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Brain function during central-fatigue induced by intermittent high-intensity cycling

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ABSTRACT:

Background The central-governor model putatively explains the mechanism of endurance exercise-induced central-fatigue, however, high-intensity exercise-induced central-fatigue strategies have not been investigated yet. This study aimed to examine how central fatigue affects neural response alterations, as measured by electroencephalographic (EEG) recordings, in intermittent high-intensity cycling.

Methods Neural responses were assessed by measuring the alteration of brainwaves based on spectral energy band estimates during an intermittent, high-intensity, 60-minute exercise-bout on a cycle ergometer. The cycle ergometer incline was changed every 10 minutes in an intermittent pattern (10-20-5-20-5-10 degrees). EEG was used to analyze altering brain function. Heart rate (HR), blood lactate (BL), and rating of perceived exertion (RPE) were measured after the participants completed each change in incline.

Results The results showed that HR, BL, and RPE increased at an incline of 20 degrees in comparison to a 5-degree incline. The spectral power of EEG was significantly increased ($P<0.01$) in the alpha and beta frequency ranges with a change in inclines between 5 and 20 degrees. The spectral power of the EEG was significantly increased ($P<0.01$) over the whole frequency range from rest (theta: +251%, alpha: +165%, beta: +145%).

Conclusion Higher, relative, intensities (10 and 20 degrees) increased brain function, regardless of fatigue occurrence. HIIT (high-intensity interval training) led to an alteration in the neural response. Further work investigating the usefulness of HIIT to improve brain function is warranted.

Keywords high-intensity interval training, EEG, central-fatigue, cycling training.

New & Noteworthy

The brain adjusts for varying commands by changing its functional and structural characteristics, which result in learning and acquiring skills; in this article, the function is the high-intensity interval cycling was investigated. We discuss the variations in brain activity induced by fatigue, attributed to two leading causes: 1. Local Muscular Fatigue, and 2. Mental (central) Fatigue. It is evident that high-intensity interval training may have a significant impact on the central nervous system and cognitive functions.

Introduction

Central fatigue is a phenomenon that is manifest in both healthy (during physical activity) and non-healthy (as part of various diseases) populations. In healthy people, fatigue is a predicted mechanism for a prolonged and intensive activity that is recovered by rest (18, 27, 28), and is experienced in both physical and psychological aspects (14, 47). It should also be distinguished between ‘central’ and ‘peripheral’ fatigue; where central fatigue is known as the failure of the performance because of the improper function of the central nervous system (CNS). In general, prolonged or intensive exercise during physical activity leads to central fatigue (49).

High-intensity interval training (HIIT) is asserted to improve function and mental health in patients with cardiopulmonary diseases by increasing brain-derived neurotrophic factor (BDNF), and enhancing neural plasticity (33), where neural plasticity is an expected property of neurons that is vital to adaptation and improvement in new situations (2). Much previous work has explicated the physiological adaptations (i.e., peripheral nervous system; PNS) to exercise), especially the cardiovascular and respiratory systems (48, 49). In addition to a vast

evidence base regarding cycle ergometer performance, from recreational to elite athletes (15, 16). However, changes in the CNS and brain activity, and changes in the behavioral pattern of neurons during exercise have not been completely considered as a neural response strategy during high-intensity interval exercises (9, 10).

Brain activity can regulate homeostasis in athletes to delay fatigue and help achieve optimal performance during endurance competitions (36, 46), whilst active recovery can increase aspects of central, rather than muscular, recovery (19, 22, 44). The study of brain activity by using electroencephalography (EEG) recording has many advantages in sports and training (46). Brainwaves are produced by synchronized electrical pulses from masses of neurons communicating with each other, and neural response patterns concerning brain activity in a high-intensity intermittent protocol yields valuable information regarding different parts of the brain (43).

