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Effects of Transcranial Direct Current Stimulation on Cycling Time Trial Performance and Prefrontal Cortex Activation

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Abstract: Background: Transcranial direct current stimulation (tDCS) is a neuromodulatory technique that delivers low levels of a constant current via scalp electrodes to specifically targeted areas of the brain. The effects of tDCS on whole-body exercise performance has been of interest in recent literature. The purpose of the current investigation was to investigate if tDCS, administered via Halo Sport, influences time trial performance in trained cyclists, and if changes in exercise performance are associated with prefrontal cortex (PFC) activation and/or muscle oxygenation (SmO_2). Methods: Twelve recreationally trained cyclists volunteered to participate in a crossover study design involving two 10-kilometer time trials following 20 min of tDCS or a sham condition. Results: *t*-tests showed there was no significant difference in performance (time to completion) or physiological measures (blood lactate (BL) concentration, heart rate (HR), SmO_2, PFC oxygenation) between the Halo and sham conditions. Conclusions: These results indicate that the application of tDCS via Halo Sport does not induce changes in exercise performance or related physiological parameters during a 10-kilometer cycling time trial.

Keywords: tDCS; cycling time trial; exercise performance; prefrontal cortex; muscle oxygenation

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1. Introduction

The limiting factors of exercise performance have been the focus of many current and past exercise science research discussions [1–3]. During continuous submaximal exercise, the ability of the skeletal muscle fibers to contract and the excitability of motor neurons projecting from the central nervous system are significantly decreased [4]. To accommodate for this reduction in force or power output, the output signals from the motor cortex of the brain to the periphery (i.e., skeletal muscle) must be increased to generate enough force to maintain exercise intensity. Supraspinal fatigue can be described as a reduction in motor cortical neuronal drive or the lack of ability to generate output from the motor cortex, and in combination with peripheral factors (i.e., changes at or distal to the neuromuscular junction), it can cause muscular fatigue. Previous research has suggested that the development of supraspinal fatigue is often coupled with changes in the excitability of the motor cortex [5].

A multitude of electrical and magnetic stimulation techniques have been developed and extensively researched to modulate excitability and output signals from the motor cortex [6]. Increasing the output from the motor cortex can delay the onset of supraspinal fatigue and likely improve exercise capacity [7]. Of these techniques, transcranial direct current stimulation (tDCS) and specifically its effects on physical performance have gained much interest in current literature [8–10]. tDCS is a neuromodulatory intervention that delivers low levels of a constant current to specifically targeted areas of the brain, such as the motor cortex, which create excitability changes [10]. tDCS is a non-invasive stimulation technique that is safe, affordable and easy to administer. For these reasons, interest in the potential ergogenic effects of tDCS on physical performance has increased greatly.

Excellence in sport performance not only requires a high level of physical capability, but also mental capability. Previous neuroimaging studies have reported that during whole-body aerobic exercise, the prefrontal cortex (PFC) increases neuronal activation (as measured by brain oxygenation via functional NIRS (fNIRS)) during submaximal aerobic exercise (up to approximately 80% of peak ability) but then decreases when intensity reaches a very hard or maximal effort [11]. More specifically, at very high or maximal intensities of exercise where competitive exercise may take place, there may be a shift in resources from areas required for cognitive function to areas required for motor control and maintenance of vital function (e.g., thermoregulation) [12]. This shift in resources may explain the reduction in PFC activation during very high intensities of aerobic exercise. While the effect of tDCS on changes in PFC activation during whole-body aerobic exercise is not well understood, noninvasive fNIRS is a commonly used tool which would allow investigation into these changes. The advantages of fNIRS is that it is also portable and provides live feedback regarding physiological changes associated with brain activity. This may provide us with mechanistic insight into how tDCS can alter PFC activation during competitive exercise.

Therefore, the present study seeks to evaluate if tDCS (administered via Halo Sport) influences exercise time trial performance in recreationally trained cyclists. An additional objective is to explore if the change in exercise performance is associated with changes in PFC and muscle oxygenation. Results may provide important insights into the mechanisms of how tDCS influences both competitive exercise and brain and muscle activity, and further allow sports performance personnel to identify and utilize appropriate techniques to improve competitive performance.

