A Real-World Investigation into the Benefits of Transcranial Direct Current Stimulation to the Primary Motor Cortex on Muscular Performance in Elite Athletes

Halo Neuroscience

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ABSTRACT: As interest in non-invasive brain stimulation grows, many potential users are seeking applications for the heightened learning state associated with this technology. One possible application is in sports, where stimulation has shown promising results in the form of increased training efficiency, improving both motor skills and raw power. In this study, athletes training for strength- and power-intensive sports received neurostimulation treatment in the form of transcranial direct current stimulation (tDCS) from the Halo Neurostimulation System during their normal training routine. Athletes who received stimulation showed significantly greater improvement in their jumping ability compared to non-stimulation athletes. The current study demonstrates the ability of non-invasive brain stimulation to improve athletic performance; however, further testing with larger populations and sham controls is needed in the future.

INTRODUCTION

The traditional approach to athletic training focuses on improving the body, thereby building stronger and more efficient muscles. However, training the brain and central nervous system (CNS) to optimize the neural activity associated with movement can also provide significant benefits in sports as described below. Therefore, we propose to train the central nervous system using non-invasive neurostimulation, paired with conventional athletic training of the body, to maximize results.

Transcranial neurostimulation technology has evolved greatly over the past decades, and since the late 1990s non-invasive methods of brain stimulation have become widely known and are becoming better understood. One such method for non-invasive brain stimulation is transcranial direct current stimulation (tDCS). Here, a researcher or user applies a small amount of current (generally 1 - 2 mA) through a specific area or areas of the scalp. The resulting electrical field changes the resting state of neurons, depolarizing or hyperpolarizing the neurons in order to excite or inhibit a particular area of the brain and promote neurons firing together. By altering the resting state, tDCS changes the functionality of the target area. Short-term increases in plasticity (e.g., rate of long-term potentiation or depression) yield long-term gains by shortening learning times and, in the case of motor cortex stimulation, maximizing muscular signal (Nitsche *et al.*, 2015, Cogiamanian *et al.*, 2007).

Enhancement of motor function is one exciting application for improving brain functionality. By stimulating specific areas of the motor cortex, researchers have been able to increase fine motor skills as well as modulating gross motor properties such as fatigue and explosiveness in human subjects. Vines *et al.* (2008) and Cuypers *et al.* (2013) improved motor skills and motor learning using tDCS and a finger tapping task. Vines *et al.* (2008) had participants match numbers on a screen with keys on a keyboard, with each key assigned to a particular finger. The participants who received bihemispheric stimulation were faster and more accurate when completing the task, producing both more responses and a greater fraction of correct responses, compared to participants who received unihemispheric or sham stimulation. Cuypers *et al.* (2013) used a similar protocol to test how increased stimulation (1.5 mA vs 1 mA) affects motor learning. Here, researchers replicated the findings of Vines *et al.* (2008) while showing that increased stimulation yielded a further increase in speed and accuracy when completing the task. Waters-Metenier *et al.*

(2014) also studied improvement in fine motor skills using a chord configuration (motor synergy) task instead of finger tapping. Researchers quantified motor learning by testing participants both during and after stimulation. Participants who trained while receiving anodal tDCS to primary motor cortex (M1) performed significantly better on the task both during and after stimulation compared to participants who trained with sham stimulation. Waters-Metenier *et al.* (2014) demonstrated that longer lasting benefits to training with stimulation are possible, with 4 days of repeated stimulation leading to at least 4 weeks of benefit, and effects lasting well beyond the stimulation period.

Having observed such effects on fine motor skill learning, researchers began to explore broader effects that tDCS could have on physical performance and neuromuscular fitness. Cogiamanian *et al.* (2007) studied the effect of stimulation on muscular fatigue in a time-to-failure task with elbow flexion. Participants who received the stimulation were able to maintain the contraction for longer, compared to participants who did not receive stimulation. More recently, Williams *et al.* (2013) reproduced these findings, showing increased time to task failure with stimulation compared to sham. However, Williams et al. found improvement only during stimulation and saw no effects on post-stimulation testing. Other researchers have looked at increasing the maximal output (e.g., explosiveness or maximum voluntary contraction force) of a muscle group using tDCS. Tanaka *et al.* (2009) used tDCS to increase the maximal toe pinch of subjects. Researchers found that training with stimulation improved maximal output by approximately 20% during stimulation and approximately 10% at a point 30 minutes after stimulation had ended.

