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Транс-спинальная стимуляция с интенсивностью 2,5 мА не влияет на активность кортикоспинальной системы и моторные навыки

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АННОТАЦИЯ

Обоснование. Неинвазивная стимуляция мозга является эффективным способом воздействия на двигательные пути человека на уровне как головного, так и спинного мозга. Известно, что разные параметры и монтажи одной и той же стимуляционной процедуры могут существенно влиять на результаты, так как вовлекают разные нейрональные механизмы.

Цель — оценить влияние анодной транс-спинальной стимуляции постоянным током (tsDCS) интенсивностью 2,5 мА на уровне шейного утолщения спинного мозга (сегменты C7–Th1) на возбудимость кортикоспинальной системы и коррекцию двигательных навыков здорового человека.

Материал и методы. В исследовании приняли участие 54 здоровых взрослых человека в возрасте 21,19±3,20 года. Эффект tsDCS оценивали с помощью вызванных моторных ответов от первой дорсальной межкостной (FDI) мышцы путём транскраниальной магнитной стимуляции в первичной моторной коре в трёх временны́х периодах: до стимуляции, сразу после и через 15 мин после стимуляции.

Результаты. Применение 11-минутной анодной tsDCS на уровне шейного утолщения спинного мозга (C7–Th1) с интенсивностью 2,5 мА не оказывает влияния на изменение амплитуды вызванных моторных ответов мышцы FDI. Статистический анализ показал, что динамика амплитуды вызванных моторных ответов не отличалась между группами, получавшими анодную tsDCS и плацебо-стимуляцию. Анодная tsDCS не влияла также на двигательные навыки. Способность человека эффективно манипулировать мелкими объектами (показатель ловкости рук) в тесте с девятью отверстиями (9-HPT) и нажимать клавишу в ответ на визуальный стимул в задании на время последовательной реакции (SRT) не отличалась от плацебо-стимуляции.

Заключение. Можно предположить, что анодная tsDCS с интенсивностью 2,5 мА на уровне шейного утолщения спинного мозга (сегменты C7–Th1) не влияет на возбудимость кортикоспинальной системы и не изменяет двигательные навыки, связанные с точными движениями рук.

Ключевые слова: транс-спинальная стимуляция постоянным током; транскраниальная магнитная стимуляция; вызванные моторные ответы.

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Transspinal direct current stimulation with an intensity of 2.5 mA does not affect the corticospinal system excitability and motor skills

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ABSTRACT

BACKGROUND: Noninvasive brain stimulation effectively affects movements, including the spinal cord level. Stimulation effects are very sensitive to montage and protocols of applied stimulation because they can involve different neuronal mechanisms.

AIM: This study aimed to estimate the effect of anodal transspinal direct current stimulation (tsDCS) with an intensity of 2.5 mA applied at the spinal cord level (C7–Th1 segments) with cervical enlargement on the corticospinal system excitability and motor skills.

METHODS: The study involved 54 healthy adults aged 21.19±3.20 years. The effect of tsDCS was assessed using motorevoked potentials from the first dorsal interosseous (FDI) muscle by transcranial magnetic stimulation in the primary motor cortex before stimulation, immediately after stimulation, and after 15 min.

RESULTS: The application of an 11-min anodal tsDCS with a current value of 2.5 mA at the C7–Th1 level did not affect the motorevoked potentials of FDI. Statistically, changes in motorevoked potentials amplitudes did not differ between groups receiving anodal tsDCS and sham stimulation. In addition, anodal tsDCS did not affect motor skills. An individual's ability to coordinate fingers and manipulate objects effectively (a measure of dexterity) in the nine-hole peg test and pressing a key in response to a visual stimulus in the serial reaction time task did not differ from that with sham stimulation.

CONCLUSION: 2.5 mA anodal tsDCS on cervical enlargement does not affect the corticospinal system excitability or change motor skills associated with precise hand movements.

Keywords: transspinal direct current stimulation; transcranial magnetic stimulation; motor evoked potentials.

