



# Brain activity during self-paced vs. fixed protocols in graded exercise testing

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## Abstract

Electroencephalography research surrounding maximal exercise testing has been limited to male subjects. Additionally, studies have used open-looped protocols, meaning individuals do not know the exercise endpoint. Closed-loop protocols are often shown to result in optimal performance as self-pacing is permitted. The purpose of this study was to compare brain activity during open- and closed-loop maximal exercise protocols, and to determine if any sex differences are present. Twenty-seven subjects (12 males, ages  $22.0 \pm 2.5$  years) participated in this study. A pre-assembled EEG sensor strip was used to collect brain activity from specific electrodes (F3/F4: dorsolateral prefrontal cortex, or dlPFC; and C3/Cz/C4: motor cortex, or MC). Alpha (8–12 Hz) and beta (12–30 Hz) frequency bands were analyzed. Subjects completed two maximal exercise tests on a cycle ergometer, separated by at least 48 h: a traditional, open-loop graded exercise test (GXT) and a closed-loop self-paced  $\text{VO}_{2\text{max}}$  (SPV) test. Mixed model ANOVAs were performed to compare power spectral density (PSD) between test protocols and sexes. A significant interaction of time and sex was shown in the dlPFC for males, during the GXT only ( $p = 001$ ), where a peak was reached and then a decrease was shown. A continuous increase was shown in the SPV. Sex differences in brain activity during exercise could be associated with inhibitory control, which is a function of the dlPFC. Knowledge of an exercise endpoint could be influential towards cessation of exercise and changes in cortical brain activity.

**Keywords** Electroencephalography · GXT · Perceptual regulation · Inhibitory control

## Introduction

Exercise performance within an individual is manipulated based on feedback by various physiological systems controlled by the brain (Brümmer et al. 2011b). For example, growing evidence has suggested that the onset of fatigue leading to exercise termination is linked to afferent feedback, a neural factor that is controlled and interpreted by the brain (Robertson and Marino 2015b); specifically, this afferent feedback relates to sensory information recognizing unpleasant stimuli such as lactate accumulation in working muscles (Ishii and Nishida 2013), peripheral locomotor muscle fatigue (Amann 2011) or an increase in core temperature

(Thompson 2006), to which the brain initiates a response (Robertson and Marino 2015b). There is evidence that the prefrontal cortex (PFC) plays an important role in cessation of exercise by inhibiting activity within the motor cortex (Noakes 2012; Robertson and Marino 2015b). Afferent feedback from periphery is sent to the PFC, where it is then interpreted and influences the decision to stop (Amann 2011). Therefore, monitoring changes in brain activity during exercise could be highly advantageous (Bailey et al. 2008) and help researchers and practitioners understand more about the relationship between exercise duration, modality, and intensity (Bailey et al. 2008). With this, electroencephalography (EEG) has been proposed as a pragmatic, noninvasive method of providing useful information surrounding changes in brain activity during rest and exercise.

EEG measures cortical brain activity, which is separated into frequency ranges (e.g., alpha: 8–12 Hz and beta: 12–30 Hz), each associated with different actions or reactions regulated by the brain (Schneider et al. 2009). Alpha is a low-frequency band associated with perceptual awareness and inhibition of non-essential processing, which

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facilitates task performance (Klimesch et al. 2007). Beta is a high-frequency band associated with voluntary contractions, alertness and arousal, allowing for greater perception of stimuli (Gola et al. 2013). Spectral analysis is used for quantifying the frequency content of these bands and the primary output, power spectral density (PSD), refers to the strength, or energy, of variations as a function of frequency (Dressler et al. 2004). When oscillations within cortical regions increase, a corresponding increase in EEG spectral power occurs (Moazami-Goudarzi et al. 2008).

Existing research on the changes in cortical brain activity during incremental exercise testing has indicated mixed results. In particular, a study conducted by Bailey et al. (2008) revealed that there were increases in both alpha and beta frequencies, in comparison to rest, throughout the duration of a graded exercise test (GXT). Conversely, Robertson and Marino (2015b) showed that increases in both frequency bands occurred, but only for a portion of the GXT; once subjects reached the respiratory compensation point (RCP), determined as the point in which the body attempts to remove carbon dioxide (CO<sub>2</sub>) from the body at a faster rate by increasing the depth and frequency of breathing (Takano 2000), EEG activity thereafter decreased until the cessation of exercise.

