mm; Control Graphique Medical, Brie-Comte-Robert, France). SENIAM recommendations were followed for electrode placement (Hermens et al. 2000). Briefly, VL and VM electrodes were positioned on the distal part of respective muscles in the direction of muscle fibres. For the RF, electrodes were positioned at 50 % on the line from the anterior spina iliaca superior to the upper boarder of the patella. The reference electrode was placed on the contralateral patella. The position of the electrodes was marked on the skin to ensure consistent positioning between sessions, and low resistance (<5 kΩ) between the two electrodes was obtained by abrading and cleaning the skin with alcohol. EMG signals were amplified (gain: 1000), recorded with a sampling frequency of 2 kHz (common mode rejection ratio = 90 dB; impedance input = 100 MΩ), filtered with a bandwidth frequency between 10 and 500 Hz and stored for off-line analysis with the same software used for torque signal.

2.4. Intervention phase

Selective NMES was applied to the VL using a commercially-available stimulator (Sport P, Compex Medical SA, Ecublens, Switzerland) and two square electrodes (5x5 cm, Compex SA, Ecublens, Switzerland). Electrodes were placed over the VL muscle belly on the antero-lateral aspect of the thigh, ~5 cm proximal to the superior aspect of the patella and ~ 10 cm distal to the greater trochanter (Akima et al. 2002). The NMES intervention lasted 17 min and included 30 electrically-evoked contractions (on–off ratio: 6.25–27 s; rise time: 1.5 s; fall time: 0.75 s; pulse duration: 250 μs; pulse frequency: 90 Hz) (Zory et al., 2005). Stimulation intensity was set to evoke 20 % MVC torque (63 ± 14 mA) and was maintained constant during the 30 contractions. The peak torque evoked by NMES decreased from 24 ± 9 % to 13 ± 5 % MVC torque from the first to the last electrically-evoked contraction. The CTRL intervention consisted of passive rest for the same duration (17 min) and in the same position as the NMES intervention.

2.5. Sustained contraction

Participants were asked to sustain an isometric contraction of the knee extensors at 20 % MVC torque recorded at Pre until task failure. Visual feedback of the torque exerted during the sustained contraction was displayed on a screen located 1 m in front of the subject; the gain of the visual feedback was kept constant between the two sessions for each subject. Torque feedback was displayed as a horizontal line and the subjects were required to reach a target line fixed at the target level. They were stopped when they could no longer maintain the required torque for more than three consecutive seconds despite strong verbal encouragements (Neyroud et al., 2012). TTF and EMG activity of the VL, VM and RF muscles were recorded (see Data Analysis). Participants were not informed of the TTF until the completion of the second session.

2.6. Assessment of neuromuscular fatigue

The test battery conducted at Pre, Mid and Post consisted of two single stimuli delivered at rest immediately before the MVC (to quantify M-wave amplitude and twitch peak torque), a 5-s MVC with superimposed paired stimuli (to quantify MVC torque and voluntary activation level according to the twitch interpolation technique), and paired stimuli delivered at rest ~ 2 s after the MVC (to quantify doublet peak torque and calculate voluntary activation level) (see Fig. 1). Single and paired supramaximal stimuli (interpulse interval: 10 ms) of 1 ms were delivered to the femoral nerve with a constant-current stimulator (model DS7A, Digitimer, Welwyn Garden City, United Kingdom). A cathode-pen electrode (diameter: 0.5 cm) was pressed into the femoral triangle by the same experienced investigator while the anode (10x5 cm, Compex, Ecublens, Switzerland) was located in the gluteal fold. The site of stimulation, i.e., the position giving the greatest visible contraction of the whole quadriceps muscle group, was marked on the skin.

The optimal stimulation intensity was determined at the beginning of each session on an individual basis and was considered to be reached when an increase in stimulation intensity of a single pulse did not induce a further increase in VL M-wave amplitude and peak twitch torque. Stimulation intensity was further increased by 20 % to ensure supramaximality of all stimuli throughout the session (Neyroud et al. 2014). For the MVC, participants were asked to build up torque progressively (1–2 s) until a plateau was reached and then to maintain this torque for 3–4 s. Strong verbal encouragements were consistently provided during each MVC and participants were provided with visual torque feedback. Paired stimuli were manually superimposed during the plateau phase and then delivered again at rest ~ 2 s after the end of the MVC. At Pre, participants completed two to three MVCs (with respective paired pulses) separated by 1–2 min to obtain < 5 % difference between the two last trials, while at Mid and Post, only one MVC was realized (to limit the recovery from fatigue).