As clinical and basic research continues to confirm that brain stimulation, and in particular tDCS, can improve motor function and learning, some researchers have begun to investigate applying tDCS in an athletic environment, developing specific skills for competitive sports. In a 2013 review, Banissy and Muggleton explored the potential for tDCS to enhance performance in sport. They reviewed tDCS applications in both healthy individuals and stroke patients, concluding that the research suggests that tDCS can benefit sports training; however, the literature on tDCS in sports was solely theoretical at the time. Zhu *et al.* (2015) took the first steps towards using tDCS as a training tool by applying stimulation during a golf putting task. Participants who trained with stimulation putted significantly better than their counterparts who trained with only sham stimulation. Researchers then tested whether the enhanced improvements during training would carry over to testing with the same task the next day. Once again, participants who had trained with stimulation performed significantly better than their sham counterparts. These findings demonstrate the long-lasting benefits possible from training with neural stimulation.

Based on this body of literature, we examined the use of tDCS during athletic training; specifically, strength, power, and explosiveness training of elite athletes, with the goal of enhancing the effects of training. We hypothesized that athletes training with stimulation will see greater performance gains than athletes training without stimulation.

METHODS

Participants

We recruited 14 athletes (aged 19-30 years old) from Michael Johnson Performance, an elite training facility in Dallas, Texas. Of the 14 athletes recruited, 9 were men and 5 were women. Participants were not compensated for their participation and testing occurred during the athletes' normal training routines.

Pro Training Readiness Questionnaire

Athletes completed the Pro Training Readiness Ques-

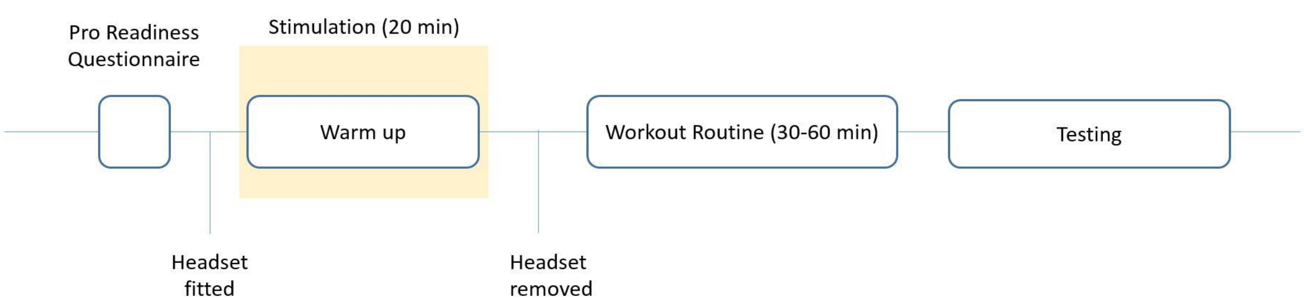

Figure 1. Experimental design.

tionnaire to assess their subjective state of readiness at the start of every workout. Each dimension was measured on a scale of 1 (low/poor) to 5 (high/good). The dimensions measured were Fatigue, Sleep Quality, General Muscle Soreness, Stress Level, and Mood (Appendix A).

Physical Tests

Participants were tested and improvement assessed in three lower body tests. The first test was the Keiser Air Squat (KAS), which measured maximum squat power in watts. Participants assumed a squatting position with their shoulders resting beneath the pads. They then pushed with their legs, pushing up on the pads against the resistance of a pneumatic cylinder with maximal force. The second test was the Squat Jump, which measured vertical leap on a Fusionsport Jump Mat from a squatting starting position. The height of the jump was calculated using an accelerometer attached at the hip. The third test was a Counter Jump, which measured vertical leap on the same Fusionsport Jump Mat, starting from a standing position and allowing for a full initial countermovement prior to the jump. All exercises were performed 3 times per testing period.

Procedure

Data were collected over two time periods: an initial 5-week period in which 9 participants received stimulation and a subsequent 2-week period in which 9 participants trained in the usual manner, without stimulation. 4 of these participants were tested in both the stimulation and non-stimulation periods. Testing was done during workouts on Monday, Tuesday, and Friday each week during both testing periods.

During the stimulation period (Fig 1), athletes began workouts by filling out the Pro Training Readiness Questionnaire. Once completed, athletes were fitted with the system and began receiving stimulation during warm up or initial exercises of a given workout. Once stimulation was completed, the system was removed and the workout continued for another 30-60 minutes of exercises depending on the day's normal training schedule. At the end of the workout, testing was conducted and the results were recorded by either an experimenter or by the athlete's trainers.

