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Title: Improvements in short sprint performance by combining hopping and transcranial direct current stimulation

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Abstract:

The optimization of descending motor commands from the central nervous system is essential for maximizing performance during short-distance running. Recent studies have shown that transcranial direct current stimulation (tDCS) can modulate central nervous system excitability and enhance exercise performance. Additionally, plyometric exercises are known as a measure to enhance instantaneous motor performance. However, the combined effects of tDCS and plyometric exercise remain poorly understood. Therefore, we investigated the combined effects of anodal tDCS and plyometric conditioning exercises on short-distance sprint running.

Eleven university athletes were asked to perform a 20-meter sprint test both before (pre-test) and after tDCS (post-test). Before the pre-test, the participants engaged in jogging, stretching, and incremental 20-meter sprint exercises. After the pre-test, anodal tDCS was applied to the cortical leg area. Following tDCS, plyometric hopping exercises were performed, and a post-test was conducted. The intensity and duration of the stimulation were 2 mA and 15 min, respectively. Sham stimulations were performed on different days using the same experimental procedure.

The post-test time was significantly shorter than the pre-test time in both the anodal and sham tDCS conditions. Further, the improvement rate in the post-test was significantly higher in the anodal tDCS condition than in the sham tDCS condition.

These findings indicate that combined anodal tDCS and prior plyometric exercise can optimize descending motor commands and peripheral motor function, thereby improving short-sprint running performance.

Keywords: Direct current stimulation, Sprint running, Conditioning exercise, Plyometric exercise, Neuromodulation.

タイトル: 直流電気刺激とプライオメトリックエクササイズの組み合わせが短距離走タイムに及ぼす影響について

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日本語抄録：

短距離走のパフォーマンスを最大限に高めるには、中枢神経系からの下降指令を最適化することが不可欠である。近年の研究は、経頭蓋直流刺激(tDCS)は下行性指令を修飾可能であり、様々な運動パフォーマンスを向上させることを明らかにしている。また、瞬発的な運動パフォーマンスを向上させることが知られている。しかしながら、tDCSとプライオメトリック運動の組み合わせ効果については不明な点が多い。したがって、本研究では、短距離のスプリントランニングに対する陽極tDCSとプライオメトリック運動の組み合わせ効果を検討した。11人の大学競技者は、tDCSの前（pre-test）と後（post-test）に20mのスプリント走を行った。参加者はpre-test前にジョギング、ストレッチ、20mスプリント練習を実施し、その後、陽極tDCSを下肢の皮質領域に与えられた(陽極刺激条件)。tDCSに続いて、参加者はプライオメトリック運動としてホッピング運動

を行い、その後 post-test を実施した。刺激の強度と継続時間はそれぞれ 2 mA、15 分であった。対象条件として偽刺激を用いた実験を、陽極刺激実験日とは異なる日に実施した(偽刺激条件)。

post-test のタイムは、陽極刺激条件および偽刺激条件の両方において、pre-test タイムよりも有意に短縮された。さらに、post-test タイムの改善率は、偽刺激よりも陽極刺激の方が有意に高かった。

本結果は陽極 tDCS と事前のプライオメトリック運動を組み合わせにより、さらなるスプリント走パフォーマンスの向上効果が得られる事を示した。この刺激は筋へ伝達される下行性指令のコンディショニングとして利用できる可能性がある。

Introduction

Instantaneous sprinting ability is a critical factor affecting athletic performance in various sports. As such, elucidating the mechanisms that enable high-intensity sprint performance and developing appropriate training methods are important research topics in sports sciences. Sprint performance is not determined solely by the function of peripheral organs such as muscles and tendons. Indeed, when running speed increases, the patterns of muscle activity and sensory feedback may change continuously; consequently, muscle activity increases *1,2)*. In other words, appropriate descending commands transmitted from the central nervous system (CNS) to the muscles are essential for maximizing sprint performance *3)*.

