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Effects of spinal cord transcutaneous stimulation priming on single-leg balance control

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Abstract

BACKGROUND

Balance control relies on proprioceptive, visual and vestibular inputs, contributing to functional performance and injury prevention. Neuromodulation strategies targeting the spinal circuitry controlling lower limbs are emerging as potential approaches to enhance lower limb neuromuscular performance. For example, non-invasive lumbosacral spinal cord transcutaneous stimulation (scTS) applied to prime the nervous system can improve lower limb performance during repeated, high-level efforts. However, it is unclear whether such neural priming approach can influence low-level motor outcomes and balance control.

AIM

To assess the effects of scTS priming on single-leg stance balance control with and without visual input.

METHODS

Twelve young active males (age: 22.7 ± 2.1 years) participated in this randomized crossover, sham-controlled study. Single-leg stance balance control with eyes open and eyes closed was assessed before and after the priming protocol with scTS or sham stimulation for approximately 25 minutes over a total of two different experimental sessions. Anterior-posterior, medio-lateral and a composite of the two directions were assessed on the force platform as well as electromyography of tibialis anterior (TA) and medial gastrocnemius muscles.

RESULTS

Priming protocols with scTS or sham application did not influence single-leg stance performance, as reflected by trial duration, kinetic and electromyography outcomes (priming effect: P-values ranging from 0.343 to 0.759). A significant effect of vision emerged, with shorter trial duration (P = 0.018), larger anterior-posterior (P = 0.004), medio-lateral (P < 0.001) and total displacement (P < 0.001), as well as longer co-contraction between TA and medial gastrocnemius (P < 0.001) with eyes closed compared to eyes open. Also, a time × priming × eyes interaction was found for the TA muscle activation (P = 0.046), indicating increased TA activation at the end *vs* beginning of eyes open trials following scTS priming.

CONCLUSION

The scTS priming did not affect single-leg stance balance performance under both eyes closed and open conditions. Also, as expected, impaired balance control was found with eyes closed.

Key Words: Balance; Center of pressure displacement; Priming; Spinal cord neuromodulation; Vision

Core Tip: Previous studies showed that non-invasive, spinal cord transcutaneous stimulation (scTS) priming can improve lower limb neuromuscular performance during high-intensity, fatiguing efforts but not during a low-level, torque steadiness task. Here, balance control with eyes open and eyes closed was assessed before and after the application of scTS or sham stimulation. scTS did not affect single-leg stance balance control in young active males. Also, as expected, balance control was impaired with visual deprivation (*i.e.*, eyes closed). These findings, together with previous observations, contribute to define the potential framework and applications of scTS priming.

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INTRODUCTION

Balance control is a fundamental component of human movement. For example, effective balance control is critical for injury prevention and to achieve high performance in individual and team sports[1]. On the other hand, ageing and neurological conditions negatively impact balance control. For instance, age-related deterioration in sensory and cognitive integration, neuromuscular coordination, and the progression of loss of muscle mass associated with sarcopenia progressively impair balance control mechanisms[2]. Also, neurological conditions affecting the central nervous system and cognitive functions, such as multiple sclerosis[3], stroke[4], and Parkinson's disease[5], further reduce balance control. Impaired balance control has a negative impact on quality of life, limiting daily life activities, reducing functional independence, and increasing the risk of falls and injuries[6-8].

Balance control is a complex function of the central nervous system that relies on the detection and processing of sensory information to result in the generation of appropriate motor responses to maintain an upright position[9]. This process primarily involves sensory inputs deriving from the vestibular, proprioceptive, and visual systems[10]. For example, the vestibular input contributes to detect both linear and angular head motion in space[11]. Proprioceptive input continuously provides information about body and limb position, muscle length, muscle spindle activity, and joint angles[1,12,13]. Visual input also contributes to balance control by interacting with cerebellar activities, and its deprivation (*i.e.*, eyes closed) results in impaired balance control[14]. These three sensory inputs interact with both spinal and supraspinal systems controlling balance[15]. Specifically, the spinal cord loop, which is primarily driven by proprioceptive inputs and spinal reflexes, generates corrective motor responses. The supraspinal loop integrates visual, vestibular, and mechanoreceptive information, which is processed at supraspinal level and conveyed to the spinal cord through descending pathways, forming a long-latency reflex loop that contributes to postural stability[16].

Balance and strength training can be effective to improve balance control[8]. These functional interventions predominantly enhance neuromuscular control, dynamic stability of the joints and postural control outcomes[17,18]. Another approach that has been investigated to modulate balance control is non-invasive neuromodulation. For example, transcranial magnetic stimulation and transcranial direct current stimulation have been employed to modulate neural activity as a prospective strategy to maximize balance control; however, the results are quite inconsistent. For instance, enhanced upright postural control with eyes closed was shown following a 20-minute session of anodal cerebellar transcranial direct current stimulation during perturbations and subsequent recovery phase[19]. Similar improvements were observed during stimulation applied over the bilateral motor representation cortex area of the legs, compared to sham stimulation[20]. In contrast, upright postural control, whether with eyes open or closed, did not change before and after stimulation applied over the left dorsolateral prefrontal cortex, compared to sham stimulation[21].