Some previous work has investigated changes in brain activity in response to cycling (11), and it has been suggested that brain activity changes by altering functional properties in response to demands, in line with the central governor model and the homeostasis phenomenon (24, 37, 38). However, there is a dearth of evidence regarding the EEG responses to intermittent, high-intensity cycling. The evaluation of the patterns of neural response of the cerebral cortex (neuroplasticity) (6) during high intensity intervals, with resulting fatigue, would contribute to a new insight into functional connectivity between different parts of brain activity (47, 48, 20, 11). We hypothesized in the present study that neural response patterns induced by the central fatigue in the cortical area would change with increased exercise intensity. The purpose of this research was, therefore, to evaluate the effects of central fatigue during high-intensity intermittent cycling on brain activity.

2. Methods

2.1. Participants

Fourteen active, female, sprint cyclists (age: 25.9 ± 3.8 years; height: 170 ± 1.6 cm; body weight, 62.4 ± 2.2 kg) volunteered to take part in this study. In line with previous work, all participants regularly achieved 4 to 6 hours or 200 to 240 kilometers (15 - 40 km/h) training on flat surfaces per week (30, 31). Prior to participation, the study design, potential risks, and benefits were explained to the participants, and each signed an informed consent form prior to participation. Exclusion criteria included any cardiovascular and respiratory, metabolic, psychiatric diseases, or orthopedic trauma that could restrict training. All participants were

informed of their right to withdraw from the study at any time. The ethics committee of the Medical faculty of the Azad University of science and research branch of Tehran confirmed this study by the number of IR.IAU.PS.REC. 1397-115, and all aspects of this study were performed in accordance with the Declaration of Helsinki.

2.2. Testing Protocols

Briefly, the entire protocol lasted for 105 minutes; 10 min (rest), 15 min (warm up), 60 min interval pacing, 10 min cool down, and 10 min rest. For all participants, anaerobic capacity, maximum oxygen consumption (VO_{2max}) and maximum load (Pmax) were determined on a cycle ergometer (Monark 894E, Anaerobic Wingate testing), performed according to previous guidelines (50), and evaluated using an online spirometry system (cortex, Meta max 3b, Germany). In addition, blood lactate maximum steady-state lactate concentration (MLSS) threshold was identified [(mmol. l^{-1}) $(watt)^{-1}$] (34). Blood lactate was measured using an enzymatic-amperometric method (29) in 10 µl blood sampled from the earlobe, and was analyzed via WinLactat 4.1.0.1 (XE Version, German).

Participants subsequently performed a 60-minute cycling test at different inclines at an intensity equivalent to 90% VO_{2max}. The staging test included; standard warm-up (10 minutes at 100 watts); the main protocol (6 ten-minute steps) and cool-down (10 minutes at 100 watts). The intermittent incline (10-20-5-20-5-10 degrees) changed every 10 minutes during the exercise. The rating of perceived exertion (RPE) scale was used to assess the intensity of the training interval (4). The HR as determined by EEG, blood lactate (BL) and RPE were recorded at the end of each 10 min; during rest, after the warm-up, after every 10-minute incline, and after the cool-down (21).

3.2. EEG Recordings and Analysis

Electroencephalography (64-Channel QuickAmp-EEG system, Brain Products, Germany) was used for continuous brain cortical activity recording. The changes in brain wave signal were recorded with 21 active surface electrodes symmetrically (Brain Products, EasyCap, Germany; Fp1, Fp2, F7, F8, F3, Fz, F4, FC7, FC8, T7, T8, C3, CZ, C4, CP1, P7, P3, P4, PZ, P8, CP2, 10:20 Fixed EEG flexible caps (EasyCAP, Germany) (25, 26). We implemented the active Ag/AgCl electrodes in an active circuitry–actiShield- a system that allowed the recording of high contact resistance to 60 kΩ. The electrode impedances were controlled by EasyCAP Drivers 6.10.70.001 Software version of 1.2.5.3 (Brain Products, Germany) and the signal was recorded by Brain, Vision Recorder 1.03 (Brain Products, Germany), the data were sampled at