Transcranial direct current stimulation (tDCS)

tDCS was conducted using the Halo Neurostimulation System. The anode (6.4x4.4 cm sponge soaked in 0.9% saline solution) was located at Cz (based on the 10-20 system) and the cathode (5 x 10 cm self-adhesive TENS electrode) was placed on the right shoulder. Stimulation consisted of 2.0 mA current delivered for 21 minutes total (20 minutes at 2.0 mA with 30 seconds ramp up and ramp down at either end). The maximum current density delivered was 0.071 mA/cm^2. These parameters are consistent with the literature on motor cortex stimulation, for instance Tanaka (2009).

RESULTS

Participant Exclusion

Data were analyzed from a total of 9 participants. 5 participants (2 from the stimulation group, 3 from the non-stimulation group) were excluded due to insufficient data (less than 3 testing periods).

	Stimulation Group	Non-Stimulation Group	*p*
n (number of participants)	8	6	-
Keiser Air Squat			
Raw Gain (watts)	45.2 +/- 26.6	9.3 +/- 39.8	0.066†
Percent Gain	2.83% +/- 1.76%	1.50% +/- 3.16%	0.32
Squat Jump			
Raw Gain (in)	0.36 +/- 0.31	-0.05 +/- 0.34	0.038*
Percent Gain	2.27% +/- 2.14%	-0.05% +/- 2.14%	0.15
Counter Jump			
Raw Gain (in)	0.34 +/- 0.29	0.01 +/- 0.28	0.058†
Percent Gain	1.97% +/- 1.76%	0.36% +/- 2.14%	0.15

Table 1. Means, standard error, and significance values for both weekly raw and percent gains of the 3 tests based on the independent *t*-tests. * denotes significance and † denotes a trend.

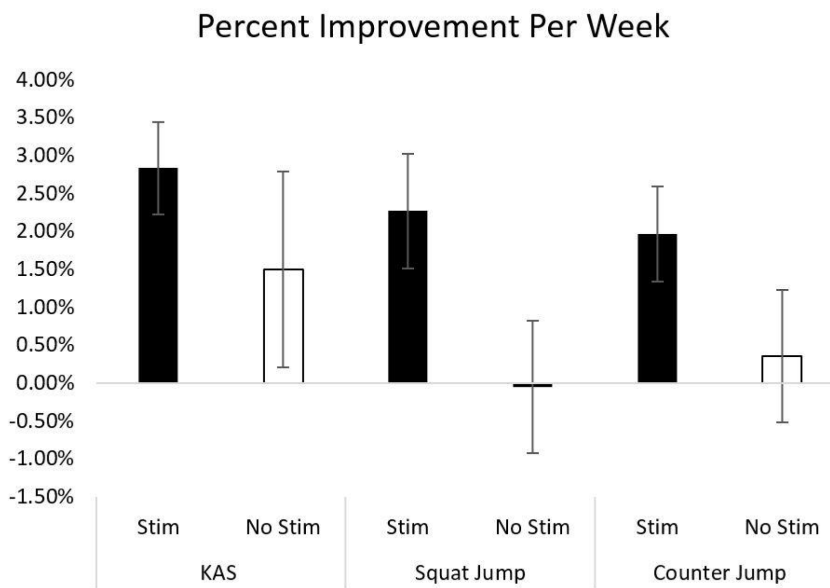

Figure 2. Percent improvement per week separated into independent groups. Error bars represent standard error.

Data Analysis

For the 10 participants with complete data, data were compared based on both percent and raw increases with respect to baseline maximum for each exercise. For the stimulation group, the baseline maximum for a given athlete was defined as the best result from that athlete's first testing period. For the non-stimulation group, if an athlete also participated in the stimulation trials, their baseline maximum was defined as the maximum from the stimulation period; otherwise, their maximum was defined as the best result from their first test. For each phase (either stimulation or no), the maximum achieved during the entire phase was compared with the baseline maximum to determine the total percent and raw gains made during the period. The total gain was then divided by the number of weeks for the stimulation (5 weeks) or the no-stimulation (2.5 weeks) phases to yield the rate of improvement (gain per week).

Testing

An independent samples *t*-test was conducted for the Keiser Air Squat data, finding no significant difference between the two groups for percent gains (M_{dif} = 1.34%, p = .33) but a trend towards greater raw gains (M_{dif} = 35.8 watts, p = .066), with the stimulation group producing more power than the non-stimulation group (Figure 2). Means and standard errors can be found in Table 1.

