Received: 10 April 2020 | Revised: 17 July 2020 | Accepted: 12 August 2020

DOI: 10.1111/sms.13815

ORIGINAL ARTICLE

WILEY

Task failure during sustained low-intensity contraction is not associated with a critical amount of central fatigue

Robin Souron[1,2] | **Anne-Cloé Voirin**[1] | **Djahid Kennouche**[1] | **Loïc Espeit**[1] | **Guillaume Y Millet**[1,3] | **Thomas Rupp**[4] | **Thomas Lapole**[1]

[1]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, Saint-Etienne, France

[2]Laboratory of Impact of Physical Activity on Health (IAPS), UR n°201723207F, University of Toulon, France

[3]Institut Universitaire de France (IUF)

[4]Inter-university Laboratory of Human Movement Biology (LIBM), University Savoie Mont Blanc, Chambéry, France

Correspondence
Thomas Lapole, Laboratoire Interuniversitaire de Biologie de la Motricité, Bâtiment IRMIS, 10 rue de la Marandière, 42270 Saint Priest en Jarez, France.
Email: thomas.lapole@univ-st-etienne.fr

Funding information
The present study was supported by a post-doctoral research grant from Université Jean Monnet Saint-Etienne assigned to R. Souron.

Fatigue-related mechanisms induced by low-intensity prolonged contraction in lower limb muscles are currently unknown. This study investigated central fatigue kinetics in the knee extensors during a low-intensity sustained isometric contraction. Eleven subjects sustained a 10% maximal voluntary contraction (MVC) until task failure (TF) with neuromuscular evaluation every 3 minutes. Testing encompassed transcranial magnetic stimulation to evaluate maximal voluntary activation (VA_{TMS}), motor evoked potential (MEP), and silent period (SP), and peripheral nerve stimulation to assess M-wave. Rating of perceived exertion (RPE) was also recorded. MVC progressively decreased up to 50% of the time to TF (ie, $50\%_{TTF}$) and then plateaued, reaching ~50% at TF ($P < .001$). VA_{TMS} progressively decreased up to $90\%_{TTF}$ and then plateaued, the decrease reaching ~20% at TF ($P < .001$). SP was lengthened early (ie, from $20\%_{TTF}$) during the exercise and then plateaued ($P < .01$). No changes were reported for MEP evoked during MVC ($P = .87$), while MEP evoked during submaximal contractions decreased early (ie, from $20\%_{TTF}$) during the exercise and then plateaued ($P < .01$). RPE increased linearly during the exercise to be almost maximal at TF. M-waves were not altered ($P = .88$). These findings confirm that TF is due to the subjects reaching their maximal perceived effort rather than any particular central event or neuromuscular limitations since MVC at TF was far from 10% of its original value. It is suggested that strategies minimizing RPE (eg, motivational self-talk) should be employed to enhance endurance performance.

KEYWORDS
central fatigue, RPE, sustained contraction, task failure, transcranial magnetic stimulation, voluntary activation

1 | INTRODUCTION

In some sport activities (eg, hiking sailing), muscles are continuously contracted at low intensities, which can subsequently induce neuromuscular fatigue. The latter is defined as an exercise-induced reduction in maximal voluntary contraction (MVC) force or the inability to produce a certain expected force or power.[1] Despite fatigue, the target force can still be maintained,[2-4] and fatigue should not be confounded with the moment of task failure (TF). The development of fatigue during a prolonged fatiguing task can be tracked by regularly performing brief maximal MVCs during exercise. When peripheral electrical nerve stimulation[5] or transcranial magnetic stimulation (TMS)[6] is used during these MVCs to evoke superimposed twitches (SIT) and calculate the maximal voluntary activation (VA) level, it is possible to

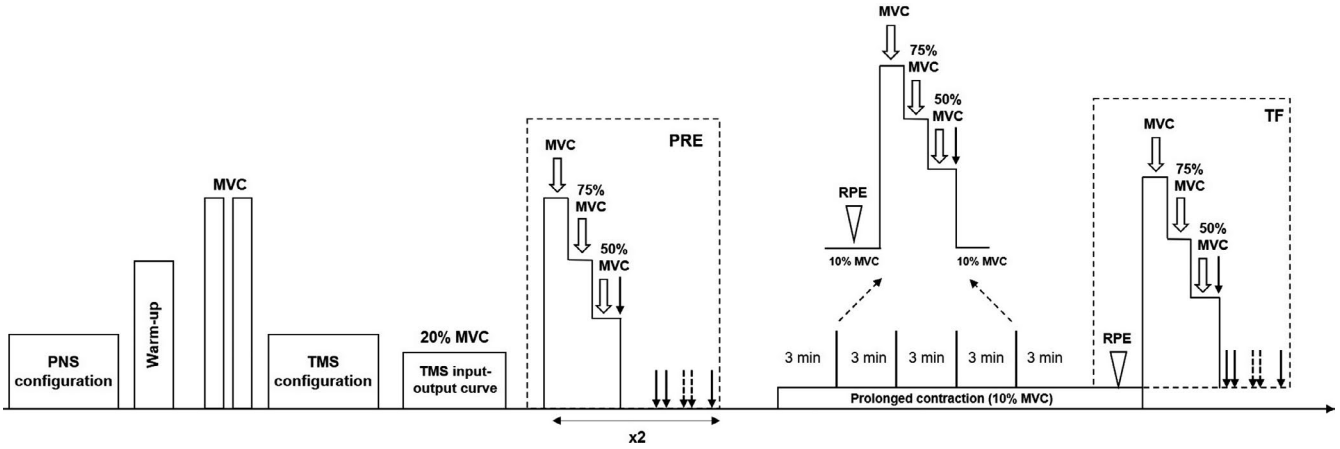

FIGURE 1 Experimental design of the study. Each subject performed a single session with neuromuscular evaluation (NME) performed before (PRE) and at task failure (TF) of the fatiguing protocol that consisted in a sustained submaximal voluntary contraction at 10% MVC until TF. NME (without the stimulations on the relaxed muscles) was also performed every 3 min during the time to exhaustion. Transcranial magnetic stimulations are represented by white arrows. Peripheral nerve stimulations are represented by single (single stimulation), double (double stimulations at 100 Hz), and double-dotted black arrows (double stimulations at 10 Hz)

investigate the occurrence of central fatigue, which refers to the processes within motoneurons and/or the other components of the central nervous system that may influence force reduction.[7]

While many studies have examined central fatigue during maximal or submaximal contractions,[8] studies that investigated low-intensity contractions are scarce. This is important because fatigue is known to be task-dependent.[8] While muscles are frequently contracted at low levels for prolonged periods (as it is the case in some sport activities, eg, hiking sailing), neural drive[3] as well as peripheral consequences (influenced by the level of ischemia) associated with this type of effort may differ from the fatigue induced by stronger contractions.

To the authors' knowledge, only two studies have investigated central fatigue kinetics during low-intensity sustained isometric contraction.[3,4] A gradual increase in TMS-induced SIT has been reported during a 43-minute elbow flexion at 15% MVC.[4] The same group also reported a gradual decline in VA assessed through TMS (ie, VA_{TMS}) during a 70-min elbow flexion at 5% MVC.[3] The results of the last two-cited studies led to the hypothesis that suboptimal output from the motor cortex could explain, at least in part, the progressive decline in maximal force-generating capacities during a prolonged submaximal effort in upper limbs. Yet, no similar findings exist for locomotor muscles, although our group recently showed that fatigue etiology may differ between upper and lower limb muscles.[9] Moreover, it is important to study sustained low-intensity contraction until TF, because setting a given contraction duration, as previously performed,[3,4] may have prevented the capture of the changes that occurred close to TF.[10]

Therefore, the main purpose of the current study was to provide a comprehensive description of central fatigue appearance in knee extensors during a very low-intensity sustained contraction performed to TF. We hypothesized that reduced neural drive would partly explain the gradual decrease in MVC throughout the sustained submaximal contraction.