a frequency of 500 Hz. Matlab EEGlab Software was used for offline processing EEG raw data. EEG data were analyzed at rest, after warm-up, and before each change in incline, after cool-down, rest, and exercise. After editing the markers, data were filtered (High-pass: 1.5 Hz, octave-1 12 dB slope, and, low-pass: 50 Hz, octave-1 48 dB) between 1-2 Hz and > 50 Hz for the removal of muscle artifact. Artifacts up to theta-frequencies (4 Hz) and minimum frequencies of beta (30 Hz) were eliminated by frequency-analysis, and then, a manual raw data inspection was carried out to identify the artifacts, also, independent components analysis (ICA) was calculated to remove artifacts from the main signals (15, 16). This control was fixed off-line and was analyzed only EEG sections without artifacts. Based on the edited markers, the signals were divided into four S4-s data-sets with a corrected baseline (1) at the last minute of each time point. Each subject and five artifact-free segments were analyzed by using the Fast-Fourier transform method (Maximum resolution, power in μV2, full range use, Hanning window, window length: 20%). The received frequency spectrum was divided into four frequencies; Theta 4-7 Hz, Alpha: 8-15 Hz, Beta: 16-30 Hz and Gamma: 31-50 Hz. For further processing, the values were transferred to Microsoft Excel 2016. The analysis of all 21 electrodes for each frequency range and time point was measured. The absolute values of spectral power as a percentage change from individual resting conditions (100%) were calculated to extract the effect of the different base EEG types (15, 16).

4.2. Statistical Analysis

All data were analyzed using SPSS Statistics 24.0 software. The Kolmogorov - Smirnov test was performed to evaluate the normal distribution of data. In the case of a normal distribution, physiological variables (HR, BL, EEG) were submitted to a repeated measures ANOVA with the 8-level within subject factor, incline (warm-up, 10, 20, 5, 20, 5, 10, cool-down).. Whilst for ordinal data (RPE), the Wilcoxon test was used. Statistical significance was accepted at $p \leq 0.01$ (denoted by **).

3. Results

Participants achieved a mean P_{max} of 308.92 ± 20.61 (90% of the anaerobic lactate threshold: 224.71 ± 19.00 W), and the maximum oxygen consumption (VO_{2max}) was 40.43 ± 3.67 ml· $min^{-1} \cdot kg^{-1}$. The results showed that the values of heart rate and blood lactate during warm-up and at the beginning of the exercise test were significantly increased ($F= 62.07$, $p<0.001$). Rating of perceived exertion (RPE) increased significantly ($p<0.01$) at the beginning of the exercise test compared to the warm-up period. At 20-degrees, heart rate, blood lactate, and RPE

were significantly higher than 5 degrees. All physiological values were decreased significantly ($p<0.01$) during the cool-down stage (Table 1, Fig1 and Fig 2).

Table 1. Variables; RPE, BL, and HR during Pedaling states; Warm-up, six states of changing inclines and Cool-down. Data are presented as mean ± S.D.

	Variables			
Pedaling states	**Incline [degrees]**	**RPE [6-20]**	**Blood Lactate [mmol.l^{-1}]**	**Heart Rate [min^{-1}]**
Warm-up	10	9.25 ± 1.97	0.8 ±0. 4	118 ± 8.67**
	10	13.05 ± 1.17**	1.5 ± 0.57**	144.5 ± 9.69**
	20	15.85 ±1.17**	3.5 ± 1.12**	163.81 ± 9.85**
Workload	5	13.74 ± 1.48**	1.57 ± 0.57**	150.25 ± 10.47**
90 % of the LT	20	16.50 ± 1.79**	3.5 ± 1.16**	168.85 ± 10.74**
	5	14.35 ± 1.58**	1.8 ± 0.45**	154.58 ± 10.67**
	10	14.25 ± 1.37	1.75 ± 0.57	157.55 ± 11.71**
Cool-down	10	8.31 ± 1.85**	1.0 ± 0.25**	118.65 ± 8.57**
Rest	-	-	1.02 ± 0.34**	62.55 ± 8.77

** $p<0.01$ vs previous state; S.D: standard deviation; RPE: Rating of perceived exertion; incline: revolutions per minute; BL: Blood Lactate; HR: Heart Rate.