2.7. Data analysis

MVC torque was considered as the highest value (single data point) attained during the MVC. Twitch and doublet peak torque were quantified as the highest value (single data point) of respective responses. Voluntary activation level was estimated according to the following equation: $\left[100 - \frac{D \times (MVC_{@stim}/MVC)}{DPT}\right]$, where D = difference between the torque attained just before ($MVC_{@stim}$) and after the superimposed stimulation, DPT = doublet peak torque at rest (Strojnik and Komi 1998). M-wave amplitude was measured for VL, VM and RF muscles as the amplitude of the first phase of the M-wave (Lanfranchi et al., 2024). When more than one response was obtained (2–3 trials), the mean value was retained. Torque time integral was calculated as the area under the torque curve during the submaximal contraction (NMES and CTRL) as well as during the 30 electrically-evoked contractions (NMES). The submaximal EMG signal recorded during the sustained contraction was quantified as the root mean square (RMS) value for consecutive sampling intervals that were 10 % of TTF and then normalized to the maximal EMG RMS obtained during the MVC at Pre and Mid (500 ms around MVC torque). We chose this rather long time-window intervals as in previous works (Neyroud et al. 2012; Rochette et al. 2003) to provide a sufficient sampling resolution and reduce the variance for the subsequent statistical analysis. The summed EMG RMS (VL + VM + RF, expressed relative to MVC RMS) measured during exercise was multiplied by entire TTF (in s) to obtain the RMS time integral from both sustained contractions.

2.8. Statistical analysis

After checking normality of the data with a Shapiro-Wilk test, a Wilcoxon signed-rank test (TTF) or a bilateral paired *t* test (RMS time integral and torque time integral) was used to compare the values between NMES and CTRL. A linear mixed model was used to examine the main effect of time (Pre vs. Mid vs. Post), condition (NMES vs. CTRL) as well as their interaction on MVC torque, voluntary activation level, twitch peak torque, doublet peak torque and M−wave amplitude. Another linear mixed model was used to examine the main effect of muscle (VL vs. VM vs. RF), TTF section (10–100 %), condition (NMES vs. CTRL) as well as their interaction on the submaximal EMG activity recorded during the sustained contraction. Post-hoc analysis (Bonferroni) was used to test for differences among pairs of means when appropriate. The *Jamovi* software (version 1.6, Sydney, Australia) was used for all the statistical analyses. The significance level was set at a value of $P \leq 0.05$.

3. Results

3.1. TTF, submaximal EMG activity and torque time integral

TTF was significantly shorter for NMES (186 ± 75 s) compared with CTRL (251 ± 128 s; P = 0.002) for all participants, with a mean difference of 23 ± 10 % (Fig. 2). Original recordings of submaximal EMG activity from a representative participant are shown in Fig. 3 by muscle and condition. In both conditions, EMG activity increased non-linearly throughout the sustained contraction (P = 0.002), with a greater increase in the second half of the TTF (Fig. 4). In the CTRL condition, EMG activity did not differ significantly between the VM, VL and RF muscles (P = 1.0). In the NMES condition, EMG activity of VM and RF was greater than VL (P < 0.001), on average by 28 ± 21 % and 17 ± 26 % respectively. VM EMG activity was also greater compared to RF (P < 0.001), on average by 17 ± 27 %. EMG activity of the VL muscle did not differ significantly between NMES and CTRL (P = 1.0), while VM and RF EMG activity was higher in NMES than in CTRL (P < 0.001), on average by 25 ± 8 % and 15 ± 15 %, respectively. The RMS time integral was not different between the two conditions (15103 ± 6583 AU vs. 16815 ± 7025 AU, P = 0.084). Torque time integral of the sustained contraction summed with torque time integral of the evoked contractions in the NMES condition (13045 ± 3009 N.m.s) was greater than the torque time integral of the sustained contraction in the CTRL condition (8263 ± 2665 N.m.s; P < 0.001).