2 | MATERIALS AND METHODS

2.1 | Subjects

Eleven recreationally active healthy men (age: 24 ± 5 years; height: 181 ± 6 cm; weight: 71 ± 8 kg) volunteered for this study. The sample size was calculated using G*Power (version 3.1.9.2; Kiel University), based on an expected moderate effect size ($f^2 = 0.25$) for MVC PRE-POST differences, with an α level of 0.05, power ($1 - \beta$) of 0.8 and correlation among repeated measures of 0.85. Written informed consent was obtained from all subjects before their participation. This study conformed to standards from the latest revision of the Declaration of Helsinki and was approved by the University of Saint Etienne ethics committee. All subjects were free of lower limb injury during the previous three months, had no contraindications to TMS (as assessed through a safety checklist for the use of TMS[11] prior to the beginning of any testing) and had no acute or chronic neurological disorders and trauma. Subjects were instructed to avoid the consumption of caffeine on the day of the experiment and avoid performing any strenuous exercise for 48 hours before testing.

2.2 | Experimental design

During a separate visit, subjects were familiarized with the correct development of knee extension maximal isometric

force as well as magnetic and electrical stimulations. Then, subjects were tested during a single experimental session (Figure 1). The experimental sessions consisted of a sustained isometric contraction at 10% MVC (based on the PRE MVC, see below) force until TF, that is, when the subject was unable to maintain the submaximal voluntary contraction target for 3 consecutive seconds. Neuromuscular evaluation (NME) was performed before (PRE), every 3 minutes during the submaximal sustained contraction, and immediately at TF (see experimental procedures section for further details).

2.3 | Force and electromyographic recordings

Subjects were seated upright in a custom-built chair with knees and hips at 90° of flexion. A non-compliant strap connected to a force transducer was attached 3-5 cm above the subject's lateral malleolus. Subjects were instructed to push against the strain gauge (ie, knee extension) with their dominant (right) leg, determined as the preferred leg used to kick a ball. Force data were acquired using a PowerLab data acquisition system (16/30-ML880/P, ADInstruments) at a sampling rate of 2 kHz. Movements of the upper body were minimized using two belts across the thorax. During all measurements, subjects were provided with real-time feedback of their force trace on a screen, and guidelines were plotted when subjects had to maintain a targeted percent of MVC. Strong verbal encouragements were given during MVCs as well as during the sustained fatiguing contraction. EMG signals were recorded from rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) muscles with pairs of self-adhesive surface electrodes (Meditrace 100; Covidien) in a bipolar configuration with a 30-mm interelectrode distance. According to SENIAM recommendations, RF electrodes were placed at 50% on the line from the anterior spina iliaca superior to the superior part of the patella; VL electrodes at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella; VM electrodes at 90% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament. Electrodes were also placed on the antagonist biceps femoris (BF) at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. The ground electrode was positioned on the patella. Low impedance (<5 kΩ) between electrodes was obtained by shaving and gently abrading the skin and then cleaning it with isopropyl alcohol. Signals were amplified with an octal bio-amplifier (ML138, ADInstruments), band-pass-filtered (5-500 Hz), and analogue-to-digitally converted at a sampling rate of 2 kHz by PowerLab System (16/30, ADInstruments). All data were analyzed offline using LabChart 7 software (ADInstruments).

2.4 | Peripheral nerve stimulation

Single rectangular electrical pulses with 0.2-ms duration and 400 V maximal output voltage were delivered via constant-current stimulator (DS7AH, Digitimer) to the right femoral nerve via a 30-mm diameter surface cathode (Meditrace 100) taped to the skin into the femoral triangle and a 50 × 90 mm anode (Dura-Stick Plus; DJO Global Vista) in the gluteal fold. To determine the optimal intensity of stimulation, single stimuli were delivered incrementally by steps of 10 mA until resting M-wave and twitch amplitudes plateaued. The optimal intensity was then increased by 20% to ensure supramaximality. The mean intensity for peripheral nerve stimulation (PNS) was 370 ± 120 mA.

2.5 | Transcranial magnetic stimulation

The left motor cortex was stimulated by a magnetic stimulator (Magstim 2002, The Magstim Company Ltd) with a 110-mm double-cone coil (maximum output of 1.4 T). The coil was positioned to induce a postero-anterior current and manually controlled by the same investigator throughout all the testing sessions. A cervical collar was worn during all TMS measures to stabilize the head and neck, and a swim cap was worn to ensure consistent coil placement relative to the optimal position. To determine this site, six marks were drawn on the cap: the vertex, 1 and 2 cm posterior to the vertex, and 1 cm to the left of these 3 marks along the midline. Optimal coil position was determined as the site eliciting the largest SIT as well as VL, VM, and RF MEP amplitudes, with a small MEP amplitude in the antagonist BF in response to stimulation at a known suprathreshold stimulator output (50% of maximal stimulator output) during a 10% MVC knee extension. When optimal agonist MEP and peak force were not recorded at the same coil position, the optimal coil position was chosen according to MEP amplitude, because the evoked peak force may be influenced by activation of other muscles.[12] This position was marked on the swim cap and was the same for RF, VL, and VM muscles.

The optimal stimulus intensity was determined from SIT and MEP stimulus-response curves obtained during brief (2-3 seconds) voluntary contractions at 20% MVC. In brief, intensities of 40%, 50%, 60%, 70%, and 80% of maximal stimulator output were tested in random order. At each intensity, four contractions were performed at 10-s intervals. A rest period of 10 seconds separated each intensity. The optimal stimulation intensity was considered as the one that elicited maximal MEP on VL, VM, and RF with minimal MEP on the antagonist BF. Since no M-waves were recorded on the BF, a low BF MEP was arbitrary fixed at an amplitude <10% of VL MEP.[13] The

mean TMS intensity (62 ± 6% stimulator output) allowed to record MEP >50% M-wave, as recently recommended for VA_{TMS} calculation.[12]

2.6 | Experimental procedures

The experimental procedures are illustrated in Figure 1. First, the optimal configuration (ie, position and intensity) was determined for PNS. After a standardized warm-up consisting of 3 brief (~3 seconds) knee extensor isometric voluntary contractions at 20%, 40%, 60%, and 80% of the MVC recorded during the former and separated familiarization session, subjects performed 2 brief (~3 seconds) MVCs interspersed by 1 minute. Optimal coil position and intensity for TMS were then established. VA_{TMS} was then calculated based on a continuous method where subjects were asked to perform a single voluntary contraction including an initial ~3 seconds MVC followed by a voluntary reduction in force output to match 75% MVC and then 50% MVC with no rest period in-between (Figure 2A).[14] This was done using a specific macro on the LabChart software that automatically calculated 75% and 50% of the preceding MVC once the TMS stimulation was delivered. Single TMS pulses were delivered during each level of contraction and a single PNS pulse was delivered during the 50% MVC contraction. To permit accurate determination of the SP, subjects were instructed to momentarily (<1 second) re-contract as quickly as possible immediately after delivery of the single TMS pulse. This procedure was performed twice during PRE and once during measurements at the other time points. For PRE and TF measurements, single and double electrical (ie, 100 and 10 Hz) nerve stimulations were delivered on the relaxed muscle after the MVC (Figure 2A). Immediately after the beginning of the task and twenty seconds before each NME during the sustained submaximal contraction (Figure 1), subjects were asked to verbally report their rating of perceived exertion (RPE, not pain), that is, how hard they perceived the exercise, using a 100-mm visual analogue scale, with "no effort" on one end (0 mm) and "exhaustion" on the other (100 mm). NME during and at TF was performed as an extension of the prolonged submaximal voluntary contraction, that is, subjects were not permitted to relax and went straight into the MVC at the moment of TF (Figure 1).