These previous studies (Bailey et al. 2008; Robertson and Marino 2015b; Takano 2000) have limited their methodology to open-looped test protocols, which have no specified endpoint. To our knowledge, no research exists examining EEG changes during a closed-loop protocol. This type of protocol, where subjects have full knowledge of the endpoint of exercise, has been shown to result in more optimal performance, as individuals are able to self-select their pace and perform more efficiently (Billaut et al. 2011; Hanson and Buckworth 2015). Additionally, self-paced VO<sub>2max</sub> (SPV) tests have been shown to elicit values that are equal or higher than those from open-loop protocols (Faulkner et al. 2015; Hogg et al. 2015). These differences could be due to the control and facilitation of anticipatory regulation of work rate up to a known endpoint, e.g., RPE20, which is “maximal exertion” on the Borg 6–20 rating of perceived exertion (RPE) scale (Borg 1982). This provides support for the role of the brain in potentially limiting maximal exercise performance (Eston et al. 2012). Furthermore, studies previously conducted by Bailey et al. (2008) and Robertson and Marino (2015b) used only male subjects, eliminating the investigation of sex effects.

Previous research that explored EEG responses to incremental exercise has focused on two particular areas of the brain, the dorsolateral prefrontal cortex (dlPFC; F3, F4) and the motor cortex (MC; Cz, C3, C4) (Bailey et al. 2008; Robertson and Marino 2015b). The response of the dlPFC during exercise is not well understood, but preceding research has suggested it influences goal-directed behavior (Robertson

and Marino 2015b) and exercise tolerance and termination (Robertson and Marino 2016b), which heavily influence exercise performance (Brümmer et al. 2011b). Conversely, the MC does not directly influence the cessation of exercise (Robertson and Marino 2015b), but it is guided by afferent feedback, which is regulated in the dlPFC (Robertson and Marino 2015b). This link between these brain regions and their potential significant influence on incremental exercise test performance has made these areas key focuses for analysis.

Therefore, the main purpose of this study was to compare cortical brain activity during closed- and open-loop maximal exercise protocols (GXT and SPV, respectively). Additionally, we sought to examine any sex differences, as previous research has indicated sex-related difference in EEG during exercise are plausible (Bond et al. 2018; Corsi-Cabrera et al. 1993; Ludyga et al. 2015). We hypothesized that the power spectral density for alpha and beta frequency bands would increase during both protocols, but during the SPV, there would be a greater change in relative PSD due to the increase demand for perceptual awareness.

## Methods

### Subjects

This study included twenty-six individuals (12 males, 14 females; BMI  $24.2 \pm 3.3$ ) with an age range of 18–27 years ( $22.04 \pm 2.51$ ). Subjects were recruited from a university student body. Subjects regularly participated in endurance-related exercise. This was defined as participating in a minimum of 30 min of aerobic exercise, at least 3 days per week, for the past 3 or more months. An American College of Sports Medicine (ACSM) health-screening document was completed by each participant to ensure a low risk status (1 or less risk factors) for cardiovascular disease. Subjects who sustained a lower extremity musculoskeletal injury within the last 6 months were unable to participate. The study was approved by the university’s Human Subjects International Review Board. All subjects read and signed an informed consent document prior to participation in the study.

### Procedures

Each subject reported to the laboratory for two separate testing sessions. During the initial visit, they were asked to read and sign the informed consent document. Thereafter, they completed the ACSM health screening document. Height and weight were measured and the subjects were familiarized with the laboratory equipment. The Borg 6–20 RPE scale that was to be used during testing (Borg 1982) was described in detail. Prior to testing, subjects were asked to

practice exercising at each specified RPE for 20 s, to ensure that they had full understanding of the scale and were comfortable adjusting the resistance to maintain specific RPE levels during testing.

During each visit, subjects were seated comfortably in a chair while being fitted with the wireless EEG and electrode strip (B-Alert X10, Advance Brain Monitoring, Carlsbad, CA), which was placed on their head using the 10–20 international system. Each subject was also fitted with a chest strap heart rate monitor (Polar H10, Polar, USA). The first visit included a short (9–10 min), benchmark session to create an individualized EEG profile for each participant; this information is also used by the software for analysis and for calculation of relative PSD. The benchmark session included three tasks: (1) 3-choice vigilance tasks (3CVT), (2) visual psychomotor vigilance task (VPVT), and (3) auditory vigilance task (AVT). After completion of the benchmark session, subjects were fitted on an electromagnetically braked cycle ergometer (Lode, Groningen, Netherlands) and performed a 3-min warm-up at a self-selected intensity. Thereafter, subjects were asked to complete a maximal oxygen consumption ( $VO_{2max}$ ) test. There were two protocols, an open-loop, graded exercise test, or a 10-min self-paced maximal exercise test (SPV); only one protocol was completed during each visit. The order in which each was completed was randomized.

