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Assessing corticospinal excitability to the biceps brachii during maximal repeated arm cycling sprints

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Research Article

Keywords: Neuromuscular fatigue, supraspinal excitability, spinal excitability, peripheral excitability, electromyography

Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11354096/v1

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Additional Declarations: No competing interests reported.

Abstract

This study examined the feasibility of assessing corticospinal and spinal excitability of the biceps brachii during maximal repeated arm cycling sprints. Twelve recreationally active participants (10 male, 2 female) completed five maximal arm cycling sprints (17–22s) against a torque factor of 5% body weight, separated by 90s of rest. Corticospinal, spinal and peripheral excitability were assessed via transcranial magnetic stimulation (TMS) transmastoid electrical stimulation (TMES), Erb's point stimulation, respectively. Stimuli were delivered during arm cycling at the 3 o'clock crank position (start of elbow flexion) at an intensity of 130% of active motor threshold (AMT) (determined during submaximal cycling). Mean power and total work both declined by 36.8% from sprints 1–5 ($p < 0.001$). Motor evoked potential (MEP), cervicomedullary evoked potential (CMEP), and compound muscle action potential (M_{max}) amplitudes did not change during the sprint protocol ($p > 0.05$). However, following the sprint protocol, the TMES intensity required to evoke CMEPs was reduced by 4.57% compared to pre-sprint values ($p = 0.01$), and M_{max} amplitude increased ($p = 0.01$) from pre- to post-sprinting by 12.1%. Despite substantial declines in performance, corticospinal and spinal excitability assessed via evoked response amplitudes remained unchanged during maximal sprinting, likely reflecting saturation of the motoneuron pool during high voluntary drive. In contrast, the post-sprint reduction in CMEP threshold and increase in M_{max} indicate enhanced spinal excitability following repeated arm cycling sprints. These findings demonstrate both the feasibility and limitations of assessing corticospinal excitability during sprint exercise and highlight the importance of stimulation intensity selection when probing neural adaptations during high-intensity, dynamic tasks.

Introduction

Neuromuscular fatigue (NMF) refers to an exercise-induced reduction in the capacity of the neuromuscular system to produce force or power (Gandevia et al. 1999; Gandevia 2001). The development of NMF during exercise reflects the combined influence of peripheral (Billaut et al. 2006; Mendez-Villanueva et al. 2008a; Pearcey et al. 2015; Zinner et al. 2016; Pearcey et al. 2016) and central mechanisms (Collins et al. 2018a), which interact dynamically to limit voluntary motor performance. Peripheral fatigue arises from processes that occur distal to the neuromuscular junction and includes factors such as increased metabolite accumulation, impaired excitation-contraction coupling, decreased muscle membrane excitability, and alterations in muscle fibre conduction velocity (Juel 1988; Maclaren et al. 1989; Taylor et al. 1997; Wan et al. 2017). In contrast, central fatigue involves changes in neural drive originating within the central nervous system, including supraspinal (e.g., corticospinal neurons) and spinal (e.g., spinal motoneurons) mechanisms (Carroll et al. 2006; Taylor and Gandevia 2008) along the corticospinal pathway. In humans, researchers commonly use transcranial magnetic stimulation (TMS) of the motor cortex (Barker et al. 1985; Rossini et al. 1994; Chen 2000) and transmastoid electrical stimulation (TMES) of the descending corticospinal axons (McNeil et al. 2013; Collins et al. 2018a; Lockyer et al. 2021) to measure corticospinal excitability (motor evoked potentials: MEPs) and spinal excitability (cervicmedullary motor evoked potentials: CMEPs), respectively. When combined with measurement of peripheral excitability (i.e., compound muscle action potential (M_{max})), these techniques permit differentiation between supraspinal, spinal, and peripheral contributions to NMF (Collins et al. 2018a). While the mechanisms of peripheral fatigue have been extensively characterized, the neural mechanisms contributing to central fatigue following exercise remain less understood, particularly during dynamic, high-

intensity exercise where maximal voluntary effort is repeatedly required to sustain performance (Collins et al. 2018a).

Previous work has demonstrated that NMF can alter corticospinal and spinal excitability, although the direction and magnitude of these changes are inconsistent and appear highly dependent on the exercise performed, the muscle examined, and the methodologies employed (Weavil and Amann 2018). The majority of studies that have assessed nervous system excitability during NMF do so by assessing the excitability of the corticospinal pathway either at rest or during low-force isometric contractions before and after exercise. From this work, it has been shown that corticospinal excitability is reduced (i.e., decreased MEP amplitudes) in resting muscles following fatiguing running (Verin et al. 2004; Ross et al. 2007), rowing (Fulton et al. 2002), and leg cycling (Ross et al. 2010). However, when assessed during isometric contractions following fatiguing locomotor exercise, MEP amplitudes increase (Goodall et al. 2012; Fernandez-del-Olmo et al. 2013; Temesi et al. 2013; Jubeau et al. 2014, 2017), decrease (Sidhu et al. 2014; Thomas et al. 2015; Pearcey et al. 2016), or remain unchanged (Sidhu et al. 2009; Klass et al. 2012; Girard et al. 2013a; Goodall et al. 2015; Thomas et al. 2016) depending on the details of the exercise task performed and the muscle examined. Few studies have examined corticospinal and spinal excitability during repeated sprint exercise, particularly in upper-limb tasks such as arm cycling. In one of the few studies to examine NMF during upper body repeated sprinting, Pearcey et al. (2016) examined alterations in corticospinal and spinal excitability before, midway, and following the performance of ten, 10-second upper body cycling sprints. They found that the repeated sprint protocol resulted in a reduction in supraspinal excitability (as evidenced by reduced MEP amplitude) and an increase in spinal excitability (increased CMEP amplitudes) following the sprint protocol. The authors suggested that the distinct post-sprint effects reflect an inhibitory influence on supraspinal drive, which may attenuate motor output and, consequently, impair arm-cycling sprint performance (Pearcey et al. 2016). However, corticospinal and spinal excitability were measured during weak isometric contractions pre-, mid-, and post-sprinting, so it remains unknown whether similar findings would occur during the sprint itself. Indeed, corticospinal excitability is strongly mediated by various factors specific to the task being performed, including the phase (Forman et al. 2014a; Spence et al. 2016), motor unit recruitment and contraction intensity (Martin et al. 2006; Lockyer et al. 2018), afferent feedback (Amann et al. 2008), and the magnitude of central motor drive (Weavil and Amann 2018). As a result, measurements obtained at rest or during isometric contractions likely do not accurately reflect the neural demands present *during* the dynamic, high-intensity fatiguing tasks themselves