2. Materials and Methods

2.1. Study Design

All participants served as their own control in a placebo-controlled, counterbalanced, crossover study with a repeated measures design. The participants visited the lab on three separate occasions. On the first occasion, participants completed an 8 min submaximal bike test on a Monark stationary bike at the same time of the day as the 10 km time trials to eliminate any effects of circadian variations. On the two other occasions, the participants performed a 10 km cycling time trial following stimulation of a 20 min Halo Sport session either with (Halo) or without (sham) electrical current delivered to the primers. During stimulation, participants were seated, quiet and relaxed while listening to music of their choosing. All trials were separated by at least 72 h (during which time the participants refrained from any normal training activity) but no more than 10 days (to minimize the likelihood of dropouts). Participants were wearing brain (fNIRS) and muscle (Moxy) oxygenation devices during both time trials. See Figure 1 for a detailed outline of the study design, including duration between exercise testing sessions.

2.2. Participants

All participants were informed of the study protocol approved by the University of Northern Iowa's Institutional Review Board (IRB) before obtaining written consent prior to participation in the study. Following IRB approval, recruitment flyers were posted. Twelve male, recreationally trained cyclists were recruited. All participants were active (no less than 30 min·day^{-1}, 3 days·week^{-1}, for at least 3 consecutive months) and were between the ages of 18 and 45 years. See Table 1 for subject demographics. All participants were administered a health history questionnaire which indicated that no subject had a history of musculoskeletal injuries, metabolic, cardiovascular or pulmonary disease, mental disorders/diseases or were on medications during the study. Participants were asked to refrain from alcohol, caffeine and physical activity for 24 h before testing sessions. Participants were instructed to consume a meal of similar nutritional composition at the same time interval prior to all trials.

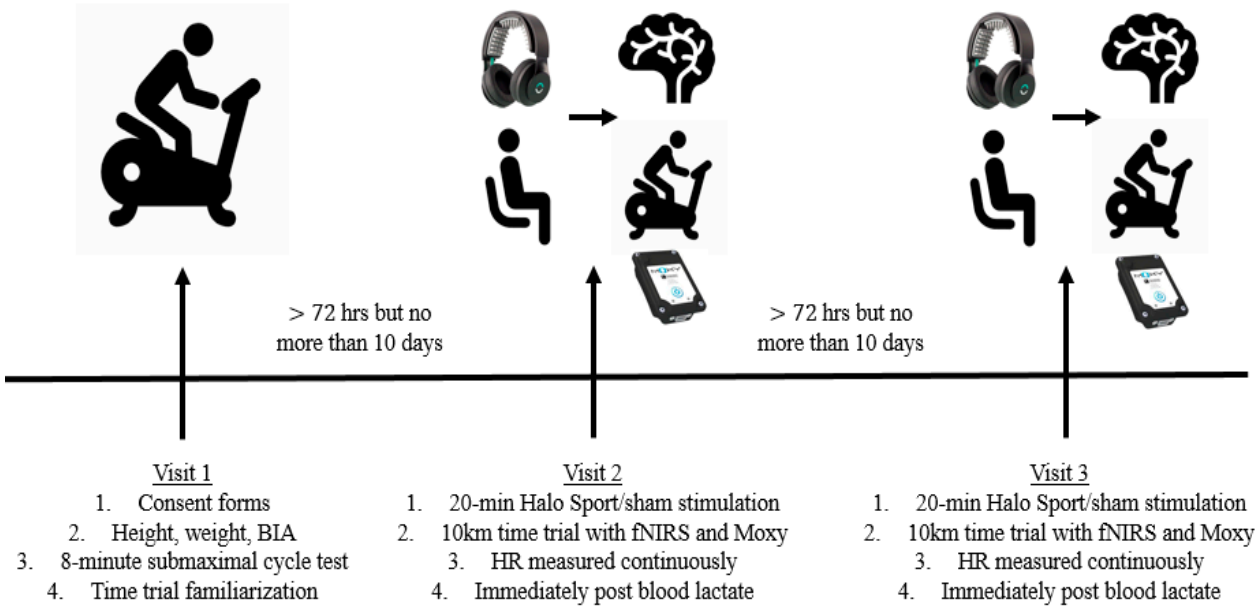

Figure 1. Detailed outline of the study. BIA = bioelectrical impedance analysis, fNIRS = functional near-infrared spectroscopy, HR = heart rate, Moxy = muscle oxygenation device.