3.2. MVC torque

MVC torque decreased significantly from Pre to Mid in NMES (−26 ± 10 %, P < 0.001) but not in CTRL (−9 ± 4 %, P = 0.089), while the sustained contraction caused a significant decline of MVC torque between Mid and Post (CTRL: −29 ± 11 %, NMES: −18 ± 14 %, P < 0.001; Fig. 5A). MVC torque at Post was significantly lower than Pre in both conditions (CTRL: −35 ± 11 %, NMES: −40 ± 9 %; P < 0.001), with no difference at Post between NMES and CTRL (P = 1.0).

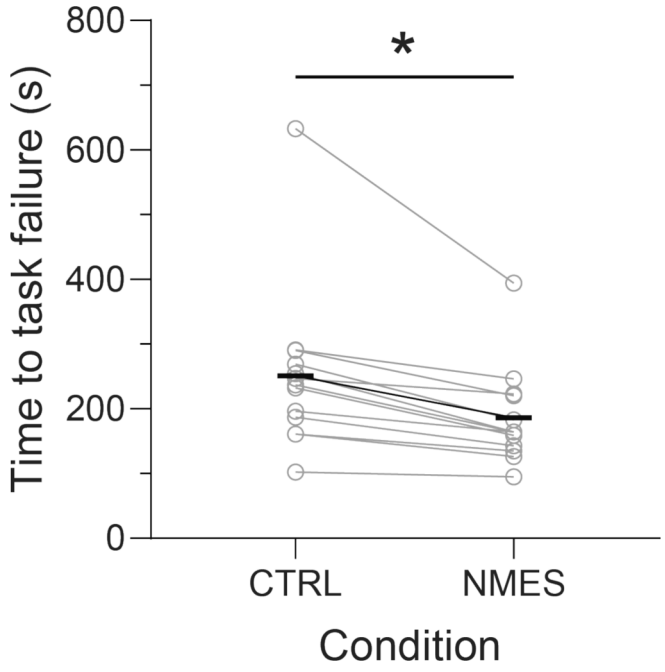

Fig. 2. Time to task failure in CTRL and NMES conditions. Black lines represent mean values while grey dots and lines represent individual values. * NMES shorter than CTRL at P < 0.05.

3.3. Central fatigue

Voluntary activation level did not change from Pre to Mid in both conditions (P = 0.91) while a significant decrease was observed between Mid and Post regardless of the condition (CTRL: −9 ± 8 %; NMES: −5 ± 8 %; P < 0.001) (Fig. 5B). Voluntary activation level at Post was significantly lower than Pre in both conditions (CTRL: −9 ± 9 %, NMES: −7 ± 9 %; P < 0.001), with no difference between NMES and CTRL.

3.4. Peripheral fatigue

VL M-wave amplitude decreased significantly from Pre to Mid only in the NMES condition (P = 0.008), with a mean reduction of −4 ± 6 % for CTRL and −34 ± 26 % for NMES (Table 1). The VL M-wave amplitude Pre-to-Post decline was also significant only in the NMES condition (P = 0.04) with a mean reduction of −2 ± 12 % for CTRL and −29 ± 21 % for NMES. RF M-wave amplitude decreased significantly from Pre to Mid in both conditions (P = 0.02), with a mean reduction of −4 ± 25 % for CTRL and −13 ± 15 % for NMES (Table 1), but not from Pre to Post (P = 0.63).

No time-related changes were observed for VM M-wave amplitude (P = 0.50), while a main condition effect was observed showing higher VM M-wave amplitude in the NMES condition (P = 0.001). Twitch peak torque decreased significantly from Pre to Mid (−14 ± 14 %, P = 0.007) and from Mid to Post (−24 ± 21 %, P < 0.001) in the NMES but not in the CTRL condition (Table 1). Doublet peak torque decreased significantly from Pre to Mid (CTRL: −7 ± 6 %, NMES: −16 ± 10 %, P < 0.001) and from Mid to Post (CTRL: −15 ± 13 %, NMES: −20 ± 19 %, P < 0.001), with no difference between conditions (Fig. 5C). A main condition effect was observed for doublet peak torque (P < 0.001), which was on average 9 ± 10 % lower for NMES than CTRL.