Another non-invasive neuromodulation strategy is transcutaneous spinal cord stimulation, which was initially developed to promote motor recovery in individuals with spinal cord injury[22]. More recently, this approach has been also implemented in able-bodied individuals, although only a few studies have specifically examined its effects on balance control, providing inconclusive outcomes. For instance, a 90-second quiet standing task, assessed before, during, and after 20-minute of transcutaneous spinal direct current stimulation applied over the thoracic (T)10 vertebra, caused no statistically significant effects on postural sway with eyes closed compared to sham stimulation[23]. Another group showed that transcutaneous spinal cord stimulation applied between the lumbar (L)1-L2 vertebrae in the upright position with eyes closed affected postural stability when delivered at the midline or over the dorsal roots corresponding to the non-dominant leg[24]. Conversely, it did not affect postural control when stimulation was applied over the dorsal roots of the dominant leg. In contrast, stability improved when stimulation was applied between T11-T12 vertebrae over the dorsal roots ipsilateral to the non-dominant leg[25]. Also, a recent study showed that spinal cord stimulation applied midline at the L2-L3 intervertebral space impaired the control of forward perturbations, which was associated with an increase in electromyography (EMG) amplitude of some lower limb muscles[26].

Overall, these studies suggest that spinal cord transcutaneous stimulation (scTS) over the thoraco-lumbar vertebral levels could either improve or impair postural control[23] by modulating the integration of voluntary descending commands and sensory signals, as well as altering muscle activation during postural tasks[27]. We have also recently implemented scTS to prime the nervous system prior to different lower limb motor tasks, showing positive effects during fatiguing high-intensity efforts[28], and no effect on low-level torque steadiness[29]. Here, we aimed at assessing whether scTS priming could improve single-leg stance balance control. Our hypothesis was that scTS priming would improve balance control with eyes closed. In fact, in this condition, balance control lacks visual input and relies to a greater extent on its spinal control circuitry, which is targeted and conceivably modulated by scTS priming. Specifically, our mechanistic hypothesis was that scTS priming would increase the excitability of the spinal circuitry involved in balance control, bringing the related neural network closer to activation threshold. This adaptation would facilitate the corrective sensory-motor responses resulting in enhanced balance control.

MATERIALS AND METHODS

Research participants

Twelve healthy and physically active young male individuals (age: 22.7 ± 2.1 years; stature: 178 ± 7.2 cm; body mass: 77.5 ± 10.1 kg; body mass index: 24.4 ± 2.0 kg/m^2) were recruited at the School of Sport Sciences, University of Udine (Italy) to participate in this study. The research participants were non-professional athletes who practiced team sports (soccer and basketball), individual sports (mixed martial arts, fencing) and/or related conditioning training activities for 3 ± 1 days/week. Subjects had no history of neurological and orthopedic injuries. Participants had not taken any medication during the experimental sessions. The experimental protocol was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Boards of the University of Udine (Approval No. 197/2023). Before the start of the study, subjects were carefully informed about its purpose and risks, and written informed consent was obtained from all of them.

Experimental protocol

This randomized crossover, sham-controlled study consisted of 3 experimental sessions (Figure 1). Their duration ranged between 1 hour (session 2 and session 3) and 1.5 hours (sessions 1). Each participant performed all experimental sessions at the same time of the day ± 1 hour. Consecutive sessions were separated by an interval of 2 days to 5 days.

The first experimental session was devoted to the assessment of anthropometric characteristics and the acclimation with scTS procedures and laboratory equipment. The second and third sessions were devoted to assessing the effects of the priming protocol with scTS or sham stimulation on single-leg stance with eyes open and eyes closed. The order of scTS and sham experimental sessions, as well as the order of eyes open and eyes closed conditions, were randomized using a random number generator program (MATLAB version 2025b, The Mathworks, MA, United States).

Anthropometric characteristics

Body mass was measured to the nearest 0.1 kg using a manual weighing scale (Seca 709, Hamburg, Germany) with the subject wearing only light underwear and no shoes. Stature was measured to the nearest 0.5 cm on a standardized wall-mounted height board. The dominant lower limb was considered as the limb used to kick a ball[30].

Balance control test

Single-leg balance stance with the dominant lower limb was examined under (i) eyes open and (ii) eyes closed conditions, in a randomized order, before and after the priming protocol with the application of the scTS or sham stimulation. Balance control was assessed as previously described by other research groups[14,31]. Briefly, each test was performed two times, and the trial with the longest stance duration was used for further analysis. Trial duration was the period of time during which the participant managed to stay in the required stance. In cases where the trial duration reached 60 seconds, the trial was ended and taken as the participant’s best trial. Subjects were barefoot throughout the whole exercise and were asked to stand quietly with arms hanging vertically down and to look straight ahead at a target (*i.e.*, black circle with a 15 cm diameter against a white background) placed at eye level, 3 m away. Thereafter, an auditory cue

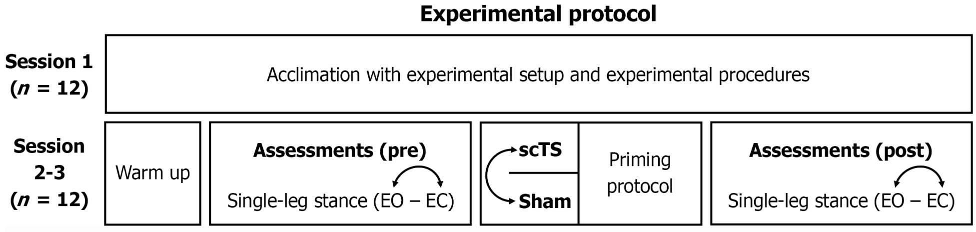

Figure 1 Overview of the experimental protocol. All subjects enrolled (*n* = 12) completed the experimental protocol. In sessions 2-3, testing of spinal cord transcutaneous stimulation or sham stimulation priming, as well as the assessments of single-leg stance with eyes open and eyes closed conditions, was proposed in a randomized order. scTS: Spinal cord transcutaneous stimulation; Sham: Sham stimulation; EO: Eyes open; EC: Eyes closed.