Despite their simplicity, conditioning exercises performed immediately prior to a motor task are known to modulate descending commands, thereby facilitating subsequent motor performance. Rapid finger abduction over a few minutes results in changes in the muscle activity patterns and CNS excitability, thereby improving movement acceleration *4)*. Improvements in sprint performance occur after movements that require instantaneous and large-force production *5)*. These findings suggest that the CNS does not necessarily continually optimize motor output. Therefore, appropriate conditioning exercises could potentiate peripheral functions and refine descending commands from the CNS to the muscles, which would maximize sprint performance.

Transcranial direct current stimulation (tDCS) is a method to modulate descending commands, which involves the delivery of a weak direct current to the CNS via electrodes attached to the scalp for several to tens of minutes to modify excitability *6)*.

Anodal stimulation, which involves placing an anode near the motor cortex, increases the amplitude of motor-evoked potentials (MEP) in the muscles associated with the stimulated area 7) and improves voluntary activation 8). Anodal tDCS applied before exercise enhances toe grip strength, 9) and prolongs the duration of fatiguing exercise 10-12). Therefore, if the descending commands transmitted to the muscles during sprinting are not optimized, performance may be improved by prior anodal tDCS.

Previous studie have reported the effects of anodal tDCS on sprint performance following a single bout of sprinting performance 10,13). These studies evaluated sprint power during cycling after applying anodal tDCS; however, the observed improvement in power was not significant 10,13). Conditioning exercises are commonly performed prior to an event to maximize the performance in sports that require short-distance running or sprinting. The excitability-modulating effects of tDCS vary depending on the excitability of the CNS before and after stimulation 14,15). As such, different effects of anodal stimulation from those of previous studies were observed in sprint performance after practical conditioning exercises.

Therefore, this study investigated whether anodal tDCS applied after practical conditioning exercises could improve sprinting performance. One practical conditioning exercise used in this study was the plyometric exercise, which involves the rapid stretching and contraction of muscles to produce vital force 16); it has also been reported to shorten sprint times 17). In addition, repetitive high-force contractions modulate the CNS 4). Thus, in this study, a plyometric-like hopping exercise was performed after anodal stimulation and sprint times were compared between the stimulus conditions.

Materials and Methods

Participants

The participants included 11 healthy university athletes (5 men, 6 women; Table 1), all of whom were university track and field team members affiliated with the Kanto Student Athletics Federation who engaged in daily training. This study was conducted in accordance with the Declaration of Helsinki and ethical guidelines for medical research involving human subjects, with the approval of the Chiba University Ethics Committee (approval number: 38). Before the experiment, participants were provided with an explanation of the experimental procedure and purpose, and the experiment was conducted after obtaining their consent to participate. In addition, prior to the experiment, we confirmed the presence of intracranial implants or surgical experience, and inquired about hospital visits or medication use related to psychological symptoms. None of the participants met the exclusion criteria.

[Insert table 1 here]

Experimental Procedure

The participants performed two sets of experiments under anodal and sham tDCS conditions. A 20-meter sprint running test was conducted before and after tDCS with conditioning exercise. First, the participants performed conditioning exercises (preconditioning) with 5 min of jogging, 2 min of stretching, 6 min of familiarization practice with the 20-meter sprint, and a 5 min break. Subsequently, they performed a 20-

meter sprint test (pre-test). Following the pre-test, tDCS was applied for 15 min while the participant was seated. After tDCS was terminated, the participants performed plyometric-like hopping exercises (postconditioning). The hopping exercise consisted of 30 hopping steps for 150 s. Participants performed a sequence of five hopping steps with one leg, following which they switched to the opposite leg; this sequence was repeated three times with a 25 s duty cycle (Fig.1). During the hopping exercise, the participants were instructed to "bounce as quickly as possible and jump as far horizontally as possible." After the hopping exercise, a 2.5-min break was taken, after which the participants performed the 20-meter sprint test (post-test) again.