Assessing neural excitability during maximal, dynamic exercise presents several technical challenges, including maintaining consistent stimulation conditions and accounting for variability in background muscle activation. Thus, the purpose of this study was twofold: (1) to determine the feasibility of assessing CSE and spinal excitability *during* repeated maximal arm cycling sprints, and (2) to examine how the development of NMF during sprinting influences CSE and spinal excitability measured from the dominant arm biceps brachii. The biceps brachii is a primary mover during arm cycling and has been the muscle of interest for assessing changes in CSE during submaximal arm cycling studies (Forman et al. 2014a; Pearcey et al. 2016) and pre-, mid-, and post-arm cycling sprints under weak isometric contractions (Power and Copithorne 2013; Forman et al. 2019a). We hypothesized that the sprinting protocol would induce NMF and that corticospinal excitability would decrease and spinal excitability would increase over the duration of the sprint protocol.

Methods

Participants

Ten male and two female recreationally active (~10 hours of activity/week) participants (177.3 ± 10.2cm, 81.9 ± 12.1 kg, 26.4 ± 5.8 years) were recruited from the university population. All participants completed the magnetic stimulation safety checklist (Rossi et al. 2011) and Physical Activity Readiness Questionnaire (Crone et al. 1999) to determine if any contraindications to TMS existed and to evaluate participants' levels of physical activity, respectively. Participants were instructed to refrain from heavy exercise 24 hours before testing and to follow the Canadian Society for Exercise Physiology preliminary instructions (no eating, drinking caffeine, smoking, or drinking alcohol for 2, 2, 2, or 6 hours, respectively) before the start of testing. All participants were also told they would complete 5 maximal intensity arm cycling sprints between 17 and 22 seconds each. Participants were verbally informed of all procedures and read and signed a written consent form. The Memorial University of Newfoundland Interdisciplinary Committee on Ethics in Human Research approved the study (#20192592-HK) and was in accordance with the Tri-Council guidelines in Canada, with full disclosure of potential risks to participants.

Repeated arm cycling sprint protocol

All experimental data were recorded from the participant while being seated on a computer-controlled, electrically braked cycle ergometer modified for arm cycling (Dynafit Pro, Racemate, Seattle, Wash., USA). Participants sat in an armless chair at a comfortable distance from the crankshaft. The seat distance was adjusted for each participant to ensure there was no reaching or twisting throughout the cycling revolution. Chair height was also adjusted so the participant's shoulders were approximately in line with the axis of rotation of the ergometer. Straps were placed around participants' shoulders and feet to prevent them from moving during the performance of the sprints (See Figure 1 for the cycle ergometer set-up).

The primary sprint protocol began with 20 seconds of moderate cycling preceding each sprint at a workload of 0.5 kg of resistance. This portion was considered a ramp-up phase, whereby the participant was instructed to increase to and maintain ~100 revolutions per minute (RPM). A tracer line guided this entire process on a screen placed directly in front of the participant. Immediately following the 20 seconds of moderate cycling, the participants began the sprint phase where the mechanical brake applied a 5% torque factor (i.e., the participant cycled against a resistance that was equal to 5% of their body weight), and participants were given verbal encouragement to cycle as fast as they could for 17-22 seconds, followed by 90 seconds of rest. The 17-22 second timeframe was necessary because, as fatigue increased and cadence decreased during sprinting, it took longer for the pedal to reach the crank location where the stimulus was triggered. Thus, there was some variance for each participant during each sprint. The participants repeated this process five times. All power output data were recorded using Velotron Wingate Version 1.0.1 software and stored on a computer. The mean and peak power (Watts) were measured during each sprint. Additionally, mean RPM, anaerobic capacity, anaerobic power, fatigue index, and total work were recorded for each sprint. At the end of each sprint, participants were shown a Borg scale and questioned about their perceived exertion rate (RPE).

Electromyography

Electromyography (EMG) signals were recorded from the biceps brachii of the dominant arm using a pair of disposable Ag-AgCl surface electrodes (MeditraceTM 130 ECG conductive adhesive electrodes). With a

bipolar configuration, electrodes were positioned ~2 cm apart (center to center) over the midline of the biceps brachii. A ground electrode was positioned on the lateral epicondyle of the dominant arm. Preceding the electrode placement, the skin was thoroughly prepared by removing the hair (via a handheld razor) and dead epithelial cells (via abrasive paper), followed by sanitization using isopropyl alcohol swabs. This was done to reduce the impedance for EMG recordings. An interelectrode impedance of <5 kO was obtained via a standard multimeter before recording to ensure an adequate signal-to-noise ratio. The raw EMG signals were DC bias removed and bandpass filtered using a 3-Pole Butterworth filter with cut-off frequencies ranging from 10 to 1,000 Hz (Common mode rejection (at x100 gain) 80 dB at 50 Hz). The signals were amplified (gain of 300) and sampled at a rate of 5 kHz using a 16-bit CED 1902 interface and the associated Signal 5 (Cambridge Electronic Design, Cambridge, UK) software.

Stimulation conditions

Brachial Plexus (Erb's Point) Stimulation

Stimulation of the brachial plexus (i.e., Erb's point) was used to induce a maximal compound muscle action potential (M_{max}) to measure peripheral excitability. All stimulations were obtained under the same pedalling conditions. Erb's point was electrically stimulated via adhesive Ag-AgCl electrodes (diameter 10 mm) fixed to the skin over the supraclavicular fossa (cathode) and the acromion process (anode). Current pulses were delivered as a singlet (200 µs duration, 175-250 mA, model DS7AH, Digitimer Ltd, Welwyn Garden City, UK) via a constant current stimulator.