was provided by the experimenter counting down from 4 seconds to 1 second, with the understanding that the subject would lift the required foot off the floor when the number ''1'' was called out. The experimental environment would then remain silent, and light intensity remained constant for the duration of the trial. When the subject was able to maintain single-leg posture for the maximum time allowed of 60 seconds or the participant was not able to stay in the required stance, the experimenter would say ''stop'', at which point the participant was allowed to rest and sit down in a chair provided, for a 2-minute rest between trials[14].

scTS cathode site

Experimental session 1 was focused on the selection of scTS cathode placement by means of recruitment curves, as previously described in details[28,29,32]. Briefly, while the participant was relaxed in supine position on a standard examination table, a constant current stimulator (DS7A, Digitimer, Hertfordshire, United Kingdom; maximal voltage: 400V) connected to a trigger box (GeMS TRIGGER BOX, EMS, Bologna, Italy) was controlled by dedicated software (Direct USB for TRIGGER BOX, Version 1.00, EMS, Bologna, Italy). Single, 1 millisecond monophasic square-wave pulses were delivered every 4 seconds by self-adhesive electrodes. Two 100 mm × 50 mm electrodes (20021, Axion GmbH, Leonberg, Germany) were placed symmetrically on the skin over the iliac crests as anodes, and a circular electrode (diameter: 25 mm; E-CM25, TensCare, Surrey, United) was placed onto the skin at the T11-12 or T12-L1 intervertebral space as cathode. The order of placement between these two sites was randomized, and 4 minutes of rest were provided in between stimulation applied to these two sites. Stimulation intensity began at 5 mA and reached 100 mA by 5 mA increments. Five stimuli were delivered at each stimulation intensity. All participants reached 100 mA as highest intensity without discomfort. We selected as stimulation site for session 2 and session 3 the intervertebral space that promoted the preferential recruitment of medial gastrocnemius (MG) muscle, as defined by (i) lower stimulation intensity at motor threshold and (ii) higher peak-to-peak amplitude of evoked potentials to spinal stimulation[29].

Priming protocol with scTS or sham stimulation

The exercise-based intervention with the application of scTS or sham stimulation previously proposed by our group[28,29] was implemented as priming protocol during experimental session 2 and session 3. The investigators told the research volunteers that two different types of stimulation were applied during the priming protocols of these sessions. scTS or sham stimulation were applied in a randomized order during standing and warm up activities for approximately 25 minutes implementing the same stimulation setup described above (scTS cathode site section). The self-adhesive electrodes were secured using elastic bandages wrapped around the participant's trunk, and a small foam piece was placed between the circular electrode and the bandage.

During scTS priming, tonic, monophasic stimulation with 1000 μs pulse width was delivered at 28 Hz and an average intensity of 25.2 ± 5.7 mA. Stimulation intensity was gradually increased to achieve the highest intensity that was not uncomfortable for the volunteers. scTS was well tolerated by all participants but one, who frequently reported an itchy sensation in the abdominal area around the electrodes; nevertheless, he completed the entire study protocol. No visible lower limb muscle contraction was elicited by scTS.

During sham priming, stimulation intensity was gradually increased for approximately 60 seconds and subsequently decreased for approximately 10 seconds, after which the stimulator was turned off and remained off for the remaining approximately 24 minutes of the sham priming protocol[33]. The stimulation device remained switched on throughout the entire priming session, during which the operator periodically asked participants whether the stimulation was comfortable or not. While we did not assess credibility and expectance of sham stimulation, three participants self-reported perception of spinal stimulation (*e.g.*, whole-body pinching sensation) at the end of the sham priming. Further, nine of the twelve participants expressed surprise that no stimulation was applied during one of the experimental sessions when we met with them individually after the completion of the study.

The scTS or sham stimulation were applied during 10 minutes of quiet standing and during the subsequent 15 minutes of warm up. Warm up included stepping in place, joint mobilization, unilateral balance control, unilateral quarter squats and jumps (free movements without overload) interleaved by quiet standing. Participants were instructed to perform warm up at a self-selected intensity that would not lead to fatigue. scTS was applied during an active warm up and weight-bearing standing, rather than with the participant relaxed in supine or seated position, with the rationale that spinal cord stimulation would interact with supraspinal inputs and peripheral sensory information entering the spinal cord[34].

Data collection

EMG and ground reaction force signals were recorded by a dedicated acquisition system (Smart DX I, BTS Bioengineering, Milan, Italy) with a sampling rate of 1000 Hz, and the related software (Smart Motion Capture System Version: 1.10.0469, BTS Bioengineering, Milan, Italy). Surface EMG was collected using a wireless EMG system (BTS FREEEMG1000, BTS Bioengineering Milan, Italy) and pre-gelled electrodes (BlueSensor N-00-S/25, Ambu, Penang, Malaysia) placed with inter-electrode distance of 20 mm. Prior to the application of the EMG electrodes, the participant's skin was properly shaved, scrubbed, cleaned and dried. EMG activity was recorded from (1) The MG, on the most prominent bulge of the muscle; and (2) The tibialis anterior (TA), at one-third on the line between the tip of the fibula and the tip of the medial malleolus[35]. Ground reaction forces were collected by a force platform (Kistler, Type 9287CA, Switzerland).

Data analysis

LabChart Reader (ADInstruments, Inc., New Zealand) was the software used for data analysis. The EMG signal was band pass-filtered (10-499 Hz) and the vertical ground reaction force signal was lowpass filtered (13 Hz). Only the best attempts (*i.e.*, longest trial duration) within each experimental condition (scTS or sham stimulation) and part of the session (before or after the priming protocol) were taken into consideration for further analysis.