Table 2. Variables; percent (%) of EEG spectral power (Alpha, Beta, and Theta waves) during Pedaling states; REST, Warm-up, six states of changing inclines and Cool-down and then REST. All data are presented as Mean ± S.D.

Pedaling states	**Variables**			
	Incline [degrees]	**Theta [%]**	**Beta [%]**	**Alpha [%]**
REST	-	100	100	100
Warm-up	10	350 ± 160**	230 ± 130**	282 ± 200**
	10	345 ± 194	230 ± 110	308 ± 284
	20	317 ± 201	255 ± 145	361 ± 395
	5	200 ± 133**	145 ± 82**	171 ± 112**
Workload at	20	260 ± 175	210 ± 166	335 ± 455
90 % of the LT	5	165 ± 90**	112 ± 57**	143 ± 80
	10	170 ± 85**	152 ± 111**	150 ± 85
Cool-down	10	147 ± 114**	103 ± 75**	114 ± 78
REST	-	35 ± 22**	38 ± 21**	41 ± 22**

** $p<0.01$ vs previous state; incline: revolutions per minute.

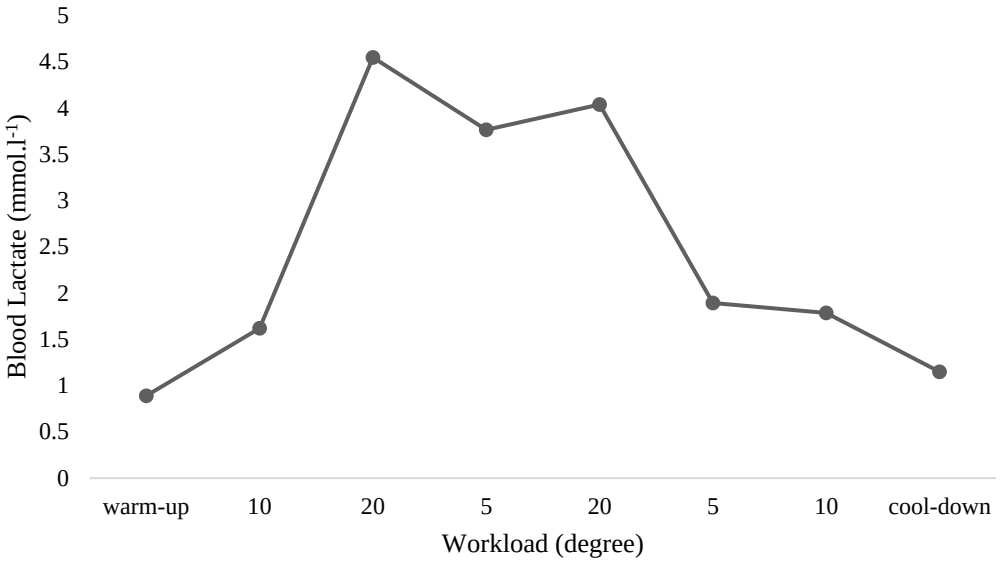

Figure 1. Blood Lactate [mmol. l^{-1}] variability during the 8 steps of workload pedaling states; Warm-up, 6 states of changing Inclines, and Cool-down.

