

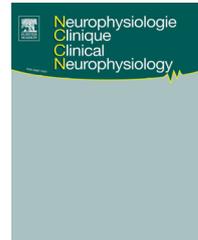


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## EDITORIAL

# Boosting physical exercise with cortical stimulation or brain doping using tDCS: Fact or myth?

**KEYWORDS**

Brain stimulation;  
Cortex;  
Endurance;  
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Sport

In an interview for The Guardian [22], published in March 2015, Sir David Brailsford, the manager of the world's leading British professional cycling team Sky, stated that he was experimenting with "cranial stimulation" and was interested "in research that suggests cranial stimulation could help endurance capacity". This was referring to the use of transcranial direct current stimulation (tDCS), a method of brain stimulation that was reintroduced in the late 1990s in the field of clinical neurophysiology [36,39]. This non-invasive cortical stimulation technique consists of delivering a low intensity current (1-2 mA) transcranially, which modulates the excitability of brain circuits by modifying the resting membrane potential, leading to either excitatory depolarization or inhibitory hyperpolarization [29,30]. This technique is safe [5] and sufficiently effective to be applied for therapeutic purposes [32,33,43].

Referring to tDCS, Dave Brailsford mentioned that "the military have been using it for their snipers to reduce the time it takes them to acquire a skill. What they are suggesting is that this increases the plasticity of the cortex to enable fast-track learning. They think that it can override the brain" [22]. Dave Brailsford also mentioned a personal experience, claiming that the delivery of an electrical current by electrodes placed on his head while playing darts had allowed him to improve his play. This interview paved

the way for media buzz around the use of techniques of cranial stimulation as a method of "brain doping" in the field of sport [11,18]. For example, one year after The Guardian's article, the journal Nature published a letter in which a journalist stated that preliminary studies showed that tDCS could boost sport performance [41]. The article reported that the US Ski and Snowboard Association were working with a start-up company focused on neurostimulation technology for enhancing cognitive function (Halo Neuroscience, San Francisco, CA, USA) to test "the efficacy of a device that delivers electricity to the motor cortex" and "whether stimulating the brain with electricity can improve the performance of ski jumpers by making it easier for them to hone their skills". The article mentioned an experiment based on four ski jumpers from the American elite national team who received active tDCS during their training, four times a week for two weeks. The procedure led to increasing their jumping force by 70% and their coordination ability by 80%, compared to 3 other members of the US team who received sham stimulation. The journalist also alleged that tDCS could improve recovery from injury or endurance, since "other research suggests that targeted brain stimulation can reduce an athlete's ability to perceive fatigue" [41].

However, is the impact of tDCS on physical performance and sport competition results really supported by scientifically proven facts? The first study reported in this domain [13] showed that anodal tDCS of the primary motor cortex (M1) could improve endurance time of an elbow flexion task by increasing motivation and decreasing fatigue-related muscle pain. Further studies showed that anodal tDCS of M1 could also improve strength very slightly (+3–5%), but significantly more than sham stimulation [19] or at least in a more prolonged manner [20]. One study showed an increased mean power output during a sprint cycling task, which was significantly greater after anodal vs. cathodal but

not sham tDCS [42]. Conversely, in another study, the beneficial effect of anodal tDCS of M1 performed during a cycling task was seen in terms of tolerance to effort (the time to exhaustion (TTE) being prolonged), but not power output, electromyographic activity, mood state, or heart rate [47].

One group found that anodal tDCS of the left M1 could increase endurance to exercise (prolonged TTE) and reduce ratings of perceived exertion (RPE), only in the case of an extracephalic cathode, placed at the shoulder [3]. In a subsequent study [4], the same group showed that the benefit was even greater in the case of bihemispheric anodal stimulation of M1 (vs. cathodal or sham stimulation). A session of bilateral anodal stimulation of M1 was also shown to increase height, peak power, and flight time of a vertical jumping task, compared to cathodal or sham procedures [26]. In another original study, the combination of anodal M1 stimulation with visual feedback (mirror) further promoted motor performance [48], according to the motor simulation theory [10].

