Altered neural response induced by central-fatigue in the cortical area during high-intensity interval pedaling

Introduction: The central-governor model was considered for explaining the mechanism of endurance exercise-induced central fatigue, but high-intensity exercise-induced central-fatigue strategies have not been investigated yet. This study aimed to examine how central fatigue affects neural responses alterations as measured by electroencephalographic (EEG) recordings.

Methods: We assessed neural responses by measuring the alteration of brainwaves based on spectral energy bands estimates during an intermittent high-intensity 60-minute exercise on an ergometer-cycle. The cadences were changed every 10 minutes, according to intermittent pattern altering (90-120-60-120-60-90 rpm). 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 cadence.

Results: The results showed that HR, BL, and RPE increased at a cadence of 120 rpm in compared comparison with 60 rpm on the ergometer cycle. The spectral power of EEG, according to cadence × brain waves was significantly increased (P˂0.01) in the alpha and beta frequency ranges with a change in cadences between 60 and 120 rpm. The spectral power of the EEG, was significantly increased (P˂0.01) over the whole frequency range from rest to warming (theta: 251%, alpha: 165%, beta: 145%) and was significantly reduced in theta, alpha and beta (Theta: 176%, alpha: 142%, beta: 77%) (p≤0.01).

Conclusion: High intensities (90 and 120 cadences) increased brain function, regardless of fatigue occurrence. HIIT (high-intensity interval training) led to altering the neural response. It would be required investigating the usefulness of HIIT to treat some of the psychosis disorders.

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

Introduction

Central fatigue is a less well-known phenomenon that exposes in both populations of healthy (during physical activity) and non-healthy (in the diseases), people. In healthy people, fatigue is a predicted mechanism for a prolonged and intensive activity that is recovered by rest (Gandevia, 2001; Kluger, Krupp, & Enoka, 2013). Fatigue is experienced in both physical and psychological aspects (Kluger, Krupp, & Enoka, 2013; Enoka & Stuart, 1992; Taylor & Gandevia, 2008). It should also be distinguished between "central" and "peripheral" fatigue. Central fatigue is known as the failure of the performance because of the improper function of the central nervous system (CNS). The prolonged or intensive exercises in human physical activity lead to central fatigue (Weavil, Sidhu, Mangum, Richardson, & Amann, 2016). High-intensity interval training (HIIT) improves function and mental health in patients with cardiopulmonary diseases by increasing brain-derived neurotrophic factor (BDNF) and also enhancing neural plasticity in the rats (Luo et al., 2019). Neural plasticity is an expected property of neurons that is vital to adaptation and improvement in new situations (Assenza, 2015).

Many researchers have already investigated physical and physiological adaptations (i.e., peripheral nervous system; PNS), especially the cardiovascular and respiratory systems (Weavil et al., 2016; Taylor et al.,
Vast research has been organized on ergometer cycle performance from recreation to the expert levels in elite athletes, especially among endurance athletes (Faria, Parker, & Faria, 2005). However, changes in the central nervous system, and brain activity, and changes in the behavioral pattern of neurons during exercise were not completely considered as a neural response strategy during high-intensity interval exercises. Adaptation to HIIT could use lead to rises in sports performance and also brain function in men and women similarly (Coetsee & Terblanche, 2017; Chun Kao et al., 2017). Brain activity can regulate homeostasis in athletes to delay fatigue and achieve optimal performance during endurance competitions (Noakes, 2011; Skorski & Abbiss, 2017), but HIIT induced fatigue to involve organism’s mechanisms rather than modulating modulation of homeostasis, because of recovery strategies. Active recovery increased aspects of central, rather than muscle recovery (Rattray et al., 2015; Giboin et al., 2018; Gruet et al., 2014). The study of brain activity by using electroencephalography (EEG) recording has many advantages in sports and training (Skorski & Abbiss, 2017). The root of all our thoughts, emotions, and behaviors is the communication between neurons within our brains. Brainwaves are produced by synchronized electrical pulses from masses of neurons communicating with each other. Neural response patterns concerning brain activity in a high-intensity intermittent protocol that is useful to increase cardiac function, provides valuable information to different parts of the brain, to obtain the general idea of treating many diseases as mentioned (Nobrega et al., 2014).

