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Effects of post-tetanic potentiation induced by whole-body electrostimulation and post-activation potentiation on maximum isometric strength

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ABSTRACT: It is currently unknown the most effective potentiation protocol to increase maximum strength. Hence, we investigated the separated and combined effects of post-tetanic potentiation (PTP) induced by whole-body electrostimulation (WB-EMS) and post-activation potentiation (PAP) induced by voluntary maximum isometric contractions on maximum isometric strength. Ten trained males were randomly evaluated on four occasions. In session A, maximum isometric strength (split squat) was measured in minutes 1, 4, and 8. In session B, the measurements were taken in minutes 2, 6, and 10. In session C, a WB-EMS protocol was applied to elicit PTP and the measurements were performed in minutes 1, 4, and 8. In session D, the same WB-EMS protocol was applied and the measurements were taken in minutes 2, 6, and 10. No significant differences in maximum isometric strength were observed between: (i) the control and WB-EMS in minutes 1 vs. 1 and 2 vs. 2; (ii) the control and PAP in minutes 1 vs. 4, 1 vs. 8, 2 vs. 6, and 2 vs. 10; and (iii) the PAP and WB-EMS plus PAP in minutes 4 vs. 4, 8 vs. 8, 6 vs. 6, and 10 vs. 10. In contrast, the WB-EMS plus PAP revealed a significant increase of 54% (~450 N) compared to the WB-EMS in minutes 4 and 8 compared to the minute 1 ($p < 0.001$), but not between minutes 2 vs. 6 and 2 vs. 10. The present results showed that PTP induced by WB-EMS in isolation or combined with PAP induced by voluntary maximum isometric contractions did not produce a significant increase in maximum isometric strength compared to the control and PAP alone, respectively.

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INTRODUCTION

It is widely known that previous skeletal muscle contractions may have a profound impact on the contractile capacity of the muscles inducing either favourable or unfavourable adaptations [1]. Fatigue (i.e., reductions of muscle strength, velocity, and power) occurs when the stimulus is excessively demanding in intensity and/or volume [2], which impairs sports performance [1]. It is also plausible that the conditioning activity is too soft and does not significantly influence the contractile capacity of the muscles nor physical performance [3, 4]. Therefore, the objective is to apply an adequate protocol of muscle pre-activation that results in subsequent improvements in muscle contractile responses (i.e., greater force production) and physical performance [5].

The phenomenon responsible for the acute increase in the contractile capacity of the muscles after applying a conditioning stimulus is known as "potentiation" [5]. The phenomenon of potentiation can be classified according to the origin of the conditioning contraction as: (i) staircase, when it is exogenously induced by repeated, low-frequency electrical stimulation (e.g., 0.5–20 Hz), (ii) post-tetanic potentiation (PTP), when it is exogenously induced by brief high-frequency electrical stimulation (e.g., 70–100 Hz), and (iii) post-activation potentiation (PAP), when it is endogenously originated by maximal or near-maximal voluntary contraction(s) [6, 7]. Moreover, potentiation can also be categorized according to the functional outcome as: (i) PAP, when the change in muscles' function is assessed by twitch contractions, and (ii) post-activation performance enhancement, when the change in muscles' function is assessed by voluntary performance tests [6, 8]. For simplicity, hereinafter this article uses the potentiation classification according to the origin of the conditioning contraction (PTP and PAP), but it should be noted that we explored their effect on a maximal voluntary performance test.

Much interest has been given to the idea that potentiation could be used during warm-up to improve sports performance [1, 5]. However, there is no current consensus regarding the most effective potentiation protocol [3, 6]. Moreover, although PTP and its mechanisms have been broadly studied [6, 7], their application to induce potentiation of muscular performance has received less attention. Only a few studies have examined the effect of PTP on subsequent physical performance and they generally used local electrostimulation protocols [9–11]. In this sense, it has been hypothesized that the potentiation induced by PTP could be higher than the potentiation induced via PAP [11]. For instance, Requena et al. [11] observed a different – but not higher or lower-twitch potentiation magnitude in knee extensor muscles after PTP evoked by local electrostimulation compared to PAP induced by a maximal voluntary contraction. However, other studies have reported no effects of PTP induced by local electrostimulation on bench press performance [9], nor on jumping, sprinting, and running performance [10]. Nevertheless, it is possible that a higher potentiation effect could be achieved by whole-body electrostimulation (WB-EMS) devices that allow simultaneous exogenous activation of several muscle groups [12, 13]. However, to our knowledge, no study has examined the influence of PTP induced by WB-EMS on subsequent muscle performance. Hence, it would be useful to determine the effect of WB-EMS on strength performance and to elucidate whether these effects could be more positive than those induced by PAP.

Therefore, this study aimed to investigate in trained males individuals: (i) the effects of PTP induced by WB-EMS on maximum isometric strength, (ii) the effects of PAP induced by voluntary maximum isometric contractions on maximum isometric strength, and (iii) the effects of PTP induced by WB-EMS plus PAP induced by voluntary maximum isometric contractions on maximum isometric strength.

MATERIALS AND METHODS

Subjects

Ten trained males (18–35 years old) participated in this study. The inclusion criteria were: (i) no previous experience with WB-EMS, (ii) having a normal and stable body mass (body mass index [BMI] between 18.5–25 kg/m^2 and a variation of less than 5 kg in body mass over the previous 3 months), (iii) being free of medication (i.e., beta-blockers, statins, levothyroxine, among others), and (iv) not suffering from any chronic metabolic disease, epilepsy, cancer, or any health problem that might be aggravated by exercise. All subjects provided oral and written informed consent to be included as participants. The study was approved by the Ethics Committee on Human Research of the University of X (Nº X) and was conducted following the latest revision of the Declaration of Helsinki (i.e., 2013).