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INTRODUCTION

This study aimed to evaluate the possibility of modulating corticospinal system (CSS) excitability using noninvasive transspinal direct current stimulation (tsDCS) while executing precise voluntary movements. Transcranial direct current stimulation is widely used to modulate various cognitive, motor, and sensory functions of the brain at the cortex level [1]; however, data are limited on the use of this type of stimulation protocol at the spinal cord level. This is probably because most protocols related to spinal cord stimulation have a pulse structure (in contrast with cortex stimulation) and affect locomotor activity patterns [2]. However, correcting voluntary movements may require approaches similar to those affecting cognitive functions when there are no strict movement patterns, such as the rhythmic activation of several motoneuronal pools.

The CSS is one of the main human systems associated with the control of precise voluntary movements. It is a unique pathway through which the brain can exert control over certain actions such as voluntary limb movements and fine movements of the fingers and hands [3]. In the CSS, a somatotopic organization exists such that individual pools of neurons in the cerebral cortex are associated with motor neurons that are suitable for certain muscles located in different body parts [4]. With this organization, a change in the activity of one of the parts of the CSS causes selective muscle contractions and ultimately leads to the performance of a certain action (e.g., bending the index finger to press a button) [5]. Selective studies have shown that depending on the electrode location, tsDCS can enhance the corticospinal drive of one muscle preferentially over another, showing the targeting of the tsDCS intervention [6].

CSS excitability can be investigated through motorevoked potentials (MEPs), which can be obtained in target muscles using single-pulse transcranial magnetic stimulation (TMS) in the primary motor cortex (M1). MEP amplitudes provide time-accurate and muscle-specific testing of CSS excitability circuits in the cortex and spinal cord [7, 8].

A previous study showed that tsDCS with an anterior–posterior electrode configuration at the C7 level with a current of 2.0 mA for 20 min increases the amplitudes of MEPs (flexor carpi radialis) up to 2 h after stimulation, although the effects of cathodal and anodal stimulations were not significantly different [9].

Contradictory data showed that tsDCS, both cathodal, and anodal, with anterior–posterior cervical electrode configuration (3 mA, 20 min, C6–T1, biceps brachii, flexor carpi radialis) [10] and with parallel electrode configuration (2.5 mA, 15 min, C3–T3, abductor digit minimi) did not change the amplitudes of MEPs [11]. The varying effects may be due to the differences in the study protocols used, which involved various factors, such as stimulation polarity, electrode installation, and current strength [12]. This study demonstrates the importance of finding more suitable tsDCS parameters to influence responses in the muscles of the upper extremities.

Aim — in this paper, we focused on the effect of tsDCS with an intensity of 2.5 mA on the first dorsal interosseous (FDI) muscles of the upper limb. Specifically, this study aimed to scrutinize the effect of anodal tsDCS, when applied at the spinal cord level with cervical enlargement, on CSS excitability, and the ability of tsDCS to affect motor skills. TMS of M1 is used as a test for CSS excitability. Importantly, because CSS excitability may reflect important aspects related to the control of voluntary movements, we investigated the effects of tsDCS in the context of M1 TMS as a probe and its potential to influence fine voluntary movements.

MATERIAL AND METHODS

Experimental design

The study involved 54 healthy adults aged 21.19±3.2 years. Before inclusion in the study, all participants voluntarily signed an informed consent form, which was approved as part of the study protocol by the HSE Commission for Intrauniversity Surveys and Ethical Evaluation of Empirical Research Projects dated January 19, 2019, with protocol number HSE 19/01/2019. In study 1, participants (n=24) received 11 min of anodal or sham tsDCS at 2.5 mA. The anode electrode was located above the C7–Th1 segments, and the cathode electrode was on the clavicle. The effect of tsDCS was assessed using MEP. To generate MEP, TMS was used in the "hot spot" of the FDI muscle in M1 (controlled using a navigation system) with single impulses whose intensity was 115% of the resting motor threshold in three time intervals before stimulation, after stimulation, and 15 min after stimulation.

The electromyogram was registered with the help of an additional BrainAmp EXG block. Surface electromyography (EMG) was recorded from the right FDI muscles.

In study 2, participants (n=30) received either anodal or sham tsDCS in the same way as for study 1, and during the tsDCS session, the participants performed motor tests, namely, the nine-hole peg test (9-HPT) and the serial reaction time task (SRT). Motor tests were also repeated the next day without stimulation.