Transcranial Magnetic Stimulation

MEP responses of the biceps brachii were elicited via TMS (49-92% maximal stimulator output) over the motor cortex in the left hemisphere using a circular coil (13.5 cm outside diameter) attached to a Magstim 200 stimulator (Magstim, Dyfed, UK). Electrical current flows in an anticlockwise direction through the circular coil. The coil was placed horizontally over the vertex so that the direction of the current flow in the coil preferentially activated the left motor cortex. Vertex was determined by marking the intersection of the measured halfway points from nasion to inion and from tragus to tragus.

Transmastoid Electrical Stimulation

CMEP responses of the biceps brachii were elicited via adhesive Ag-AgCl electrodes fixed to the skin over the mastoid processes, and the current was passed between them (100 µs duration, 150–250 mA; model DS7AH, Digitimer Ltd, Welwyn Garden City, UK) with the anode on the right side and the cathode on the left side.

Experimental Protocol

Familiarization session

Participants completed a familiarization and an experimental session, which were separated by at least 48 hours. During the familiarization session, participants were subjected to TMS, TMES, and Erb's Point stimulation. Several stimulations were given with each form of stimulation at similar intensities that participants would encounter during the experimental day. A brief cycling warm-up was done, followed by

several short sprints (5-10 seconds in duration) to familiarize the participants with the arm cycling sprint protocol.

Experimental session

Participants began the experimental session with a five-minute warm-up on the custom cycle-ergometer at an intensity of ~60 RPM and a resistance of 0.5 kg. Participants were then prepped for the stimulation conditions and EMG. Immediately before and after the sprint protocol, AMT was determined for TMS and TMES while participants cycled at ~60 RPM. AMT for TMS and TMES was determined by finding a discernible MEP and CMEP from the background EMG 50% of the time (4/8 or 5/10 discernible MEPs or CMEPs). Once AMT was found, the stimulator's intensity was increased by 30%, and these stimulation intensities were delivered during the sprint protocol. M_{max} was also found during cycling at ~60 RPM by gradually increasing the stimulator electrical current until the M-wave amplitude of the biceps brachii no longer increased (i.e., M_{max}). A supramaximal stimulation current (i.e., 30% higher than that required to elicit M_{max}) was used for the remainder of the experiment (Crone et al. 1999). Participants then completed five consecutive arm cycling sprints of ~17-22 seconds in duration, interspersed with 90 seconds of rest. During each sprint, participants received three TMS, TMES and Erb's point stimulation. Stimulations were triggered automatically when the dominant arm started to initiate elbow flexion (i.e., 3 o'clock made relative to a clock face) via two magnetic sensors, whereby one was attached to the sprocket and the other was attached to the crankshaft. Participants provided their rate of perceived exertion using a Borg scale following each sprint.

Data Analysis

All data were stored and analyzed offline using Signal 5.08 data collection software (CED). The peak-to-peak amplitudes of MEPs, CMEPs, and M_{max} were measured from the biceps brachii of the dominant arm from the initial deflection of the voltage trace to the return of the trace to baseline background EMG levels. Additionally, latencies of all evoked responses were examined and monitored. To account for changes in peripheral neuromuscular propagation during exercise (Taylor 2006), averaged MEP and CMEP amplitudes were normalized to the averaged M_{max} evoked during the same trial. Pre-stimulus EMG, defined as a 50-ms window of the mean rectified EMG immediately before the stimulation artifact, was measured from the rectified traces. Sprint performance measures, including mean and peak power output, mean and peak RPM, and anaerobic performance measures, including anaerobic capacity and power, fatigue index, and total work, were recorded.

Statistical Analysis

All statistics were performed using GraphPad Prism version 9.2.0. Assumptions of sphericity were tested using Mauchly's test, and if violated, the appropriate correction was made to the degrees of freedom using the Greenhouse-Geisser or the Huynh-Feldt method (Field 2024). One-way repeated measures ANOVAs were done for measures of sprint performance (mean power, mean RPM, RPE, and anaerobic power), within-sprint corticospinal excitability (MEP, CMEP, and M_{max} amplitudes), and mean rectified biceps brachii EMG. A one-way repeated measures ANOVA was also performed on average MEP and CMEP amplitudes and biceps brachii EMG for each sprint and compared across sprints. Because there were 10 missing M_{max} values over the 5 sprints, a mixed-effects model was performed on the average MEP/M_{max} and CMEP/M_{max} ratios and compared across sprints as opposed to one-way repeated measures ANOVAs. A Tukey post hoc comparison

test was used to determine where significant differences may exist for each measure only if main effects were found. Eta and partial eta-squared (ηp^2) measures indicating the magnitude of changes associated with significant main effects were provided and reported as small (<0.01), medium (≥0.06), or large (≥0.14) (Cohen 2013). Paired *t*-tests were used to compare stimulation intensities to elicit AMT for TMS, TMES, and M_{max} amplitudes before and after sprinting and effect sizes were computed using Cohen's *d*. Significance levels were set at $p<0.05$. All data in the text are presented as percentage change and/or mean ± standard deviation (SD), in the tables as mean ± standard deviation (SD), and in the figures as box and whisker plots.

Results

Sprint and Anaerobic Performance Measures

There was a significant main effect for mean power output ($F_{(4, 55)}$= 9.247, $p<0.001$, ηp^2 =0.402), peak power ($F_{(2.459, 27.05)}$=23.53, $p<0.001$, ηp^2 =0.681), mean RPM ($F_{(1.427, 15.70)}$=39.93, $p<0.001$, ηp^2 =0.784), and peak RPM ($F_{(4, 55)}$=18.02, $p<0.0001$, ηp^2 =0.567) to decrease from sprint 1-5. Likewise, there was a significant main effect for anaerobic capacity ($F_{(4, 55)}$=20.16, $p<0.001$, ηp^2 =0.594), anaerobic power ($F_{(4, 55)}$=10.11, $p<0.001$, ηp^2 =0.424), and total work ($F_{(4, 55)}$=9.165, $p<0.001$, ηp^2=0.40) to decrease from sprint 1-5. However, no significant main effect was found for fatigue index ($F_{(4, 55)}$=0.89, $p=0.47$, ηp^2 =0.061). Table 1 shows average values for sprint and anaerobic performance measures from sprints 1-5, percentage change between sprints 1 and 5, and significance values for the change between sprints 1 and 5.