Design

A within-subjects repeated measures design was used being the order of the experimental conditions randomized using a simple random function of the software MS Excel for Windows®. Subjects completed four testing sessions over 2 weeks (i.e., Tuesday and Thursday or Wednesday and Friday). In session A, maximum isometric strength (split squat) was measured in minutes 1, 4, and 8. In session B, the measurements were taken in minutes 2, 6, and 10. In session C, a WB-EMS protocol was applied after the same warm-up implemented in sessions A and B to elicit PTP and the measurements were performed in minutes 1, 4, and 8. In session D, the same WB-EMS protocol was applied to elicit PTP and the measurements were taken in minutes 2, 6, and 10. The measurement minutes started to be counted after the warm-up in sessions A and B and after the WB-EMS protocol in sessions C and D. All sessions were held at the same time of the day within-subjects (17:00–20:30) and were preceded by a 3-hour fast and abstention from moderate or vigorous physical activity 24 and 48 h before the testing day, respectively. The experimental protocol is presented in Fig. 1. To clarify, four conditions are distinguished: (i) control which refers to the first measurement in sessions A and B, (ii) PAP which refers to the second and third measurements in sessions A and B, (iii) WB-EMS which refers to the first measurement in sessions C and D, and (iv) WB-EMS plus PAP which refers to the second and third measurements in sessions C and D.

Procedures

Anthropometric and body composition variables

On day 1, body mass and height were measured using a Model 799 electronic column scale (SECA, Hamburg, Germany). BMI was determined as body mass (kg)/height (m^2). Fat mass and lean mass were assessed by dual-energy X-ray absorptiometry using a Discovery Wi device (Hologic, Inc., Bedford, MA, USA) following the manufacturer's recommendations. The fat mass index (FMI) and lean mass index (LMI) were calculated as fat body mass (kg)/height (m^2) and lean body mass (kg)/height (m^2), respectively.

Conditioning activity (Warm-up and WB-EMS protocol)

At the beginning of all testing sessions, a dynamic and standardized warm-up was performed, which included: (i) 3-min running at 50% of heart rate reserve, and (ii) mobility and muscle activation exercises (i.e., hip anteversion and retroversion, hip abduction and adduction, and dynamic abductor stretching). Subsequently, the subjects completed 2 sets of 3 repetitions of a split squat (dominant leg) with 5 kg and a range of motion from 90º to 65º of knee flexion (i.e., 0º full extension), using a functional electromechanical dynamometer (Dynasystem Research, SYMOTECH, Granada, Spain), which served as familiarization to the testing protocol.

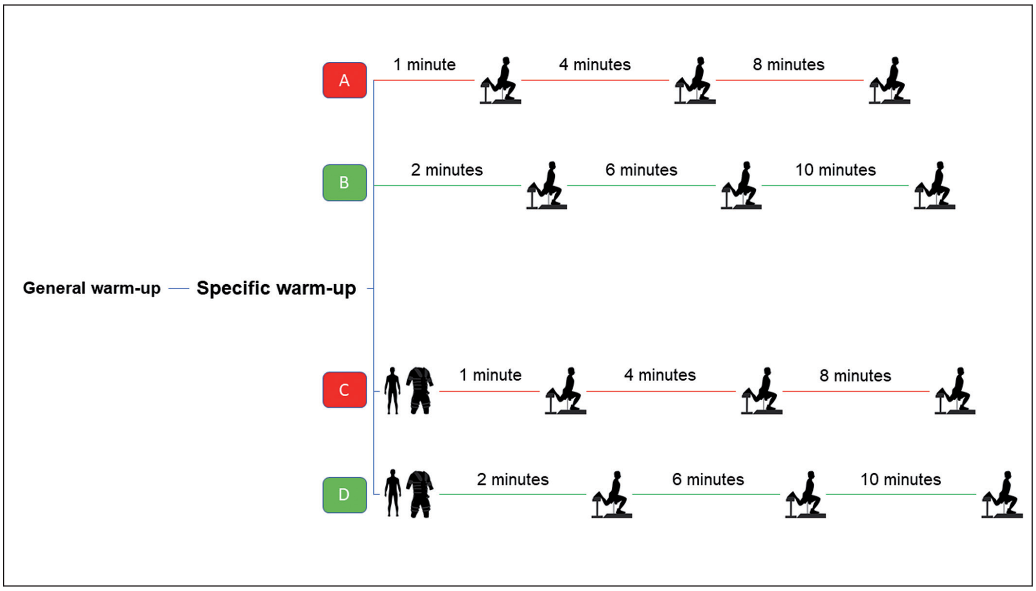

FIG. 1 Experimental design. Subjects were randomly evaluated on four occasions using a within-subjects repeated measures design. Maximum isometric strength was measured by performing a split squat (A) in the minute 1, 4 and 8 after the warm-up, (B) in the minute 2, 6 and 10 after the warm-up, (C) in the minute 1, 4 and 8 after the WB-EMS protocol, and (D) in the minute 2, 6 and 10 after the WB-EMS protocol. Abbreviation: WB-EMS, whole-body electrostimulation.

Subsequently, the same WB-EMS protocol was applied in two of the experimental sessions. The WB-EMS protocol was designed following specific recommendations of methodological studies published by our research group [14]. Briefly, the stimulation involved bipolar, symmetrical, and rectangular electric pulses using: (i) a frequency of 100 Hz, (ii) an intensity of maximum perceived tolerance until 100 mA, which was the top intensity of the device, (iii) an impulse breadth of 200–400 μs, and (iv) a duty cycle (ratio of on-time to the total cycle time: % duty cycle = 100/[total time/on-time]) of 99%. A wireless WB-EMS device (Wiemspro®, Malaga, Spain) was used which enables simultaneous exogenous muscle activation in up to 18 regions covering a total area of 2800 cm^2 (e.g., upper legs, upper arms, gluteal, abdomen, chest, lower back, upper back, and shoulders). The WB-EMS protocol consisted of 5 sets of 6 seconds (s) interspersed with 30s of recovery. The WB-EMS protocol was applied in a standing position and subjects were also instructed to produce a maximal voluntary contraction of the whole body.