Table 1. Subject demographics.

Age (Years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Body Fat (%)	Estimated VO_2 Max (mL/kg/min)
25.5 ± 7.8	181.7 ± 5.9	85.9 ± 12.3	25.7 ± 3.0	15.3 ± 7.0	41.5 ± 5.0

Data are expressed as means ± standard deviations. cm = centimeters, kg = kilograms, kg/m^2 = kilograms per meter squared, ml/kg/min = milliliter per kilogram per minute.

2.3. Anthropometric and Body Composition Measurements

Prior to the first testing session, height (cm) and body weight (kg) were measured using a stadiometer and floor scale, respectively. Upon arrival for the first exercise testing trial (submaximal bike test), body fat percentage was also determined using bioelectrical impedance analysis (InBody 720).

2.4. Exercise Testing and Screening

All submaximal bike testing was performed on a Monark stationary bike (Ergomedic 828 E, Monark Exercise, Vansbro, Sweden) while wearing a Polar heart rate monitor (V800, Polar Electro Inc., Woodbury, NY, USA). The test began with a three-minute warm-up at 50 watts and then the intensity was increased to 150 watts and participants were asked to maintain 60 rpm for the duration of 5 min. Heart rate was recorded at the cessation of the test and prediction equations were used to estimate VO_2max [13]. A 2 km familiarization of the time trial was also performed following the submaximal bike test to ensure participants understood the protocol and felt comfortable with the cycling intensities and the self-paced nature of the work intensity in the time trials. After a minimum of 72 h following the submaximal bike test, participants returned to the exercise laboratory for one of the following two counter-balanced trials: tDCS (Halo) or no tDCS (sham).

2.5. Time Trial Task

Immediately after either tDCS via Halo or sham stimulation, participants performed a self-selected warm up. To assess endurance performance, participants performed a 10 km time trial test on a VeloTron bike (VeloTron RacerMate, RacerMate Inc., Seattle, WA, USA). VeloTron bikes have a fully adjustable frame to fit multiple users and generates variable load ranges from 5 to 2000 watts, selected by the user.

After a five-minute, self-selected warmup, participants started the 10 km cycling time trial under as consistent environmental conditions as possible. All time trials began from a standing start at a gear ratio of 53 × 17 and were completed using a virtual flat (i.e., zero gradient) course programed into the VeloTron software. Participants were asked to complete the time trial as quickly as possible, manipulating gearing as needed. Total time needed to complete the 10 km time trial was recorded from the VeloTron software. Overall rating of perceived exertion (RPE) was also collected 10 min after exercise had ceased, to provide an accurate quantification of session load [14].

2.6. Blood Lactate and Heart Rate

A blood lactate (BL) measurement (Lactate Plus, Nova Biomedical, Waltham, WA, USA) was collected immediately post-exercise as a proxy of the intensity of that particular trial. All BL samples were collected at the earlobe using a lancing device, obtained in duplicate and averaged for analysis. Heart rate was also continuously measured and averaged throughout all trials using a Garmin heart rate monitor (HRM-Dual, Lenexa, KS, USA), which was integrated with the Moxy NIRS device.

2.7. Halo Sport Procedures

The Halo Sport headset itself is similar in appearance to an audio headset. The headset has 28 cm^2 foam electrodes (termed primers) which are wetted prior to use to initiate the electrical current with the scalp. The headset is positioned over the vertex of the head, with the primers lying across the top of the head, from ear to ear. The aim is to stimulate both (left and right) sides of the motor cortex, with the anodal electrode being positioned over the top of the head and the cathodal electrode being positioned on the left and right sides.

Prior to exercise, participants were seated in a chair, in a resting state. The Halo Sport headset was correctly positioned and the electrical current was turned to 2.0 mA over the course of 30 s. In the active Halo group, 2.0 mA was maintained for 20 min. In the sham group, intensity was ramped down after 30 s. This procedure is similar to previous studies conducted using Halo Sport [7,15].