Statistical analysis

The modulation of MEPs was evaluated by a linear mixed-effects model. Specifically, the group factor (df=1, stimulation or sham) and time factor (df=2, recordings performed before tsDCS (T_{before}), immediately after tsDCS (T_0), or 15 min after tsDCS (T_{15}) were used as fixed effects, whereas participant's ID was used as a random intercept effect. The pre-stimulation MEP amplitudes of the stimulation group participants were used as a baseline condition for the model.

Approximations of the degrees of freedom for the fixed effects were obtained with Satterthwaite approximation using the lmerTest package [13] following Luke's recommendation [14]. The main effects were assessed by Wald Chi-squared tests. Considering that the main effect of the factors and their interaction were significant, estimated marginal means (EMMs) of pairwise comparisons were acquired for post hoc testing using emmeans package for R. The resulting p-values of the pairwise comparisons were corrected concerning the false discovery rate according to Benjamini and Hochberg adjustment [15].

RESULTS

Effects of the tsDCS on MEP amplitudes

The significance of the main effects (group and time) and interactions within the linear mixed-effects model were examined. In turn, neither the group factor ($F(2, 76)=1.67$, $p=0.19$) nor the time factor ($F(2, 4655)=0.99$, $p=0.37$) explained the data significantly. However, the effect of their interaction ($F(4, 4655)=5.57$, $p<0.001$) was significant. Specifically, the linear mixed model fit of the MEP amplitudes recorded before (T_{before}), immediately after (T_0), and with a 15-min delay after the stimulation or sham session (T_{15}) was performed with restricted maximum likelihood criterion at convergence of 26554.5.

A set of pairwise comparisons was also performed between EMMs between sets of MEP aptitudes within 1 day, which showed no significant deviation from the baseline condition for all the pairwise comparisons (Fig. 1).

Effect of tsDCS on the development of new motor skills in healthy participants

The effects of tsDCS stimulation on the development of new motor skills were assessed using the 9-HPT and SRT. The results of the analysis of variance modeling showed that participants spent significantly less time finishing both motor tasks on the first day of the experimental session regardless of their group (Fig. 2).

Specifically, for the 9-HPT, the group factor did not explain the variance in the data significantly ($F(2,39)=0.083$, $p=0.92$), as well as the group x day interaction ($F(2,39)=0.682$, $p=0.51$), whereas the effect of the day factor was significant ($F(1,39)=46.98$, $p<10^{-7}$).

Similarly, for the SRT, the group factor did not explain the variance in the data significantly ($F(2,37)=1.510$, $p=0.23$),