Post-activation performance measurement

The split squat was used as the performance test because it is a unilateral and functional movement applicable to various sports disciplines [15]. While standing upright on the functional electromechanical dynamometer, subjects placed the forefoot of the non-dominant leg on a stable bench of 75cm height, with 90° of knee flexion and a slight hip extension. The knee of the dominant leg was exactly placed at 65° using a universal goniometer [16], positioning the foot on the base of the functional electromechanical dynamometer which was coupled to the subject with a harness located above the iliac crests. The stance width was horizontally measured from the heel of the dominant foot to the edge of the bench and maintained constant during all testing sessions. Subjects were asked to maintain a neutral spine while facing forward. Hands were separated at shoulder width and rested on the wall at face height to maintain a balanced posture. Using this stable position, the subjects performed an 8s maximum isometric split squat (Fig. 2).

FIG. 2 Position of the subjects during the 8 seconds maximum isometric split squat evaluated with a functional electromechanical dynamometer.

Maximum isometric strength was the performance variable used in the present study since it is more reliable than the rate of force development [17] and it is positively associated with performance in several sport disciplines [18]. Maximum isometric strength was evaluated with a validated functional electromechanical dynamometer (Dynasystem Research, SYMOTECH, Granada, Spain) which presents a precision of 3 mm for displacement, 100 g for a sensed load, and a sampling frequency of 1,000 Hz [19].

Statistical Analysis

Statistical analyses were performed in the first 1.5s of the 8s records of maximum isometric strength since these were the most stable intervals in which data from all subjects were available. Sensitivity analyses were performed with 8s records of maximum isometric strength when data were available. For zero-dimensional data, the Shapiro-Wilk test, visual check of histograms, and Q-Q plots were used to check the distribution of all variables. Since all data were normally distributed, parametric tests were used. Descriptive variables are reported as mean ± standard deviations. For one-dimensional data (i.e., force curves), Statistical Parametric Mapping one-dimension (SPM1D) [20] package available for Matlab (v.0.4, http://www.spm1d.org) was used to test the study hypothesis. SPM1D is a statistical tool based on the random field theory that allows conducting conventional statistical tests on one-dimensional data [20]. We performed paired t-tests in SPM1D to compare maximum isometric strength curves in the following conditions: (i) the control vs. WB-EMS (i.e., minutes 1 vs. 1 and 2 vs. 2); (ii) the control vs. PAP (i.e., minutes 1 vs. 4, 1 vs. 8, 2 vs. 6, and 2 vs. 10); (iii) the WB-EMS vs. WB-EMS plus PAP (i.e., minutes 1 vs. 4, 1 vs. 8, 2 vs. 6, and 2 vs. 10); and (iv) the PAP vs. WB-EMS plus PAP in the same minute (i.e., 4, 6, 8, and 10). Before the paired t-tests, smooth data function in Matlab was applied to all force curves to smooth noisy data. Smooth data returns a moving average of the force curve using a fixed window length that is determined heuristically.

RESULTS

Baseline characteristics of the subjects are presented in Table 1.

TABLE 1. Descriptive characteristics of participants (N = 10)

	$\overline{X}$	SD
Age (years)	22.7	(4.4)
Height (cm)	1.8	(0.1)
Body mass (kg)	78.7	(8.4)
Body mass index (kg/m^2)	24.1	(2.6)
Lean mass index (kg/m^2)	17.1	(1.9)
Fat mass index (kg/m^2)	5.5	(1.3)
Fat mass percentage (%)	23.2	(4.5)

Paired t-tests in SPM1D showed no significant differences in maximum isometric strength between the control and WB-EMS conditions in the minutes 1 vs. 1 and 2 vs. 2 (Fig. 3). Similar results were obtained considering the 8s records of maximum isometric strength (Supplementary Fig. S1 and S2).

Paired t-tests in SPM1D showed no significant differences in maximum isometric strength between the control and PAP conditions in the minutes 1 vs. 4, 1 vs. 8, 2 vs. 6, and 2 vs. 10 (Fig. 4).

Paired t-tests in SPM1D, used to compare WB-EMS vs. WB-EMS plus PAP conditions, showed a significant increase of 54% (i.e., 450 N or a force impulse of 298 N*s) in maximum isometric strength from 0.183s (13%) to 0.846s (60%) (cluster $p < 0.001$) in the minute 4 compared to the minute 1 (Fig. 5A). Similarly, paired t-tests in SPM1D showed a significant increase of 54% (i.e., 461 N or a force impulse of 390 N*s) in maximum isometric strength from 0.155s (11%) to 1.001s (71%) (cluster $p < 0.001$) in the minute 8 compared to the minute 1 (Fig. 5B). No significant differences in maximum isometric strength were observed between the minutes 2 vs. 6 and 2 vs.10 (Fig. 5C and 5D).

Paired t-tests in SPM1D showed no significant differences in maximum isometric strength between the PAP and WB-EMS plus PAP conditions in the minutes 4 vs. 4, 8 vs. 8, 6 vs. 6, and 10 vs. 10 (Fig. 6).

DISCUSSION

The present results indicated that, separately, PTP induced by WB-EMS and PAP induced by voluntary maximum isometric contractions elicited a comparable potentiation effect on split squat performance compared with a control condition. Moreover, WB-EMS plus PAP did not produce a further increase in maximum isometric strength compared to PAP alone. Lastly, our results showed that the combination of WB-EMS and PAP increased maximum isometric strength in minutes 4 and 8 compared to WB-EMS alone (minute 1). These findings could be useful in the pursuit of potentiation protocols that allow improving sports performance.