2.8. Functional Infrared Spectroscopy Recording Procedures

Prefrontal cortex (PFC) oxygenation was continuously measured using a dual wavelength (760 and 850 nm), portable fNIRS system (OctaMon, Artinis Medical Systems) during both time trial sessions. This device has been previously used to illustrate ecological validity during self-paced running [16]. Four LED optodes (transmitters) and one receiver were placed over the right (RPFC) and left PFC (LPFC) regions (4 × 2 configuration). Optode placement is based on the modified international electroencephalogram 10/20 system [17]. The fNIRS cap was positioned 2 cm (cm) above the nasion, centering on the Fpz location (distinctly depressed area directly between the eyes, just superior to the bridge of the nose). An optode receiver distance of 3.5 cm was used, which is recommended as an optimal distance to detect cortical activity among adults [16,17]. The signal sampling rate was 10 Hz. In order to reduce possible disruptions in signals such as movement or heart rate, a moving 2 s average filter was applied to all raw data and then this was averaged across both trials. Relative concentration changes from baseline within each trial for oxygenated (O_2Hb) and total hemoglobin (tHb) were measured. Baseline was the first 10 s following a 2 min resting period and defined as 0 µmol. Neural activity induces changes in blood flow to activated areas of the brain. When blood flow is increased in activated areas of the brain, local supply of oxygen is greater than consumption—which was shown through a higher concentration of oxyhemoglobin (O_2Hb) and decreased concentration of deoxyhemoglobin [18].

2.9. Muscle Oxygenation Procedures

During both Halo and sham 10 km time trials, a Moxy NIRS monitor (Fortiori Design, Hutchinson, MN, USA) was placed on the dominant leg's vastus lateralis (VL) (10–15 cm above the proximal border of the patella) [19]. The monitor was attached following cleaning with an alcohol wipe and secured with a double-sided adhesive disk and covered by a dark athletic tape to reduce intrusion of light [20]. The Moxy monitor position on the participant's skin was marked to ensure the monitor was placed on the same site in the following testing session. A moving 5 s average was applied on the raw muscle O_2 saturation (SmO_2) signal to reduce the noise created by movement [21]. During exercise, SmO_2 represents the balance between O_2 delivery and O_2 extraction by the muscle [22]. All SmO_2 values were normalized, so that 0% and 100% represent these minimum and maximum SmO_2 of the participant, respectively. Average SmO_2 values are presented in this normalized fashion in the results section below. McManus et al. [23] provided evidence that in this subject group, both Moxy and PortaMon produce physiologically credible tissue oxygen saturation index measures during rest and exercise.

2.10. Statistical Analysis

In previous research studies in which the Halo Sport device was used to enhance exercise performance in healthy adults, researchers reported significant results ($p < 0.05$) with a total of 9 [7] and 12 participants [15] in crossover studies with repeated measures design. Therefore, we aimed to include a similar sample to those described in these previous studies [10,24–26] to ensure accurate analysis of the effects of the Halo Sport intervention. All results are expressed as means ± standard deviation and evaluated for normality and homogeneity of variance. Average brain and muscle (SmO_2) oxygenation changes from baseline within each time trial (Halo and sham) were analyzed using data from the LPFC (fNIRS channels 1–4 averaged) and RPFC (fNIRS channels 5–8 averaged) and VL muscle, respectively. Paired *t*-tests were used to compare Halo and sham 10 km time to completion, overall RPE, immediately post-exercise BL, average SmO_2 and average PFC O_2Hb and tHb (for both left and right regions). Data were analyzed using GraphPad Prism 9.0.2.

3. Results

3.1. Time to Completion

A *t*-test revealed that there was no significant difference ($p = 0.92$) in time to complete a 10 km cycling time trial between Halo and sham conditions (17.58 ± 1.88 min; 17.68 ± 1.92 min) (Table 2).

3.2. Prefrontal Cortex Oxygenation

As shown in Figure 2, *t*-tests were used to compare oxygenated hemoglobin (O_2Hb) and total hemoglobin (tHB) in the right prefrontal cortex (RPFC) and the left prefrontal cortex (LPFC) between Halo and sham conditions. Results showed no significant difference ($p = 0.70$) in average RPFC oxygenation (26.85 ± 24.10 µmol, 23.18 ± 17.96 µmol) and no significant difference ($p = 0.98$) in average LPFC oxygenation (13.53 ± 3.84 µmol, 13.56 ± 4.18 µmol) between conditions. Additionally, results showed no significant difference ($p = 0.86$) in average LPFC tHB (18.63 ± 5.17 µmol, 18.23 ± 5.44 µmol) and no significant difference ($p = 0.73$) in average RPFC tHB (40.87 ± 39.86 µmol, 35.46 ± 30.65 µmol) between conditions.