2.7 | Data analysis

Because the exercise duration and thus the number of completed NMEs were different between subjects, interpolation was used to present the data. First, each actual NME was considered to refer to a given percentage of the total exercise duration,

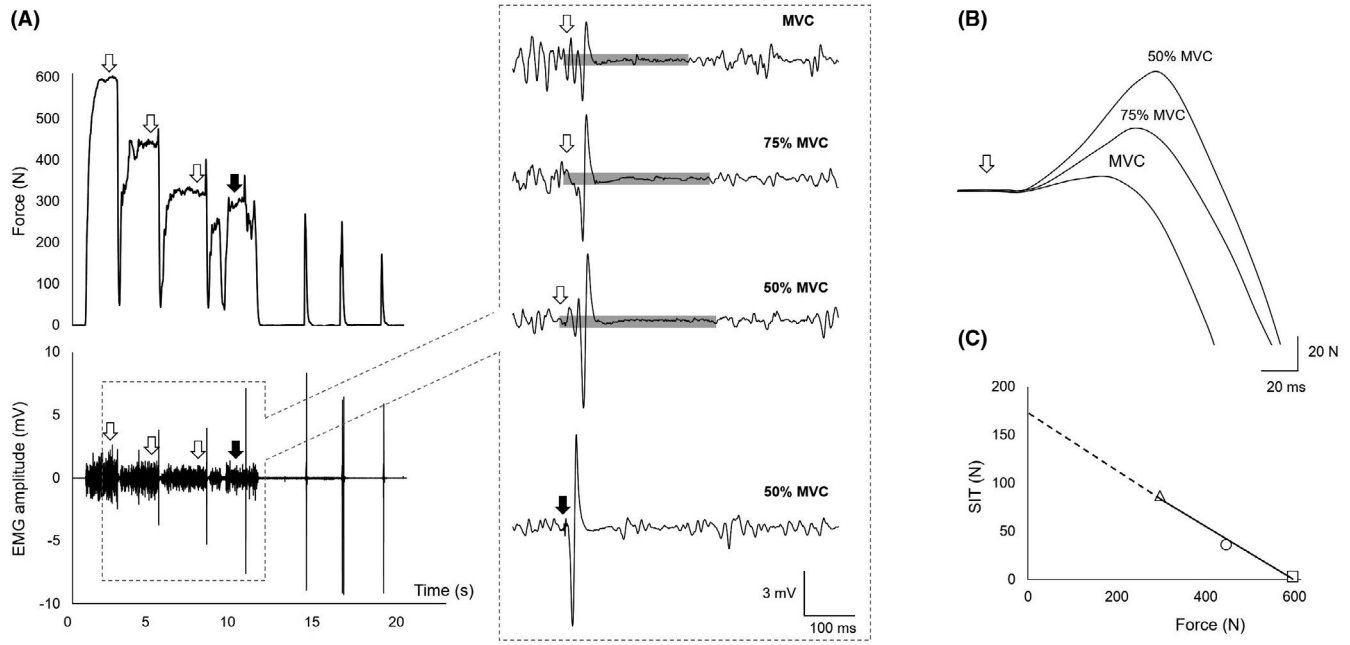

FIGURE 2 A, Typical force trace and EMG recordings for the vastus lateralis muscle before the fatiguing task. The bottom part of the panel A shows EMG background and the MEP and SP evoked during maximal (MVC) and submaximal voluntary contractions at 75% and 50% MVC and followed by the M-wave evoked at 50% MVC. Open arrows represent TMS, and filled arrows represent PNS. The gray box represents the silent period duration, that is, the time interval between TMS stimulus and the return of continuous voluntary EMG. B, Raw traces of the TMS superimposed twitches (SIT) evoked during MVC and submaximal contractions at 75% and 50% MVC. C, Amplitude of SIT produced by TMS during maximal (white square) and submaximal contractions at 75% (white circle) and 50% MVC (white triangle). The linear regression was extrapolated, and the *y*-intercept (dashed line) was interpreted as the ERT amplitude. Data are from a representative subject

assuming the last evaluation (ie, TF) corresponds to 100% of the time to task failure (TTF). For instance, a subject maintaining the task for 33 minute performed 11 NMEs throughout the exercise, the first NME then corresponding to 9.1% of the total duration, the 5th and the 6th NMEs, respectively, corresponding to 45.5% and 54.5%$_{TTF}$ and the last NME corresponding to 100%$_{TTF}$ (ie, TF; exhaustion). Data were then linearly interpolated between actual NMEs to obtain values corresponding precisely, for each subject, to 10% (10%$_{TTF}$), 20 (20%$_{TTF}$), etc until TF.

Areas of the evoked MEP and M-waves were measured offline. Evoked EMG data (M-waves, MEP, and SP) are presented as the average values of all responses collected for each time points. A representative trace of the three types of evoked potentials obtained during maximal and submaximal voluntary contractions is displayed in Figure 2A.

2.7.1 | Peripheral nerve stimulation

M-wave areas (Msup) were measured from electrical nerve stimulations in VL, RF, and VM muscles during voluntary contractions at 50% MVC during each NME. The amplitudes of the potentiated peak twitch (Pt), as well as low- and high-frequency doublets (Db10 and Db100, respectively) were determined only for PRE and TF measurements. Low-frequency fatigue was then assessed from the change in the ratio Db10 to Db100 (Db10:100).

2.7.2 | Force and voluntary EMG

Maximal force was considered as the peak value recorded before the first TMS stimulus. At PRE, the highest MVC over the two trials was chosen for further analysis. Maximal root-mean-square EMG (RMS_{MAX}) was calculated for VL, RF, and VM muscles over a 500-ms period during MVC before TMS delivery. RMS EMG was also measured during the 10% MVC sustained voluntary contraction over 500 ms before brief MVCs (ie, $RMS_{10\%MVC}$). RMS recorded on each muscle was then normalized to the peak-to-peak amplitude of the maximal M-wave.

2.7.3 | Transcranial magnetic stimulation

Motor evoked potential motor evoked potential areas were recorded during maximal (MEP_{MVC}) and submaximal voluntary contractions at 75 (MEP_{75}) and 50% MVC (MEP_{50}) for VL, RF, and VM, and normalized to M_{sup} areas.

Transcranial magnetic stimulation to evaluate maximal voluntary activation (VATMS) was measured by the modified twitch interpolation technique.[14] Estimated resting twitch (ERT) was determined by linear regression of the relation between superimposed twitch (SIT) amplitude evoked when TMS was delivered at MVC, 75% and 50% MVC (Figure 2B), and voluntary force. This relation was extrapolated, and the *y*-intercept was interpreted as the ERT amplitude (Figure 2C). At PRE, the highest VA_{TMS} from the two trials performed was retained. VA_{TMS} was calculated as follows:

$$VA_{TMS} = \left(1 - SIT_{MVC}/ERT\right) \times 100$$

where SIT_{MVC} is the superimposed twitch evoked during contraction at 100% MVC. VA_{TMS} was considered appropriate when (a) TMS delivered over the motor cortex at 100% MVC produced a large MEP in the agonist muscles with a small MEP in the antagonist muscle, that is, <10% of VL, VM, and RF MEP,[13] and (b) the regression of voluntary force and the SIT force evoked during the contractions was linear ($r^2 > .9$). Based on these two criteria, one subject was excluded for VA_{TMS} analysis because of $r^2 < .9$.

Silent period durations were recorded during maximal (SP_{MVC}) and submaximal voluntary contractions at 75 (SP_{75}) and 50% MVC (SP_{50}) for VL, RF, and VM. SP was determined visually and defined as the duration from the TMS stimulus to the return of continuous voluntary EMG, that is, when clear EMG bursts could be identified (Figure 2A).

2.8 | Statistical analysis

Statistical analyses were performed with Statistica software (StatSoft Inc). All variables were normally distributed (Kolmogorov-Smirnov normality test). Shapiro-Wilk and Mauchly tests were used to ensure the assumptions of normality and sphericity, respectively, for all dependent variables. Greenhouse-Geisser correction factor was applied when the assumption of sphericity was violated. For ANOVAs, homogeneity of variance was verified by Levene's test. A one-way analysis of variance (ANOVA) for repeated measures was performed for MVC, VA_{TMS}, and RPE to test for time effects during the prolonged submaximal voluntary contraction (ie, PRE, 10%$_{TTF}$, 20%$_{TTF}$, 30%$_{TTF}$, 40%$_{TTF}$, 50%$_{TTF}$, 60%$_{TTF}$, 70%$_{TTF}$, 80%$_{TTF}$, 90%$_{TTF}$, TF). Two-way repeated-measures ANOVA were performed for $RMS_{10\%MVC}$, RMS_{MAX}, M_{sup}, MEP, and SP [muscle (VL, RF, VM) × time]. Changes in peripheral function were not investigated during the fatiguing task (with the exception of M_{sup}) so paired *t* tests were used to test the effect of time (PRE, TF) for Pt, Db10, Db100, and Db10/Db100 ratio (Db10:100). If significant main or interaction effects were detected, Bonferroni-corrected post-hoc tests were performed. Pearson's correlations were used to determine relationships between MVC drop and VA_{TMS} changes during

exercise. Partial eta square ($p\eta^2$) was reported as an estimate of effect size, with $p\eta^2 \geq 0.07$ and $p\eta^2 \geq 0.14$ used as moderate and large effects, respectively.[15] Statistical significance was set at $P < .05$. All data are presented in the text and figures as mean ± standard deviation (SD).