PTP is mainly explained by two physiological mechanisms, although slight contributions from other mechanisms are possible. First, the phosphorylation of the light chain regulating myosin occurring in muscle fibres during the tetanic contraction, which makes actin-myosin more responsive to Ca^{2+} release from the sarcoplasmic reticulum in consecutive contractions [7, 21]. Second, an increase in the recruitment of higher-order motor units [21]. This is the first study examining the influence of PTP induced by WB-EMS on maximum isometric strength. In line with our results, other studies showed no influence of PTP evoked by local electrostimulation on bench press performance [9] and jumping, sprinting, and running performance [10]. In contrast, Requena et al. [22] showed that PTP induced by local electrostimulation produced significant improvements in isometric twitch peak force (i.e., 17%) and maximal rate of force development (i.e., 38%) in knee extensor muscles. PTP mainly depends on the intensity, frequency, and duration of the electrical

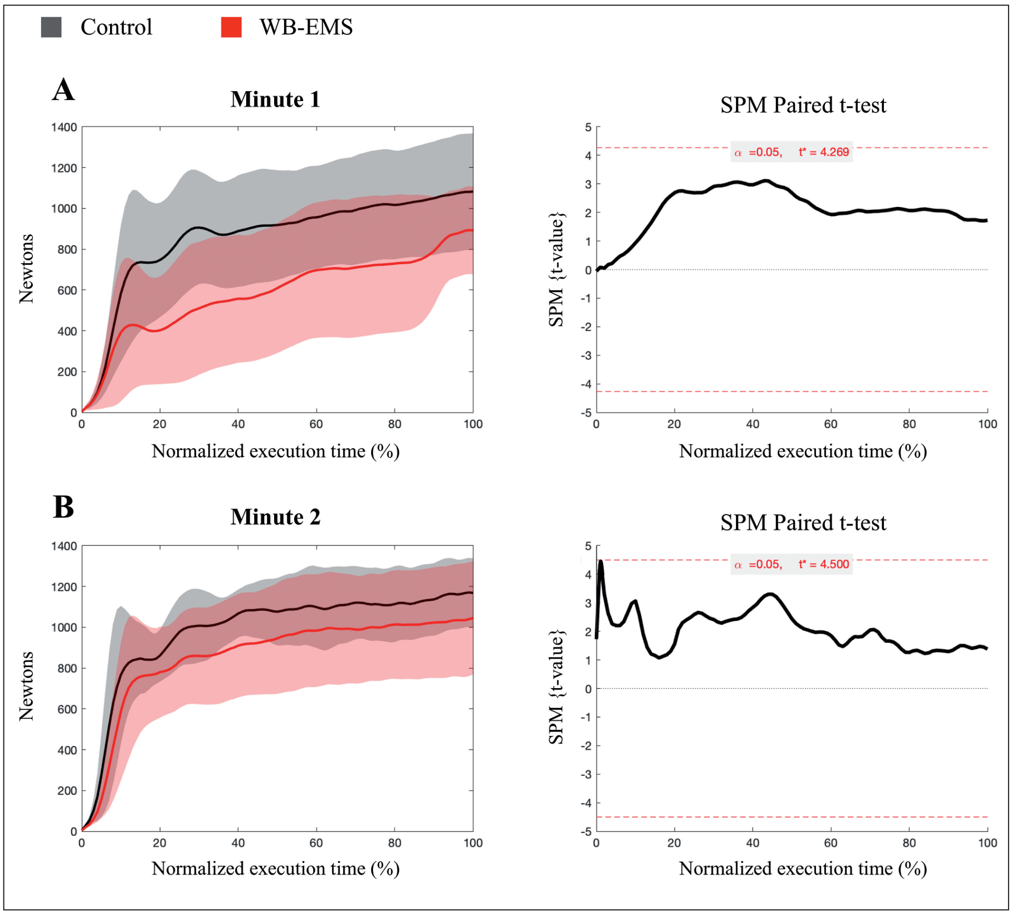

FIG. 3 SPM1D-analysis for the comparisons between the control and WB-EMS conditions in maximum isometric strength kinematic curves for the minute 1 (Panel A) and 2 (Panel B). Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. No significant results were observed. Abbreviation: WB-EMS, whole-body electrostimulation.

stimulation [7]. It has been proposed that the greatest PTP is caused immediately after a maximum intensity and high-frequency electrical stimulation for 5–10 s [23]. For these reasons, we used an impulse intensity of maximum perceived tolerance, a frequency of 100 Hz for 6s, and the measurements were taken in minutes 1 and 2 after the WB-EMS protocol, which is quite similar to the PTP protocol applied in the majority of previous studies [9, 22], but not in all studies [10]. Nonetheless, it seems that a longer recovery period is necessary after the application of WB-EMS. Indeed, the recovery interval between the voluntary contraction(s) used as a conditioning stimulus and the subsequent performance test has a great influence on the contractile capacity of the muscles, since they determine the thin line between fatigue and potentiation [3, 4, 6, 21]. Hence, this would explain the lower, albeit not significant, levels of maximum isometric strength in the WB-EMS condition compared to the control condition. Furthermore, the lack of significant increments in strength performance and the contradictory results obtained by other studies could also be partially explained by the application of different warm-up and potentiation protocols, morphological characteristics of stimulated muscles [9], training experience of the subjects, and the measured functional outcomes.