3.3. Muscle Oxygenation

A *t*-test revealed that there was no significant difference ($p = 0.40$) in average muscle oxygenation between Halo and sham conditions, shown in Figure 3 below (18 ± 9 percent, 23 ± 15 percent).

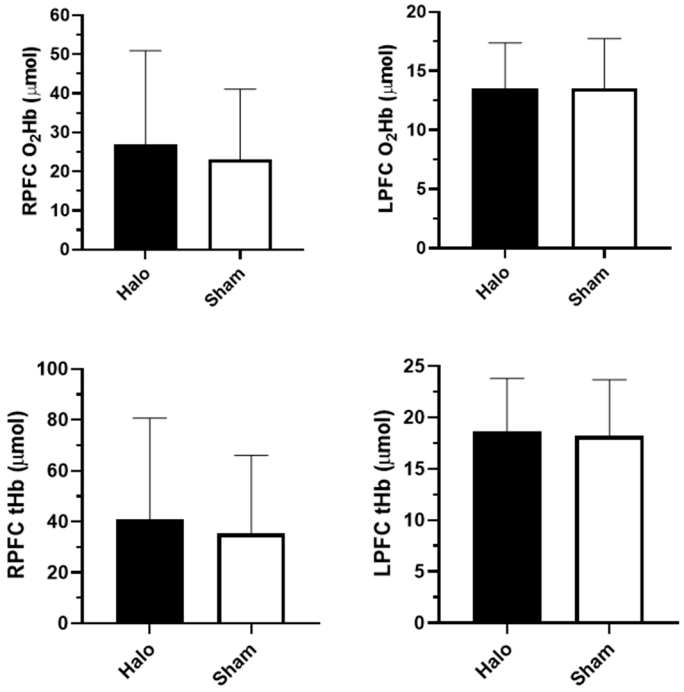

Figure 2. Brain oxygenation results.

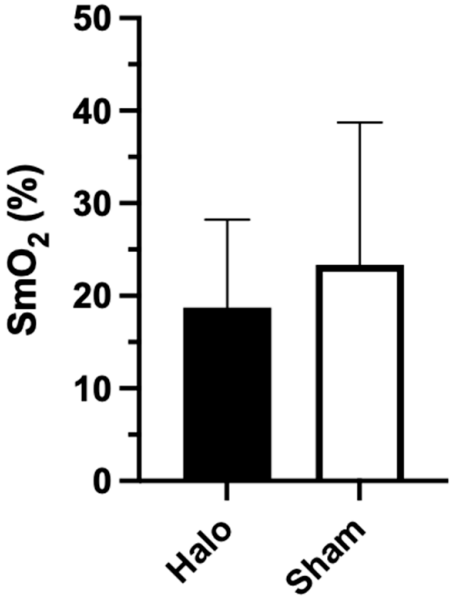

Figure 3. Muscle oxygenation results.

3.4. Heart Rate, Blood Lactate and Rating of Perceived Exertion

Despite the application of tDCS, average HR did not show a significant difference (p = 0.74) compared to sham conditions (163.5 ± 17.2 bpm, 160.9 ± 20.1 bpm). There was no significant difference (p = 0.78) observed in overall RPE between Halo and sham conditions (16.20 ± 1.99, 15.95 ± 2.03). Lastly, we analyzed the effects of tDCS on post-exercise BL levels and found no significant difference (p = 0.56) between Halo and sham conditions (10.66 ± 2.47 mmol/L, 9.99 ± 2.88 mmol/L). These results are displayed in Table 2 below.

Table 2. Results of Halo and sham on BL, RPE, HR and Time.

Characteristic	Halo	Sham
BL (mmol/L)	10.66 ± 2.46	9.98 ± 2.88
RPE	16.20 ± 1.99	15.95 ± 2.03
HR (bpm)	163.5 ± 17.2	160.9 ± 20.1
Time (min)	17.58 ± 1.88	17.67 ± 1.92

Data are presented as means ± standard deviations. BL = blood lactate, RPE = rating of perceived exertion, HR = heart rate, mmol/L =millimoles per liter, bpm = beats per minute, min = minutes.