In contrast, there was no difference between anodal or sham tDCS procedure in modulating force or endurance (TTE) of an isometric task of elbow flexion in one study [24]. In another study, only a subset of subjects improved their endurance (increased TTE) when anodal tDCS of M1 was performed during a fatiguing task of elbow flexion, but at the expense of greater muscle fatigue [52]. In two additional studies performed in recreational endurance runners [6] and cyclists [7], neither anodal nor cathodal tDCS of M1 modified the physiological responses to exercise (including cardiorespiratory variables, such as heart rate increase and oxygen consumption) nor the affective responses, perceived exertion, or tolerance to effort. Various causes can explain the variability of results among the different studies, such as stimulation parameters (e.g., duration, intensity, and arrangement of electrodes, including usual bipolar montages with cephalic or extracephalic reference and high-definition Laplacian montages), poor statistical power (the maximum sample size being about 15 subjects in these studies), the nature and the level of effort requirement of the physical exercise task, or the level of physical fitness and competitive status of the enrolled subjects. For example, in elite athletes, likely because of a ceiling effect, motor performance (power output) cannot be improved by anodal tDCS of M1, but the procedure can modulate affective or mood aspects, as recently shown in a study on 8 male triathletes [46]. Thus, various studies showed a reduction of exercise-induced pain but no improvement in force production or exercise performance or endurance (TTE) after anodal tDCS of M1 [2,17].

Other studies aimed at assessing the effects of anodal tDCS applied to the left dorsolateral prefrontal cortex (DLPFC). For example, one study showed in 10 recreationally trained individuals that stimulation of the left DLPFC improved muscular endurance and reduced the ratings of perception of effort (RPE) in the repetition of an elbow flexion exercise [25]. The same group showed an increased tolerance (TTE) to an exercise performed in a cycloergometer with maximum load in 11 moderately active women, but without reduction of RPE [27]. Another study showed that anodal tDCS of the DLPFC increased post-exercise oxygen consumption [35]. One group showed that cathodal tDCS over the left DLPFC improved motor learning and

performance in the practice of a golf putting task [55]. Finally, one study showed no effects of high-definition tDCS delivered to the DLPFC (or M1) on endurance time or fatigue indices during a sustained task of elbow flexion [40]. However, the right hemisphere was targeted. Overall, the results for prefrontal stimulation appear even more disparate than those for motor stimulation.

Finally, one team decided to target the left temporo-insular cortex and showed that anodal tDCS improved exercise performance (peak power output), reduced the sensory perception of effort (lower RPE increase), and delayed parasympathetic vagal withdrawal (measured on heart rate variability) after a cycling exercise test in 10 trained cyclists [37]. However, in a subsequent study performed on 13 sedentary males, neither heart rate variability, nor RPE and affective aspects of exertion were modified by anodal tDCS of the left temporo-insular cortex [38].

Thus, to date, the beneficial effects of anodal tDCS (mostly concerning the M1 target) on sport and exercise performance are largely controversial and probably more relevant in statistical than clinical terms. While brain plasticity is likely boosted by physical exercise [15], the reverse remains to be demonstrated. In addition, cranial electrostimulation could promote brain plasticity in a way that is difficult to control. Actually, tDCS was proposed as a neuroenhancement technique to enhance cognitive capacities in military, gaming, or sport applications [9,12]. For example, anodal tDCS of the left DLPFC for 10 consecutive weekdays was found to improve cognitive performance (attention and memory) in 10 professional athletes [8]. Conversely, the performance of young volunteers was found to worsen on a working memory task after DLPFC stimulation using a commercial tDCS headset (foc.us, Redwood City, CA, USA) [45].

Although the repetitive use of anodal or cathodal stimulation of M1 appears to be safe [53,54], if care is taken to avoid the risk of burning the skin [34], something could go wrong because of misuse or deleterious effects on the brain of repeated sessions over the long term. It appears especially difficult to restrict the use of tDCS to the medical setting since there is a community performing unsupervised tDCS procedures, using commercial headsets or caps available on the internet (such as provided by the aforementioned Halo Neuroscience or foc.us companies) or even do-it-yourself (DIY) kits [16,23]. These products are not approved by official regulatory agencies, such as the Food and Drug Administration (FDA), and have especially no aspirations to be marketed for medical indications. Therefore, there is a need for regulatory framework or official guidelines for the personal use of these over-the-counter tDCS devices [23,49,51]. It is even doubtful that some of these wearable devices provide tDCS and they could instead be based on pulsed currents, stimulating cranial nerves rather than actually performing transcranial brain stimulation (e.g., Thync, Inc., Los Gatos, CA, USA).

Attempts to stimulate the brain at home with electrical devices are not novel and have been known since the end of the XIXth century [50]. In the domain of sport doping, cerebral stimulation was in fact a "boosting method" already experienced by Soviet athletes since the early 1970s [14]. Electrical brain stimulation can be assimilated to doping, as an expedient capable of enhancing physical or mental

performance, and anyway if there is prohibition, it will probably have no effect on the diffusion of the technique as tDCS is undetectable. Thus, beyond personal “DIY” use, sport application of tDCS procedures adds a supplementary regulatory problem. Even if tDCS cannot be considered as a proven means of improving performance, it could add a “marginal gain”, which may be sufficient to provide a competitive advantage and make a crucial difference in performance. This concept of “marginal gain” was advanced by Sir David Brailsford [22,44] as one of the factors that could explain his impressive results at the head of British cycling teams in the Olympic Games or in the Tour de France throughout the 2010s.