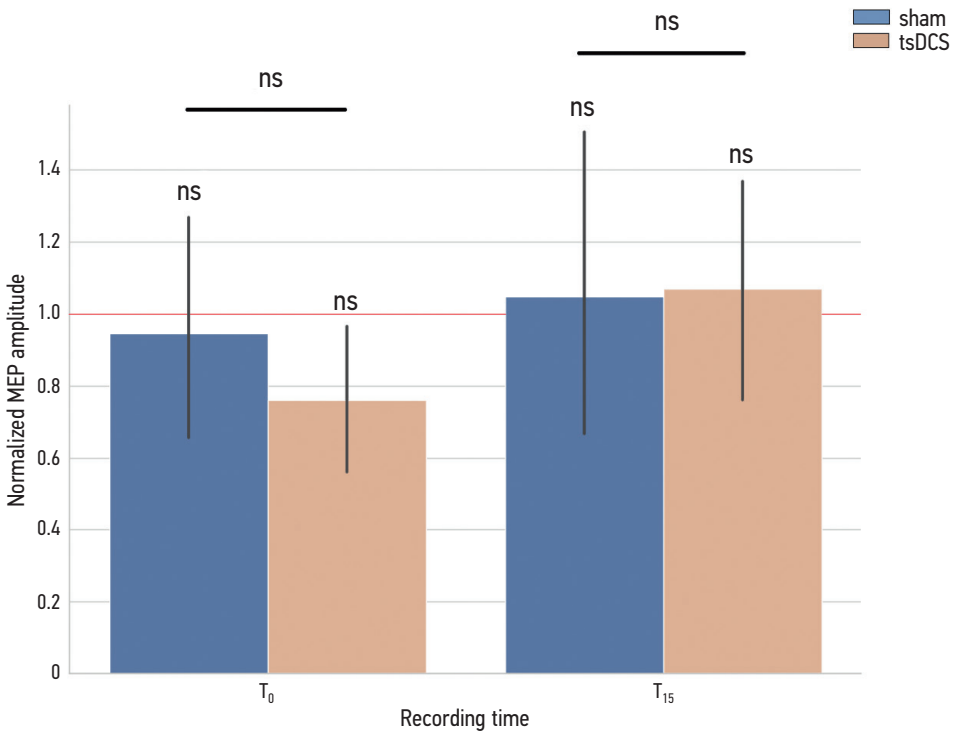

Fig. 1. MEP (motorevoked potentials) amplitudes normalized by prestimulation (T_{before}) values for groups receiving tsDSC and sham stimulation. The MEPs are recorded immediately after the stimulation (T_0) and within a 15-min delay (T_{15}). Error bars represent 95% CI of the estimates (ns, not significant).

Рис. 1. Амплитуды МЕР, нормализованные по значениям до стимуляции (T_{before}) для групп, получавших tsDSC и плацебо-стимуляцию. МЕР регистрируют сразу после стимуляции (T_0) и с 15-минутной задержкой (T_{15}). Столбики погрешностей представляют собой 95% доверительный интервал оценок; ns — не имеет статистической значимости.

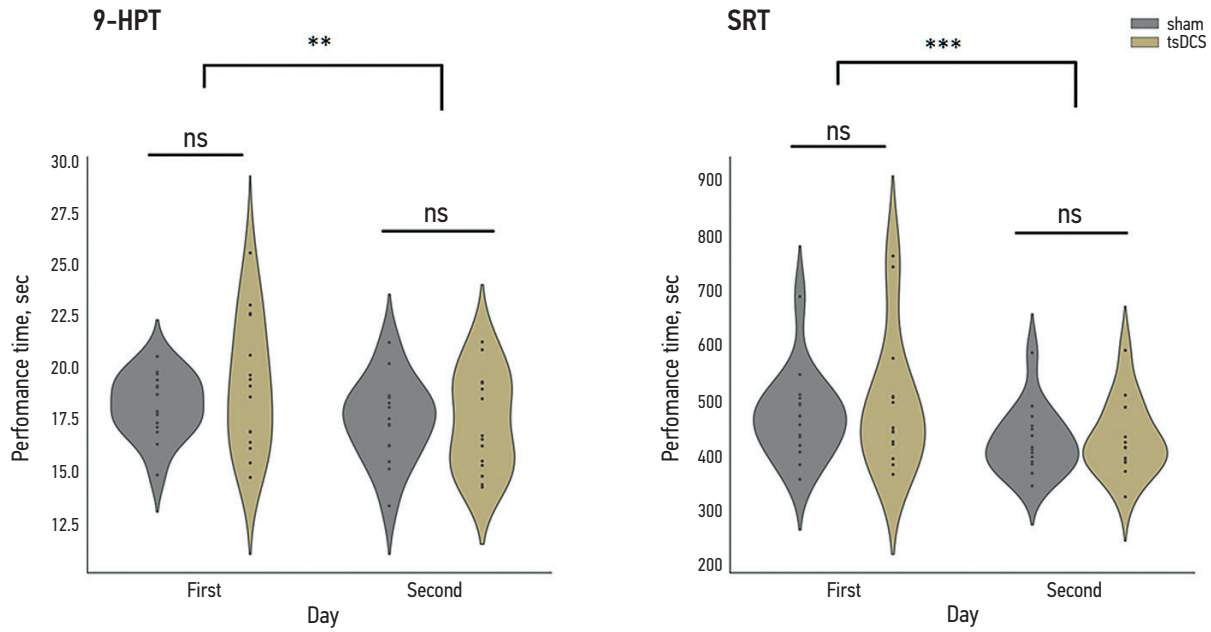

Fig. 2. Performance timing of participants receiving anodal tsDSC and sham stimulation assessed separately for the nine-hole peg test (9-HPT) and the serial reaction time task (SRT). No significance was observed for the group factor indicated by the special symbols between bars (ns, p >0.05, not significant). The special symbols between groups of bars indicate the significance of the day factor in the two ANOVA models; ** p <0.01; ***p <0.001).