4. Discussion

The major finding in this study was that 10 km cycling time trial performance was unaffected by tDCS via the Halo Sport device. Results confirm some previous findings showing that tDCS has minimal effect on exercise performance and related physiological parameters [8,24–26]. In addition, it was shown that both PFC and muscle oxygenation of the vastus lateralis were maintained over the entire portion of this self-paced, 10 km time trial. Moreover, brain and muscle oxygenation show similar trends, whereby PFC and SmO_2 are well maintained and do not hinder or help self-paced exercise. That said, this study provides novel evidence to suggest that PFC oxygenation and SmO_2 are well preserved during time trial cycling following Halo Sport administration when the intensity of exercise is free to vary in response to external and internal physiological cues.

Interest in the potential ergogenic effect of non-invasive brain stimulation has grown in recent years and although there are various studies using tDCS and exercises, there are few focusing specifically on the Halo Sport device. Initial research focused on single-joint isometric exercises; however, whole-body exercise better simulates actual sporting competition. Therefore, whole-body exercise may be a more accurate method for assessing the ergogenic effects of tDCS on exercise performance. Of those studies conducted on whole-body exercise, results are inconsistent. Park et al. [15] found increased time to exhaustion during a constant load treadmill test after tDCS administered by the same Halo Sport device. Similarly, Vitor-Costa et al. [27] also saw increased time to exhaustion during an incremental cycling test following application of tDCS with larger electrodes (35 or 36 cm^2), with no other significant results in other parameters (HR, RPE, Power output). However, this study found no significant difference in time to complete a 10 km cycling time trial. Our results are similar to those of Barwood et al. [24], who observed no changes in performance measures (time to exhaustion or power output) during a 20 km time trial following 20 min of anodal tDCS. That said, electrodes in this study were only 3.5–4.5 cm^2 in size and in different locations (anode over the T3 area of the skull and the cathode over the contralateral supraorbital area) to the Halo Sport device. Additionally, Angius et al. [5] found no significant difference ($p = 0.06$) in a time to exhaustion task between 10 min of tDCS and sham conditions. This investigation also utilized smaller electrodes (12 cm^2) in differing locations (anode over the motor cortex and cathode over the dorsolateral right prefrontal cortex). Therefore, one possible explanation for the ineffectiveness of tDCS on sport performance may be that results are dependent on the experimental environment, duration and intensity of stimulation and electrode configuration/size or placement on the head. Additionally, Halo Sport is a commercially made tDCS device that allows minimal adjustments to these factors [7].

To the authors' knowledge, no studies have investigated the relationship between tDCS, PFC oxygenation and whole-body self-paced exercise. This study found an increase in activation from baseline but no changes in average left and right PFC O_2Hb or tHB and no related time trial performance changes between Halo and sham conditions. O_2Hb and tHB represent the relative concentrations of arterial oxygen content and total oxygen content (i.e., blood flow), respectively. There is evidence that submaximal aerobic exercise increases activation of the PFC, as suggested by increases in O_2Hb and tHb saturation [28]. Therefore, oxygenation of the PFC seems to be related to the intensity of exercise, when

compared to the baseline period. Nonetheless, the effect of Halo Sport on any intensity parameters or cortical oxygenation remains unclear. Our results are similar to those of Muthalib et al. [29], who found no changes in levels of PFC activation with the application of anodal tDCS over the right motor cortex and no significant changes in an isometric contraction task of the elbow flexors. Additionally, Holgado et al. [30] found that 20 min of tDCS over the LPFC does not affect HR, RPE or EEG during a 20 min self-paced time trial in male cyclists. It is possible that through repetition and experience, the act of success in self-pacing exercise becomes more automatic and requires less thought and less activation in the area of the brain used for processing.