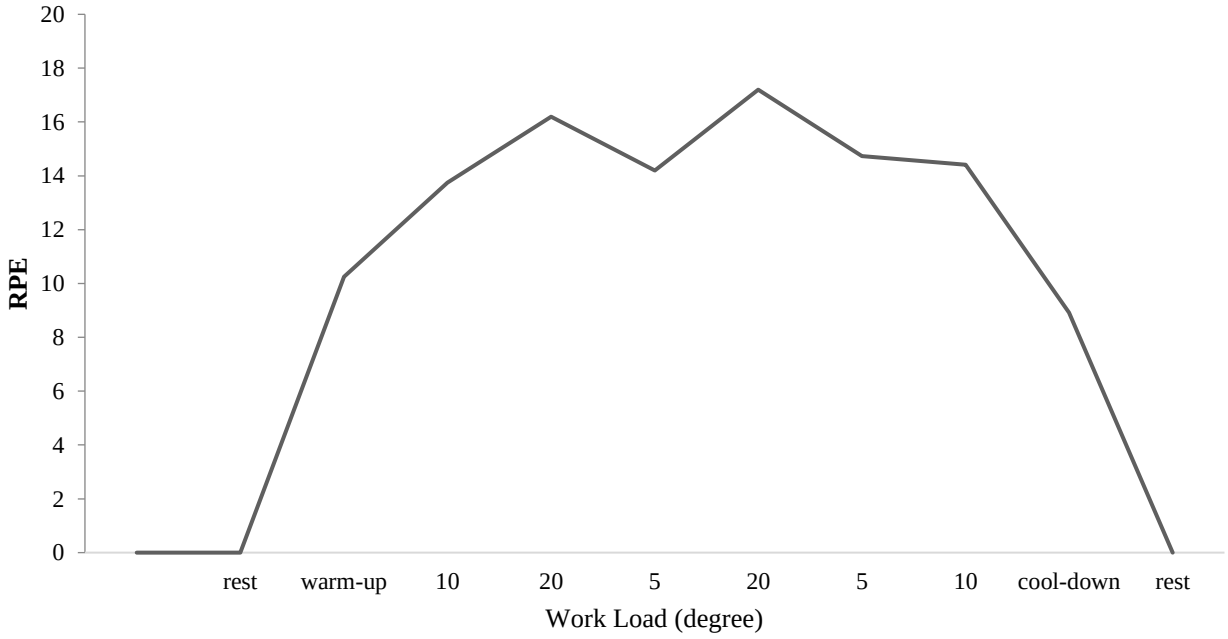

Figure 2. RPE variability during workload Pedaling states; Warm-up, 6 states of changing Incline [degrees] and Cool-down.

The spectral EEG power was significantly higher ($p<0.01$) for the entire rest-to-warm-up frequency ranges (Theta: +251%, alpha: +182%, beta: +131 %). The incline changes are reflected in the spectral power of the EEG (see Table 2). The brain activity at the resting stage was significantly lower (Theta: -67%, alpha: -58%, beta: -63%) compared to 10- and 20-degrees incline. According to the EEG brain map, the incline of 20 degrees' elicited higher values of the theta-wave spectral power (white) (Figure 4).