RPE (Borg Scale)

There was a significant main effect for rate of perceived exertion (RPE) to increase from sprints one to five ($F_{(4, 55)}$=17.15, $p<0.0001$, ηp^2 =0.551) (Table 1).

Corticospinal excitability to the biceps brachii

There was no significant main effect for MEP amplitudes during sprint 1 ($F_{(2,32)}$=1.393, $p=0.26$, ηp^2=0.08), sprint 2 ($F_{(1.624)}$=17.87, $p=0.082$, ηp^2=0.215) sprint 3 ($F_{(1.573, 17.30)}$=3.678, $p=0.055$, ηp^2=0.251), sprint 4 ($F_{(1.888, 20.77)}$=0.5517, $p=0.574$, ηp^2=0.048), and sprint 5 ($F_{(1.514, 16.65)}$=0.7456, $p=0.454$, ηp^2 =0.064) (Table 2). Since MEPs were not significantly different within each sprint, the average MEP amplitudes were computed and then subsequently compared between sprints. Results from these analyses revealed no significant main effect for the average MEP amplitude ($F_{(1.811, 19.92)}$=1.620, $p=0.223$, ηp^2=0.128) (Figure 2A) or MEP/M_{max} ratio ($F_{(2.568, 26.96)}$=0.435, $p=0.702$) (Figure 2E) across sprints. There was also no significant difference between pre- and post-AMT TMS intensities ($p>0.05$) (Figure 3A).

Spinal excitability to the biceps brachii

There was no significant main effect for CMEP amplitudes during sprint 1 ($F_{(2, 32)}$=0.318, $p=0.72$, ηp^2=0.019), sprint 2 ($F_{(1.398, 15.38)}$=2.772, $p=0.10$, ηp^2=0.20), sprint 4 ($F_{(1.286, 14.15)}$=1.564, $p=0.23$, ηp^2=0.123), and sprint 5 ($F_{(1.786, 19.64)}$=0.92, $p=0.40$, ηp^2=0.077). However, there was a significant main effect for sprint 3 CMEP

amplitudes ($F_{(1.440, 15.84)}$=5.135, p=0.0274, ηp^2=0.318). Pairwise comparisons revealed that there was a significant difference between CMEP #2 and CMEP #3 (p=0.002) during sprint 3 (Table 2). There was no significant main effect for the average CMEP amplitude across sprints ($F_{(2.467, 27.14)}$=1.365, p=0.2744, ηp^2=0.11) (Figure 2B). There was a significant main effect for CMEP/M_{max} ratios across sprints ($F_{(1.982, 20.81)}$=4.025, p=0.033) (Figure 2F). The CMEP/M_{max} ratio decreased 14.6% from sprint 1 to sprint 5. However, pairwise comparisons did not reveal any significant differences for CMEP/M_{max} ratios between sprints (p>0.07). TMES stimulation intensity significantly decreased by 4.57% ($t_{(12)}$=3.445, p=0.005, d=0.99) from pre (134.00±31.52 mA) to post (124±30.08 mA) AMT (Figure 3B).

Peripheral excitability to the biceps brachii

There were no significant main effects for M_{max} amplitudes during sprint 1 ($F_{(2,27)}$=0.267, p=0.767, ηp^2=0.019), sprint 2 ($F_{(1.423, 15.65)}$=3.688, p=0.0612, ηp^2=0.251), and sprint 5 ($F_{(1.645, 18.09)}$=2.831, p=0.0932, ηp^2=0.205). There was a significant main effect for M_{max} amplitudes during sprint 3 ($F_{(1.274, 14.01)}$=5.109, p=0.0333, ηp^2=0.317) and sprint 4 ($F_{(1.337, 13.37)}$=6.440, p=0.0180, ηp^2=0.391). Pairwise comparisons revealed that there was a significant difference between M_{max} #1 and M_{max} #2 amplitudes (p=0.03) in sprint 3 and between M_{max} #2 and M_{max} #3 amplitudes (p=0.005) in sprint 4 (Table 2). There was no significant main effect for the average M_{max} amplitudes across all sprints ($F_{(1.582, 16.22)}$=3.148, p=0.0793) (Figure 2C). M_{max} amplitude significantly increased by 12.1% ($t_{(11)}$=4.261, p=0.001, d=1.23) from pre (12.73±3.973 mV) to post (14.27±4.402 mV) sprinting (Figure 3C).

Background EMG

There was no significant main effect for pre-stimulus bicep brachii mean EMG during sprint 1 ($F_{(8, 93)}$=0.463, p=0. 879, ηp^2= 0.038), sprint 2 ($F_{(8, 99)}$=0.277, p=0.974, ηp^2=0.023) sprint 3 ($F_{(8, 117)}$=0.862, p=0.551, ηp^2=0.056), sprint 4 ($F_{(8, 117)}$=0.374, p=0.934, ηp^2=0.025), and sprint 5 ($F_{(8, 117)}$=0.943, p=0.484, ηp^2=0.099). There was no significant main effect for the average background EMG for the biceps brachii ($F_{(4, 55)}$=1.510, p=0.2120, ηp^2=0.099) (Figure 2D).

Discussion

The present study investigated the feasibility of assessing CSE and spinal excitability *during* repeated arm cycling sprints. As expected, the repeated maximal sprint protocol induced NMF, evidenced by the significant reduction in sprint performance and the increase in RPE across the sprint protocol (Table 1). Despite the marked fatigue, CSE and spinal excitability remained unchanged throughout the sprint protocol. In contrast, following the sprint protocol, spinal excitability appeared to increase, as indicated by a reduction in the TMES intensity required to evoke CMEPs during submaximal arm cycling, alongside increases in M_{max} amplitudes. However, no changes in overall corticospinal excitability were observed at post-sprinting. Taken together, the lack of change in overall corticospinal excitability and the increased spinal excitability suggest that supraspinal excitability may be reduced following the sprint protocol. Collectively, these findings indicate that the sprinting protocol was fatiguing and appears to have led to a nervous system adaptation following, but not during, the

sprinting exercise. Alternatively, the present findings suggest that while it is possible to elicit measurable evoked responses during arm cycling sprinting, the sensitivity of these measures to detect potential fatigue-related changes in CSE during maximal sprinting may be limited, at least with the stimulation paradigm utilized.