### Graded exercise test (GXT)

Recent recommendations for incremental load testing in athletes were used (Julio et al. 2017). Subjects began cycling at a pre-determined power output (PO) (Julio et al. 2017), which was 70 Watts (W) for both males and females, and as each minute of the test progressed, PO was increased by a pre-determined value, based on the subject's sex (25 W for females, 35 W for males). Subjects were instructed to cycle between 60 and 90 repetitions per minute (rpm). When the subject's cadence fell below 60 rpm for five consecutive seconds, the test concluded.

### Self-paced $VO_{2max}$ (SPV) test

The protocol was exactly 10-min in length, consisting of five, 2-min stages. Each stage was perceptually regulated, using RPE values from the Borg 6–20 scale. RPE values were 11 (light), 13 (somewhat hard), 15 (hard or heavy), 17 (very hard), and 20 (maximal), in that exact order. Subjects were blind to the control panel on the bike but were in control of adjusting their cadence and/or resistance to maintain the prescribed RPE throughout the duration of the test.

## Measurements

### Metabolic cart

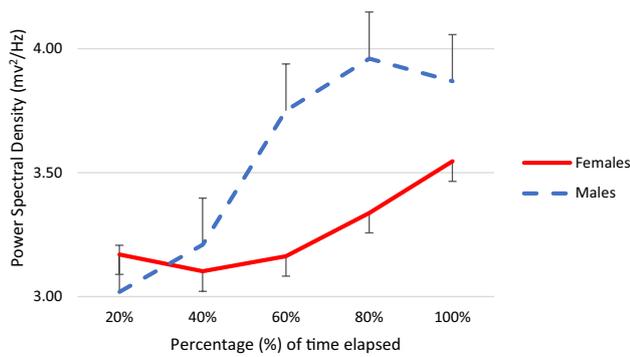
A TrueOne 2400 metabolic cart (ParvoMedics, Sandy, UT) was used to collect expired gases during both maximal exercise tests. Both flow and gas calibrations were performed 5–10 min prior to each test. Fifteen-breath rolling averages (Robergs et al. 2010) were calculated for the following variables: relative oxygen consumption ( $VO_2$ ), carbon dioxide production ( $VCO_2$ ), respiratory exchange ratio (RER), and ventilation (VE). Both the average and maximal values of these variables were recorded.

### EEG recording

The B-Alert X10 Wireless EEG system (Advance Brain Monitoring, Carlsbad, CA) was used for EEG data acquisition. This wireless device uses a nine-channel system. Using the 10–20 international system, a pre-assembled EEG sensor strip was placed over the subject's head. The vertical distance between the nasion and inion, and horizontal distance from left to right pre-auricular, were measured to determine the precise placement of the center electrode (Cz). Electrodes were placed on the right and left mastoids and clavicles for reference. Using Cz as a reference point, the remainder of the electrode strip was placed on the subject at points of estimation. The B-Alert X10 EEG collects activity coming from nine electrodes. The electrodes used for analysis were F3 and F4 (dorsolateral prefrontal cortex, or dlPFC) and Cz, C3 and C4 (motor cortex, or MC). The alpha and beta frequency bands were separated into specific frequency ranges (e.g., alpha: 8–12 Hz and beta: 12–30 Hz). Prior to executing a testing protocol, an impedance check was performed to ensure placement of all electrodes was kept under 40 k $\Omega$ , which is suggested by the manufacturer for optimal data acquisition.

### Statistical analyses

Analyses were performed using IBM SPSS Statistics (Version 25, Armonk, NY). Mixed model ANOVAs were performed to compare the within-subjects (percentage of test that had elapsed: 20, 40, 60, 80 and 100%), and the between-subjects (sex: male or female) factors between the GXT and SPV testing protocols. When the assumption of sphericity was violated, Greenhouse–Geisser corrections were used. Significance was set a priori at <0.05.