Kinetic data analysis: Center of pressure (COP) displacements were assessed using the force platform. The anterior-posterior (AP), medio-lateral (ML) and a composite of the two directions (total) were quantified in terms of root mean square (RMS)[31]. AP displacement is equal to $\{[\sum(x_i - x_{mean})^2]/n\}^{0.5}$, ML displacement is equal to $\{[\sum(y_i - y_{mean})^2]/n\}^{0.5}$, and total displacement is equal to $[(AP)^2 + (ML)^2]^{0.5}$, where n is the total number of samples[31].

EMG data analysis: EMG amplitude of MG and TA muscles of the dominant lower limb was assessed within the trial duration for each single-leg stance condition by RMS, and expressed as a percentage of the highest EMG amplitude found within a 1-second time window during an isometric maximal voluntary contraction (MVC). At the beginning of the experimental session (*i.e.*, prior to the placement of the stimulating electrodes), the subject lay prone on an examination bed. His dominant foot was tightened around a custom-made attachment connected to an isometric dynamometer. The anterior part of the foot sole was placed against the attachment in a flat standardized position, to obtain an ankle angle of 90 degrees. At this stage, participants were asked to perform a dorsal or plantar flexion MVC of 4-5 seconds for each isometric effort. A total of four MVCs (two dorsal and two plantar flexions), interleaved by a 2-minute rest between attempts, were performed by the participants in an alternated manner. A dedicated 5-min warm up was performed prior to MVCs.

The EMG RMS of each muscle at the end of each trial (95%-100% of trial duration) was divided by that at the start of the trial (0%-5% of trial duration) as a measure of change in muscle activation during the balance test. This ratio of EMG (rEMG) was taken as an index of neuromuscular fatigue[14]. To investigate a co-contraction feature at the ankle joint during the balance test, we calculated the amount of single-leg stance duration in which MG and TA muscles, as antagonist muscles, were active at the same time above their respective 10%MVC (co-contraction). The greater the value of this index, the longer the co-contraction duration[36].

Statistical analysis

Statistical analysis was performed using JASP 0.19 (Amsterdam, The Netherlands). A P-value less than 0.05 was considered statistically significant. Results were expressed as mean and standard deviation. The Shapiro-Wilk test was used to verify the normality of distributions. When the original data violated the normality assumption, a logarithmic transformation was applied prior to analysis. A three-way within-subjects ANOVA was implemented, with "time" (*i.e.*, pre priming protocol *vs* post priming protocol), "priming" (*i.e.*, priming protocol with scTS or sham stimulation) and "eyes" (*i.e.*, eyes open or eyes closed conditions) as repeated measures factors. Assumption of sphericity was met, as factors with only two levels of repeated measures were included in the analysis. η^2 is reported as an effect size measure for the ANOVA analysis, defining small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) magnitudes[37-39]. When significant differences were found, a Bonferroni *post hoc* test was used to determine the exact location of the differences. For such *post hoc* comparisons, 95% confidence interval (CI) calculated on the model implemented for analysis (*i.e.*, original dataset or logarithmic transformation) as well as Cohen's d effect size were assessed[38]. Effect size values lower than 0.20 were considered negligible, between 0.20 and 0.49 small, between 0.50 and 0.79 medium, and equal or greater than 0.80 large.

RESULTS

Representative COP displacements in the AP and ML directions as well as EMG activity of the dominant lower limb muscles are shown throughout a trial of single-leg stance with eyes open and eyes closed in Figure 2.

Overall, the effects of the priming protocols considered in this study during single-leg stance on trial duration and COP displacements data were negligible (Figure 3). No significant Priming effect was observed for trial duration or kinetic data (ranging from $P = 0.343$; $\eta^2 = 0.01$ to $P = 0.759$; $\eta^2 < 0.01$). Also, no significant time × priming × eyes interactions or meaningful trends were found for trial duration ($P = 0.408$; $\eta^2 < 0.01$; Figure 3A) or COP displacement (ranging from $P = 0.346$; $\eta^2 = 0.01$ to $P = 0.724$; $\eta^2 < 0.01$; Figure 3B). A significant main effect of eyes was observed for all single-leg stance variables, with shorter trial durations ($P = 0.018$; $\eta^2 = 0.24$) and greater AP ($P = 0.004$; $\eta^2 = 0.18$), ML ($P < 0.001$; $\eta^2 = 0.32$),