Many scientists focused on changes in brain activity caused by cycling (Comani et al., 2013). Brain activity change by altering functional properties in response to demands by using the central governor model and the homeostasis phenomenon (Inzlicht & Marcora, 2016; Noakes T., 1997; Noakes, T., 2000; Noakes, T., 2012). The evaluation of the patterns of neural response of the cerebral cortex (neuroplasticity) (Budde, Wegner, Soya, Rehage, & McMorris, 2016) during intervals with resulting fatigue contributes to a new insight into functional connectivity between different parts of brain activity in a high intensity interval training (Taylor & Gandevia, 2008; Taylor, Amann, Duchateau, Meeusen, & Rice, 2016; Comani, et al., 2013; Gotshall, Bauer, & Fahrner, 1996). We hypothesized in the present study, neural response patterns induced by the central fatigue in the cortical area change with the increasing intensity of training. Therefore, the purpose of this research was to evaluate the effects of central fatigue during high intensity pedaling with changing intermittently on brain activity by altering functional properties, which results in spectral power frequencies of brain waves.
Methods

Participants

Fourteen active sprint cyclist women (Age: 25.9 ± 3.8 years; height: 170 ± 1.6 cm; body weight, 62.4 ± 2.2 kg) according to inclusion criteria included; 4 to 6 hours or 200 to 240 kilometers (15 - 40 km/h) training background on the flat surface per week took part in this research (Ludyga, S., Gronwald, T., & Hottenrott, K., 2015). It explained the study design, potential risks, and benefits to participants; each signed the informed consent form to participate in the study. Exclusion criteria included any cardiovascular and respiratory, metabolic, psychiatric diseases, or orthopedic trauma that could restrict the training. The subjects; Further informed that they were free to leave the study whenever they want. 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 according to the Declaration of Helsinki.

Testing Protocols

To determine the anaerobic capacity of the participants, they accomplished a high-intensity performance test on an ergometer cycle (Monark 894E, Anaerobic Wingate testing) include; start: 110W, Increase: 10 W, Duration: 4 minutes. It evaluated anaerobic capacity by a spirometry system (cortex, Meta max 3b, Germany). It executed this stage of the test to the failure of power output, and voluntary fatigue has occurred. After completing the test, it determined maximum oxygen consumption (VO2max) and maximum load (Pmax). Aerobic and anaerobic blood lactate "maximum steady-state lactate concentration" (MLSS) threshold was identified [(mmol. l⁻¹). (watt)⁻¹] (Mann, Lamberts, & Lambert, 2013) BL was measured by an enzymatic-amperometric method (Lin, Chen, & Lin, 2018) in 10 μl blood sampled from the earlobe and was analyzed via WinLactat 4.1.0.1 (XE Version, German).

After a week and 3 hours, a meal, the participants performed a 60-minute pedaling test in different cadences with 90% VO2max. The staging test included; standard warm-up (10 minutes with 100 watts); the main protocol (6 ten-minute steps) and cool-down (10 minutes at 100 watts). The cadence intermittent (90-120-60-120-60-90-60 rpm) changed every 10 minutes during the exercise. The rate of perceived exertion (RPE) was used to assess the intensity of the training interval using the Borg scale (Borg, 1998). The HR on EEG setup, blood lactate (BL) and RPE have recorded at the end of each 10 min; the rest, after the warm-up, after every 10-minute cadence, and after the cool-down (Amann, 2011; Gronwald, Hoos, Ludyga, & Hottenrottd, 2018).
EEG Recordings and Analysis