4. Discussion

The main purpose of this study was to investigate the neuromuscular adjustments occurring during and at task failure of a sustained submaximal contraction of the knee extensors with vs. without selective-fatigue of the VL muscle induced by NMES. The main findings show a reduced TTF along with an increased EMG activity of the non-stimulated synergist muscles during the sustained contraction, which did not affect the extent and origin of the resulting neuromuscular fatigue.

As expected, 17 min of selective NMES of the VL muscle induced some specific peripheral adjustments. First, M-wave amplitude, a proxy of neuromuscular excitability, was reduced for the stimulated VL muscle after the selective NMES protocol (−34 %). Impaired neuromuscular excitability, as classically proposed when a reduction in M-wave amplitude is observed, has previously been shown to be the main peripheral change associated to high-frequency NMES (Badier et al. 1999; Boerio et al. 2005; Zory et al. 2005; Jubeau et al. 2007). As for previous studies, this reduction was accompanied by a decrease in twitch and doublet peak torque. Unsurprisingly, peripheral fatigue induced by selective NMES of the VL muscle resulted in a reduced MVC torque of the knee extensors before starting the sustained submaximal contraction.

In CTRL, TTF was ~ 4 min on average, which is in the range of what has been observed in previous studies using a similar exercise paradigm (Bouillard et al. 2014; Matkowski et al. 2011; Neyroud et al. 2012; Rochette et al. 2003). During the contraction, the EMG activity more than doubled, which is also consistent with the findings of Rochette et al. (2003) who observed an increase from ~ 22 to ~ 45 % MVC during a similar task. As extensively discussed in the literature, the main factor responsible for these EMG changes is an increased recruitment of higher-threshold motor units (de Ruiter et al. 2004; Garland et al. 1997; Maton and Gamet 1989) with a possible contribution from the change in action potentials waveform (Fallentin et al. 1993; Maton and Gamet 1989). Selective NMES of the VL muscle resulted in a TTF that was ~ 1 min shorter than CTRL. We also observed compensatory strategies, i.e., VM

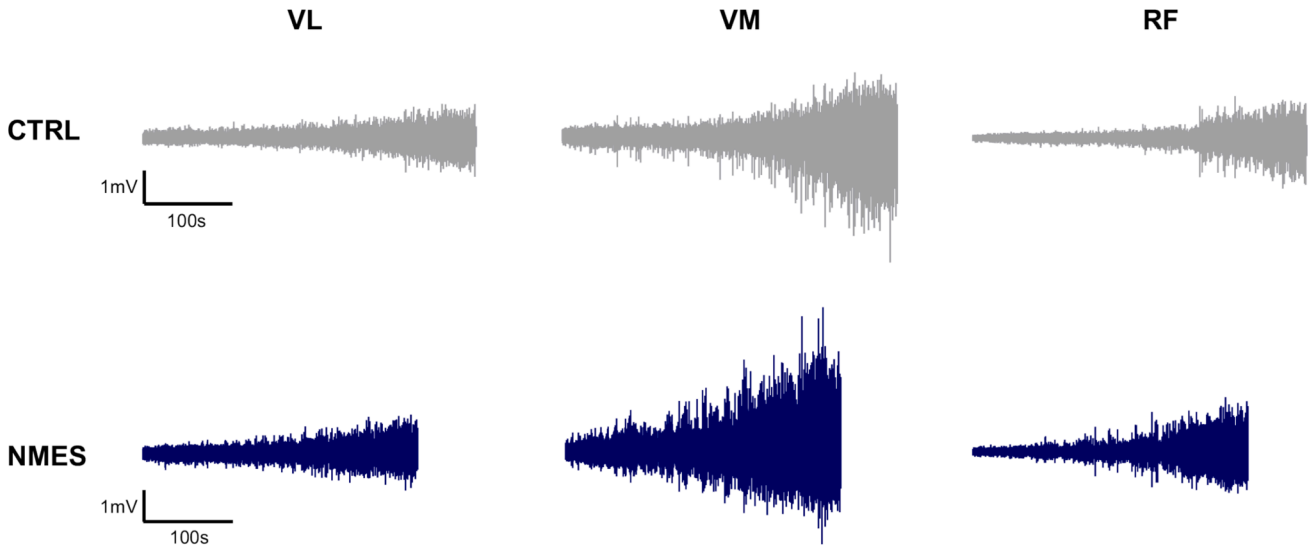

Fig. 3. Original recordings of EMG activity from a representative participant during a sustained contraction until failure in CTRL and NMES conditions for the VL, VM and RF muscles.