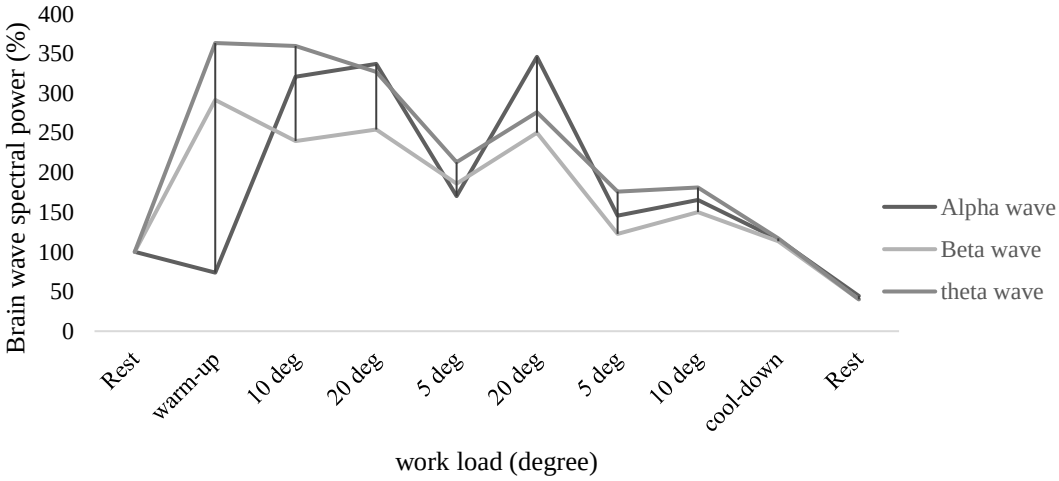

Figure 3. Percent variation in spectral power calculated over 21 electrodes compared to the rest situation (100%) and averaged over the full EEG frequency dominant (4-30 Hz) of participants.

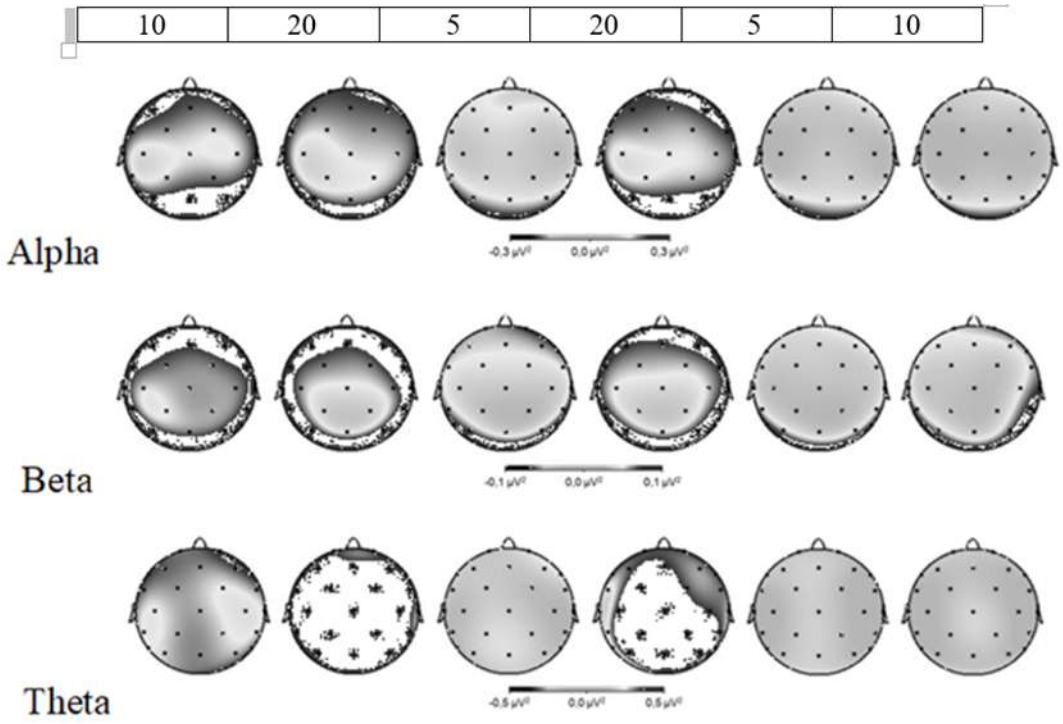

Figure 4. EEG map and spectral analysis frequency ranges; higher values of the spectral power (white) by increasing incline to 20 degrees and decreasing of the spectral power (gray) or dark gray after diminishing the incline to 5 degrees. Lower spectral EEG power at the end of the workload (10 degrees).