3 | RESULTS

The mean duration of the sustained voluntary contraction was 33 ± 23 minutes (range: 13-91 minutes). An increase in $RMS_{10\%MVC}$ was observed during the sustained low-intensity contraction for VL, VM, and RF, as reported by a significant time effect ($P < .001$; $p\eta^2 = 0.66$; Figure 3D). $RMS_{10\%MVC}$ recorded during the sustained low-intensity contraction was significantly increased from $30\%_{TTF}$ and onward when compared to the first 10% of the task ($P = .001$-0.0001). The increase in $RMS_{10\%MVC}$ plateaued at $60\%_{TTF}$ (ie, the plateau was determined when the time point, in this specific case $60\%_{TTF}$, was not statistically different with the value recorded at TF).

3.1 | MVC and central fatigue

A significant time effect was found for MVC ($P < .001$; $p\eta^2 = 0.82$; Figure 3A). At TF, MVC was decreased by 49.2 ± 17.1% when compared to PRE. While MVC recorded at $10\%_{TTF}$ was not different compared to baseline ($P = .97$), the decrease was found to be significant from $20\%_{TTF}$ ($P < .001$). While MVC "visually" decreased up to $80\%_{TTF}$, values recorded from $50\%_{TTF}$ were not statistically different from TF ($P = .49$-1).

The force decrease was accompanied by a decrease in VA_{TMS} as indicated by a significant time effect ($P < .001$; $p\eta^2 = 0.60$; Figure 3B). At TF, VA_{TMS} was decreased by 20.8 ± 18.1%. The decrease in VA_{TMS} was significant from $40\%_{TTF}$ ($P = .04$) when compared to baseline. While VA_{TMS} seems to "visually" decrease until $90\%_{TTF}$ before plateauing, there was no statistical

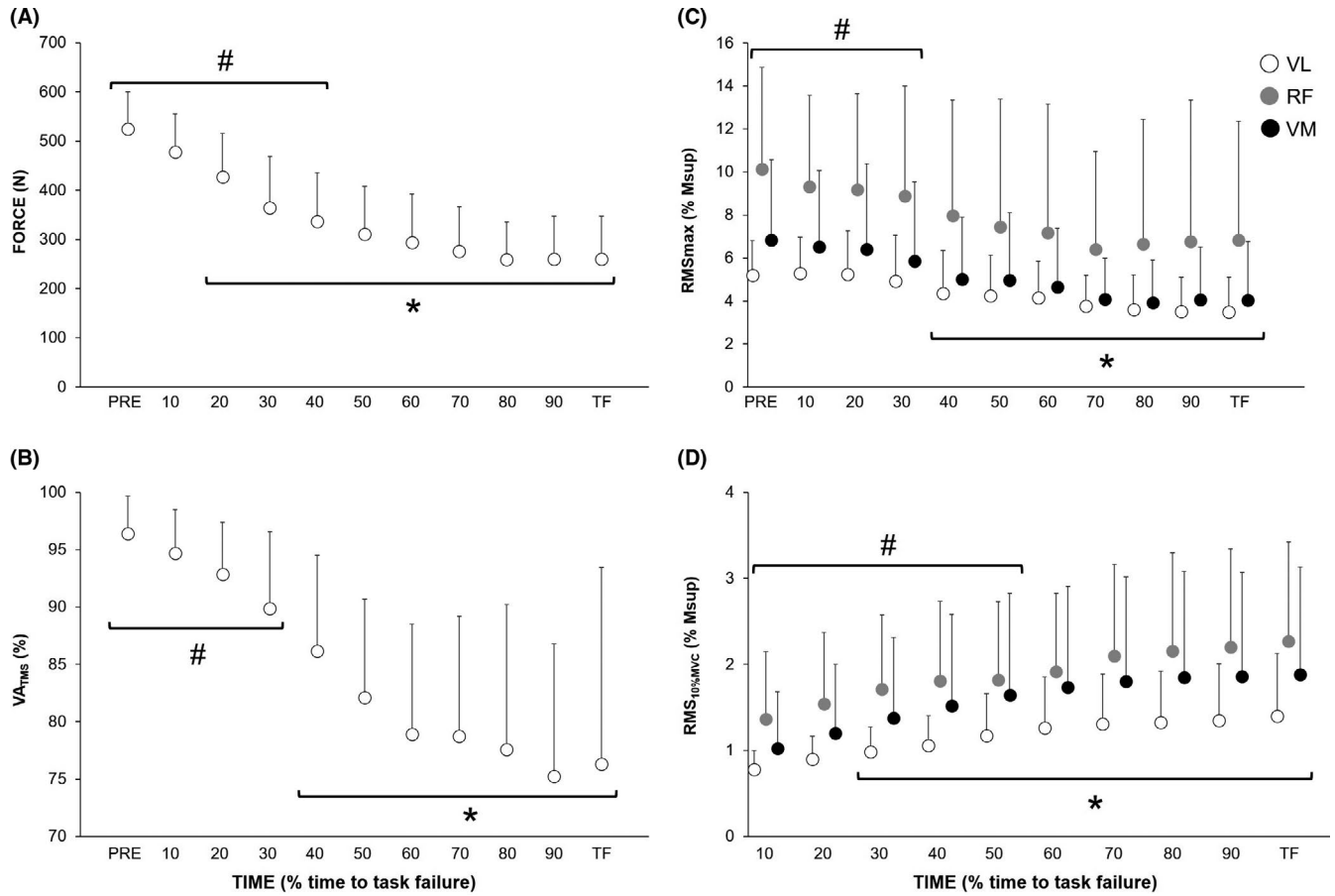

FIGURE 3 Changes in knee extensors maximal voluntary contraction (MVC) isometric force (A), voluntary activation (VA_{TMS}; B), and maximal root-mean-square EMG (RMS_{MAX}; C) during (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the time to task failure) and immediately at task failure (TF, performed as an extension of the prolonged submaximal voluntary contraction). *Panel D* displays the root-mean-square EMG recorded 500 ms before the brief MVCs during the sustained submaximal voluntary contraction. Data are presented as mean ± SD. Significantly different from PRE: *$P < .05$. Significantly different from TF: #$P < .05$

difference between VA_{TMS} values from $40\%_{TTF}$ and TF (eg, $P = .07$ between $40\%_{TTF}$ and TF). Yet, VA_{TMS} was lower at $90\%_{TTF}$ than $40\%_{TTF}$ ($P = .02$). The relationship between MVC drop and VA_{TMS} changes across exercise showed a strong and significant linear regression ($r = .97$; $P < .001$).

While there was no significant muscle × time interaction for normalized RMS_{MAX} ($P = .55$; $p\eta^2 = 0.09$), a significant time effect was reported ($P < .001$; $p\eta^2 = 0.49$). At TF, the mean decrease in RMS_{MAX} was 35.3 ± 25.9% (pooled data for the three muscles). When compared to baseline and regardless of the investigated muscle, post-hoc analysis revealed a significant decrease in normalized RMS_{MAX} from $40\%_{TTF}$ ($P = .03$-0.0001; Figure 3C).

3.2 | Corticospinal excitability and inhibition

There was no significant muscle × time interaction for any TMS-induced EMG parameters. A significant time effect was reported for MEP areas recorded during 75% ($P < .0021$; $p\eta^2 = 0.34$) and 50% ($P < .001$; $p\eta^2 = 0.50$) but not 100% ($P = .87$; $p\eta^2 = 0.06$) MVC. When compared to baseline and regardless of the investigated muscle, post-hoc analysis revealed a significant decrease in MEP_{75} and MEP_{50} from $20\%_{TTF}$ ($P = .001$-0.0001; Figure 4A).

A significant time effect was also reported for SP recorded during MVC ($P < .001$; $p\eta^2 = 0.62$), 75% MVC ($P < .001$; $p\eta^2 = 0.59$), and 50% MVC ($P < .001$; $p\eta^2 = 0.58$). When compared to baseline and regardless the investigated muscle, post-hoc analysis revealed a significant increase in SP duration from $20\%_{TTF}$ for MVC, 75% MVC, and 50% MVC $_{TTF}$ ($P = .04$-0.0001; Figure 4B).