[Insert figure 1 here]

Prior to the above experiments, the participants were asked to answer a questionnaire regarding their physical condition, and their body composition was measured using a body composition meter (InnerScan DUAL, TANITA, Japan). The two sets of experiments were conducted on separate days, with a minimum interval of 48 h between each set. The 20-meter sprint test was conducted outdoors on track and field ground, and all tests were performed on the same surface. The participants used the same shoes for both measurements in the 20-meter sprint test. A mobile device application (Sprint Timer Pro; Sten Kaiser, Sweden) was used to measure the time required for the 20-m sprint test. The participants used the same shoes for both measurements. A loudspeaker was placed ~50 cm in the starting position, and after the words "on your mark" and "set," a beep sound was delivered randomly within the range of 2.5 seconds ± 0.5 seconds. The participants performed a full-effort sprint in response to beeps. A camera was installed at the goal point, and the time was measured in units of 0.01 seconds by photo judgment. The time from the start of the sound signal to crossing of the finish line was measured. Before the pre-test, all participants engaged in two practice sessions of incremental 20-meter sprint with audio cues. Time was measured during these practice sessions to ensure that all familiar with the measurement protocols.

Transcranial direct current stimulation (tDCS)

tDCS was performed according to previous studies *10,13,18)*. The stimulation device used was a DC-STIMULATOR (NeuroConn, Germany) with a rubber electrode (5 × 7 cm, 35 cm^2) covered with a sponge soaked in physiological saline. The anode was placed at the vertex (Cz) and the cathode was placed at the center of the forehead. The stimuli consisted of anodal and sham stimulations. Anodal stimulation was applied at an intensity of 2mA (current density of 0.057mA/cm^2) for 15 min, with a fade-in/fade-out time of 15 s. In the sham stimulus condition, the current was increased to 2mA for the 15-s fade-in time and then immediately decreased to 0mA for the 15-s fade-out time. During both stimulus conditions, the participants were instructed to immediately report any itching, discomfort, or pain. However, there were no such reports during the experiment.

The tDCS-induced electrical fields were estimated using a free and open-source software package designed to simulate noninvasive brain stimulation (SimNIBS v.4.1.0), which can create a volume conductor model and perform electric field simulations from segmented MRI images [19]. Fig.2 presents the simulated spatial distribution of the electrical field with its default parameters and the head model (m2m_MNI152). The electrode size and current intensity corresponded to the aforementioned tDCS parameters. The center positions of the anode and cathode were set as Cz and Fpz, respectively.

[Insert figure 2 here]

Statistical analysis

Statistical analyses were performed using SPSS software (Statistics 25 and 27, IBM, Japan; JASP 0.19, University of Amsterdam, Netherlands). A two-way analysis of variance (ANOVA) with repeated measures was conducted to compare the 20-m sprint times before and after the intervention (pre-test vs. post-test) and between the stimulus conditions (anodal vs. sham stimulation). The degrees of freedom were adjusted using the Greenhouse–Geisser epsilon, depending on the sphericity of the data. Bonferroni's multiple comparison test was conducted as a post-hoc test to determine the main effects and interactions. A paired t-test was applied to compare the changes in the post-test relative to the pre-test between stimulus conditions. Pearson’s correlation coefficient was calculated between the mean pre-time and the degree of change in both stimulus conditions. The mean pre-time was averaged as the pre-time between the sham and anodal stimulus conditions. The significance level was set at less than 5% for all tests.

Results

Fig.3A shows the grand means and standard deviations of the 20-m sprint time for each stimulus condition. The average time for the anodal stimulus condition was 3.85 ± 0.10s before stimulation (pre-time) and 3.78 ± 0.13s after stimulation (post-time). The pre-time for the sham stimulus condition was 3.85 ± 0.14s, and the post-time was 3.82 ± 0.15s. A significant main effect of the stimulation intervention (pre- vs. post-time) was found using repeated measures of two-way ANOVA ($F_{(1,10)} = 21.406$, $p = 0.001$, *partial* $\eta^2 = 0.682$). However, the stimulus condition (anode vs. sham) showed no significant main effect ($F_{(1,10)} = 0.515$, $p = 0.489$, *partial* $\eta^2 = 0.049$). A significant interaction was found between stimulus intervention and condition ($F_{(1,10)} = 5.998$, $p = 0.034$, *partial* $\eta^2 = 0.375$). The post-time was significantly shorter than the pre-time in both the anodal ($p = 0.019$) and sham stimulus conditions ($p = 0.010$), using Bonferroni's post hoc test. In contrast, the two stimulus conditions showed no significant differences in either the pre-time ($p = 1.000$) or the post-time ($p = 1.000$).