Table 1
Average (mean ± SD) raw data for repeated sprint performance and anaerobic performance measures recorded during each sprint. Revolutions per minute (RPM).

Sprint and Anaerobic Performance									
Sprint	**Mean Power (W)**	**Peak Power (W)**	**Mean RPM**	**Peak RPM**	**Anaerobic Capacity (W/kg)**	**Anaerobic Power (W/kg)**	**Fatigue Index (W/s)**	**Total Work (Joules)**	**Borg Scale**
1	380.2 ± 91.2	457.3 ± 104.0	133.0 ± 18.0	143.42 ± 20.4	4.6 ± 0.8	5.6 ± 0.8	12.3 ± 4.3	6989.4 ± 1674.5	14.5 ± 2.4
2	324.6 ± 69.8	428.3 ± 88.0	120.5 ± 12.5	128.67 ± 11.3	3.9 ± 0.6	5.2 ± 0.7	10.6 ± 2.7	5955.9 ± 1290.5	16.4 ± 1.8
3	277.1 ± 58.9	381.6 ± 84.2	106.5 ± 10.2	115.08 ± 7.7	3.4 ± 0.4	4.6 ± 0.4	10.0 ± 3.4	5099.4 ± 1084.9	17.8 ± 1.4
4	249.2 ± 55.1	364.1 ± 66.8	99.2 ± 10.6	111.92 ± 5.9	3.0 ± 0.5	4.5 ± 0.5	10.8 ± 2.3	4583.4 ± 1015.1	18.6 ± 1.0
5	240.2 ± 48.0	350.1 ± 68.9	96.7 ± 9.6	110.08 ± 4.8	2.9 ± 0.4	4.3 ± 0.4	10.3 ± 3.3	4417.7 ± 884.0	19.3 ± 0.8
% Change (Sprints 1–5)	**↓ 36.8**	**↓ 23.5**	**↓ 27.3**	**↓ 23.2**	**↓ 37.0**	**↓ 23.1**	**↓ 16.5**	**↓ 36.8**	**↑ 32.8**
P Value	**$p < 0.001$**	**$p < 0.001$**	**$p < 0.001$**	**$p < 0.001$**	**$p < 0.001$**	**$p < 0.001$**	$p > 0.999$	**$p < 0.001$**	**$p < 0.001$**

Table 2

Average (mean ± SD) motor evoked potential (MEP), cervicomedullary MEP (CMEP) and maximal coumpound muscle potential (M_{max}) amplitudes during each sprint. * represents significant ($p < 0.05$) differences between CMEP #2 and #3 and between M_{max} #1 and #2 in sprint 3 and between M_{max} #2 and #3 in sprint 4.

Corticospinal Excitability Measures									
Sprint	**MEP #1 (mV)**	**MEP #2 (mV)**	**MEP #3 (mV)**	**CMEP #1 (mV)**	**CMEP #2 (mV)**	**CMEP #3 (mV)**	**M_{max} #1 (mV)**	**M_{max} #2 (mV)**	**M_{max} #3 (mV)**
1	8.7 ± 2.0	8.9 ± 1.6	9.9 ± 2.0	7.7 ± 3.3	8.9 ± 4.3	8.1 ± 4.3	10.9 ± 2.7	11.8 ± 3.1	11.6 ± 3.1
2	8.9 ± 1.7	9.3 ± 1.4	9.7 ± 1.9	7.6 ± 3.5	8.6 ± 3.5	8.2 ± 3.5	11.1 ± 2.2	11.7 ± 2.5	12.2 ± 2.2
3	9.3 ± 1.8	10.2 ± 2.5	10.3 ± 3.2	8.3 ± 2.8	***8.9 ± 4.5**	***7.4 ± 4.2**	***11.1 ± 2.4**	***12.1 ± 2.5**	13.1 ± 4.3
4	9.7 ± 2.1	10.2 ± 3.7	10.4 ± 3.8	7.3 ± 2.9	7.9 ± 3.7	6.8 ± 4.7	11.8 ± 2.9	***12.1 ± 3.3**	***13.5 ± 3.8**
5	9.8 ± 2.9	9.6 ± 3.0	10.2 ± 3.9	7.9 ± 3.6	7.8 ± 4.0	7.3 ± 4.1	11.8 ± 3.3	11.9 ± 3.5	12.9 ± 4.0

Dissociation Between Sprint Performance and Corticospinal Excitability

A key finding of the present study was that corticospinal excitability remained unchanged despite substantial declines in sprint performance during the repeated sprint protocol. In line with our initial hypothesis and consistent with previous repeated sprint exercise studies, the sprint protocol used successfully induced NMF (Billaut et al. 2006; Billaut and Bishop 2009; Goodall et al. 2015; Pearcey et al. 2016; Hureau et al. 2016; Weavil et al. 2016; Monks et al. 2017). In the present study, power output decreased, and RPE increased as the number of sprints performed increased. Reductions in power output were apparent as early as the second sprint and persisted throughout the sprint protocol, confirming the presence of NMF. Both mean and peak power showed significant reductions from sprints 1 to 3, indicating that the greatest decline in mechanical performance typically occurs early in repeated sprint protocols (Mendez-Villanueva et al. 2008b; Girard et al. 2013b; Pearcey et al. 2016).

Despite the obvious reduction in sprint performance, however, MEP and CMEP amplitudes remained stable throughout the exercise protocol, suggesting that the overall excitability of the corticospinal pathway was maintained in the presence of NMF. This finding is in direct opposition to our initial hypothesis, in which we had suggested, based on previous work (Pearcey et al. 2016), that supraspinal and spinal excitability would decrease and increase, respectively, as NMF developed throughout the sprinting protocol. Importantly, the unchanged corticospinal responses should not necessarily be interpreted as evidence that the neural state remained unchanged or that central fatigue was not present during the repeated sprint protocol (Weavil and Amann 2018). Rather, evoked responses obtained during maximal dynamic exercise likely reflect the net summation of multiple simultaneously changing facilitatory and inhibitory processes occurring at both cortical

and spinal levels. During fatiguing exercise, cortical excitability, spinal motoneuron responsiveness, afferent feedback, intracortical inhibition, motor unit recruitment, and descending voluntary drive are all dynamically modulated. Consequently, stable net corticospinal output may emerge despite substantial underlying physiological alterations within the central nervous system.