In Squat Jump results, an independent samples *t*-test did not find a significant difference between stimulation and non-stimulation group for percent gains (M_{dif} = 1.60%, p = .068), but there was a significant difference in raw gains (M_{dif} = 0.41 in, p = .038) was observed. Means and standard errors can be found in table 1.

Finally, an independent samples t-test examining the Counter Jump data was not significant for percent gains (M_{dif} = 1.61%, p = .15). However, there was a trend toward greater raw gains (M_{dif} = 0.32 in, p = .048) in the stimulation group compared to the non-stimulation group (Figure 2). Means and standard errors can be found in table 1.

Because the samples were not truly independent and because of the conservative nature of an independent samples *t*-test, we also conducted paired samples *t*-tests comparing the stimulation phase with the non-stimulation phase for the four participants who experienced both. A paired samples *t*-test found no significant difference for the Keiser Air Squat percent gains (M_{dif} = 2.06%, p = .30), Keiser Air Squat raw gains (M_{dif} = 34.7, p = .34), Squat Jump percent gains (M_{dif} = 0.02 in, p = .26), nor Squat Jump raw gains (M_{dif} = 0.50 in, p = .25). Means and standard errors can be found in table 2.

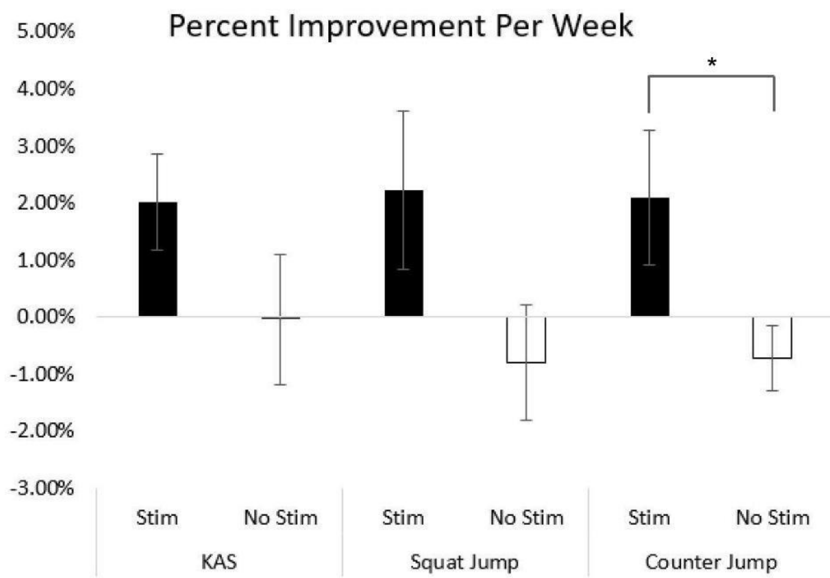

Figure 3. Percent Improvement per week separated into paired groups. Error bars represent standard error. * $p < .05$

A paired samples *t*-test of the Counter Jump data was significant for both percent gains (M_{dif} = 1.61%, *p* = .04) and raw gains (M_{dif} =0 .33 in, *p* = .04). For both percent and raw gains, the stimulation group exhibited significantly more improvement than the non-stimulation group (Figure 2). Means and standard errors can be found in table 2.

Pro Training Readiness Questionnaire

A paired samples analysis of 6 of the participants (in the stimulation testing only) looked at whether the responses to the Pro Training Readiness Questionnaire varied depending on whether the participant received stimulation the previous day. Two participants were removed from the analysis due to a complete lack of data. A paired samples *t*-test found a significant difference for Fatigue (M_{dif} = 0.41, *p* = .042). Another paired samples *t*-test found a significant difference for Sleep Quality (M_{dif} = 0.03, *p* = .033). Both Fatigue and Sleep Quality were rated significantly better after receiving stimulation the previous day. A Pearson correlation coefficient was calculated between Fatigue and Sleep data, producing a value of 0.54. No significant differences were found for General Muscle Soreness, Stress Level, or Mood.