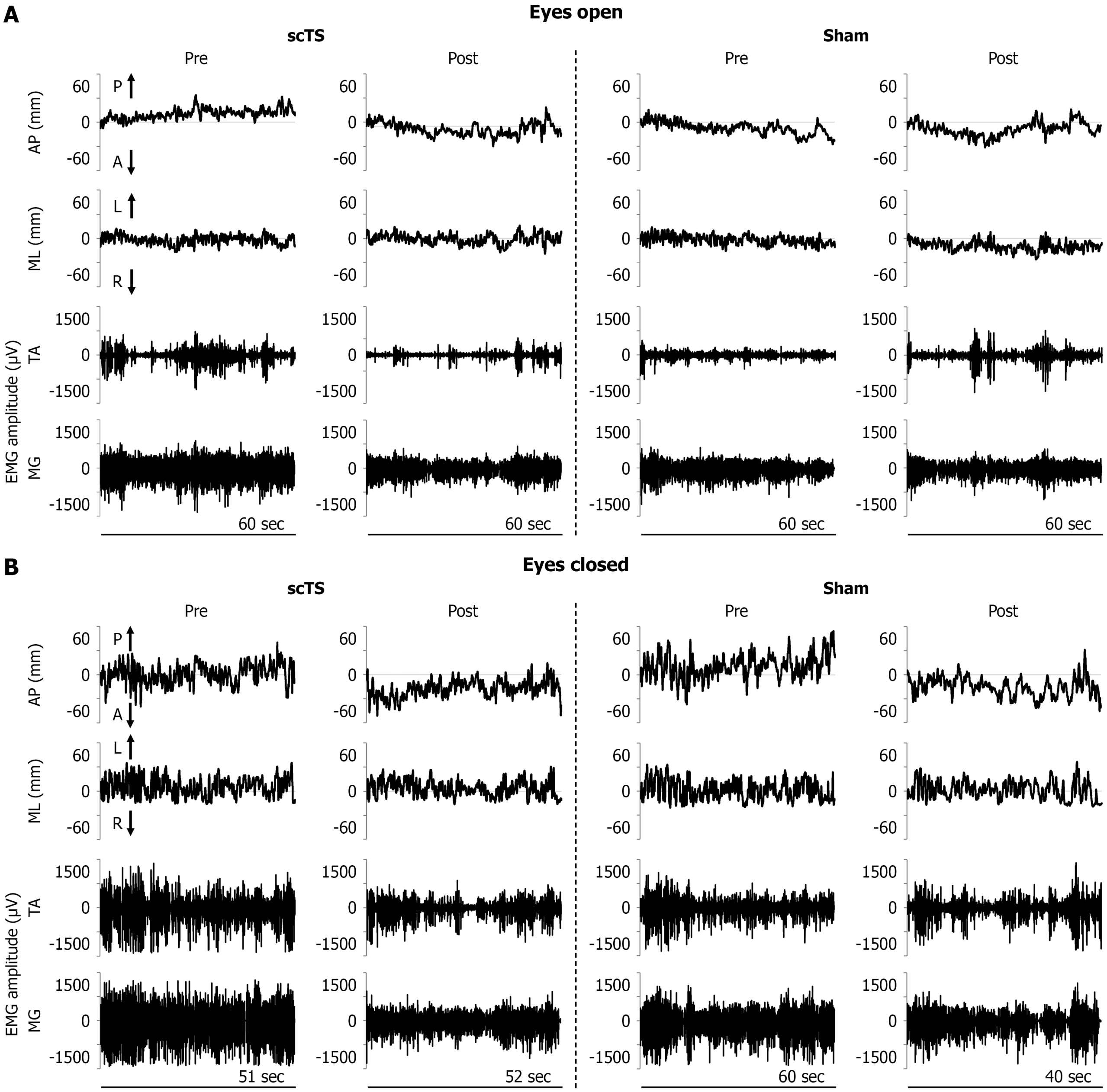

Figure 2 Exemplary time course of center of pressure displacement and electromyographic activity. A: Time course of the center of pressure displacements in the anterior-posterior and medio-lateral directions, as well as electromyographic activity of tibialis anterior and medial gastrocnemius, during a representative single-leg stance performed before and after the priming protocol with spinal cord transcutaneous stimulation or sham stimulation with eyes open; B: Time course of the center of pressure displacements in the anterior-posterior and medio-lateral directions, as well as electromyographic activity of tibialis anterior and medial gastrocnemius, during a representative single-leg stance performed before and after the priming protocol with spinal cord transcutaneous stimulation or sham stimulation with eyes closed. scTS: Spinal cord transcutaneous stimulation; Sham: Sham stimulation; EMG: Electromyographic; AP: Anterior-posterior; ML: Medio-lateral; TA: Tibialis anterior; MG: Medial gastrocnemius; P: Posterior; A: Anterior; L: Left; R: Right.

and Total COP displacements ($P < 0.001$; $\eta^2 = 0.30$) with eyes closed compared to eyes open. *Post hoc* analysis further detailed the specific location of these differences between eyes closed and eyes open conditions, which ranged between $P = 0.007$ (effect size = 1.46, 95%CI: -17.55 to -1.60; total COP displacement, scTS, pre priming protocol) and $P = 0.028$ (effect size = 1.26, 95%CI: -0.41 to -0.01; ML COP displacement, scTS, pre priming protocol; Figure 3B).

When evaluating the trial end *vs* start rEMG, no significant Priming effect was observed for both the TA and MG muscles ($P = 0.705$; $\eta^2 < 0.01$ and $P = 0.450$; $\eta^2 = 0.01$ respectively). Conversely, significant time × priming × eyes interaction was observed ($P = 0.046$; $\eta^2 = 0.04$; Figure 4A) for rEMG of the TA muscle. *Post hoc* analysis revealed a significantly higher TA rEMG after scTS priming compared to Pre priming in the eyes open condition ($P = 0.042$; +78.4%, effect size = 1.16, 95%CI: -0.54 to -0.01). Also, no significant time × priming × eyes interactions or trends were found for rEMG of the MG muscle ($P = 0.369$; $\eta^2 < 0.01$; Figure 4A). Conversely, a significant main effect of Eyes was observed for rEMG of the MG muscle, with higher MG rEMG ($P = 0.008$; $\eta^2 = 0.10$) with eyes closed compared to eyes open.