Similarly, no studies have investigated the effects of tDCS on muscle oxygen saturation. This study found similar values for average muscle oxygen saturation between Halo and sham conditions. As expected, muscle saturation decreased progressively throughout the time trial task and recovered quickly after the cessation of exercise. These responses of muscle oxygen saturation during whole-body exercise have been well documented [28,31]. Belardinelli et al. [31] observed that oxygen saturation in the vastus lateralis decreased progressively during an incremental VO_2max test. They further observed that SmO_2 decreased rapidly during a medium work rate range and leveled off when nearing VO_2max or very hard work rates. Rupp and Perrey [28] noted similar results in local muscle oxygen saturation in the vastus lateralis during a maximal time to exhaustion cycling test. In tandem, these results suggest that during moderate and hard intensities of exercise, there is a discrepancy between local muscle O_2 delivery and utilization. Rupp and Perrey (2007) further observed an increase in deoxygenated hemoglobin (HHb), which may indicate a limitation in delivery of O_2 to the working muscles rather than an inability to utilize available O_2.

Our study also found no effect on cardiorespiratory (HR) or physiological (BL) response during the 10 km time trial with the application of tDCS. These results are similar to those of Park et al. [15], who found no change in HR responses during a constant load treadmill test after 20 min of Halo stimulation. Additionally, there are various studies that found no changes in HR responses during different exercises tasks following tDCS [8,24,26]. However, results of studies investigating tDCS and exercise related cardiovascular responses are conflicting. Okano et al. [10] saw a decreased HR trend following anodal tDCS during an incremental exercise test. The autonomic nervous system and cardiac responses are regulated by both sympathetic and parasympathetic neural pathways. Parasympathetic pathways are said to regulate HR during rest and exercise at lower intensities, whereas at higher intensities, HR becomes controlled by sympathetic pathways. This may indicate that the intensity of a 10 km time trial at full effort triggered a mostly sympathetic HR response, which may be unaffected by tDCS. Furthermore, previous studies have also reported no effect of tDCS on HR during exercise intensities that are near VO_2max [24]. This study further found no significant difference in post-exercise BL levels between Halo and sham conditions. Similarly, Barwood et al. [24] found similar blood lactate results following a 20 km time trial after tDCS (9.96 ± 3.29 mmol/L, 8.08 ± 3.21 mmol/L). Although this study observed no significant difference in levels of BL between Halo and sham conditions, these results indicate that this 10 km time trial was a high-intensity task.

Results of studies investigating tDCS and RPE are inconsistent. Okano et al. [10] found RPE to increase more slowly following anodal tDCS stimulation over the temporal cortex. However, our study showed no difference in RPE after stimulation. Barwood et al. [24] and Vitor-Costa et al. [27] found similar results for RPE during time to exhaustion cycling tasks after tDCS. These results may indicate that the motor cortex is not related to perceptual responses; rather, perceptions of effort may be regulated by different parts of the brain (e.g., insular cortex, thalamus). Further, Angius et al. [26] found no changes in perceptions of pain in a time to failure task following anodal stimulation of the motor cortex. Many factors have been proposed as to why perceptions of effort and pain may be insensitive to the analgesic effects of tDCS such as attentional focus, release of endogenous opioids or catecholamines and supraspinal inhibitory mechanisms.

There are several limitations to the current study that should be noted. Several studies using tDCS to target specific areas of the brain have shown promise, but Halo Sport is a commercially made device that does not allow for many adjustments. Due to anatomical differences between participants, it is possible that stimulation via Halo Sport may have not targeted the motor cortex and may have influenced other areas of the brain. Conventional tDCS sessions are also usually performed at rest in a quiet room unlike the Halo Sport device, which delivered music during the session; this may act as a source of bias in this case. Additionally, this study focused on recreationally trained males, ages 18–45. Our results may not translate to other populations, as tDCS may have different effects on more novice or elite individuals, females or different age groups. Lastly, this study used a 10 km time trial to measure performance. It is possible that tDCS would produce different results with different modes of exercise or different distances.

5. Conclusions

The results of this study indicate that the application of tDCS through Halo Sport has no effect on 10 km time trial performance and related physiological parameters in recreationally trained male cyclists. Future research conducted using tDCS should examine the potential long-term impact of training using tDCS on exercise performance, the potential benefits of tDCS on different modes and intensities exercise and the potential differences between different populations (e.g., females, younger/older adults). Additionally, the impact of tDCS on decision-making and accuracy during sport situations may be of interest.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of the University of Northern Iowa (protocol code 20-0027 and 6 October 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The group data presented in this study are available on request from the corresponding author. The individual data are not publicly available due to privacy and confidentiality.

Conflicts of Interest: The authors declare no conflict of interest.

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