Рис. 2. Время выполнения участников, получавших анодную (tsDSC) и плацебо-стимуляцию, оценивали отдельно для теста с девятью отверстиями (9-HPT) и для задания на время последовательной реакции (SRT). Для фактора группы, обозначенного специальными символами между столбцами, значимости не наблюдалось (ns, p >0,05; статистически не значимо). Специальные символы между группами столбцов указывают на значимость фактора Day в двух моделях ANOVA; ** p <0,01; *** p <0,001.

as well as the group x day interaction ($F(2,37)=1.711$, $p=0.19$), whereas the effect of the day factor was significant ($F(1,37)=24.00$, $p < 10^{-4}$).

DISCUSSION

In this study, we estimated the effect of tsDCS on CSS excitability and the development of fine motor skills in healthy people. This study showed that the use of 11-min anodal tsDCS at the C7–Th1 level with a current of 2.5 mA did not affect changes in CSS excitability. The amplitude of the TMS-induced MEPs did not change after stimulation and 15 min after stimulation, which was confirmed statistically.

In this study, tsDCS at the level of cervical enlargement cannot induce a change in MEP amplitudes. Our findings are consistent with some previous observations. Dongés and D'Amico demonstrated that applying a 20-min cervical tsDCS at 3 mA using an anterior–posterior electrode configuration did not alter the response of upper limb muscles to TMS. This may indicate that cervical tsDCS using this set of stimulation parameters does not change corticospinal conduction at different levels (cortical and spinal) [10]. However, Lim and Shin reported that cervical tsDCS (2 mA, 20 min at C7, anterior–posterior configuration) increased CSS excitability regardless of the polarity and that excitability remained high up to 2 h after stimulation [9].

The stimulation effect is probably susceptible to the exact parameters of the stimulation protocol. The neuromodulatory effects of tsDCS may result from local variations in the current density and induced electric field along neurons, resulting in specific polarizing effects on the transmembrane potential, with axon terminals identified as the dominant cellular target [16]. These divergences are affected by various stimulation parameters, such as the electrode placement and geometry or the injected current intensity and polarity in the tsDCS protocol [17–19].

Moreover, this study shows that anodal tsDCS with such a set of parameters does not affect the production of motor skills. The participant's ability to coordinate fingers and manipulate objects effectively (a measure of dexterity) in the 9-HPT and to produce fine movements in the SRT did not differ from the sham stimulation. Our results show that MEP amplitudes do not change either after stimulation or after 15 min. Perhaps, there was no correction of motor skills because the stimulation did not affect the CSS. In addition, stimulation acts not only on the CSS but also on other spinal tracts; for example, it can affect the lemniscal tract [20, 21] or the spinothalamic tract [22], which has previously been studied.

The mechanisms underlying tsDCS-induced plastic changes in the spinal cord are ambiguous; however, we can assume that tsDCS can affect the conduction properties of the CSS [9].

Another possibility is that tsDCS influences neuronal activity in the ascending spinal tracts, ultimately modulating excitability in their cortical targets, including motor areas. The possible support for a cortical mechanism comes from a report that noninvasive spinal stimulation appears to modulate intracortical facilitation [23].

Overall, our data support the conclusion that tsDCS with a current of 2.5 mA did not affect changes in CSS excitability. We also hypothesized that the spinal cord may act as a "pipeline" to transmit tsDCS-induced changes to the brain, thereby inducing suprasegmental effects on the brain and brainstem. The effects of tsDCS may have arisen, for example, owing to the influence of the electric field on impulse conduction, membrane excitability, and transmission of γ-aminobutyric acid GABAergic and glutamatergic [24]. We also hypothesized that using tsDCS with our parameters may have different effects on the motor skill development of people with movement disorders, and further studies are needed to confirm this assumption. Having more information about the underlying mechanisms is an important prerequisite for developing future clinical protocols and understanding how tsDCS affects the CSS. Whatever the mechanisms, by modulating spinal cord function, tsDCS could provide a future therapeutic tool to complement drugs and invasive spinal cord stimulation in the treatment of pathological conditions, including pain, spasticity, and movement disorders.

CONCLUSION

Therefore, the application of an 11-min anodal tsDCS at the C7–Th1 level with a current of 2.5 mA does not affect the amplitudes of the TMS-induced motorevoked potentials of FDI muscles. In addition, the application of anodic tsDCS at the level of the upper spinal cord segments (C7–Th1) for 11 min at 2.5 mA did not affect the motor skills in healthy people based on the nine-hole peg test and serial reaction time task.