Finally, no significant time × priming × eyes interaction was detected for the level of co-contraction between TA and MG ($P = 0.121$; $\eta^2 < 0.01$; Figure 4B). However, a significant main effect of eyes was found, with longer co-contraction in

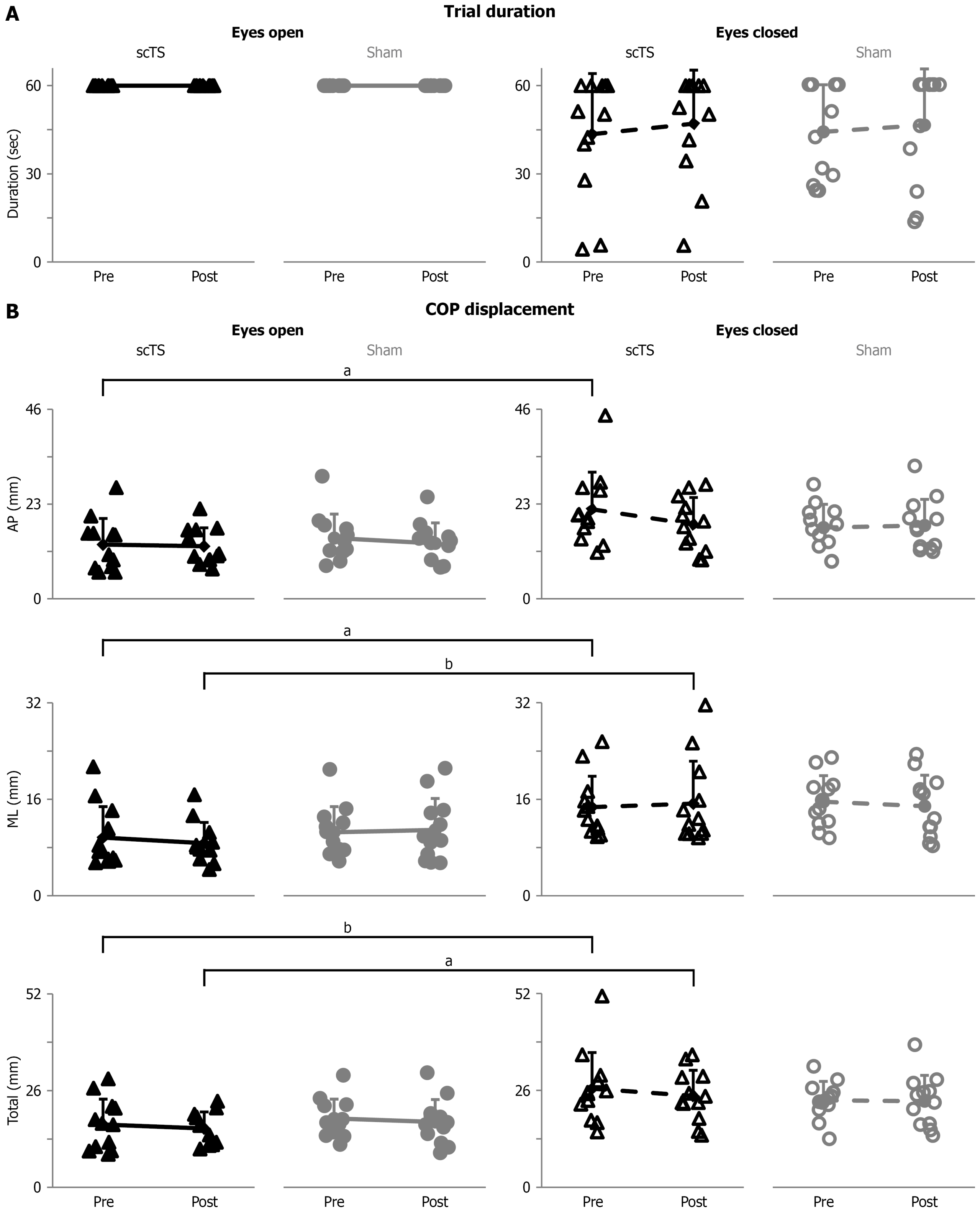

Figure 3 Group data of trial duration and center of pressure displacement. A: Trial duration (seconds) for single-leg stance attempts with eyes open and eyes closed, before and after the priming protocol with spinal cord transcutaneous stimulation (scTS) or sham stimulation (sham; $P < 0.05$); B: Center of pressure displacement in the anterior-posterior direction ($P < 0.01$), medio-lateral direction ($P < 0.001$), and composite total displacement (quantified as root mean square; $P < 0.001$) for single-leg stance attempts with eyes open and eyes closed, before and after the priming protocol with spinal cord transcutaneous stimulation or sham. Results are described as individual data points (solid black triangles: ScTS, eyes open; solid grey circles: Sham, eyes open; empty black triangles: ScTS, eyes closed; empty grey circles: Sham, eyes closed) as well as mean and standard deviation. Significant difference by Bonferroni *post hoc* test: $^{a}P < 0.05$; $^{b}P < 0.01$. scTS: Spinal cord transcutaneous stimulation; Sham: Sham stimulation; AP: Anterior-posterior; ML: Medio-lateral; COP: Center of pressure.