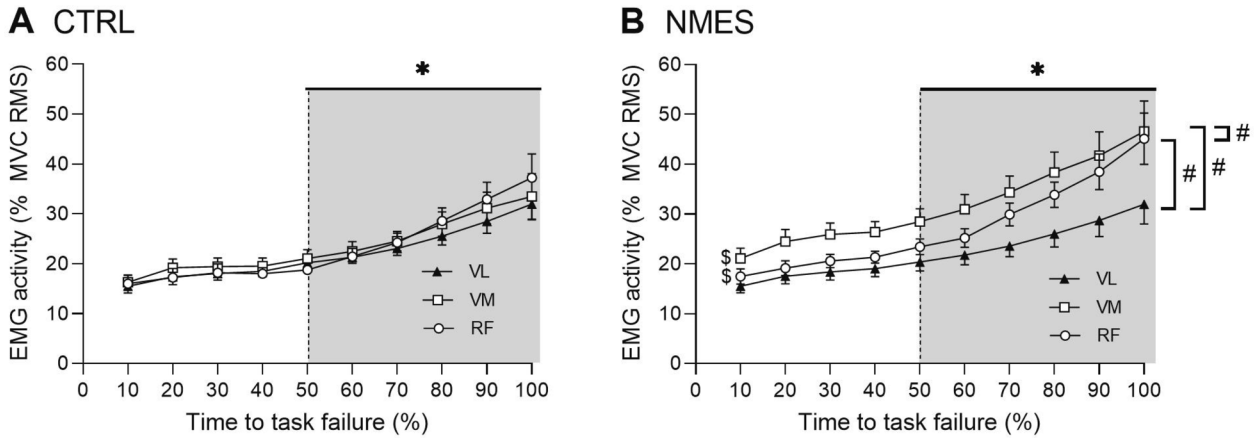

Fig. 4. Submaximal EMG activity of the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) muscles at each 10 % section of respective time to task failure. # difference between muscles at $P < 0.05$; * higher than the first time point (main time effect) at $P < 0.05$. Grey background indicates that all points within the frame are different than the first time point; $ higher mean EMG activity than CTRL at $P < 0.05$. EMG, electromyographic; MVC, maximal voluntary contraction.