When assessed during a slight tonic contraction, CSE has been shown to change throughout and following repeated arm cycling sprints (Pearcey et al. 2016). Using a ten, 10-second arm cycling sprint protocol, Pearcey et al. (2016) examined changes in evoked response amplitudes prior to and following sprints 1, 5 and 10, to examine the relationship between CSE and NMF. The authors observed a decrease in MEP amplitudes from post-sprint 1 to post-sprint 5, but an increase from post-sprint 5 to post-sprint 10. Given that CMEP amplitudes increased from post-sprint 1 to post-sprint 10, the authors concluded that supraspinal excitability was suppressed early in the sprinting protocol, whereas spinal excitability was increased throughout (Pearcey et al. 2016). In contrast, the current study did not show any changes in CSE during the sprinting protocol. Importantly, however, the study by Pearcey and colleagues (2016) investigated the CSE between and following sprints during a slight (5% MVC) tonic contraction (Pearcey et al. 2016), while in the present study, stimulations were delivered during the sprints themselves. This variation in contraction mode likely accounts, at least partially, for the differing findings, as dynamic arm cycling has been shown to produce higher CSE in the biceps brachii than an intensity-matched tonic contraction (Forman et al. 2014b).

Although in opposition to our initial hypothesis, the present findings are consistent with previous work examining corticospinal pathway excitability during fatiguing lower body cycling tasks to exhaustion. For example, Sidhu and colleagues (2012) showed that CSE during fatiguing constant-load cycling was comparable to that observed during brief, non-fatiguing high-intensity exercise, suggesting that the overall output of the corticospinal pathway is tightly regulated even under conditions of substantial physiological strain. Subsequent work has reinforced this concept, with both MEP and CMEP amplitudes remaining unchanged from the initial to final stages of exhaustive cycling, despite clear reductions in performance (Sidhu et al., 2017; Weavil et al., 2016). Although these studies were not conducted during repeated sprint exercise, the similar absence of change in corticospinal pathway excitability across exercise modes suggests that overall corticospinal output may be preserved during high-intensity cycling exercise, even with substantial NMF.

One potential explanation for the lack of change in MEP and CMEP amplitudes during sprinting in the present study is the potential of a ceiling effect within the motoneuron pool during the maximal effort exercise (Matthews 1999; Todd et al. 2003). During repeated sprinting, voluntary drive to the working musculature is high, presumably leading to near-maximal or maximal recruitment and firing rates of motoneurons (Del Vecchio et al. 2019). Under these conditions, additional synaptic input elicited by TMS or TMES likely produces minimal additional motor output, thereby perhaps masking potential changes in CSE or spinal excitability (Rossini et al. 1994). This interpretation is supported by previous work demonstrating that the amplitude of evoked potentials is highly influenced by the level of background muscle activation (Rossini et al. 1994; Collins et al. 2018b), with MEP and CMEP amplitudes often plateauing at high contraction intensities (Martin et al. 2006; Weavil et al. 2015). For example, following the performance of two 30-second leg cycling Wingate tests, Fernandez del Olmo et al. (2013) reported that rectus femoris MEPs were increased during submaximal isometric contraction intensities (50% and 75% MVC), but were unchanged at 100% MVC, suggesting a

reduced capacity to detect changes in excitability during high contraction intensities. In the present study, excitability measures remained stable during the sprinting but changed during submaximal cycling following the sprint protocol, further supporting the possibility that high levels of voluntary drive may mask fatigue-related modulation during sprinting itself. Notably, background EMG remained relatively stable across the sprint protocol in the present study despite clear reductions in mechanical output, indicating that high levels of neural drive were maintained even as fatigue developed.

It is also possible that the lack of observable change in corticospinal pathway excitability can be at least partially explained by methodological factors. In the present study, stimulation intensities were set relative to AMT, which was determined during submaximal arm cycling (i.e., ~ 60 RPM and 0.5 kg of resistance). Once determined, this stimulation intensity was then increased by 30% to ensure measurable responses could be discerned from the ongoing EMG during the maximal effort sprinting. As such, it is possible that the stimulation intensities used were not optimal for detecting potential fatigue-related modulation of CSE and spinal excitability during the sprint protocol. It is possible that the stimulus intensity was too high, resulting in a plateau of the evoked responses (i.e. a ceiling effect), limiting the ability to detect further increases in excitability throughout the sprint protocol. Ideally, stimulus-response (S–R) curves or normalizing MEPs and CMEPs to M_{max} at various stimulus intensities during sprinting would provide a more precise characterization of excitability (Forman et al. 2019b). However, performing these assessments during sprinting is impractical due to the large number of stimulations required, which would induce premature fatigue (Lockyer et al. 2021). Taken together, these findings suggest that the lack of change in MEP and CMEP amplitudes during sprinting should not be interpreted as an absence of central fatigue, but rather as a reflection of both physiological saturation and methodological constraints when assessing neural excitability during maximal dynamic exercise.

Post-Sprinting Changes in Spinal and Peripheral Excitability

Of the couple of studies that have included a measure of spinal excitability (e.g., CMEP amplitudes) in addition to overall corticospinal excitability (Pearcey et al. 2016; Sidhu et al. 2017) following fatiguing locomotor exercise, it has been shown that spinal excitability is increased post-exercise, while overall corticospinal excitability is generally unchanged. In the present study, the CMEP/M_{max} ratio did not change during the repeated sprints; however, the stimulation intensity required to evoke a discernible CMEP (i.e., AMT) significantly decreased post-sprinting. A reduction in AMT suggests increased spinal excitability in the fatigued state when assessed during submaximal arm cycling at 60 RPM (post-assessment). Although the mechanisms underlying this potential spinal facilitation are unknown, heightened feedback from group III/IV afferent fibres caused by the sprinting may enhance motoneuron responsiveness and subsequently contribute to greater spinal excitability (Amann et al. 2011). These small-diameter afferents respond to mechanical and metabolic stress and are associated with the sensation of effort and exercise-induced pain (Cook et al. 1997; Bertini et al. 2004; Martin et al. 2008). The increase in RPE during the sprinting supports this notion, as perceived exertion and group III and IV afferent feedback are moderately correlated. Another potential mechanism underlying the observed increase in spinal excitability at post-sprinting may include increased activation of the monoaminergic system following the sprint protocol (Taylor et al. 2016). Indeed, intense

exercise has been shown to enhance the release of serotonin, dopamine, and norepinephrine, which all play important roles in modulating spinal motoneuron excitability (Fedirchuk and Dai 2004).