[Insert figure 3 here]

Fig. 3B shows the degree of change in the post-time period compared to the pre-time period. Positive values indicate an increase in time (performance deterioration), while negative values indicate a reduction in time (performance improvement). The differences between the anodal and sham stimulus conditions were -1.76 ± 1.50% and -0.69 ± 0.54%, respectively, and the difference between the stimulus conditions was significant (t = 2.476, p = 0.033, *Cohen's d* = 0.746).

[Insert figure 4 here]

Fig.4 shows a scatter plot of the relationship between the pre-time (x-axis) and the degree of change in time after tDCS stimulation (y-axis). Each plot represents the data for an individual participant, and the grey dashed line represents the linear regression line obtained from these data. There was no significant relationship between the pre-time and the degree of change post-time for either stimulus condition.

Discussion

This study investigated the effects of anodal tDCS on sprint running performance following plyometric conditioning exercise. The 20-meter sprint requires the rapid coordination of the four limb muscle groups at the start of the sprint. As such, this type of sprint has been used to verify the athletic conditions in the intervention effect of plyometric exercise 20). The results showed that the 20-m sprint time following anodal tDCS was significantly shortened compared to the sham stimulus condition. Previous studies have also examined the effect of anodal tDCS on sprinting and reported a reduction in the degree of time decrease during a 15m sprint after pre-exercise anodal stimulation 21). However, they did not compare the time immediately following stimulation, and thus found no differences in sprint times between the 1st-10th and 11th-20th sprints after stimulation. In the present study, two sprint runs, tDCS stimulation and hopping exercises, were performed under each stimulus condition at intervals of approximately 20 min. The anodal tDCS and sham conditions, the post-time was significantly shorter than the pre-time in the anodal tDCS group (Fig. 3A). Thus, this study is the first to show an improvement in sprint performance due to the combination of conditioning plyometric exercise and anodal tDCS.

As a practical conditioning exercise, one-leg hopping was performed after tDCS. Plyometric exercises such as hopping are conditioning exercises that improve sprint performance 17). Performing plyometric exercises increases the maximum muscle contraction force because of muscle contraction reinforcement, known as post-activation potentiation 22). Plyometric conditioning may alter the efficiency of synaptic transmission at the neuromuscular junction 23). In addition, the phosphorylation of myosin-regulated light chains in the excitation-contraction linkage could affect exercise performance by increasing the sensitivity of actomyosin to calcium ions 24). Additionally, repeated brief and intensive force production improves muscle activity patterns, 4) and potentially increases voluntary activation 16,25). Based on previous studies, the immediate effects of this conditioning exercise may refine both peripheral and central factors. In this study, hopping was performed as a conditioning exercise before the post-test. The results showed a significant reduction in post-time compared with pre-time, even under the sham stimulus condition (Fig. 3A), which is consistent with the conditioning effect of plyometrics reported in previous studies 17).

If anodal tDCS was applied before the hopping exercise, the subsequent post-time was significantly shortened compared with sham stimulation. Several central mechanisms must be considered to explain the findings of this study. For example, tDCS affects the concentration of GABA, a primary inhibitory neurotransmitter, as well as the function of its receptors 26). Stimulation may thus decrease the activity of GABAergic synapses and reduce the inhibitory input to the motor cortex, resulting in increased excitability or efficiency of excitatory input to the motor cortex 7,27,28). In addition, the magnitude of the simulated electrical field in the preset tDCS was found to be more extensive around the prefrontal area than in the motor cortex (Fig.2). The frontal cortex also exerts a top-down influence, causing a change in pace to complete a task, prolongation of motor output, delay in motor termination, and withdrawal of motor units, which can cause motor termination through an inhibitory control system 29-31). This region is also thought to be involved in execution and change of pace in locomotion in cooperation with the basal ganglia and thalamus 32-34). As such, excitability modulation in various brain areas involved in locomotor regulation could optimize descending command, enhancing 20-meter sprint performance. In contrast, we placed the cathodal electrode at the center of the prefrontal cortex so that the excitability of the prefrontal cortex could be inhibited. However, the effective tDCS polarity in the prefrontal area remains controversial 29-31). The effect of tDCS to the prefrontal cortex on intensive motor performance should be investigated in greater detail in future studies.