PAP is also mainly explained by myosin light chain phosphorylation [7]. Overall, PAP induced by a maximal or near-maximal voluntary contraction(s) enhances sport performance [3, 4, 6, 21]. However, inconsistent findings regarding the PAP effects on sports performance have also been reported [3, 4, 6, 21]. Several studies have applied different variations of the squat exercise as a conditioning activity to induce PAP with the aim of improving sprint, jump, and other ballistic movement performances [3, 4, 15]. For example, Bishop et al. [15] reported an increase in jump performance after a split squat potentiation protocol. However, PAP effects on isometric strength have been considerably less studied. For instance, de

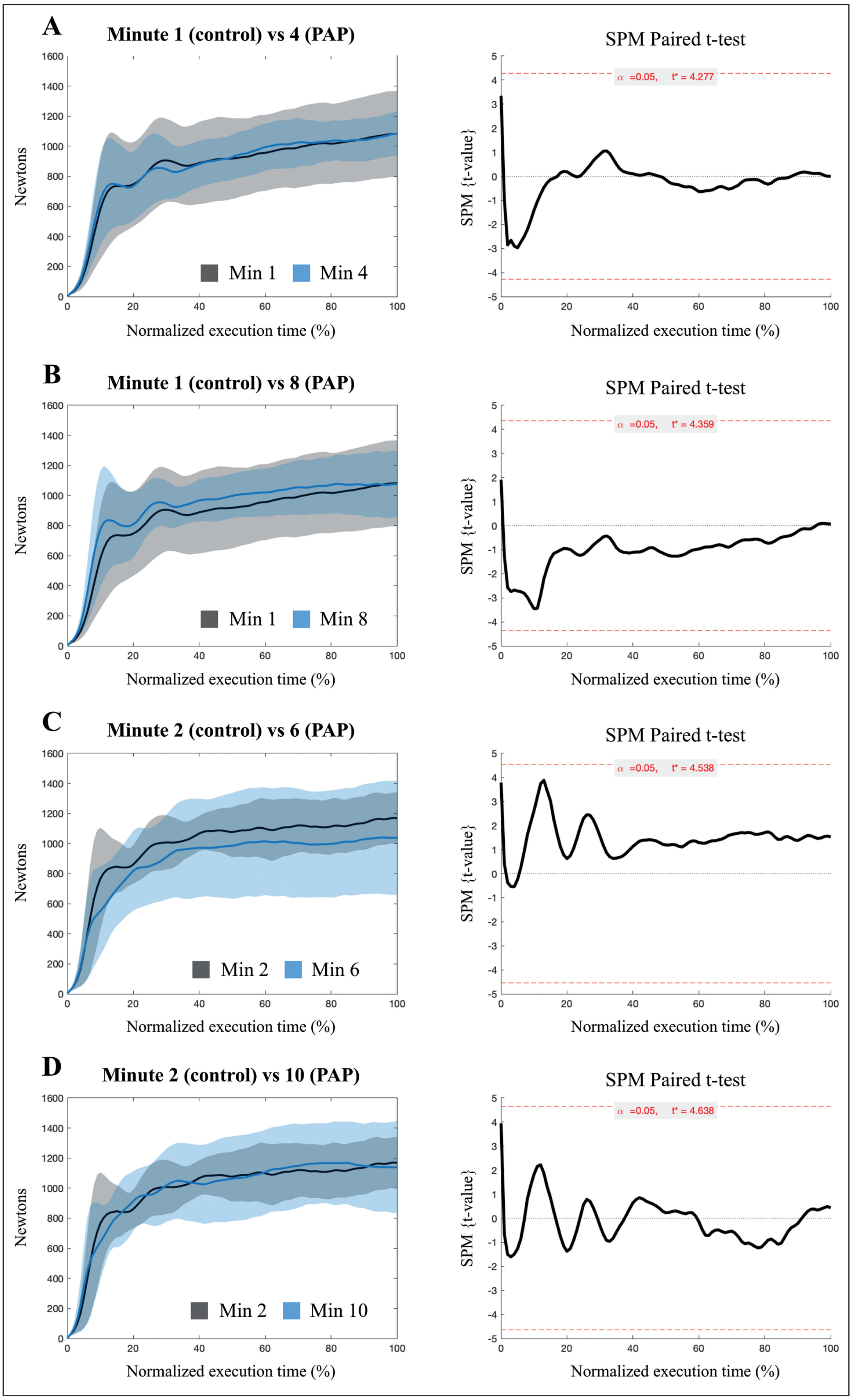

FIG. 4 SPM1D-analysis for the comparisons between the control and PAP conditions in maximum isometric strength kinematic curves for the minute 1 and 4 (Panel A), 1 and 8 (Panel B), 2 and 6 (Panel C), 2 and 10 (Panel D). Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. No significant results were observed. Abbreviation: PAP, post-activation potentiation.