In conclusion, tDCS is able to modulate cortical activity and probably synaptic brain plasticity according to complex phenomena, taking into account the polarity, size, and placement of the electrodes and the orientation of the neural fibers into the induced electric field [31]. In healthy volunteers as well as in patients with motor deficit secondary to brain lesion, tDCS has been successfully applied to enhance motor learning [1]. However, tDCS effects on muscular and athletic performance have yet to be determined. Two recent meta-analyses [21,28] conclude that there is a possibly positive impact of tDCS (mostly anodal stimulation of M1) on exercise performance (force and muscular endurance), but of rather small extent, depending on the type of exercise (e.g., simple isometric tasks vs. more complex physical activities), and provided by low-quality studies. Thus, only weak evidence supports tDCS as an effective means of improving sport competition results. The effects of the media hype, particularly with regard to uncontrolled, unscientific studies, using non-medical commercial systems, could be particularly deleterious to the fully justified objective of pursuing serious studies.

## Disclosure of interest

The author declares that he has no competing interest.

## References

- [1] Ammann C, Spampinato D, Márquez-Ruiz J. Modulating motor learning through transcranial direct-current stimulation: an integrative view. *Front Psychol* 2016;7:1981.
- [2] Angius L, Hopker JG, Marcora SM, Mauger AR. The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *Eur J Appl Physiol* 2015;115:2311–9.
- [3] Angius L, Pageaux B, Hopker J, Marcora SM, Mauger AR. Transcranial direct current stimulation improves isometric time to exhaustion of the knee extensors. *Neuroscience* 2016;339:363–75.
- [4] Angius L, Mauger AR, Hopker J, Pascual-Leone A, Santarnecchi E, Marcora SM. Bilateral extracephalic transcranial direct current stimulation improves endurance performance in healthy individuals. *Brain Stimul* 2018;11:108–17.
- [5] Antal A, Alekseichuk I, Bikson M, Brockmüller J, Brunoni AR, Chen R, et al. Low intensity transcranial electric stimulation: safety, ethical, legal regulatory and application guidelines. *Clin Neurophysiol* 2017;128:1774–809.
- [6] Baldari C, Buzzachera CF, Vitor-Costa M, Gabardo JM, Bernardes AG, Altamari LR, et al. Effects of transcranial direct current stimulation on psychophysiological responses to maximal incremental exercise test in recreational endurance runners. *Front Psychol* 2018;9:1867.
- [7] Barwood MJ, Butterworth J, Goodall S, House JR, Laws R, Nowicky A, et al. The effects of direct current stimulation on exercise performance, pacing and perception in temperate and hot environments. *Brain Stimul* 2016;9:842–9.
- [8] Borducchi DM, Gomes JS, Akiba H, Cordeiro Q, Borducchi JH, Valentin LS, et al. Transcranial direct current stimulation effects on athletes’ cognitive performance: an exploratory proof of concept trial. *Front Psychiatry* 2016;7:183.
- [9] Borriore L, Brunoni AR. Primum non nocere or primum facere meliorem? Hacking the brain in the 21st century. *Trends Psychiatry Psychother* 2017;39:232–8.
- [10] Calmels C. Using motor simulation: a novel approach to recovery after a transient sensorimotor deprivation. *Neurophysiol Clin* 2019, <http://dx.doi.org/10.1016/j.neucli.2019.01.033> [in press].
- [11] Carrey P. Brain doping: prise de tête; 2016 [[https://www.liberation.fr/sports/2016/07/21/brain-doping-prise-de-tete\\_1467755](https://www.liberation.fr/sports/2016/07/21/brain-doping-prise-de-tete_1467755), accessed 21.07.16].
- [12] Clark VP, Parasuraman R. Neuroenhancement: enhancing brain and mind in health and in disease. *Neuroimage* 2014;85:889–94.
- [13] Cogiamanian F, Marceglia S, Ardolino G, Barbieri S, Priori A. Improved isometric force endurance after transcranial direct current stimulation over the human motor cortical areas. *Eur J Neurosci* 2007;26:242–9.
- [14] De Mondenard JP, Chevallier B. *Le Dossier Noir du dopage*. Paris: Hachette; 1981. p. 118, (270 p.).
- [15] Devanne H, Allart E. Boosting brain motor plasticity with physical exercise. *Neurophysiol Clin* 2019, <http://dx.doi.org/10.1016/j.neucli.2019.01.003> [in press].
- [16] Fitz NS, Reiner PB. The challenge of crafting policy for do-it-yourself brain stimulation. *J Med Ethics* 2015;41:410–2.
- [17] Flood A, Waddington G, Keegan RJ, Thompson KG, Cathcart S. The effects of elevated pain inhibition on endurance exercise performance. *Peer J* 2017;5:e3028.
- [18] Geay N, Dalligault T. Brain doping, ou le cerveau au service de la performance; 2017 [<https://www.dailymotion.com/video/x57slsw>, accessed 08.01.17].
- [19] Hendy AM, Kidgell DJ. Anodal-tDCS applied during unilateral strength training increases strength and corticospinal excitability in the untrained homologous muscle. *Exp Brain Res* 2014;232:3243–52.
- [20] Hendy AM, Teo WP, Kidgell DJ. Anodal transcranial direct current stimulation prolongs the cross-education of strength and corticomotor plasticity. *Med Sci Sports Exerc* 2015;47:1788–97.
- [21] Holgado D, Vadillo MA, Sanabria D. The effects of transcranial direct current stimulation on objective and subjective indexes of exercise performance: a systematic review and meta-analysis. *Brain Stimul* 2019, <http://dx.doi.org/10.1016/j.brs.2018.12.002> [in press].
- [22] Ingle S. Team Sky’s Dave Brailsford on the hunt for cycling’s new technology; 2015 [<https://www.theguardian.com/sport/2015/mar/06/team-sky-dave-brailsford-cycling-new-technology>, accessed 06.03.15].
- [23] Jwa A. Early adopters of the magical thinking cap: a study on do-it-yourself (DIY) transcranial direct current stimulation (tDCS) user community. *J Law Biosci* 2015;2:292–335.
- [24] Kan B, Dundas JE, Nosaka K. Effect of transcranial direct current stimulation on elbow flexor maximal voluntary isometric strength and endurance. *Appl Physiol Nutr Metab* 2013;38:734–9.
- [25] Lattari E, Andrade ML, Filho AS, Moura AM, Neto GM, Silva JG, et al. Can transcranial direct current stimulation improve the resistance strength and decrease the rating perceived scale in recreational weight-training experience? *J Strength Cond Res* 2016;30:3381–7.