It is also possible that the effect of the hopping exercise differed between the stimulus conditions during this experimental procedure. Yamaguchi et al. (2020) investigated the effects of anodal tDCS on rapid force production while participants paid attention to the muscle activity. They showed that the acceleration of movement was enhanced by the modulation of MEP after anodal tDCS [35]. Although the experimental conditions of the previous and current studies did not match, it is worth considering that the kinematic changes and changes in intensity of the hopping exercise caused by anodal tDCS may indirectly improve sprint performance. Thus, further investigations are required to clarify the mechanisms of the performance improvement. However, the excitability modification of anodal tDCS may facilitate a conditioning effect, leading to reduced sprint time, as the participants were unable to maximize their sprint performance even after the hopping exercise.

The effects of tDCS may strongly depend on the experimental conditions. For example, the effect of tDCS on the maximal effort is influenced by the intensity and duration of the motor task[10] and the type of exercise[18]. Additionally, the excitability modification effect of tDCS may be influenced by conditioning exercises after stimulation[14,15]. This study evaluated the effect of anodal stimulation on the time to complete a 20-m sprint after a conditioning exercise. As the experimental conditions differed in exercise intensity, time, and type from those used in previous studies, it is difficult to generalize these results. However, the finding that the conditioning effect of tDCS on sprinting performance depends on the experimental conditions could be a clue for future applications. Based on the results of previous studies, it is necessary to examine the effects of tDCS under various conditions to fully understand its potential as a conditioning technique for sprint performance.

It is also necessary to consider potential changes in reaction, as the 20-meter sprint task included a rapid reaction to the go signal. tDCS of the dorsolateral prefrontal cortex may modulate selective attention and improve reaction time [36,37]. In contrast, a previous study reported no effect on reaction time following anodal tDCS performed using electrodes attached at the Cz and forehead [38]. As it was unclear whether reaction time was shortened in our study, further investigation is needed to clarify this factor for improvement in sprint time. In addition, prior reports have suggested that tDCS may increase neuronal excitability and nerve conduction velocity [39,40]. These mechanisms may allow motor commands to be transmitted more rapidly to the spinal cord and muscles, possibly improving reactions. However, changes in nerve conduction velocity are likely to contribute little to the overall complex coordinated limb movements investigated in this study. As such, tDCS-induced changes in 20-meter sprint performance may involve complex neural mechanisms; however, the results of this study do not allow us to determine which is most likely. As such, further detailed investigations are required. Nevertheless, the most critical finding of this study was that plyometric conditioning exercise failed to maximize the athletic performance of sprint running without anodal tDCS.

The modulatory effects of tDCS used in this study varied among participants [10,41], and the impact of tDCS on enhancing maximal exercise performance may depend on individual motor performance. Our research group reported that the performance-enhancing effects of anodal tDCS were more easily obtained in non-exercisers during a 20-s maximal stepping exercise[18]. However, there was no significant interaction between the pre-time and the degree of change in either the anodal or sham stimulus conditions (Fig. 4). This result may be related to the fact that all participants in this study were university athletes who were members of a track and field club, and their daily exercise habits may have influenced the results. However, we must assume an intriguing possibility of responders and non-responders at the individual level (42). As only 11 subjects participated in this study, we did not control for all factors that may contribute to the variability of responses to tDCS, due to the small number of subjects. Therefore, when applying the findings of this study, it is necessary to consider the number of subjects and physical characteristics of the study population.

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Contributions

Kiuchi and Komiyama were responsible for research design and experimental protocols. Kiuchi and Ishii were responsible for data collection. Sasada and Kiuchi conducted the data analysis. Sasada, Kiuchi, and Komiyama were responsible for data interpretation and manuscript writing and revision. All authors approved the final manuscript following careful review.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Figure Legends:

Fig.1 Experimental timeline. Motor tasks and inter-intervals are represented as boxes and arrows, respectively. Solid bold boxes indicate an example timeline of a hopping task when a subject initiates hopping using the left leg.