	During stimulation	Not during stimulation	*p*
n (number of participants)	4	4	-
Keiser Air Squat			
Raw Gain (watts)	30.5 +/- 13.2	-4.2 +/- 21.3	0.34
Percent Gain	2.01% +/- 1.70%	-0.04% +/- 2.27%	0.30
Squat Jump			
Raw Gain (in)	0.34 +/- 0.21	-0.17 +/- 0.18	0.43
Percent Gain	2.22% +/- 2.78%	-0.80% +/- 2.00%	0.25
Counter Jump			
Raw Gain (in)	0.34 +/- 0.19	-0.13 +/- 0.10	0.04*
Percent Gain	2.08% +/- 2.36%	-0.73% +/- 1.13%	0.04*

Table 2. Means, standard error, and significance values for both weekly raw and percent gains of the 3 tests based on the paired samples *t*-tests. * denotes significance

DISCUSSION

Our results demonstrate that tDCS at the beginning of a workout can increase the rate of improvement when paired with muscular training. Participants showed increased weekly gains in all three testing exercises, and while some results in this small sample size reached significance and others did not, the effect size remained approximately consistent. Using stimulation during training increased participants' maximum output in all three exercises by 2-3% per week, compared to <1% gain per week without stimulation. For these athletes, that difference translated to an average of 35 watts and .5 inches per week more with stimulation compared to without, an increase that was qualitatively reported by the athletes' coaches to be greater than expected. These data demonstrate the effectiveness of stimulation in enhancing muscular training under real-world circumstances.

Subjectively, athletes and coaches reported that many participants had plateaued in their training and felt that they were able to surpass that plateau or increase their rate of improvement with stimulation, but not without stimulation. The coaches also reported qualitatively that the non-stimulation phase athletes returned to their expected improvement rates, while retaining gains achieved during stimulation.

The results of the present study are consistent with previous literature and the effects observed in more controlled environments. For instance, Tanaka *et al.* (2009) saw improvements of 5% in toe pinch force 60 minutes after stimulation. Cogiamanian *et al.* (2007) saw a greater impact of stimulation on endurance time with subjects lasting 15% longer at the fatigue task with stimulation. While this is a greater impact than we saw here, it does point to the possibilities of stimulation in a more controlled environment.

We also found a significant effect of stimulation, improving sleep quality and decreasing fatigue on the day following stimulation. These results are quite promising and extend the literature on fatigue with tDCS. Not only did tDCS potentially reduce fatigue during the exercise, but tDCS may have improved recuperation after training.

Despite these successes, some limitations should be mentioned. First, the samples were neither truly independent nor truly paired, with four athletes participating in both phases of the study. With the small number of total participants, these four could have had a significant effect on the data; however, the effect sizes when these four are isolated are consistent with the effect sizes found throughout the data set. Another limitation is the lack of blinding or a sham control. Due to the constraints of working with elite athletes, we did not blind the athletes to their condition or use sham stimulation for the control condition in the present study. The lack of blinding opens the possibility that the effects could be due to a placebo effect. However, the fact that the effect sizes are in line with the general body of literature, including double-blinded and sham-controlled studies, suggests that the results are not due to a placebo effect. Additionally, because the present study was conducted in the real environment of athletic training, participants often missed sessions for many reasons, compromising statistical power and potentially clouding results.

Future studies should be done to confirm this effect and continue progress toward more real-world applications for tDCS in elite athletics. Results in complex, coordinated movements – such as improved catching ability under physically demanding circumstances – would be yet another step closer to a direct impact on sports performance and human motor ability. As more individual pieces of complex movement are tested, the benefits of non-invasive brain stimulation in this field can be better understood.

CONCLUSION

Overall, despite some limitations, the results of the present study offer promising, real-world evidence of the benefits of primary motor cortex tDCS for improving response to athletic training. Elite athlete participants increased their maximum output by an additional 2% per week training with stimulation, compared to without stimulation. The present study offers evidence that effects previously seen in the laboratory setting and reported in the literature do translate to real-world applications in muscle strength and explosiveness. Additionally, fatigue was decreased and sleep quality improved by stimulation.

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APPENDIX A

The Pro Training Readiness Questionnaire

	5	4	3	2	1
Fatigue	Very Fresh	Fresh	Normal	More Tired than Normal	Always Tired
Sleep Quality	Very Restful	Good	Difficulty Falling Asleep	Restless Sleep	Insomnia
General Muscle Soreness	Feeling Great	Feeling Good	Normal	Increase in Soreness/Tightness	Very Sore
Stress Levels	Very Relaxed	Relaxed	Normal	Feeling Stressed	Highly Stressed
Mood	Very Positive Mood	Good Mood	Less Interested in Others and/or Activities than Usual	Snappiness with Family/Teammates	Highly Annoyed, Irritable, or Down