The M_{max} response reflects neuromuscular transmission efficiency (i.e., sarcolemma excitability) (Collins et al. 2017). Our results indicated that M_{max} amplitudes increased from pre- to post-sprinting, which suggests an increase in sarcolemma excitability. This increase in M_{max} may represent a form of post-activation potentiation (PAP), as skeletal muscle activation immediately following intense contractions can transiently enhance muscle responsiveness (Kilduff et al. 2007). Although M_{max} does not provide a direct interpretation of PAP, the increase observed in the current study suggests that potentiation likely occurred alongside fatigue. Previous studies indicated that both potentiation and fatigue can coexist within the same muscle during a high-intensity task (Rassier and Macintosh 2000; Behm et al. 2004).

Methodological Considerations

Several methodological considerations should be acknowledged when interpreting the present results. First, determining optimal stimulation intensities during maximal effort, dynamic exercise is inherently challenging. In this study, we chose to set stimulation intensities during submaximal arm cycling at 60 rpm and 0.5 kg of resistance before the sprint protocol. Stimulation intensities were set relative to AMT and were then increased by 30% with the intention of ensuring discernible responses from the background EMG during the sprinting. A stimulus-response curve during sprinting on a separate day from the main protocol may have been a better method to determine CSE because it would allow for precise stimulus intensity and avoid the potential miss of the true evoked response. Secondly, the length of each sprint is different from the most comparable study completed by Pearcey et al (2016), being nearly double in length (Pearcey et al. 2016). Testing MEPs, CMEPs, and M_{max} on separate days would shorten sprints. Our pilot studies found that participants could not complete ten ~ 20-second sprints because of the intense amount of exhaustion. Hence, ten 10-second sprints would be more appropriate, but this short period would not allow for an appropriate number of stimuli to be measured. Thirdly, delivering MEPs, CMEPs, and M_{max} stimulations during sprinting is inherently difficult. Despite controlling head movement with a restraining device, the head can still move slightly during the sprint. Accordingly, despite the researcher's best efforts, the positioning of the TMS paddle may not have always been directly over the marked vertex. Inevitably, minor changes can alter the physiological responses being recorded.

Conclusion

The excitability of the corticospinal pathway during the performance of repeated maximal intensity arm cycling sprints was examined. Our results indicate that, despite substantial performance decrements, supraspinal and spinal excitability of the biceps brachii remained unchanged throughout the sprinting protocol. This lack of change may be due to factors such as the stimulation intensities used (i.e., ceiling effect in responses) or the motoneuron pool may be near maximal activation, potentially limiting the sensitivity of evoked responses to detect further changes. At post-sprinting, however, spinal (as evidenced by the reduced stimulation intensity at AMT) and peripheral excitability (M_{max} amplitudes) were potentiated during submaximal arm cycling, whereas no changes were observed in overall CSE. Taken together, these findings are consistent with the possibility that

arm cycling sprinting induces NMF, impairs performance, and results in altered nervous system excitability following, but not during, sprinting and raises important questions regarding the utility of these measures during maximal, dynamic exercise, where high levels of voluntary drive may obscure underlying neural adaptations. Future work is required to determine the precise mechanism(s) mediating this effect and to determine whether different stimulus intensities may provide differing results.

Declarations

Competing Interests

The authors declare they have no competing interests.

Author Contribution

GTK, EJL, SA and DCB participated in the study design and data collection. GTK, EJL, SA, HA and DCB contributed to data analysis, interpretation of results, and manuscript writing. DCB reviewed and provided feedback on the final version of the manuscript.

Acknowledgement

This work was supported by a Natural Sciences and Engineering Research Council Discovery Grant (NSERC DG) to Duane Button.