Fig.2 Simulated spatial distribution of the electrical field by SimNIBS v4.1.0. The color density indicates the magnitude of the electrical field. The positions of tDCS electrodes are represented as rectangular floating objects. The bottom panel depicts the sagittal plane placed approximately at the fissura longitudinalis cerebri using the clipping tool of Gmsh (default view [1]).

Fig. 3A: Averaged time of short sprint running before (Pre) and after transcranial direct current stimulation (Post) in each stimulus condition. B: Degree of change in the time with respect to the pre-value. Each value was calculated using the following equation: [(post-time – pre-time)/pre-time x 100]. Circular plots and gray lines indicate mean and individual data, respectively. Each error bar indicates 1 SD.

Fig. 4 Relationship between the pre-time and the effect of transcranial direct current stimulation in each stimulus condition. The dashed line indicates the linear regression line between them.

Figure 1

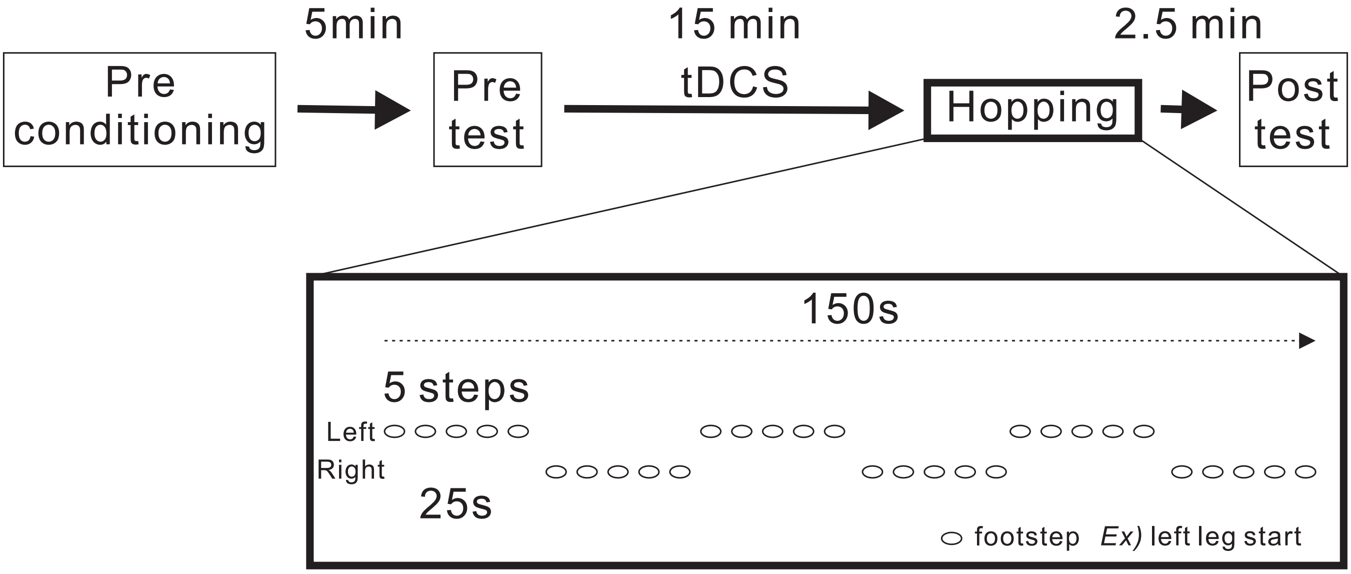
Pre conditioning
5min
Pre test
15 min
tDCS
Hopping
2.5 min
Post test
150s
5 steps
Left
Right
25s
footstep
Ex) left leg start