- [26] Lattari E, Campos C, Lamego MK, Passos de Souza SL, Neto GM, Rocha NB, et al. Can transcranial direct current stimulation improve muscle power in individuals with advanced resistance training experience? *J Strength Cond Res* 2017, <http://dx.doi.org/10.1519/JSC.0000000000001956> [in press].
- [27] Lattari E, de Oliveira BS, Oliveira BRR, de Mello Pedreiro RC, Machado S, Neto GAM. Effects of transcranial direct current stimulation on time limit and ratings of perceived exertion in physically active women. *Neurosci Lett* 2018;662:12–6.
- [28] Lattari E, Oliveira BRR, Monteiro Júnior RS, Marques Neto SR, Oliveira AJ, Maranhão Neto GA, et al. Acute effects of single dose transcranial direct current stimulation on muscle strength: a systematic review and meta-analysis. *PLoS One* 2018;13:e0209513.
- [29] Lefaucheur JP. Principles of therapeutic use of transcranial and epidural cortical stimulation. *Clin Neurophysiol* 2008;119:2179–84.
- [30] Lefaucheur JP. Methods of therapeutic cortical stimulation. *Neurophysiol Clin* 2009;39:1–14.
- [31] Lefaucheur JP. Neurophysiology of cortical stimulation. *Int Rev Neurobiol* 2012;107:57–85.
- [32] Lefaucheur JP. A comprehensive database of published tDCS clinical trials (2005–2016). *Neurophysiol Clin* 2016;46:319–98.
- [33] Lefaucheur JP, Antal A, Ayache SS, Benninger DH, Brunelin J, Cogiamanian F, et al. Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). *Clin Neurophysiol* 2017;128:56–92.
- [34] Loo CK, Martin DM, Alonzo A, Gandevia S, Mitchell PB, Sachdev P. Avoiding skin burns with transcranial direct current stimulation: preliminary considerations. *Int J Neuropsychopharmacol* 2011;14:425–6.
- [35] Montenegro R, Okano AH, Cunha FA, Fontes EB, Farinatti P. Does prefrontal cortex transcranial direct current stimulation influence the oxygen uptake at rest and post-exercise? *Int J Sports Med* 2014;35:459–64.
- [36] Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *J Physiol* 2000;527:633–9.
- [37] Okano AH, Fontes EB, Montenegro RA, Farinatti Pde T, Cyrino ES, Li LM, et al. Brain stimulation modulates the autonomic nervous system, rating of perceived exertion and performance during maximal exercise. *Br J Sports Med* 2015;49:1213–8.
- [38] Okano AH, Machado DGS, Oliveira Neto L, Farias-Junior LF, Agrícola PMD, Arruda A, et al. Can transcranial direct current stimulation modulate psychophysiological response in sedentary men during vigorous aerobic exercise? *Int J Sports Med* 2017;38:493–500.
- [39] Priori A, Berardelli A, Rona S, Accornero N, Manfredi M. Polarization of the human motor cortex through the scalp. *Neuroreport* 1998;9:2257–60.
- [40] Radel R, Tempest G, Denis G, Besson P, Zory R. Extending the limits of force endurance: stimulation of the motor or the frontal cortex? *Cortex* 2017;97:96–108.
- [41] Reardon S. 'Brain doping' may improve athletes' performance. *Nature* 2016;531:283–4.