ADDITIONAL INFORMATION

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Authors' contribution. E.D. Pomelova — data collection, search for subjects, development of a protocol, analysis of literary sources, writing a text; A.V. Popyvanova — collecting data, searching for subjects, editing the article; D.O. Bredikhin — data analysis, image preparation. M.M. Koryakina — writing the text, editing the article; A.N. Shestakova — development of the protocol. E.D. Blagoveshchensky — literature analysis, data analysis, development of study protocols. All authors confirm that their authorship complies with the international ICMJE criteria (all authors made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

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REFERENCES

1. Popyvanova AV, Koriakina MA, Pomelova ED, et al. The possibility of increasing the effectiveness of correcting motor skills and cognitive functions using noninvasive brain stimulation in humans. *Neurosci Behav Physiol.* 2023;53:230–241. doi: 10.1007/s11055-023-01412-w

2. Solopova IA, Sukhotina IA, Zhvansky DS, et al. Effects of spinal cord stimulation on motor functions in children with cerebral palsy. *Neurosci Lett.* 2017;639:192–198. doi: 10.1016/j.neulet.2017.01.003

3. Lemon RN, Griffiths J. Comparing the function of the corticospinal system in different species: organizational differences for motor specialization? *Muscle Nerve.* 2005;32(3):261–279. doi: 10.1002/mus.20333

4. Martin JH. The corticospinal system: from development to motor control. *Neuroscientist.* 2005;11(2):161–173. doi: 10.1177/1073858404270843
5. Derosiere G, Duque J. Tuning the corticospinal system: how distributed brain circuits shape human actions. *Neuroscientist.* 2020;26(4):359–379. doi: 10.1177/1073858419896751
6. Williams PTJA, Truong DQ, Seifert AC, et al. Selective augmentation of corticospinal motor drive with trans-spinal direct current stimulation in the cat. *Brain Stimul.* 2022;15(3):624–634. doi: 10.1016/j.brs.2022.03.007
7. Bestmann S, Krakauer JW. The uses and interpretations of the motor-evoked potential for understanding behaviour. *Exp Brain Res.* 2015;233(3):679–689. doi: 10.1007/s00221-014-4183-7
8. Hannah R. Transcranial magnetic stimulation: a non-invasive window into the excitatory circuits involved in human motor behavior. *Exp Brain Res.* 2020;238(7-8):1637–1644. doi: 10.1007/s00221-020-05803-0
9. Lim CY, Shin HI. Noninvasive DC stimulation on neck changes MEP. *Neuroreport.* 2011;22(16):819–823. doi: 10.1097/WNR.0b013e32834b939d
10. Dongés SC, D'Amico JM, Butler JE, Taylor JL. The effects of cervical transcutaneous spinal direct current stimulation on motor pathways supplying the upper limb in humans. *PLoS One.* 2017;12(2):0172333. doi: 10.1371/journal.pone.0172333
11. Fernandes SR, Pereira M, Salvador R, et al. Cervical trans-spinal direct current stimulation: a modelling-experimental approach. *Neuroeng Rehabil.* 2019;16(1):123. doi: 10.1186/s12984-019-0589-6
12. Jack AS, Hurd C, Martin J, Fouad K. Electrical stimulation as a tool to promote plasticity of the injured spinal cord. *Neurotrauma.* 2020;37(18):1933–1953. doi: 10.1089/neu.2020.7033
13. Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest package: tests in linear mixed effects models. *Journal of Statistical Software.* 2017;82(13):1–26. doi: 10.18637/jss.v082.i13
14. Luke SG. Evaluating significance in linear mixed-effects models in R. *Behav Res Methods.* 2017;49(4):1494–1502. doi: 10.3758/s13428-016-0809-y
15. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society Series B (Methodological).* 1995;57:289–300. doi: 10.2307/2346101
16. Ranck JB Jr. Which elements are excited in electrical stimulation of mammalian central nervous system: a review. *Brain Res.* 1975;98(3):417–440. doi: 10.1016/0006-8993(75)90364-9
17. Fernandes SR, Salvador R, Wenger C, et al. Transcutaneous spinal direct current stimulation of the lumbar and sacral spinal cord: a modelling study. *Neural Eng.* 2018;15(3):036008. doi: 10.1088/1741-2552/aaac38
18. Kuck A, Stegeman DF, van Asseldonk EHF. Modeling trans-spinal direct current stimulation for the modulation of the lumbar spinal motor pathways. *Neural Eng.* 2017;14(5):056014. doi: 10.1088/1741-2552/aa7960
19. Salvador R, Wenger C, Nitsche MA, Miranda PC. How electrode montage affects transcranial direct current stimulation of the human motor cortex. *Annu Int Conf IEEE Eng Med Biol Soc.* 2015;2015:6924–6927. doi: 10.1109/EMBC.2015.7319985
20. Cogiamanian F, Ardolino G, Vergari M, et al. Transcutaneous spinal direct current stimulation. *Front Psychiatry.* 2012;3:63. doi: 10.3389/fpsyt.2012.00063
21. Aguilar J, Pulecchi F, Dilena R, et al. Spinal direct current stimulation modulates the activity of gracile nucleus and primary somatosensory cortex in anaesthetized rats. *Physiol.* 2011;589(Pt 20):4981–4996. doi: 10.1113/jphysiol.2011.214189
22. Truini A, Panuccio G, Galeotti F, et al. Laser-evoked potentials as a tool for assessing the efficacy of antinociceptive drugs. *Eur J Pain.* 2010;14(2):222–225. doi: 10.1016/j.ejpain.2009.05.001
23. Schlaier JR, Eichhammer P, Langguth B, et al. Effects of spinal cord stimulation on cortical excitability in patients with chronic neuropathic pain: a pilot study. *Eur J Pain.* 2007;11(8):863–868. doi: 10.1016/j.ejpain.2007.01.004
24. Ahmed Z, Wieraszko A. Trans-spinal direct current enhances corticospinal output and stimulation-evoked release of glutamate analog, D-2,3-^{3}H-aspartic acid. *Appl Physiol (1985).* 2012;112(9):1576–1592. doi: 10.1152/japplphysiol.00967.2011