Figure 2

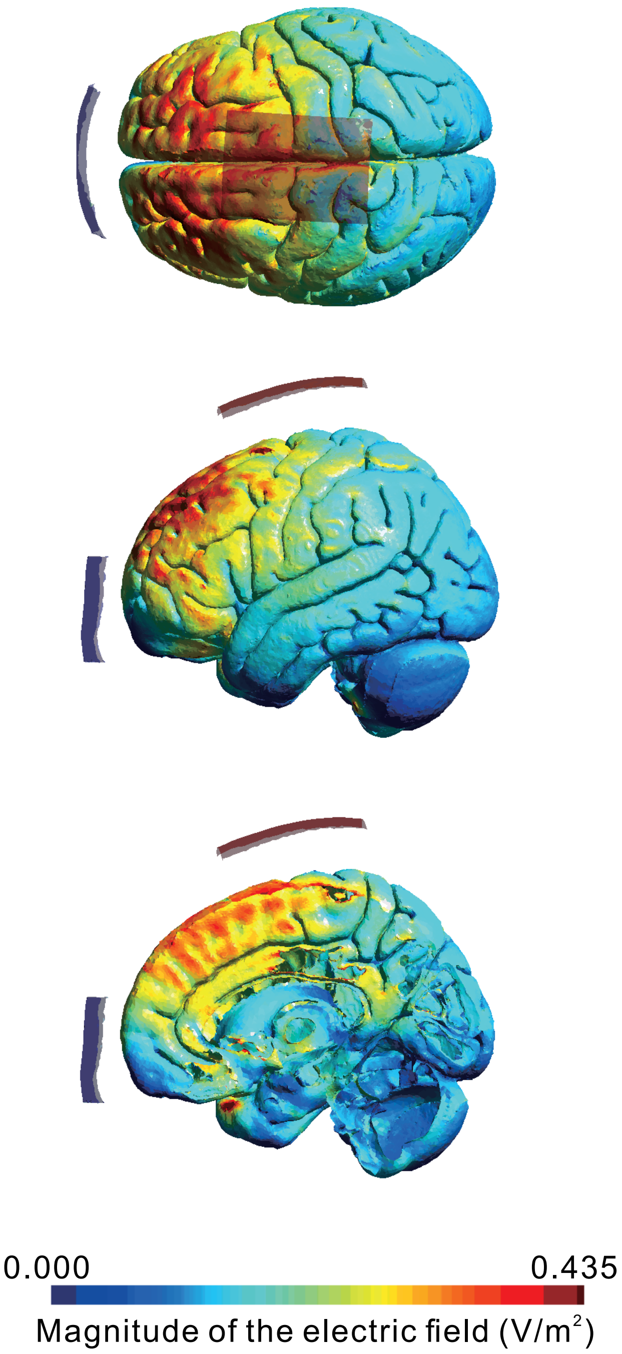

Figure 3

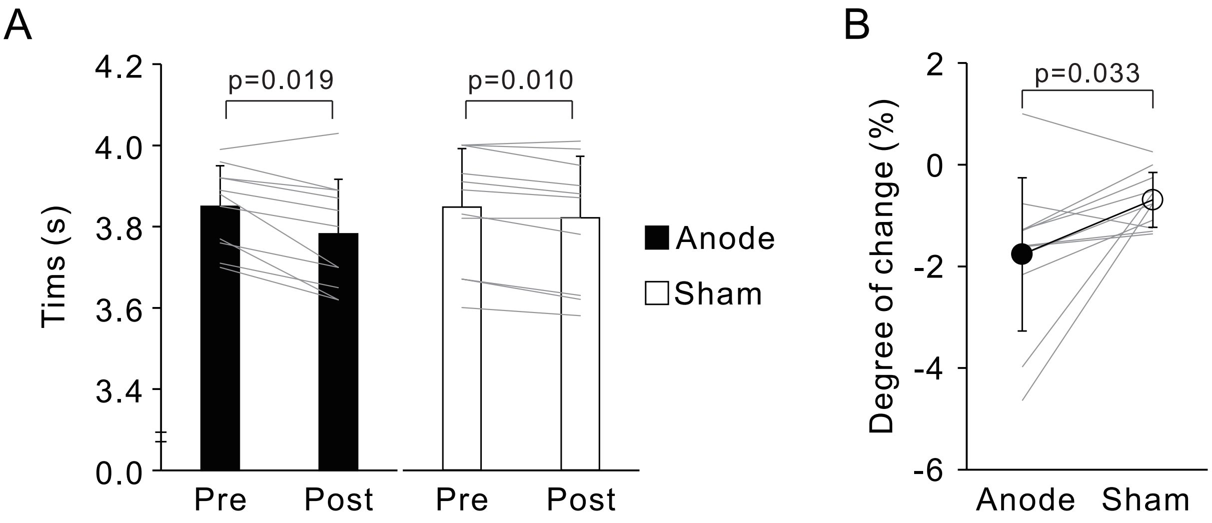
A
p=0.019
p=0.010
4.2
4.0
3.8
3.6
3.4
0.0
Tims (s)
Pre
Post
Pre
Post
■Anode
□Sham
B
p=0.033
2
0
-2
-4
-6
Degree of change (%)
Anode
Sham