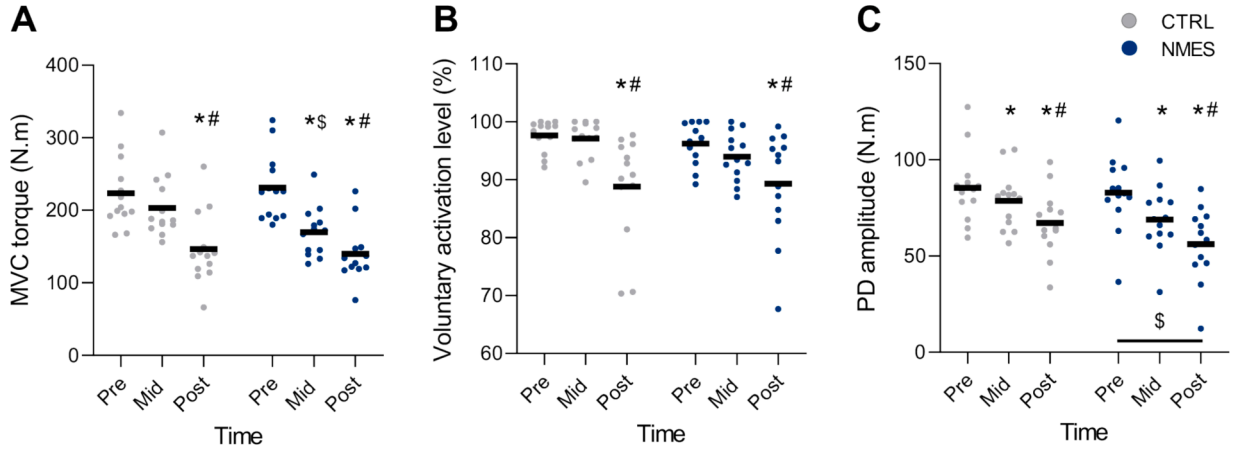

Fig. 5. Maximal voluntary contraction (MVC) torque (A), voluntary activation level (B) and peak doublet (PD) amplitude (C) before the intervention (Pre), after the intervention (Mid) and after the sustained contraction (Post). Dots represent individual values and horizontal bars represent mean values. * lower than Pre at $P < 0.05$; # lower than Mid at $P < 0.05$; $ lower than CTRL at $P < 0.05$.

Table 1
M-wave amplitude (mV) and twitch peak torque (Nm) recorded before the intervention (Pre), after the intervention (Mid) and after the sustained contraction (Post) by muscle and condition.

	VL M−wave		VM M−wave		RF M−wave		Twitch peak torque	
Time	**CTRL**	**NMES**	**CTRL**	**NMES**	**CTRL**	**NMES**	**CTRL**	**NMES**
Pre	9.6 ± 3.2	11.0 ± 3.8	9.2 ± 3.6	10.1 ± 4.5 $	3.6 ± 1.1	4.0 ± 1.4	35 ± 6	35 ± 6
Mid	9.2 ± 2.9	7.9 ± 3.8 *	8.0 ± 3.2	10.6 ± 3.5 $	3.3 ± 0.9 *	3.4 ± 1.1 *	33 ± 5	30 ± 7 *
Post	9.4 ± 3.3	8.2 ± 3.7 *	8.4 ± 3.4	10.2 ± 3.4 $	3.6 ± 0.9	3.6 ± 1.4	30 ± 10*	23 ± 9 *#$

Mean values ± SD. * lower than Pre at $P < 0.05$; $ different from CTRL at $P < 0.05$; # lower than Mid at $P < 0.05$. VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; NMES, neuromuscular electrical stimulation; CTRL, control.

and RF had a higher EMG activity in the NMES than in the CTRL condition, while VL EMG activity was unaffected. Thus, the greater EMG activity of the non-stimulated synergist muscles necessary to sustain the same torque level may explain the premature exercise termination. Although VL EMG activity (expressed as a % of Pre MVC) was similar between NMES and CTRL, normalizing VL EMG activity by the EMG activity measured during the MVC obtained at Mid (i.e., after NMES) resulted in an increased activity at the start of the sustained contraction (from 19 to 24 % MVC, $P < 0.05$) which was probably necessary to compensate for the peripheral alterations induced by NMES.

Bouillard et al. (2014) reported a lower VL force contribution during a submaximal isometric contraction following 5 min of selective NMES; this result does not necessarily contrast with our finding of unchanged VL EMG activity, as a similar EMG activity might lead to a reduced torque production in the presence of peripheral fatigue. However, while we observed compensatory EMG activity from VM and RF muscles, Bouillard et al. (2014) did not report any compensatory activity from VM or RF over time while an increased contribution of the deeper − and unmeasured − *vastus intermedius* muscle could not be excluded. Given the greater extent of muscle fatigue induced by our NMES protocol (6 s at 90 Hz with 27 s of rest for 17 min vs. 3 s at 50 Hz with 2 s of rest for 5 min in Bouillard et al. (2014), resulting in MVC torque losses of −26 vs. −18 %, respectively), it can be hypothesized that increased contribution from VM and RF muscles was needed to compensate the potential reduced participation of the VL muscle to knee extensor torque production.