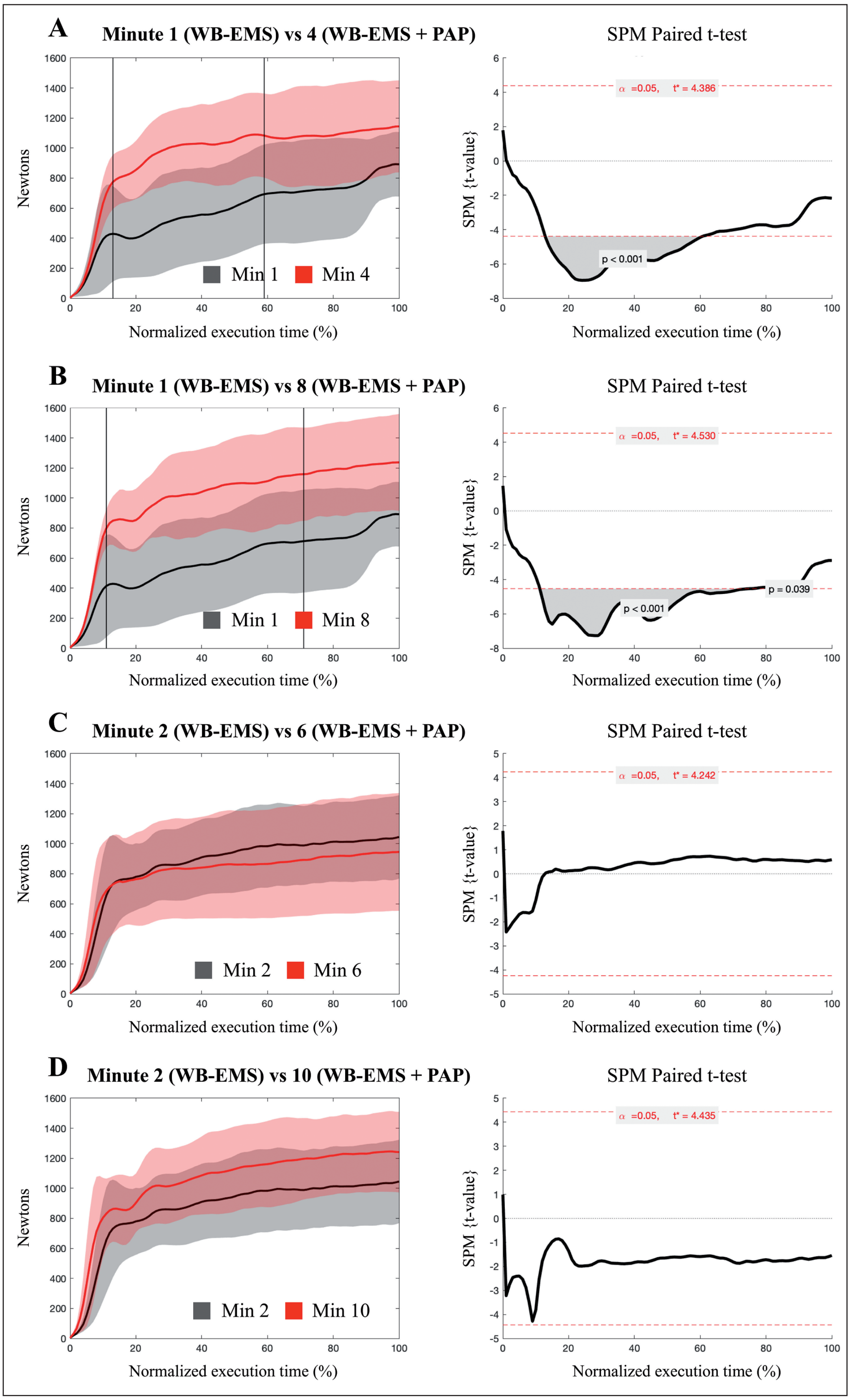

FIG. 5 SPM1D-analysis for the comparisons between the WB-EMS and WB-EMS plus PAP conditions in maximum isometric strength kinematic curves for the minute 1 and 4 (Panel A), 1 and 8 (Panel B), 2 and 6 (Panel C), and 2 and 10 (Panel D). Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. Vertical lines and right shaded areas represent the beginning and the end of the period in which significant results were observed. Abbreviation: PAP, post-activation potentiation; WB-EMS, whole-body electrostimulation.