СПИСОК ЛИТЕРАТУРЫ

1. Popyvanova A.V., Koriakina M.A., Pomelova E.D., et al. The possibility of increasing the effectiveness of correcting motor skills and cognitive functions using noninvasive brain stimulation in humans // Neurosci Behav Physiol. 2023. Vol. 53, P. 230–241. doi: 10.1007/s11055-023-01412-w
2. Solopova I.A., Sukhotina I.A., Zhvansky D.S., et al. Effects of spinal cord stimulation on motor functions in children with cerebral palsy // Neurosci Lett. 2017. Vol. 639. P. 192–198. doi: 10.1016/j.neulet.2017.01.003
3. Lemon R.N., Griffiths J. Comparing the function of the corticospinal system in different species: organizational differences for motor specialization? // Muscle Nerve. 2005. Vol. 32, N 3. P. 261–279. doi: 10.1002/mus.20333
4. Martin J.H. The corticospinal system: from development to motor control // Neuroscientist. 2005. Vol. 11, N 2. P. 161–173. doi: 10.1177/1073858404270843
5. Derosiere G., Duque J. Tuning the corticospinal system: how distributed brain circuits shape human action // Neuroscientist. 2020. Vol. 26, N 4. P. 359–379. doi: 10.1177/1073858419896751
6. Williams P.T.J.A., Truong D.Q., Seifert A.C., et al. Selective augmentation of corticospinal motor drive with trans-spinal direct current stimulation in the cat // Brain Stimul. 2022. Vol. 15, N 3. P. 624–634. doi: 10.1016/j.brs.2022.03.007
7. Bestmann S., Krakauer J.W. The uses and interpretations of the motor-evoked potential for understanding behaviour // Exp Brain Res. 2015. Vol. 233, N 3. P. 679–689. doi: 10.1007/s00221-014-4183-7
8. Hannah R. Transcranial magnetic stimulation: a non-invasive window into the excitatory circuits involved in human motor behavior // Exp Brain Res. 2020. Vol. 238, N 7-8. P. 1637–1644. doi: 10.1007/s00221-020-05803-0
9. Lim C.Y., Shin H.I. Noninvasive DC stimulation on neck changes MEP // Neuroreport. 2011. Vol. 22, N 16. P. 819–823. doi: 10.1097/WNR.0b013e32834b939d
10. Dongés S.C., D'Amico J.M., Butler J.E., Taylor J.L. The effects of cervical transcutaneous spinal direct current stimulation on motor