- [42] Sasada S, Endoh T, Ishii T, Komiyama T. Polarity-dependent improvement of maximal-effort sprint cycling performance by direct current stimulation of the central nervous system. *Neurosci Lett* 2017;657:97–101.
- [43] Sauvaget A, Tostivint A, Etcheverrigaray F, Pichot A, Dert C, Schirr-Bonnais S, et al. Hospital production cost of transcranial direct current stimulation (tDCS) in the treatment of depression. *Neurophysiol Clin* 2019;49:11–8.
- [44] Slatter M. Olympics cycling: marginal gains underpin team GB dominance; 2012 [<https://www.bbc.com/sport/olympics/19174302>, accessed 08.08.12].
- [45] Steenbergen L, Sellaro R, Hommel B, Lindenberger U, Kühn S, Colzato LS. 'Unfocus' on foc.us: commercial tDCS headset impairs working memory. *Exp Brain Res* 2016;234:637–43.
- [46] Valenzuela PL, Amo C, Sánchez-Martínez G, Torrontegi E, Vázquez-Carrión J, Montalvo Z, et al. Transcranial direct current stimulation enhances mood but not performance in elite athletes. *Int J Sports Physiol Perform* 2019, <http://dx.doi.org/10.1123/ijspp.2018-0473> [in press].
- [47] Vitor-Costa M, Okuno NM, Bortolotti H, Bertollo M, Boggio PS, Fregni F, et al. Improving cycling performance: transcranial direct current stimulation increases time to exhaustion in cycling. *PLoS One* 2015;10:e0144916.
- [48] von Rein E, Hoff M, Kaminski E, Sehm B, Steele CJ, Villringer A, et al. Improving motor performance without training: the effect of combining mirror visual feedback with transcranial direct current stimulation. *J Neurophysiol* 2015;113:2383–9.
- [49] Wexler A. The practices of do-it-yourself brain stimulation: implications for ethical considerations and regulatory proposals. *J Med Ethics* 2016;42:211–5.
- [50] Wexler A. Recurrent themes in the history of the home use of electrical stimulation: transcranial direct current stimulation (tDCS) and the medical battery (1870–1920). *Brain Stimul* 2017;10:187–95.
- [51] Wexler A. The social context of "Do-It-Yourself" brain stimulation: neurohackers, biohackers, and lifehackers. *Front Hum Neurosci* 2017;11:224.
- [52] Williams PS, Hoffman RL, Clark BC. Preliminary evidence that anodal transcranial direct current stimulation enhances time to task failure of a sustained submaximal contraction. *PLoS One* 2013;8:e81418.
- [53] Zappasodi F, Musumeci G, Navarra R, Di Lazzaro V, Caulo M, Uncini A. Safety and effects on motor cortex excitability of five cathodal transcranial direct current stimulation sessions in 25 hours. *Neurophysiol Clin* 2018;48:77–87.
- [54] Zappasodi F, Musumeci G, Navarra R, Di Lazzaro V, Caulo M, Uncini A. Safety and effects on motor cortex excitability of five anodal transcranial direct current stimulation sessions in 24 hours. *Neurophysiol Clin* 2019;49:19–26.
- [55] Zhu FF, Yeung AY, Poolton JM, Lee TM, Leung GK, Masters RS. Cathodal transcranial direct current stimulation over left dorsolateral prefrontal cortex area promotes implicit motor learning in a golf putting task. *Brain Stimul* 2015;8:784–6.

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