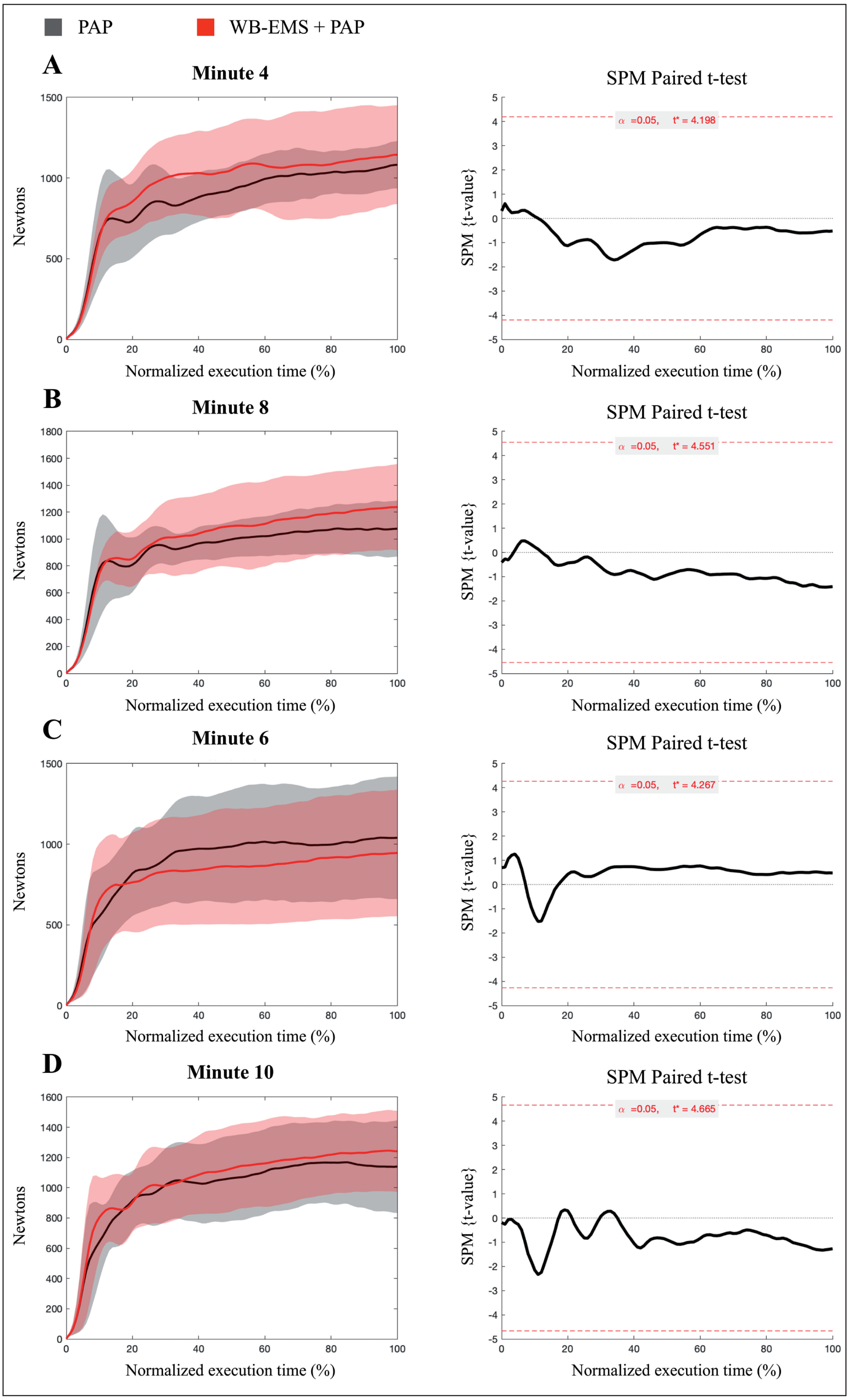

FIG. 6 SPM1D-analysis for the comparisons between the PAP and WB-EMS plus PAP conditions in maximum isometric strength kinematic curves for the minute 4 (Panel A), 8 (Panel B), 6 (Panel C), and 10 (Panel D). Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. No significant results were observed. Abbreviation: PAP, post-activation potentiation; WB-EMS, whole-body electrostimulation.

Freitas Conrado et al. [24] showed that two repetitions with 90% of one-repetition maximum in the back squat increased mean force when performing 10s of maximum voluntary isometric contraction. In line with our results, no significant changes in sprint and jump performance were reported after 3 repetition maximum back squats [25] as well as after 3s, 5s, and 7s of maximal voluntary isometric contractions [26], respectively. Numerous factors could explain the lack of PAP effects obtained in our study [3, 4, 6, 21] which can be summarized as follows: (i) Duration of the contraction(s); it has been reported that contractions of 5–10 s produce the greatest PAP [7]. Nevertheless, our 8s voluntary maximum isometric contraction may have caused fatigue because of a long time under tension, reducing the ability of the contraction(s) to induce PAP [27]. To note, Pearson and Hussain [26] did not find a positive influence on jump performance with shorter (3s and 5s) maximal voluntary isometric contractions. (ii) Intensity and type of the contraction(s); maximal voluntary isometric contractions were suggested to be the most effective intensity to produce PAP [7], but some evidence suggests that isometric stimuli may not be the most adequate type of contraction type to induce PAP [3], which could explain our results and those obtained by Pearson and Hussain [26] in comparison with those of Bishop et al. [15] and de Freitas Conrado et al. [24]. (iii) The PAP effects may be mediated by the training experience of the subjects; it has been reported that the use of sub-maximal loads seems to be more effective in untrained subjects [3]. Therefore, 8s voluntary maximum isometric contraction may have caused fatigue since subjects in the present study were not professional athletes. (iv) The recovery time between the conditioning activity and the following performance assessment [3, 4, 6, 21]. (v) The type of subsequent activity or the measured functional outcomes.

It has been shown that twitch potentiation magnitude differs when PTP is induced by local electrostimulation vs. induced by a maximal voluntary contraction in knee extensor muscle [11]. However, no previous study had investigated the combination of both potentiation stimuli. We observed significant differences in maximum isometric strength comparing minutes 1 vs 4 and 1 vs 8, while no significant differences were observed between minutes 2 vs 6 and 2 vs 10 after the combination of PTP (i.e., induced by WB-EMS) and PAP (i.e., induced by voluntary maximum isometric contractions). This result could be explained because in minute 1 of the WB-EMS condition the force production was lower than in any other minute in all conditions. Nonetheless, no significant differences in maximum isometric strength were observed between the control and WB-EMS conditions in minute 1. Therefore, this leads us to speculate that other mechanisms may be responsible for the increase in maximum isometric strength. For instance, the recruitment pattern of motor units differs between PTP and PAP [28], thus it is possible that the recruitment of motor units (concretely type IIb) would have been higher with the combination of both potentiation conditions. Indeed, muscle type fibre distribution is the most significant muscle characteristic that affects the magnitude of potentiation [29]. Furthermore, an augmentation in blood flow and muscle water may increase Ca^{2+} release, which in turn enhances muscle fibre force [6]. Although these factors have also been present in the PAP and WB-EMS conditions, perhaps they did not play a significant role. It is possible that the combination of both potentiation protocols would have reduced fatigue as well as increased these mechanisms producing greater levels of maximum isometric strength.

The current study suffers from several limitations. Firstly, we did not assess whether the PAP and WB-EMS protocols induced potentiation of muscle function using electrical stimulation (twitch contractions). Therefore, it can only be speculated the presence and effect/contribution of potentiation (PAP and PTP) on/to maximum isometric strength. Secondly, the results are representative of a trained male population aged 18–35 years; hence, they might not be extrapolated to elite athletes, females, younger or older males. Thirdly, the split squat mostly involves leg muscles and it was used as the performance test because it is a functional movement applicable to various sports disciplines [15]; nonetheless, WB-EMS stimulates mainly the torso and upper-leg muscles, thus it is possible that diverse performance tests (e.g., upper-body strength test) would elicit different results. Fourthly, the sample size was relatively small. To exceed the limitation of the sample size, we conducted a within-subjects design and controlled for several cofounders (i.e., time of day, fasting state, and previous physical activity). Future studies with a larger sample size are needed to replicate this study. Moreover, further studies should confirm that potentiation occurs through twitch contraction assessment at the same time as the performance tests are evaluated. Such research should allow a better understanding of how potentiation might be used to enhance muscle and sports performance.

Our results do not support the use of PTP induced by WB-EMS in isolation or combined with PAP induced by voluntary maximum isometric contractions as a potentiation protocol to increase maximum isometric strength during a split squat. Nevertheless, if coaches and athletes consider inducing PTP by WB-EMS as a conditioning stimulus, it is advisable that they also perform a voluntary maximum contraction before the performance test.