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Figures

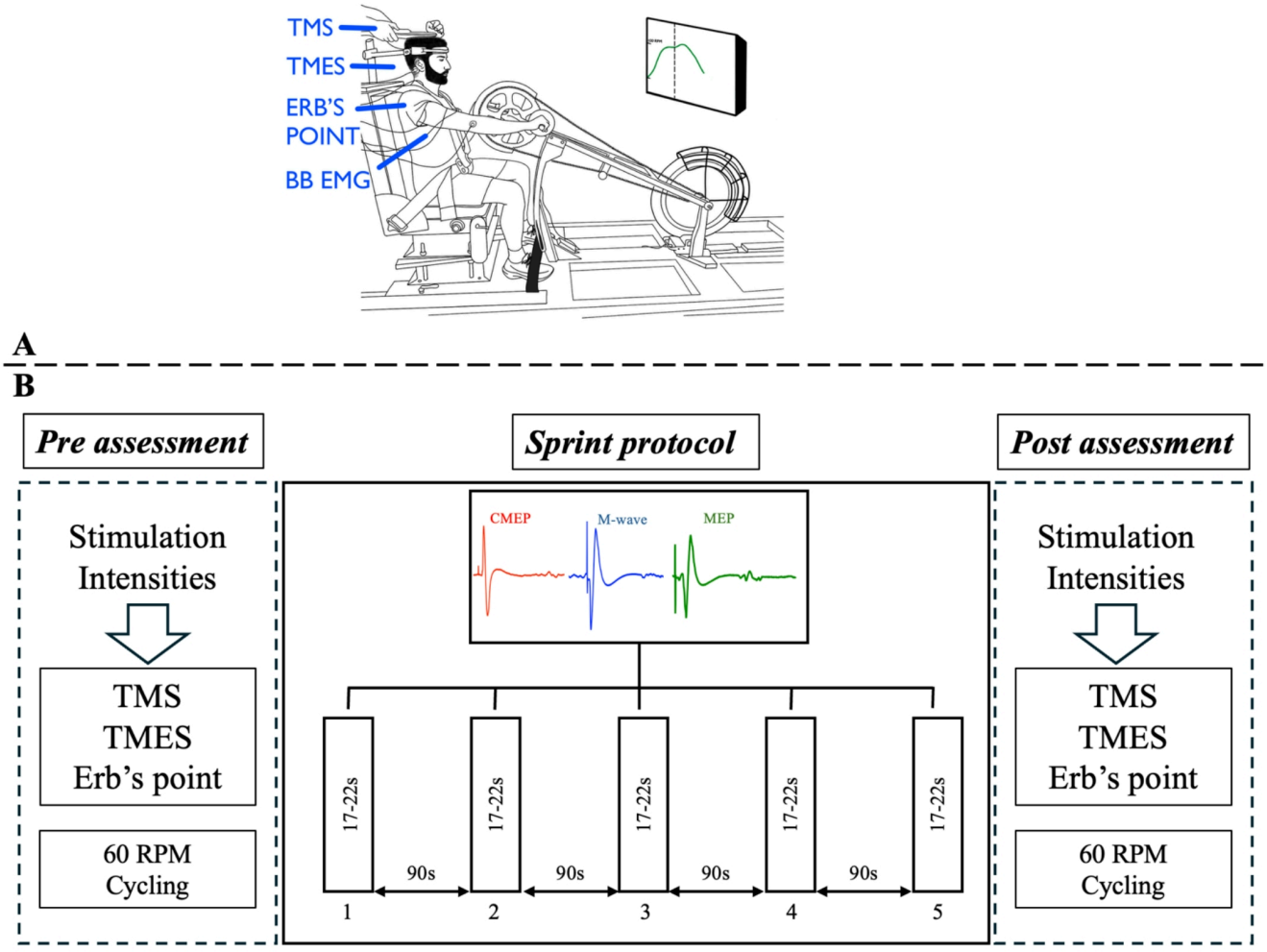


Figure 1

Schematic diagram of the experimental setup and protocol. TMS, TMES, brachial plexus stimulation (Erb's Point), and the Biceps Brachii EMG locations are delineated on the participant. The directions of the arrows demonstrate the direction that all participants cycled during the experimental protocol.

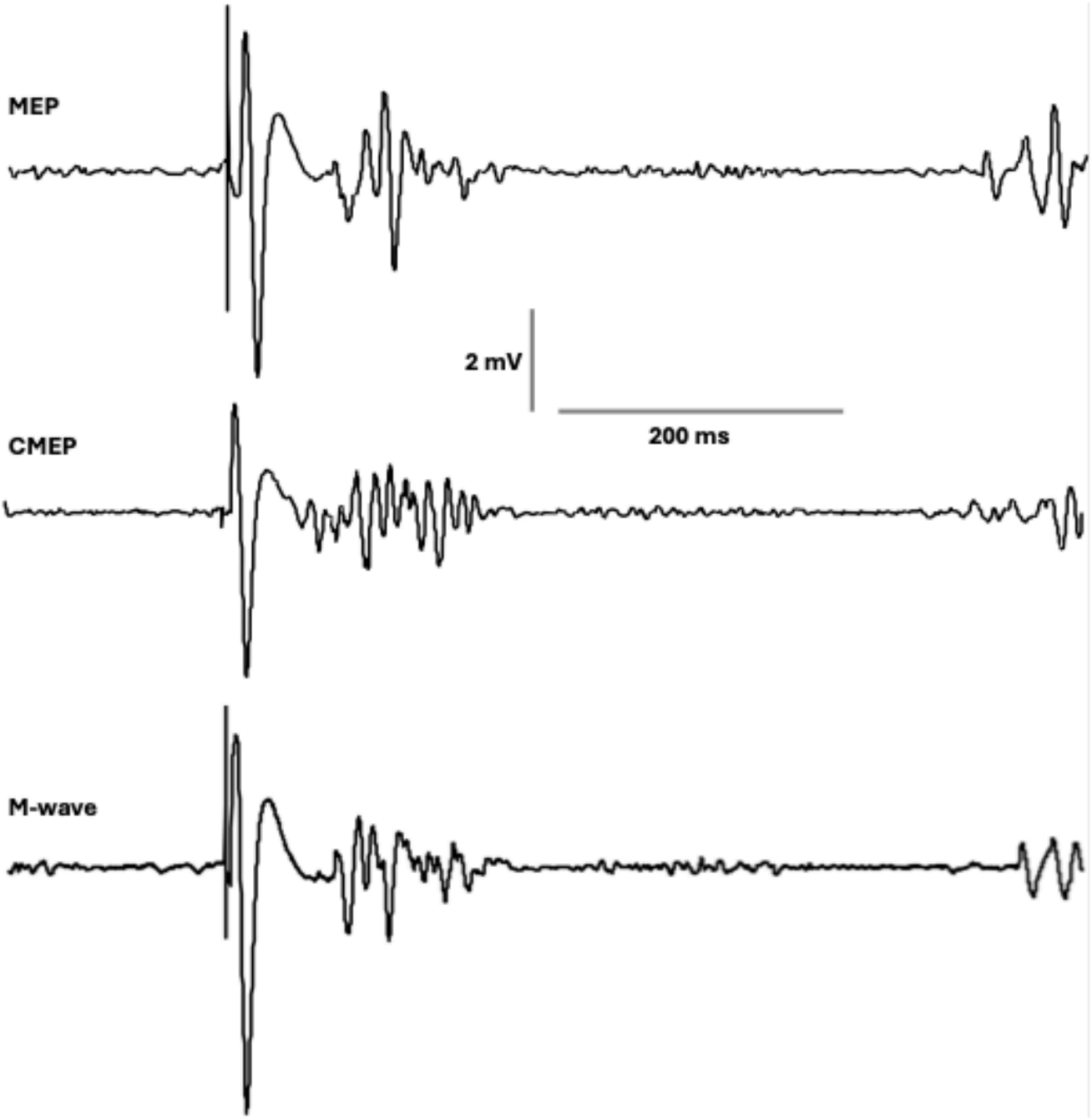


Figure 2

Raw data trace of a motor evoked potential (MEP) (top trace), a cervicomedullary MEP (CMEP) (middle trace) and a maximum compound action potential (M_{max}) (bottom trace) recorded from the biceps brachii from one participant during a repeated sprint.