**Fig. 1** Differences in changes in alpha power spectral density (PSD) in the dIPFC during a graded exercise test (GXT) between males and females. Males are denoted as the dashed line, while females are represented by the solid line

## Results

Variables calculated from the metabolic cart are presented in Table 1. There were no significant differences between test protocols.

## EEG

### Alpha (dIPFC)

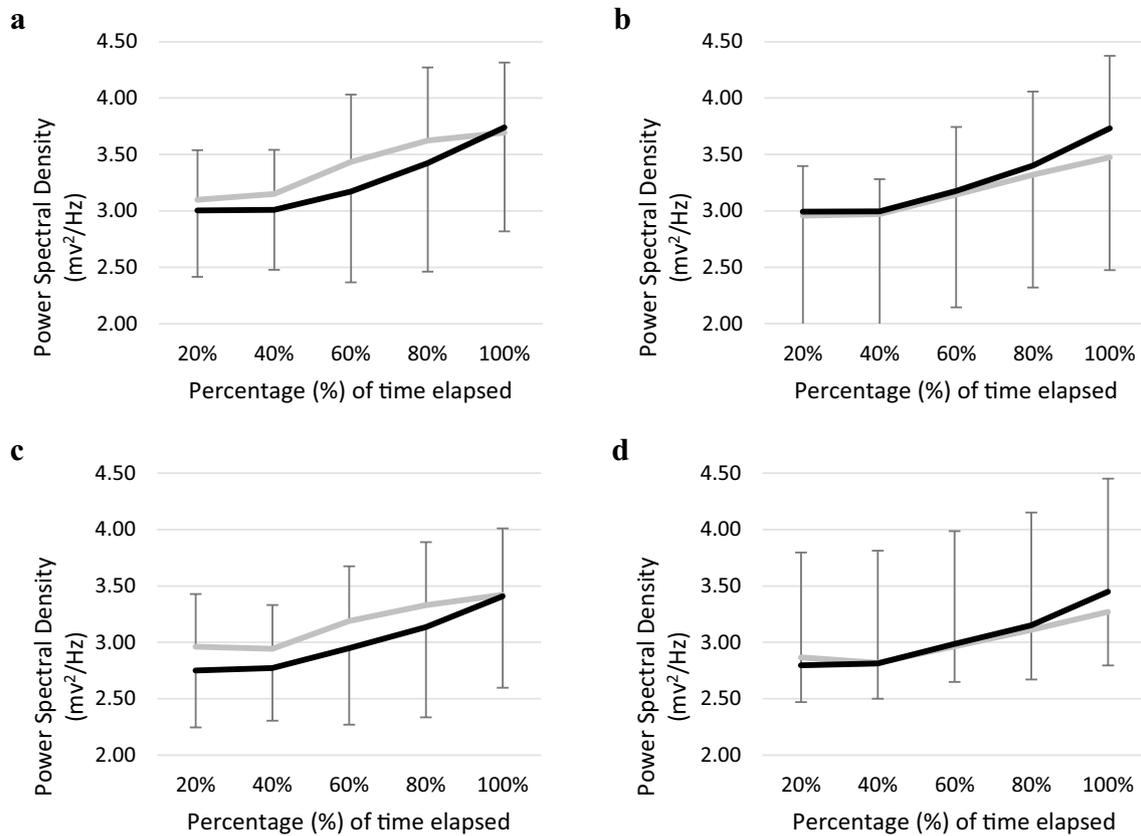
There was a significant interaction effect of time and sex ( $p=0.001$ ) for males only in the dIPFC; compared to baseline, PSD of the alpha frequency band significantly increased after 60% ( $p=0.04$ ) and after 80% ( $p=0.01$ ) of the test had been completed (Fig. 1). Thereafter, for the remainder of the test, PSD for alpha frequency bands decreased (Fig. 2). Additionally, there was a significant main effect of time ( $F(2.44, 58.58)=32.27, p<0.001$ ).

### Alpha (MC)

Similar to the dIPFC, a significant main effect of time was discovered ( $F(2.41, 57.88)=31.00, p<0.01$ ).