pathways supplying the upper limb in humans // PLoS One. 2017. Vol. 12, N 2. P. e0172333. doi: 10.1371/journal.pone.0172333
11. Fernandes S.R., Pereira M., Salvador R., et al. Cervical transspinal direct current stimulation: a modelling-experimental approach // Neuroeng Rehabil. 2019. Vol. 16, N 1. P. 123. doi: 10.1186/s12984-019-0589-6
12. Jack A.S., Hurd C., Martin J., Fouad K. Electrical stimulation as a tool to promote plasticity of the injured spinal cord // Neurotrauma. 2020. Vol. 37, N 18. P. 1933–1953. doi: 10.1089/neu.2020.7033
13. Kuznetsova A., Brockhoff P.B., Christensen R.H.B. lmer test package: tests in linear mixed effects models // Journal of Statistical Software. 2017. Vol. 82, N 13. P. 1–26. doi: 10.18637/jss.v082.i13
14. Luke S.G. Evaluating significance in linear mixed-effects models in R // Behav Res Methods. 2017. Vol. 49, N 4. P. 1494–1502. doi: 10.3758/s13428-016-0809-y
15. Benjamini Y., Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing // Journal of the Royal Statistical Society Series B (Methodological). 1995. Vol. 57. P. 289–300. doi: 10.2307/2346101
16. Ranck J.B. Jr. Which elements are excited in electrical stimulation of mammalian central nervous system: a review // Brain Res. 1975. Vol. 98, N 3. P. 417–440. doi: 10.1016/0006-8993(75)90364-9
17. Fernandes S.R., Salvador R., Wenger C., et al. Transcutaneous spinal direct current stimulation of the lumbar and sacral spinal cord: a modelling study // Neural Eng. 2018. Vol. 15, N 3. P. 036008. doi: 10.1088/1741-2552/aaac38
18. Kuck A., Stegeman D.F., van Asseldonk E.H.F. Modeling transspinal direct current stimulation for the modulation of the lumbar spinal motor pathways // Neural Eng. 2017. Vol. 14, N 5. P. 056014. doi: 10.1088/1741-2552/aa7960
19. Salvador R., Wenger C., Nitsche M.A., Miranda P.C. How electrode montage affects transcranial direct current stimulation of the human motor cortex // Annu Int Conf IEEE Eng Med Biol Soc. 2015. Vol. 2015. P. 6924–6927. doi: 10.1109/EMBC.2015.7319985
20. Cogiamanian F., Ardolino G., Vergari M., et al. Transcutaneous spinal direct current stimulation // Front Psychiatry. 2012. Vol. 4, N 3. P. 63. doi: 10.3389/fpsyt.2012.00063
21. Aguilar J., Pulecchi F., Dilena R., et al. Spinal direct current stimulation modulates the activity of gracile nucleus and primary somatosensory cortex in anaesthetized rats // Physiol. 2011. Vol. 589(Pt 20). P. 4981–4996. doi: 10.1113/jphysiol.2011.214189
22. Truini A., Panuccio G., Galeotti F., et al. Laser-evoked potentials as a tool for assessing the efficacy of antinociceptive drugs // Eur J Pain. 2010. Vol. 14, N 2. P. 222–225. doi: 10.1016/j.ejpain.2009.05.001
23. Schlaier J.R., Eichhammer P., Langguth B., et al. Effects of spinal cord stimulation on cortical excitability in patients with chronic neuropathic pain: a pilot study // Eur J Pain. 2007. Vol. 11, N 8. P. 863–868. doi: 10.1016/j.ejpain.2007.01.004
24. Ahmed Z., Wieraszko A. Trans-spinal direct current enhances corticospinal output and stimulation-evoked release of glutamate analog, D-2,3-^{3}H-aspartic acid // Appl Physiol (1985). 2012. Vol. 112, N 9. P. 1576–1592. doi: 10.1152/japplphysiol.00967.2011

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