3.2.1 | Rating of perceived exertion

A significant time effect was reported for RPE ($P < .001$; $p\eta^2 = 0.92$) with an increase throughout the sustained exercise. When compared to the value recorded immediately after the beginning of the task, RPE increased almost linearly from $10\%_{TTF}$ (all $P < .001$; Figure 5).

3.2.2 | Peripheral function

At TF, Pt, Db100, and Db10:100 were reduced by 34 ± 10% ($P < .001$; $p\eta^2 = 0.82$), 19 ± 7% ($P < .001$; $p\eta^2 = 0.72$), and 35 ± 8% ($P < .001$; $p\eta^2 = 0.90$), respectively, when compared to PRE (Figure 6A). M_{sup} was not altered during the fatiguing exercise and at TF as reported by the non-significant time effect ($P = .16$; $p\eta^2 = 0.13$) or muscle × time interaction ($P = .88$; $p\eta^2 = 0.06$; Figure 6B).

4 | DISCUSSION

The present study investigated for the first time the time course of fatigue appearance during sustained low-intensity knee extensors contraction performed until TF. Our results showed a progressive decline in MVC up to $50\%_{TTF}$, together with an increase in central fatigue as evidenced by the decline in VA_{TMS} up to $90\%_{TTF}$. Changes in corticospinal excitability (ie, MEP area) and inhibition (ie, SP duration) do not seem to have a major influence on central fatigue as they plateaued early during exercise. Performance limitation is thought to be due to the subjects' perceived effort that was nearly maximal at TF.

4.1 | Gradual decrease in maximal force-generating capacity

A large variability was reported in the time to TF (TTF) in the present study (ie, mean duration of 33 ± 23 minutes; range: 13-91 minutes). This variability cannot be explained by differences in the level of physical activity since only subjects with regular physical activity ranging between 2 and 6 hours were included. Differences in genetics, in training experience, and in the nature of the activities performed by the subjects (eg, resistance training vs endurance training) may explain the variability in TTF. Another explanation for this variability in TTF could be intersubjects' differences in critical torque, that is, the maximal sustainable work rate at which energy supply can be provided and sustained from oxidative metabolism.[16] Such differences in critical torque (thus in TTF) could rely on several mechanisms, for example, fiber type composition, muscle capillarity.[16] The fact that subjects performed brief MVC every 3 minutes during the sustained low-intensity contraction could have influenced the development of fatigue. While this has been discussed by others that used similar protocols,[3,4] our experimental design does not allow to draw any conclusion on this point. To shed light on this issue, future studies should compare fatiguing tasks with and without frequent MVCs performed during low-intensity contractions. Fatigue produced by the sustained submaximal knee extension was revealed by a ~50% decline in MVC at TF. Several studies have investigated fatigue immediately (ie, without any resting period between TF and the last measurements) after a sustained submaximal contraction of the knee extensors performed up to TF.[17-20] They reported a decreased MVC of ~30%,[18] ~35%,[17,20] and ~50%[19] after sustained isometric contractions between 10% and 50% MVC. The greater fatigue level in the present study may be explained by the longer task duration in our study, that is, mean duration of 33 minutes vs 2-14 minutes in the aforementioned studies. It has been demonstrated for the first dorsal interosseous that the lower the contraction intensity, the longer the task

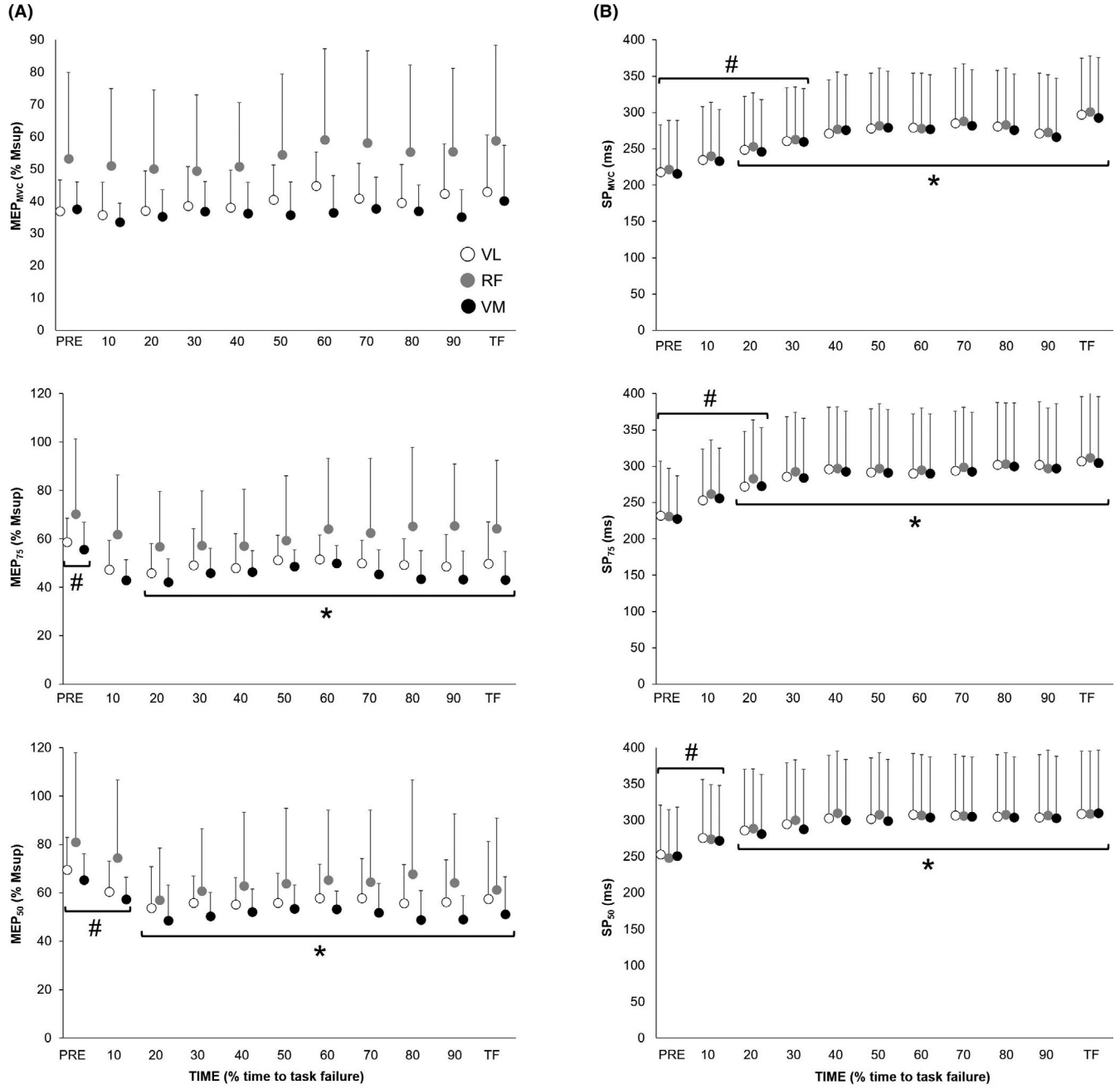

FIGURE 4 Changes in motor evoked potential (MEP; *A*) and silent period (SP; *B*) during (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the time to task failure) and immediately at task failure (TF, performed as an extension of the prolonged submaximal voluntary contraction). MEP and SP were recorded during maximal (MEP_{MVC} and SP_{MVC}, respectively) and submaximal voluntary contractions at 75 (MEP_{75} and SP_{75}) and 50%MVC (MEP_{50} and SP_{50}). Data are presented as mean ± SD. Significantly different from PRE: $^*P < .05$. Significantly different from TF: $\#P < .05$

duration and the greater the amount of fatigue.[2] While already reported during long-duration cycling[21] or running[22] exercises, the plateau observed in MVC decline (ie, MVC progressively decreased up to $50\%_{TTF}$ with no more significant decline thereafter) is an original and interesting result when a sustained submaximal modality of exercise is used. The mechanisms behind such a plateau are not clear and warrant further investigations.