VM and RF muscles showed increased EMG activity in NMES compared to CTRL, but the increase was lower for the RF muscle. This lower submaximal EMG activity of the RF muscle may be attributed to inter-muscle differences in anatomical function. Indeed, it has been suggested that the bi-articular RF muscle would play an important role in the distribution of net moment between joints to control the direction of the external force while the mono-articular VL and VM muscles would mainly produce the required torque (Doorenbosch and Van Ingen Schenau 1995; van Ingen Schenau et al. 1992). The increased RF EMG activity in the NMES condition suggests that its contribution to the knee extensor torque can increase when VL is fatigued but probably to a lower extent as compared to the VM. This finding may also be explained by a potential crosstalk activation of the RF during NMES due to its proximity with stimulation electrodes; however, if present this effect was limited as the slight reduction in RF M-wave amplitude was found in both NMES and CTRL. The EMG activity of VL and VM was previously reported to be similar even when using various types of EMG biofeedback (Place et al. 2006b), which can be explained by the high level of common drive between these two muscles (Rossato et al., 2022). Our results show that this behaviour can be altered when one of the two muscles is selectively fatigued before a sustained submaximal contraction. Nevertheless, the increased contribution of VM and RF muscles to achieve the same torque output when VL was fatigued certainly contributed to impaired endurance performance as assessed by reduced TTF but did not affect the extent of muscle fatigue induced by the sustained contraction, as MVC torque reduction did not differ between NMES and CTRL. Although the synergist EMG activity was higher in NMES compared to CTRL, there was a comparable RMS time integral – an indirect index of 'neuromuscular cost' to perform the fatiguing contraction – during both fatiguing tasks. We, therefore, propose that the shorter TTF probably offsets the greater fatigue level expected in NMES. Finally, the origin of neuromuscular fatigue was only slightly impacted by the NMES intervention as only peak twitch torque was more impaired in the NMES condition. This was however not the case for doublet peak torque, which is usually considered as a more robust index of peripheral fatigue (Place et al. 2007). The decrease in voluntary activation level and doublet peak torque (with unchanged VL, VM or RF M-wave amplitude) observed between Mid and Post suggest that both central and peripheral − intramuscular − factors accounted for the reduction in maximal force generating capacity after the sustained task, as previously reported (Neyroud et al. 2012; Place et al. 2005; Place et al. 2006a; Place et al. 2006b). The reduction in TTF in the NMES condition, together with similar neuromuscular fatigue levels between both conditions, suggest that additional factors − potentially unrelated to neuromuscular fatigue or not captured by the measurements in this study − may contribute to the reduction in TTF after selective NMES. For example, motoneuron firing behaviour and/or reflexive pathways (Hunter et al., 2004) may play an important role, which have not been considered in the present study.

5. Limitations

The present study was conducted on young healthy males which may limit the generalization of the results to other populations such as females, older individuals or frail patients. Future studies should therefore include different populations from both sexes to extend the validity of our results. We also acknowledge that while the pre-fatigue protocol was meant to mainly target the VL muscle, adjacent muscles may have been stimulated as well, thus potentially confounding the desired selective effect of the fatiguing protocol.

6. Conclusion

In conclusion, this study showed that selective fatigue of the VL muscle affected the performance of a subsequent submaximal contraction to failure. While the extent and the origin of neuromuscular fatigue observed at the end of the submaximal contraction was not different after selective fatigue as compared to the control condition, TTF was reduced in all participants. We observed adjustments in EMG activity following the NMES protocol, with a compensatory activity from VM and RF, which may explain the premature ending of the submaximal contraction. Future studies should explore the underlying neurophysiological mechanisms using for example methods that enable the investigation of motor unit behaviour (e.g., high-density surface EMG decomposition) or the potential involvement of reflex pathways.

Author contribution statement

BM, AM, NAM, RL and NP conceived and designed the research. BM and NP conducted the experiments. CL, BM, SR, and NP contributed to the data analysis. CL and NP wrote the manuscript. All authors read and approved the manuscript.

CRediT authorship contribution statement

Clément Lanfranchi: Writing – original draft, Formal analysis, Data curation. **Boris Matkowski:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sylvain Rayroud:** Writing – review & editing, Formal analysis. **Alain Martin:** Writing – review & editing, Methodology, Conceptualization. **Nicola A Maffiuletti:** Writing – review & editing, Methodology, Conceptualization. **Romuald Lepers:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Nicolas Place:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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