### Beta (dIPFC)

There was an interaction effect between time and sex for beta frequency band ( $p<0.001$ ); for males, during only the GXT,



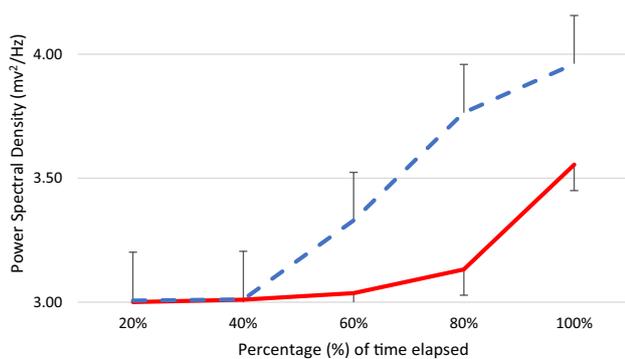
**Fig. 2** Changes in alpha band power spectral density (PSD) in the dorsolateral prefrontal cortex (dIPFC) (a) and motor cortex (MC) (b); changes in beta band PSD in the dIPFC (c) and MC (d). Data are pre-

sented as mean  $\pm$  SE. The graded exercise test (GXT) is represented by the lighter colored line, while the self-paced  $\text{VO}_{2\text{max}}$  (SPV) is represented by the darker colored line

**Table 1** Maximal values for metabolic cart variables

Variables	GXT	SPV	<i>p</i>
VE (L min <sup>-1</sup> )	108.45 ± 32.61	115.36 ± 43.79	0.36
Absolute VO <sub>2</sub> (ml kg <sup>-1</sup> min <sup>-1</sup> )	2.83 ± 0.71	2.86 ± 0.79	0.80
Relative VO <sub>2</sub> (L min <sup>-1</sup> )	38.69 ± 6.49	38.88 ± 7.96	0.89
VCO <sub>2</sub> (L min <sup>-1</sup> )	3.48 ± 0.83	3.43 ± 1.09	0.76
RER	1.26 ± 0.07	1.22 ± 0.12	0.50
HR	179.07 ± 11.05	176.70 ± 10.58	0.22

Data are presented as mean ± SD



**Fig. 3** Difference in changes in beta power spectral density (PSD) in the dlPFC during a self-paced VO<sub>2max</sub> (SPV) between males and females. Males are denoted as the dashed line, while females are represented by the solid line

PSD significantly decreased after 80% of the test elapsed and continued to decrease until the cessation of the test (Fig. 3). Additionally, there was a significant main effect of time ( $F(2.20, 52.87) = 36.61, p < 0.001$ ).

**Beta (MC)**

A significant main effect of time was shown ( $F(2.04, 48.87) = 34.83, p < 0.01$ ).

**Discussion**

The main purpose of this study was to determine if there are differences in brain activity between closed- and open-loop maximal exercise test protocols. When the male and female subjects were pooled, there were no differences between the protocols. However, an interesting finding from this study was that during the open-loop test protocol, men showed an increase in PSD of alpha frequency bands until the final 20% of the test, where then PSD declined until cessation of exercise. For females, PSD of alpha frequency bands declined during the first 20% of the GXT, followed by a

linear increase for the remainder of the test. To our knowledge, this is the first time this comparison has been reported. These results suggest that brain activity related to open-loop maximal exercise testing differs between sexes.

Because the dlPFC and the MC were the selected brain regions for analysis, the frequency bands which were investigated were those that are integral in these regions, the alpha and beta bands (Maceri et al. 2019; Robertson and Marino 2015b). These two regions of the brain are responsible for planning and movements (Lotze et al. 1999; Maceri et al. 2019; Tanji and Hoshi 2001), shown in beta wave power, which increases as individuals plan and implement actions (Feige et al. 2000; Maceri et al. 2019). Moreover, when recruitment of more muscle fibers occurs to meet demands of incremental exercise testing, it is considered an executive function, and is represented by an increase in beta frequency band power. Greater alpha wave frequency has been linked to afferent feedback signaling (Maceri et al. 2019; Robertson and Marino 2015b), an information delivery system that notifies the brain of physiological changes occurring, so the brain can process a response to regulate homeostasis and optimal physiological functioning. This afferent feedback is related to the inhibition of the MC (Robertson and Marino 2015b), and regulated by the dlPFC.