4.2 | Changes in voluntary activation, corticospinal excitability, and inhibition

To further explain the decrease observed during brief MVCs, the present study investigated for the first time the time course of central fatigue appearance on knee extensors using TMS during a sustained isometric very low-intensity contraction. VA_{TMS} decreased from $40\%_{TTF}$ to reach a decrease

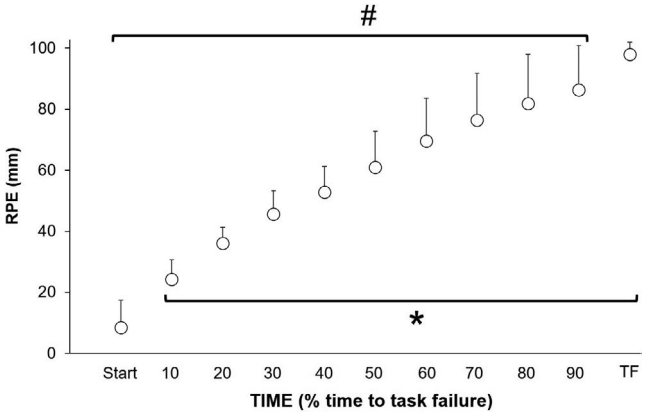

FIGURE 5 Ratings of perceived exertion (RPE) recorded immediately after the beginning of the prolonged submaximal voluntary contraction (Start), during (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the time to task failure), and immediately at task failure (TF, performed as an extension of the prolonged submaximal voluntary contraction). Data are presented as mean ± SD. Significantly different from Start: $*P < .05$. Significantly different from TF: $\#P < .05$

of ~21% at TF (ie, 96% vs 76% at PRE and POST, respectively). Similar results were reported in elbow flexors, with decrease of ~15%[3] and ~22%[4] observed at the end of sustained prolonged isometric contractions performed at 5% and 15% MVC, respectively. However, while these two studies performed on the elbow flexors are the only ones that investigated VA_{TMS} during prolonged and sustained isometric contraction, one should note that exercise duration was fixed (ie, 70 minutes[3] and 43 minutes[4]) while exercise was performed until failure in our study, limiting the comparison between results. Statistically, the decrease in VA_{TMS} plateaued (ie, absence of significant differences with TF) at $40\%_{TTF}$. Yet, one should note that the decrease in VA_{TMS} was significant between $40\%_{TTF}$ (86 ± 8%) and $90\%_{TTF}$ (75 ± 11%), suggesting that the plateau occurred far after $40\%_{TTF}$. Interestingly, this plateau does not seem to occur in a similar-designed study involving the elbow flexors.[3] As reported after a 2-minute sustained MVC,[9] additional work could be useful to investigate whether central modulations differ between upper and lower limb muscles when a sustained low-intensity contraction is used.

As previously demonstrated for knee extensors,[9,10] the relationship between force and VA_{TMS} remained linear with fatigue in our study. Thus, it was possible to estimate the contribution of central fatigue to the total force loss. For each subject, the linear force-VA_{TMS} relationship was determined immediately after TF[3,9,10] as well as at each time points of the TTF. Using the regression equation, the force corresponding to VA_{TMS} recorded at PRE was determined and compared with the real MVC recorded at every time points between $10\%_{TTF}$ and TF included. Any additional force loss was interpreted to be due to central fatigue. As previously reported in some upper-[3] and lower limb[10] muscle exercise, the contribution of central fatigue to the total force loss gradually increased throughout the sustained exercise, accounting for approximately 18%, 22%, 28%, 33%, and 38% of the total force loss at $20\%_{TTF}$, $40\%_{TTF}$, $60\%_{TTF}$, $80\%_{TTF}$, and TF, respectively.

The sustained 10% MVC induced a lengthening in SP early during exercise, that is, from $20\%_{TTF}$ for SP recorded during both maximal and submaximal contractions. SP duration increases has widely been reported after sustained maximal[9,14,23] and submaximal[24] voluntary contractions of various muscular groups. Because the initial part of SP reflects both an inhibition of descending drive and reduced excitability of the motoneurons, while the latter part reflects intracortical inhibition-related processes, we believe that the increased SP duration reported in this study reflects increased intracortical inhibition. While subjects were instructed to contract as quickly as possible after the TMS, one should note that the aim was to reach a lower force level (ie, after the MVC, subjects were asked to re-contract at 75% MVC, and after the 75% MVC, subjects were asked to re-contract at 50% MVC; Figure 2). This could have influenced the results, likely causing longer SP duration. Further studies should investigate at which degree these experimental considerations could bias the SP-related results.

Moreover, while no changes were reported in MEP_{MVC} during or at TF, agreeing with results obtained on elbow flexors during similar fatiguing exercises,[3,4] we reported decreased MEP during the task when evoked during submaximal voluntary contractions at 75% and 50% MVC. Interestingly, this decreased corticospinal excitability was observed as soon as $20\%_{TTF}$ and then plateaued until TF. Such results, however, do not agree with previous studies on elbow flexors that reported increased corticospinal excitability when recorded during the low-intensity fatiguing contraction level (ie, 5%[3] and 15%[4] MVC).[3,4] The decrease in MEP recorded during contractions at 75% and 50% MVC may rely on the fact that RMS EMG was decreased during the exercise at these submaximal levels of contractions (data not shown). While RMS_{MAX} was also decreased during the exercise, the fact that less motoneurons are in the refractory period during MVC could be a speculative explanation for why MEP recorded during MVC remained unchanged during the exercise and at TF. By combining TMS with corticospinal tract stimulation at the thoracic level, recent studies demonstrated that motoneuron excitability was quickly diminished (before plateauing) during sustained isometric knee extension performed at 25[25] and 50%[26] of the RMS EMG associated with 25% and 50% MVC, respectively. Although not directly investigated in this study, the spinal contribution to the overall fatigue cannot be ruled out. The influence of spinal mechanisms on fatigue could relate on complex mechanisms occurring at both pre- and post-synaptic levels. Similar experimental designs along with the use of specific neurostimulation techniques[27]