CONCLUSIONS

The present results showed that PTP induced by WB-EMS in isolation or combined with PAP induced by voluntary maximum isometric contractions did not produce a significant increase in maximum isometric strength compared to the control and PAP alone, respectively. Future studies are needed to determine whether the combination of PTP induced by WB-EMS and PAP induced by voluntary maximum isometric contractions prior to competition is an effective strategy to enhance sports performance.

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Conflict of interest declaration

The authors declare that there is no conflict of interest.

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SUPPLEMENTARY MATERIAL

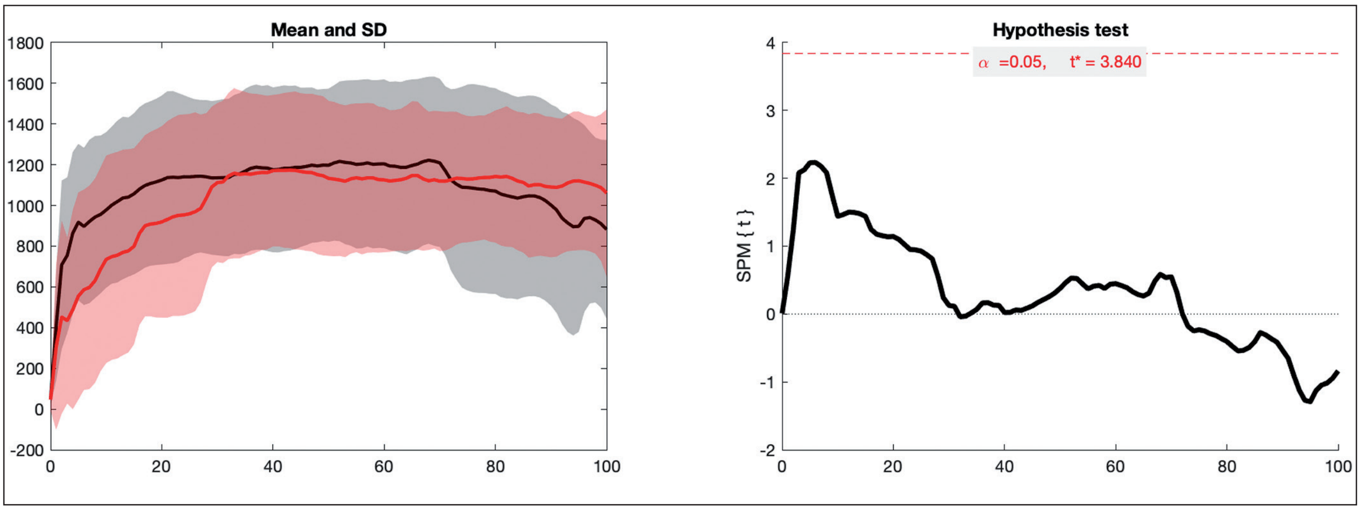

FIG. S1. SPM1D-analysis for the comparisons between the control (black line) and WB-EMS (red line) conditions considering the 8 seconds records of maximum isometric strength kinematic curves for the minute 1. Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. No significant results were observed.

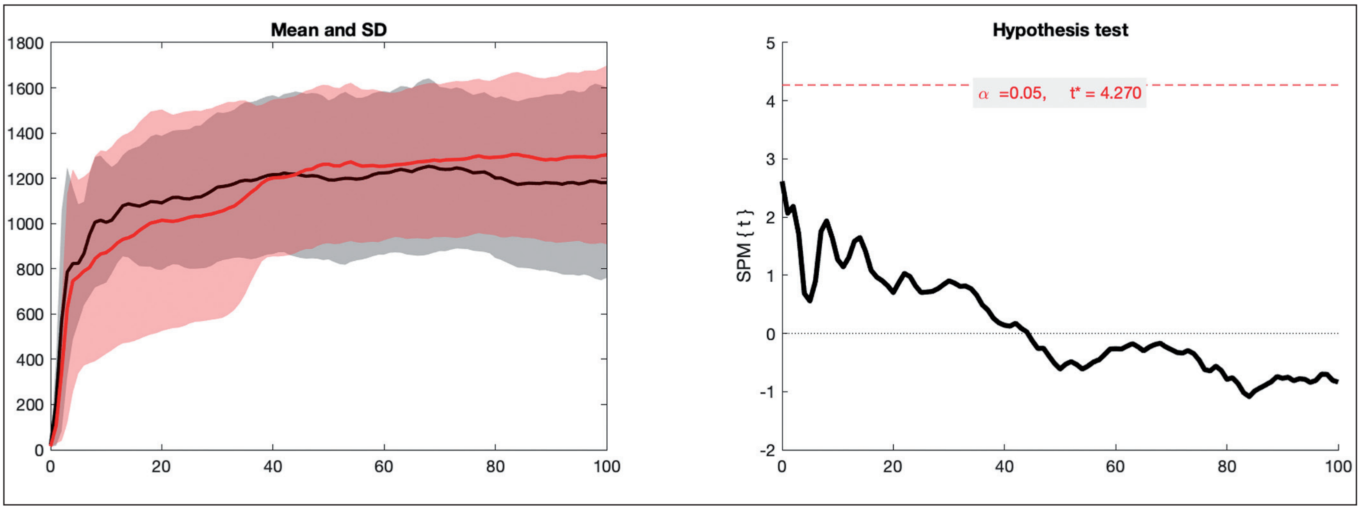

FIG. S2. SPM1D-analysis for the comparisons between the control (black line) and WB-EMS (red line) conditions considering the 8 seconds records of maximum isometric strength kinematic curves for the minute 2. Solid lines represent mean and shaded areas standard deviation. SPM{t-value} is the trajectory Student's t statistic or, equivalently, the mean difference curve normalized by sample-size normalized variance. The dotted horizontal line indicates the random field theory threshold for significance. Any clusters of SPM{t-value} that exceeded this threshold were considered significantly different. No significant results were observed.