4. Discussion:

The results of the present study show that the brain neural response decreased in a fatigued condition. EEG recordings in different intensities, unless at the same workload, showed that a higher incline pedaling frequency is associated with increased brain activity, heart rate, blood lactate, and RPE. The recruitment muscle fibers are increased, muscular coordination, and higher cardiovascular function is needed to maintain a higher incline (12, 14, 47). Blood lactate increased during high incline (20 degrees) and decreased during low incline (5 degrees) cycling. These results support past investigations regarding the impact of training intensity changes (7, 12). In a steady-state workload in the present study, blood lactate increased to a greater extent at inclines of 10 and 20 degrees, vs 5-degrees or rest. Some investigators suggest that blood flow, and, therefore blood lactate accumulation, increases in the involved muscles (7), whilst the consciousness of higher exertion is enhanced with an increased heart rate and

blood lactate accumulation (7, 12). Bailey previously confirmed that there is a correlation between brain activity oscillations and physiological aspects of performance (3). The power spectral increases in the EEG was clear during 20 degrees incline intensities. The brain activity should adapt with performance intensity and power output in sports, whist fatigue reduces brain activity. Noakes (40) also showed that brain wave oscillations reduced after a prolonged exhaustive exercise protocol, as displayed in the theta and alpha frequencies (49), and Gronwald et al. further supported these findings (21, 32). The 'neural efficiency' hypothesis is related to the adaptation of the brain with the frequency of cycling with a lower level of beta activity in cyclists (32); furthermore, Ludyga showed that a reduction in brain activity was evident after intensive ergometer cycling training (31). To describe the fatigue mechanism, Noakes pioneered the central governor model. This model introduces the unconscious mind of the brain in regulating the power output by modulating force and applying the motor units to maintain homeostasis, which keeps the body from injurious physiological disorders. In contrast, the neural efficacy assumption depends on task demands and conscious awareness, suggesting that better adaptation of the brain activation is because of the demand to meet challenges (37).

There is a correlation between high cardiac output, increased blood lactate accumulation during high intensities, and the perception of force exertion (23). In the present study, the variables such as blood lactate and heart rate changed with the intermittent intensity changes, suggesting that both central governor theory and the neural efficiency hypothesis are evident within the findings of this study. Meanwhile, in the present study, any change in incline led to concomitant significant changes in all other variables. However, longer, more intense exercise, to reduce the energy reserves of the individual, may be required to further delineate mechanistic action. Inzlicht & Marcora suggested that self-control, the ability to regulate one's body necessities, emotions, thoughts, and behavior in the face of internal or external stimulations to achieve specific goals (13), is imperative for optimal performance. The beta brainwave is regarded as a 'fast' activity, present when we are attentive, alert, engaged in decision making, judgment, problem-solving, or focused mental activity. This band was present in the frontal, occipital, and temporal lobe when cycling at 20 degrees (fig. 4). The frontal lobe includes dopamine neurons, and the dopaminergic pathways are related to attention, motivation, reward, planning, and short-run memory duties. Dopamine limits sensory information that arrives from the thalamus to the forebrain. The theta band was evident in the entire area of the brain when cycling at 20 degrees; further, the theta band is often considered to represent the subconscious

(mind condition between the conscious and the unconscious). With the onset of fatigue, the activity of the brain is believed to be decreased, however, paradoxically, with increasing intensity, the activity of the brain increases, suggesting that the pattern of brain activity oscillations depends on exercise intensity, and individually preferred inclines/intensities contribute to the positive response of the cognitive process (5). The activity of the brain cortex is crucial to achieving optimal performance and power output during sport and exercise.

Conclusion

Higher, relative, intensities (10 and 20 degrees) increased brain function, regardless of fatigue occurrence. HIIT led to an alteration in the neural response. Given that the present study demonstrated discrepancies between brain function and fatigue, further work investigating the usefulness of HIIT to improve brain function is warranted, in addition to further mechanistic work.

Ethical Considerations

Compliance with ethical guidelines

All procedures were in accordance with the ethical of Helsinki declaration and with ethical committee approval of the Medical Faculty of Azad University of science and research branch, Tehran (1397-115).

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Conflict of interest

No conflict of interest.

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