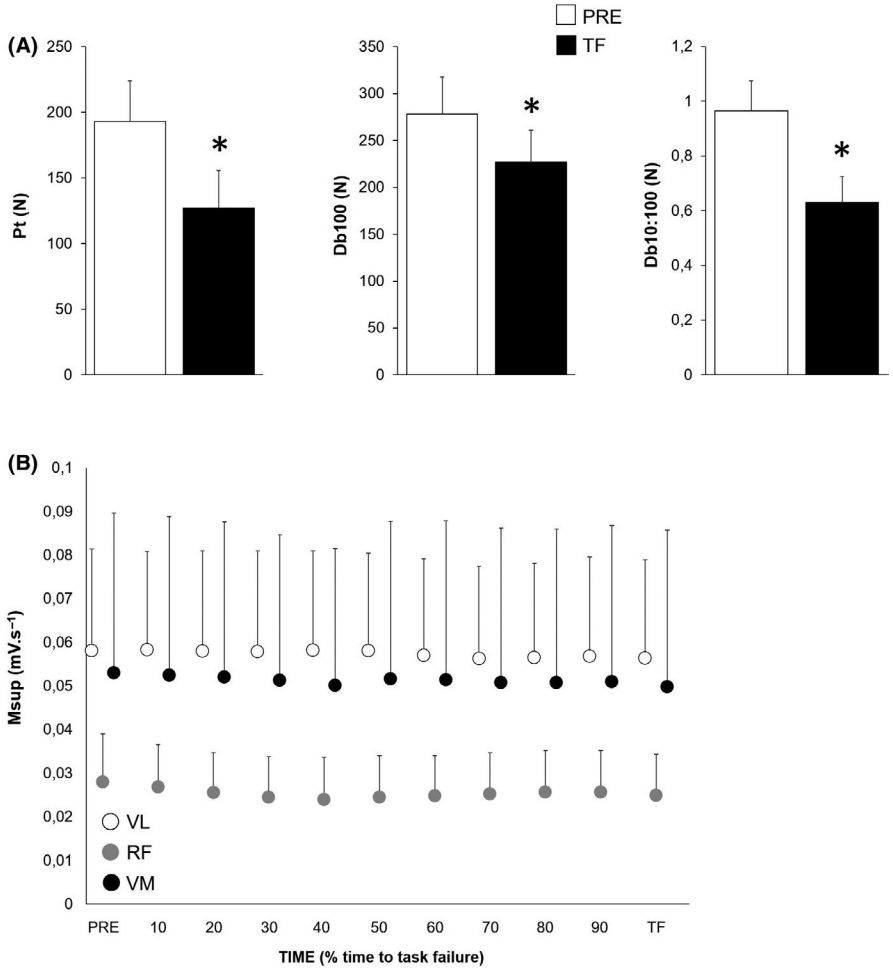

FIGURE 6 *Panel A* displays the electrically evoked force-related results with the amplitude of the potentiated peak twitch (Pt), potentiated peak doublet evoked at 100 Hz (Db100), and ratio between amplitude of the potentiated peak doublet evoked at 10 and 100 Hz (DB10:100). Pt, Db100, and Db10:100 were recorded before (PRE) the fatiguing contraction and immediately at task failure (TF). *Panel B* displays the results for M-waves recorded during 50%MVC (Msup) on vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM) muscles. Msup were recorded before (PRE), during (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the time to task failure), and immediately at task failure (TF, performed as an extension of the prolonged submaximal voluntary contraction). Data are presented as mean ± SD. Significantly different from PRE: $^{*}P < .05$

could allow to gain knowledge on the mechanisms of impaired spinal motoneuron excitability induced by this form of low-intensity prolonged exercises. Further studies should also investigate the origin of such force-dependent corticospinal excitability modulation with fatigue.

The repetitive activity within the motor pathway during the fatiguing exercise could be responsible for SP- and MEP-related changes,[28] leading to a decrease in the excitability of the corticospinal pathway (except during MVC when considering MEP-related data) that plateaued as early as at $20\%_{TTF}$, suggesting that this cannot explain the VA_{TMS} decrease up to $90\%_{TTF}$. The action of III and IV muscle afferents at the supraspinal level is known to greatly contribute to the decrease in VA_{TMS}.[4,23,28] This is especially true in lower limb compared with upper limb muscles.[9] The possible activation of such afferents in response to the increased metabolites concentration due to fatigue likely reduced VA_{TMS} without impacting MEP and SP after $20\%_{TTF}$. Firing of fatigue-sensitive muscle afferents likely exerted its effects upstream of the motor cortex explaining why VA_{TMS} was impaired up to $90\%_{TTF}$, while MEP and SP were not. Such an hypothesis relies on results supporting that VA was still altered when a muscle was held ischemic after a fatiguing exercise (thus maintaining firing of group III and IV afferents), while changes in MEP and SP induced by the fatiguing exercise recovered.[23] Yet, explaining the present decrease in VA_{TMS} by the influence of group III and IV afferents remains speculative in the context of the present study.

4.3 | The role of peripheral fatigue in MVC force loss

As shown above, central fatigue was found to contribute to almost 40% of force loss at TF, meaning that peripheral mechanisms contributed even more to the decline in force, what agrees with previous findings.[19] However, since the present study was designed to better understand the central component of fatigue, peripheral fatigue was not assessed during the sustained and prolonged exercise for methodological reasons, that is, Pt was not assessed during the task to avoid short resting periods that may have impacted central mechanisms.[14] The presence of peripheral fatigue was evidenced by the decrease in Pt (−34%) and Db100 (−19%) at TF. Db10:100 also decreased at TF (−35%), suggesting the presence of low-frequency fatigue generally associated with an excitation-contraction coupling failure.[29] The increase in the EMG required to maintain the submaximal target force

overtime before TF suggests that increased temporal and/or spatial recruitment of motor units was necessary to maintain the target force when muscle fibers became fatigued.[3,4] The absence of changes in Msup areas, as already reported after a similar fatiguing protocol,[19] suggests that phenomenon prior to the mechanisms that characterized excitation-contraction coupling are likely to be preserved during such a fatiguing exercise (at least when assessed at 50% MVC as it was the case here).

4.4 | Origin of task failure

As reported in the previous sections, we observed that maximal force and central drive were both decreased throughout the first 50% and 90% of the prolonged submaximal fatiguing task, respectively, before plateauing. This suggests that the level of fatigue was not critical (ie, subjects were able to sustain the contraction despite a plateau in central fatigue) when reaching TF. Rather, the moment of TF may rely on the fact that subjects perceived exertion near exhaustion. While it would have been difficult to expect a 90% decline in MVC in this study, even if it was asked to the subject to maintain a sustained 10% MVC until TF, one could have expected to record a larger decline in MVC than the one reported in the present study, that is, ~50%. Our results are in line with a previous study reporting a 50% decrease in MVC at the end of a protocol that consisted of a sustained 20% MVC knee extension until TF.[19] The first explanation could have been a substantial and rapid recovery of the neuromuscular system that could have allowed the capacity of the neuromuscular system to produce force to increase from ~52 N (ie, which corresponds to the 10% MVC averaged for all subjects) to ~260 N (ie, the mean MVC recorded at TF for all subjects). This explanation must be disregarded in this study since subjects were not permitted to relax and performed the MVC immediately upon reaching task failure. Second, one could consider a psychological explanation for this result. Indeed, there exists an effect of expected test duration on effort mobilization. In other words, subjects knew that the last MVC performed at TF would last only ~3 seconds, and such awareness likely motivated them to produce higher effort at TF compared to the sustained effort which had a longer and unknown duration.[30] As reported for dynamic exercises (eg, Marcora et al[30]), our results go against the long-standing assumption that neuromuscular fatigue causes exercise failure during low-intensity prolonged exercise (although still being a large component). Then, while neuromuscular fatigue does not seem to limit exercise tolerance in this study, our results are in favor of the psychobiological model of exercise tolerance. The perception of effort, that was near to maximal at TF (9.8 ± 0.4 out of 10), was likely the "exercise terminator." At some point, the central nervous system likely regulated skeletal muscle motor unit recruitment to maintain the required force level,[31] and increased motor unit recruitment and/or rate coding that should have been necessary to prolong the task was likely prevented by the fact that RPE was nearly at its maximal level.[32] Then, the fact that subjects decided to prematurely stop the exercise due to high RPE could have prevented the recruitment of high-threshold motoneurons, explaining why MVC at TF was far from the target force level, that is, non-fatigued high-threshold motor units that were not recruited during the exercise allowed the subject to reach a high MVC. It is worth noting that even in the context of fatigue, higher-threshold motoneurons are further unlikely to be recruited during a low-intensity sustained contraction as performed in the present study. Our results strengthen the role of the brain in determining the end of the exercise,[33] including motivation-related mechanisms that could involve alterations in neurotransmitter function for instance.[34] Although not investigated in this study, the high RPE values could indicate the presence of mental fatigue, both variables being related and having an important influence on muscle endurance performance.[35] Indeed, it has been stated that prolonged and sustained exercise could include a cognitive demand such as a sustained attention to maintain the target force level in the context of low-intensity sustained contraction with force feedback.[36] This cognitive demand could have led to mental fatigue that increased RPE and decreased performance. While the influence of III and IV afferents on RPE has been largely suggested, other mechanisms than the sole information from these afferents may have influenced the intensity of perceived exertion such as corollary discharge associated with central motor command.[37] Yet, $RMS_{10\%MVC}$ plateaued during the submaximal sustained contraction, which does not support an increased central drive up to TF, contrary to one of the aforementioned argument. It is, however, conceivable that motoneuron excitability decreased during the task so reducing efficacy of descending drive to excite motoneurons, and greater descending drive would then be required to maintain motoneuron output.[25] Nonetheless, the plateau in $RMS_{10\%MVC}$ (Figure 3D) highlights the fact that the end of the exercise occurred way before a complete motor unit recruitment and/or a maximal motoneuron firing rates, influenced by mechanisms located within the central nervous system.[19] For instance, $RMS_{10\%MVC}$ remained considerably lower than RMS_{MAX} (Figure 3C) throughout the fatigue task and this was still the case at TF. Although mechanisms related to amplitude cancelation might be involved,[38] these observations corroborate the aforementioned hypothesis of a prevention of additional motor unit recruitment and/or increased discharge rate, likely because the subjects were reaching maximal RPE.