Figure 4

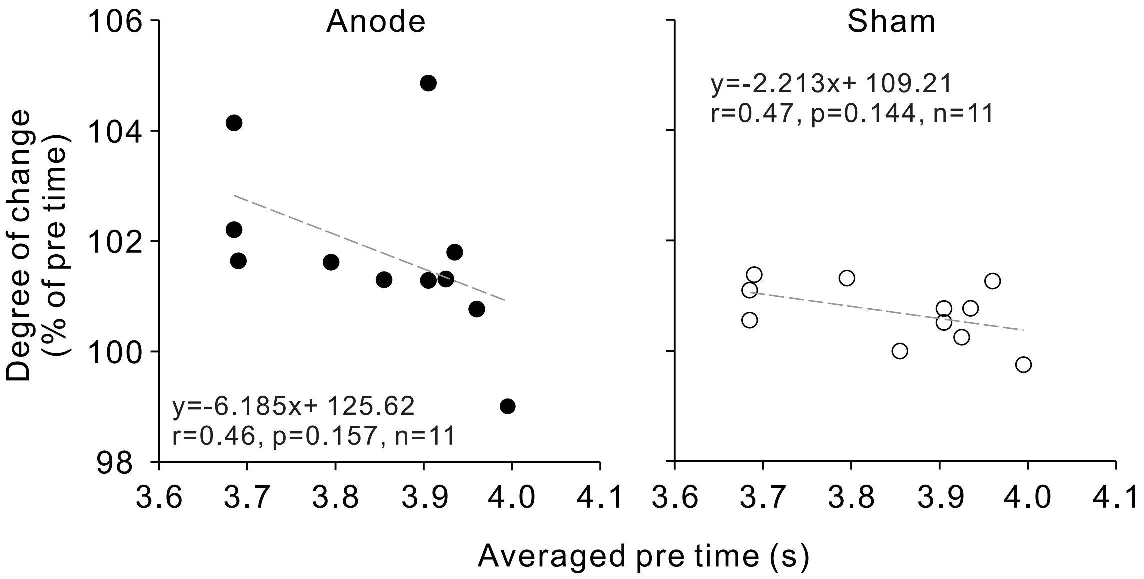
Anode
Sham
y=-6.185x+ 125.62
r=0.46, p=0.157, n=11
y=-2.213x+ 109.21
r=0.47, p=0.144, n=11
Degree of change
(% of pre time)
106
104
102
100
98
3.6
3.7
3.8
3.9
4.0
4.1
Averaged pre time (s)

Table 1. Participant profiles

Sub. Code#	Sex	Age (yr)	Height (cm)	Body weight (kg)	% Fat	Sports
1	F	23	157	49.7	19.1	Sprint
2	F	20	158	51.3	18.0	Sprint
3	F	21	150	49.0	21.0	Sprint
4	F	22	159	49.5	20.3	Jump
5	M	23	185	77.8	13.8	Sprint
6	M	25	183	61.7	5.6	Sprint
7	M	19	160	55.8	9.2	Sprint
8	M	20	185	62.4	5.0	Sprint
9	F	22	159	59.8	27.8	Sprint
10	M	19	167	65.7	14.5	Sprint
11	F	19	162	63.6	28.9	Sprint
Average		21	166	58.7	16.6	

Body weight and percentage of body fat (% fat) in all participants. Female: F, Male: M.