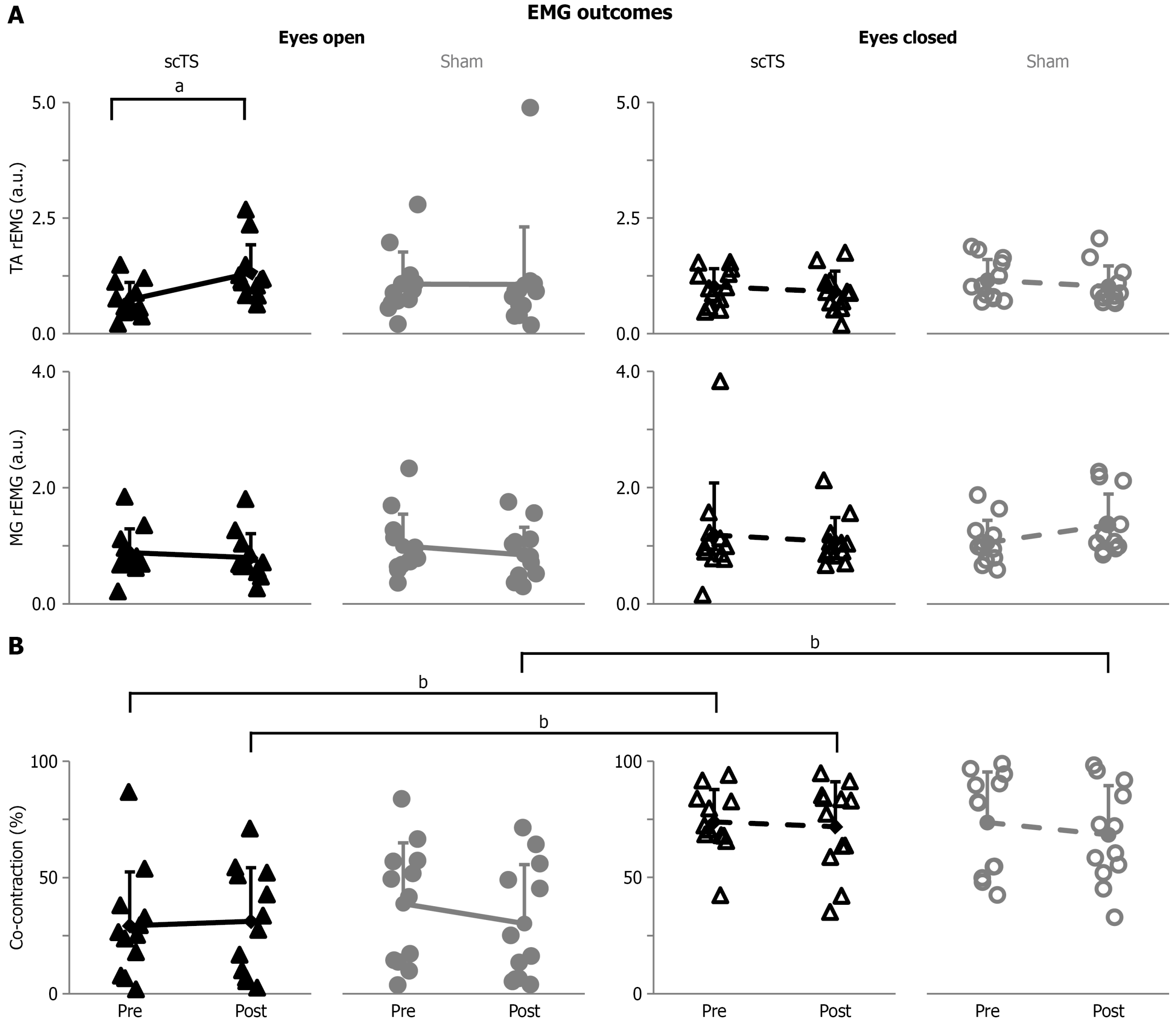

Figure 4 Group data of electromyographic activity. A: Ratio of electromyography (EMG) amplitude assessed at the end of each trial by the EMG amplitude detected at the start of the trial for the tibialis anterior ($P < 0.05$) and medial gastrocnemius ($P < 0.01$). Ratio of EMG are expressed in arbitrary units; B: Single-leg stance duration in which tibialis anterior and medial gastrocnemius muscles were active at the same time above their respective 10% maximal voluntary contraction (co-contraction; $P < 0.001$). Both metrics are reported for the single-leg stance attempts with eyes open and eyes closed, before and after the priming protocol with spinal cord transcutaneous (scTS) or sham stimulation (sham). Results are described as individual data points (solid black triangles: ScTS, eyes open; solid grey circles: Sham, eyes open; empty black triangles: ScTS, eyes closed; empty grey circles: Sham, eyes closed) as well as mean and standard deviation. Significant difference by Bonferroni *post hoc* test: $^{a}P < 0.05$; $^{b}P < 0.01$. EMG: Electromyographic; scTS: Spinal cord transcutaneous stimulation; Sham: Sham stimulation; TA: Tibialis anterior; MG: Medial gastrocnemius; a.u.: Arbitrary unit; rEMG: Ratio of electromyography.

the eyes closed compared to the eyes open condition ($P < 0.001$; $\eta^2 = 0.58$). *Post hoc* analyses further indicated significantly longer co-contraction both before ($P = 0.003$; +155%, effect size = 1.66, 95%CI: -0.96 to -0.15) and after ($P = 0.005$; +132.2%, effect size = 1.56, 95%CI: -0.93 to -0.12) scTS priming with eyes closed compared to eyes open. Following the sham priming protocol, a significantly longer co-contraction was also observed with eyes closed compared to eyes open ($P = 0.004$; +126.6%, effect size = 1.58, 95%CI: -0.93 to -0.12). Moreover, we observed a trend of increased co-contraction with eyes closed compared to eyes open ($P = 0.051$; effect size = 1.21, 95%CI: -0.810 to 0.001) at pre of the sham priming session (Figure 4B).