In conclusion, the current work is the first investigating the role of central indices in locomotor muscles performance during a very low-intensity contraction sustained to TF. The present results show that task failure is not associated with a critical amount of central fatigue. We postulate that TF occurred in this study as a form of task disengagement and that exercise tolerance was ultimately limited by perception of effort (as reported in this study by the fact that subjects perceived exertion of near exhaustion).

5 | PERSPECTIVES

We demonstrated that TF likely occurs when the required submaximal effort exceeds the limit of what subjects are willing to do, that is, potential motivation.[35] The present results, that could also be true for long-duration whole-body exercises such as cycling[21] or running,[22] strengthen the role that psychophysiological interventions may have in endurance performance. For instance, the use of mental strategies (eg, motivational self-talk) may specifically target favorable changes in perception of exertion then enhancing endurance performance. We could first question if the increase in TTF duration reported during dynamic exercise when self-talk strategies are used[39] is also applicable to a sustained and submaximal modality of isometric exercise.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Callum Brownstein for English editing.

CONFLICT OF INTERESTS

Authors declare that they have no conflicts of interest (financial or otherwise) relevant to the content of this original research article.

ORCID

Guillaume Y Millet https://orcid.org/0000-0002-6395-0762
Thomas Lapole https://orcid.org/0000-0002-1477-6614

REFERENCES

1. Asmussen E. Muscle fatigue. *Med Sci Sports*. 1979;11(4):313-321.
2. Eichelberger TD, Bilodeau M. Central fatigue of the first dorsal interosseous muscle during low-force and high-force sustained submaximal contractions. *Clin Physiol Funct Imaging*. 2007;27(5):298-304.
3. Smith JL, Martin PG, Gandevia SC, Taylor JL. Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles. *J Appl Physiol*. 2007;103(2):560-568.
4. Sogaard K, Gandevia SC, Todd G, Petersen NT, Taylor JL. The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *J Physiol*. 2006;573(Pt 2):511-523.
5. Merton PA. Voluntary strength and fatigue. *J Physiol*. 1954;123(3):553-564.
6. Todd G, Taylor JL, Gandevia SC. Measurement of voluntary activation of fresh and fatigued human muscles using transcranial magnetic stimulation. *J Physiol*. 2003;551(Pt 2):661-671.
7. Carroll TJ, Taylor JL, Gandevia SC. Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol*. 2017;122(5):1068-1076.
8. Taylor JL, Gandevia SC. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol*. 2008;104:542-550.
9. Vernillo G, Temesi J, Martin M, Millet GY. Mechanisms of fatigue and recovery in upper versus lower limbs in men. *Med Sci Sports Exerc*. 2017;50(2):334-343.
10. Gruet M, Temesi J, Rupp T, Levy P, Verges S, Millet GY. Dynamics of corticospinal changes during and after high-intensity quadriceps exercise. *Exp Physiol*. 2014;99(8):1053-1064.
11. Rossi S, Hallett M, Rossini PM, Pascual-Leone A. Screening questionnaire before TMS: an update. *Clin Neurophysiol*. 2011;122(8):1686.
12. Todd G, Taylor JL, Gandevia SC. Measurement of voluntary activation based on transcranial magnetic stimulation over the motor cortex. *J Appl Physiol*. 2016;121(3):678-686.
13. Sidhu SK, Bentley DJ, Carroll TJ. Cortical voluntary activation of the human knee extensors can be reliably estimated using transcranial magnetic stimulation. *Muscle Nerve*. 2009;39(2):186-196.
14. Mira J, Lapole T, Souron R, Messonnier L, Millet GY, Rupp T. Cortical voluntary activation testing methodology impacts central fatigue. *Eur J Appl Physiol*. 2017;117(9):1845-1857.
15. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Erlbaum; 1988.
16. Ansdell P, Brownstein CG, Skarabot J, et al. Sex differences in fatigability and recovery relative to the intensity-duration relationship. *J Physiol*. 2019;597(23):5577-5595.
17. Arnal PJ, Lapole T, Erblang M, et al. Sleep extension before sleep loss: effects on performance and neuromuscular function. *Med Sci Sports Exerc*. 2016;48(8):1595-1603.
18. Bojsen-Moller J, Schwartz S, Magnusson SP. Limited difference in time to failure between sustained force and position control contractions with the knee extensors. *Scand J Med Sci Sports*. 2011;21(6):e48-e55.
19. Neyroud D, Maffiuletti NA, Kayser B, Place N. Mechanisms of fatigue and task failure induced by sustained submaximal contractions. *Med Sci Sports Exerc*. 2012;44(7):1243-1251.
20. Neyroud D, Rüttimann J, Mannion AF, et al. Comparison of neuromuscular adjustments associated with sustained isometric contractions of four different muscle groups. *J Appl Physiol*. 2013;114(10):1426-1434.
21. Lepers R, Maffiuletti NA, Rochette L, Brugniaux J, Millet GY. Neuromuscular fatigue during a long-duration cycling exercise. *J Appl Physiol*. 2002;92(4):1487-1493.
22. Place N, Lepers R, Deley G, Millet GY. Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc*. 2004;36(8):1347-1356.
23. Gandevia S, Allen GM, Butler JE, Taylor JL. Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *J Physiol*. 1996;490(Pt 2):529.
24. Sacco P, Thickbroom GW, Thompson ML, Mastaglia FL. Changes in corticomotor excitation and inhibition during prolonged submaximal muscle contractions. *Muscle Nerve*. 1997;20(9):1158-1166.

25. Finn HT, Rouffet DM, Kennedy DS, Green S, Taylor JL. Motoneuron excitability of the quadriceps decreases during a fatiguing submaximal isometric contraction. *J Appl Physiol*. 2018;124(4):970-979.
26. Brownstein CG, Souron R, Royer N, Singh B, Lapole T, Millet GY. Disparate kinetics of change in responses to electrical stimulation at the thoracic and lumbar level during fatiguing isometric knee extension. *J Appl Physiol*. 2020;128(1):159-167.
27. Souron R, Baudry S, Millet GY, Lapole T. Vibration-induced depression in spinal loop excitability revisited. *J Physiol*. 2019;597(21):5179-5193.
28. Taylor JL, Todd G, Gandevia SC. Evidence for a supraspinal contribution to human muscle fatigue. *Clin Exp Pharmacol Physiol*. 2006;33(4):400-405.
29. Jones D. High-and low-frequency fatigue revisited. *Acta Physiol Scand*. 1996;156(3):265-270.
30. Marcora SM, Staiano W. The limit to exercise tolerance in humans: mind over muscle? *Eur J Appl Physiol*. 2010;109(4):763-770.
31. Noakes TD. Time to move beyond a brainless exercise physiology: the evidence for complex regulation of human exercise performance. *Appl Physiol Nutr Metab*. 2011;36(1):23-35.
32. Noakes TD, St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans. *Br J Sports Med*. 2004;38(4):511-514.
33. Kayser B. Exercise starts and ends in the brain. *Eur J Appl Physiol*. 2003;90(3–4):411-419.
34. Davis JM . Nutrition, neurotransmitters and central nervous system fatigue. Maughan RJ, *Nutrition in Sport*. 2000;.171–183.
35. Pageaux B, Marcora SM, Lepers R. Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Med Sci Sports Exerc*. 2013;45(12):2254-2264.
36. Halperin I, Chapman DW, Behm DG. Non-local muscle fatigue: effects and possible mechanisms. *Eur J Appl Physiol*. 2015;115(10):2031-2048.
37. Hureau TJ, Romer LM, Amann M. The 'sensory tolerance limit': A hypothetical construct determining exercise performance? *Eur J Sport Sci*. 2018;18(1):13-24.
38. Keenan KG, Farina D, Maluf KS, Merletti R, Enoka RM. Influence of amplitude cancellation on the simulated surface electromyogram. *J Appl Physiol*. 2005;98(1):120-131.
39. Blanchfield AW, Hardy J, De Morree HM, Staiano W, Marcora SM. Talking yourself out of exhaustion: the effects of self-talk on endurance performance. *Med Sci Sports Exerc*. 2014;46(5):998-1007.

How to cite this article: Souron R, Voirin A-C, Kennouche D, et al. Task failure during sustained low-intensity contraction is not associated with a critical amount of central fatigue. *Scand J Med Sci Sports*. 2020;30:2329–2341. https://doi.org/10.1111/sms.13815