When exclusively looking at the male subjects, results from our study corroborate those of Brummer et al. (2011a) where PSD of both frequency bands began to decrease near the end (after at least half of the duration of the test) and until the termination of the GXT. These findings support the notion from previous research (da Silva et al. 2017; Robertson and Marino 2015a, b) that inhibitory control, which is an individual’s ability to regulate attention and ignore unrelated information, can impact the continuation of exercise. For instance, as exercise intensity increases, individual’s attention may be drawn towards physiological changes (e.g., heart rate, breathing rate), which can lead to greater perception of discontentment, inhibiting further exercise (da Silva et al. 2017). Previous literature has suggested that the brain, specifically the dlPFC, integrates interoceptive stimuli through feedback pathways (da Silva et al. 2017). Further, the dlPFC attempts to balance cognitive and interoceptive responses (Robertson and Marino 2016b). If the body is under a higher amount of physiological demand, the dlPFC can regulate the amount of physical exertion through the detection of a homeostatic imbalance (da Silva et al. 2017; Ekkekakis 2003; Robertson and Marino 2016a, b). With this, an individual can be influenced to terminate exercise (da Silva et al. 2017; Robertson and Marino 2016a, b).

In the female subjects, a different response was elicited. Though no current research exists examining female EEG changes during maximal exercise, much current research supports the notion that females, in comparison to males, are less susceptible to distractions, therefore deterring an

increase in inhibitory control (Coleman et al. 2018). An increase in inhibitory control has been correlated to females having a greater ability to regulate the stress response, due to circulating hormones (i.e., estradiol) (Goldstein et al. 2010; Woo et al. 2010). With this, female hormonal capacity for stress regulation has been seen as superior to that of males, who are unable to inhibit the role of estradiol on arousal circuitry, which is linked to heightened cortisol response (Goldstein et al. 2010).

This regulation in females is coupled with heightened cortical capacity, attenuation (Goldstein et al. 2010) and augmented adaptive behavior (Handa and McGivern 2010). These behaviors further the idea that responses to exercise are not only influenced by physiological functions, but cognitive and perceptual responses as well (da Silva WQA 2017; Noakes 2012). Due to the preceding correlations, it is rationalized to look into the differences between open- and closed-loop protocols, as existing research has shown that knowledge of the endpoint of exercise is linked to various physiological and cognitive responses (Noakes 2012) and differences in mood states (Compton et al. 2003; Hall and Petruzzello 1999; Palmiero and Piccardi 2017; Schneider et al. 2009).

Moraes et al. (2007) tested healthy, active subjects between the ages of 21–30 years using a similar GXT protocol; subjects completed an open-looped protocol on a cycle ergometer, increasing workload by 15–30 W/min (dependent on sex). Increases in beta power were observed in both the PFC and MC, but there were no significant changes in alpha power between any stages of the test. These results are comparable to Crabbe and Dishman (2004) who examined EEG changes before, during and after exercise and concluded no significant differences in alpha band activity throughout exercise, but alpha activity was increased in relation to pre-exercise. Both of the previously mentioned results suggest alpha power remained consistent throughout testing, which is conflicting with our results, but differences in analysis could lead to this discrepancy. These researchers were comparing EEG changes with pre- and post-exercise data, whereas our focus was changes during exercise.

Additionally, differences in methodology (i.e., open- vs. closed-loop) could be attributable to showing differences in PSD of alpha frequency bands. For the SPV protocol, PSD of alpha continuously increased throughout the duration of the test for males, whereas during the GXT, it decreased at the onset of the last 20% of the test. SPV protocols allow for subjects to have control on adjusting cadence or pace, and resistance throughout the duration of exercise. For some subjects, this could alleviate stress, as knowing the duration of the test is settling (Williams 2008). Additionally, when the endpoint of exercise is known, studies have revealed that afferent feedback, or neurons transmitting information from sensory organs to the central nervous system (CNS), is

attenuated (Noakes 2012; Swart et al. 2009). Both of these rationales would correlate to a progressive increase in PSD of alpha frequency, as this frequency band is related to states of relaxation and perceptual awareness. Because no prior research with EEG changes and closed-loop protocols exist, it is difficult to provide more support to our findings.

## Conclusion

Our study reveals that changes in cortical brain activity during a GXT and an SPV differ. The novel finding is that during various maximal protocols, sex differences are present. Specifically, males exhibiting a decrease in PSD of alpha frequency during the last 20% of a GXT, whereas females have a steady increase throughout the duration of the GXT. For males, an increase in PSD of alpha frequency during the last 20% of the SPV could be influenced by differences in perception of difficulty of exercise or attenuation of afferent feedback due to knowledge of the endpoint of exercise. Future studies should continue to explore EEG during incremental exercise to determine the etiology of these sex-related differences.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethics approval and consent to participate** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional committee (Western Michigan University Human Subjects International Review Board + IRB00000254) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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