DISCUSSION

The scTS priming investigated in this study did not significantly affect single-leg stance balance control in young active males. Further, visual deprivation (*i.e.*, eyes closed condition) impaired balance control, as evidenced by shorter trial durations, greater COP displacement, increased neuromuscular fatigue and longer co-contraction duration of representative ankle muscles.

scTS priming and balance control

scTS is a non-invasive neuromodulation approach that has been implemented with the goal of improving motor function in individuals with spinal cord injury[22] and in able-bodied subjects[23,25,40,41]. It primarily recruits large, myelinated fibers associated with somatosensory information at their entry into the spinal cord, which in turn engages the spinal circuitry controlling muscle activation[42,43]. In the present work, single-leg stance balance control was assessed before and after the priming protocol with the application of scTS or sham stimulation for approximately 25 minutes to prime the nervous system. While balance can be tested during bipedal standing[19,21,24,25], we implemented a single-leg stance assessment to better identify relevant aspects to daily life and athletic performance (*i.e.*, gait, sprinting, jumping and changing direction)[44,45]. Here, neither scTS nor sham priming protocol affected single-leg stance balance control, as indicated by trial duration, COP displacements (Figure 3), or EMG parameters (Figure 4). One significant difference was observed in the rEMG of the TA muscle (Figure 4A), which showed increased TA activation toward the end of the trial compared with the beginning following scTS priming. This finding may be interpreted as a change in muscle activations strategy consistent with the occurrence of neuromuscular fatigue during the later phase of the trial, where greater TA activation was implemented to maintain comparable levels of balance control (*e.g.*, trial duration and COP displacement, Figure 3)[14]. However, further dedicated assessments are needed to confirm this interpretation.

Recent studies have provided increasing evidence that scTS can affect high-intensity motor tasks in healthy individuals. These studies suggested that scTS may increase the excitability of the spinal neuronal networks, bringing them closer to activation threshold[46-49]. Such neural modulations conceivably contributed to the enhanced performance shown during countermovement jumps[40], ballistic plantar flexions[46] as well as to the improved learning and retention of backwards locomotion[41]. Recent research from our group is also in line with these findings, showing that scTS priming supported lower limb performance during MVC of knee extensors and explosive lower limb extensions, counteracting exercise-induced fatigue trends that were instead observed with sham stimulation[29]. Moreover, scTS priming significantly and largely improved lower limb performance assessed during a subsequent simulated power training session[28].

However, this study suggests that scTS priming does not influence balance control in young active males. Previous studies investigating the effects of scTS on balance performance have reported heterogeneous findings[23-26], with some authors suggesting that scTS may interfere with inhibitory processes in the central nervous system, inducing hyperpolarization of the sensory afferents or blocking natural sensory inputs[26]. It is also worth noting that scTS priming did not have any effect on another non-fatiguing, low-intensity motor task related to knee extension torque steadiness[29]. Taken together, these findings might suggest that the neuromodulation effect of scTS priming, which conceivably brings the involved neural network closer to the activation threshold[46-49], can enhance high-level neuromuscular efforts but not submaximal, finer motor control related to balance and torque output steadiness, among others. However, future studies are needed to support this perspective. It is also important to point out that the lack of scTS priming effect on balance control in this cohort of physically active young males should not be generalized to other populations such as elderly individuals with impaired physical performance. In fact, in this population, age-related decline in balance control and neuromuscular function has been attributed, at least in part, to central nervous system impairments that could conceivably be modulated by scTS priming. Clinical populations with neurological disfunction or injury may also respond differently than young active males to scTS priming for balance control. However, dedicated studies are warranted to investigate this topic.

Effects of visual input on balance control

Visual input plays a crucial role in balance control through its interaction with cerebellar activity, and its importance is well established as visual deprivation (*i.e.*, eyes closed) consistently results in impaired balance control[14]. In the present study, as expected, visual input deprivation by eyes closed impaired balance control during single-leg stance, as evidence by shorter trial duration (Figure 3A), greater COP displacements (Figure 3B) and altered EMG features of representative ankle muscles (Figure 4). Standing with eyes open facilitates postural adjustments by providing continuous visual feedback, resulting in smoother and more precise corrections[50]. In contrast, with the lack of visual input, balance control depends more heavily on spinal control circuits, which are primarily driven by proprioceptive inputs and spinal reflexes that generate compensatory motor responses[16]. However, even with the lack of visual input by eyes closed and the consequent greater involvement of spinal control mechanisms, the neuromodulation by scTS priming of the spinal circuitry controlling the lower limbs did not promote any change in balance control (Figure 3). Future studies may implement additional strategies to further challenge balance control, such as perturbing the vestibular system[51] and/or increasing the trial duration. These approaches could contribute to further mitigate the potential ceiling effect in a population of young and physically active individuals and confirm the lack of scTS priming effects on balance control in this population.

During standing, AP sway is primarily controlled by the ankle plantar flexors and dorsiflexors[52]. In the present study, visual deprivation significantly affected the activation pattern of TA and MG (Figure 4), two antagonist ankle muscles, increasing neuromuscular fatigue and the duration of co-contraction (Figure 4B). This pattern is typically associated with ankle joint stiffening and abnormal motor unit synchronization[53], which may be interpreted as a motor control strategy to improve overall postural stability[14,54].

CONCLUSION

In conclusion, scTS priming did not influence single-leg stance balance control with eyes open or eyes closed in young, active male individuals. Also, as expected, visual input deprivation impaired balance control. Future studies may explore the implementation of scTS priming in populations with impaired balance control by ageing, disuse or neurological conditions, as a more deconditioned balance control system may respond differently to spinal cord neuromodulation than that of young, physically active individuals.

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FOOTNOTES

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Clinical trial registration statement: The study was not formally registered in a clinical trial database. This pilot human study was designed to investigate mechanisms of balance control, and not health-related outcomes.

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