Electroencephalography (64-Channel QuickAmp-EEG system, Brain Products, Germany) was used in continuous brain cortical activity recording. The changes in brain wave signal 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) (Klem, Lüders, Jasper, & Elger, 1999; Jung, Makeig, Bell, & Sejnowski, 1998). 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 cadence, after cool-down, resting and exercise. After editing the markers, data were filtered, High-pass: 1.5 Hz, octave-1 12 dB slope, low-pass: 50 Hz, octave-1 48 dB) between 1-2 Hz and > 50 Hz for removing 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 (Faria, Parker, & Faria, 2005; Faria, Parker, & Faria, 2005). This control was fixed off-line and was analyzed only EEG sections without artifact. Based on the edited markers, the signals were divided into four S4-s data-sets with a corrected baseline Amann, 2011) at the last minute of each time point. Each Subject and measuring time point five artifact-free segments were analyzed by using the Fast-Fourier transform method (Maximum resolution, power in μV2, full range use, hanging Hanning window, window length: 20%). The received frequency spectrum was divided into three 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 (Faria, Parker, & Faria, 2005).

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, the difference between the time points (spectral power of EEG [%], HR [min-1], BL [mmol. l-1]) from ANOVA for repeated measurements Cadence × spectral energy bands, and Cadence × variables (of HR, BL) were calculated. For ordinal data (RPE), the
Wilcoxon test was used. Different points of statistical significance were found out at \( p \leq 0.01 \) (**).

**Results**

Participants achieved a mean \( P_{\text{max}} \) of 308.92 ± 20.61 (90% of the anaerobic lactate threshold: 224.71 ± 19.00 W), and the maximum oxygen consumption (\( \text{VO}_2\text{max} \)) was 40.43 ± 3.67 ml· min\(^{-1}\)· kg\(^{-1}\) in ergometer cycle. The results showed; the values of the heart rate and the blood lactate during warm-up and at the beginning of the exercise test were significantly increased (\( p<0.01 \)). Rating of perceived exertion (RPE) increased significantly (\( p<0.01 \)) at the beginning of the exercise test compared to the warm-up period. At 120 rpm, heart rate, blood lactate, and RPE were significantly higher than 60 rpm. All physiological values were decreased significantly (\( p<0.01 \)) during the cool-down stage (Table 1, Fig 1 and Fig 2).

**Table 1.** Variables; RPE, BL, and HR during Pedaling states; Warm-up, six states of changing cadences and Cool-down. Data are shown via Mean ± S.D.

<table>
<thead>
<tr>
<th>Pedaling states</th>
<th>Variables</th>
<th>Cadence [rpm]</th>
<th>RPE [6-20]</th>
<th>Blood Lactate [mmolL(^{-1})]</th>
<th>Heart Rate [min(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-up</td>
<td></td>
<td>90</td>
<td>9.25 ± 1.97</td>
<td>0.8 ± 0.4</td>
<td>118 ± 8.67**</td>
</tr>
<tr>
<td>Workload</td>
<td>+80% of LT</td>
<td>90</td>
<td>13.05 ± 1.17**</td>
<td>1.5 ± 0.57**</td>
<td>144.5 ± 9.69**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120</td>
<td>15.85 ± 1.17**</td>
<td>3.5 ± 1.12**</td>
<td>163.81 ± 9.85**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>13.74 ± 1.48**</td>
<td>1.57 ± 0.57**</td>
<td>150.25 ± 10.47**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120</td>
<td>16.50 ± 1.79**</td>
<td>3.5 ± 1.16**</td>
<td>168.85 ± 10.74**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>14.35 ± 1.58**</td>
<td>1.8 ± 0.45**</td>
<td>154.58 ± 10.67**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>14.25 ± 1.37</td>
<td>1.75 ± 0.57</td>
<td>157.55 ± 11.71**</td>
</tr>
<tr>
<td>Cool-down</td>
<td></td>
<td>60</td>
<td>8.31 ± 1.85**</td>
<td>1.0 ± 0.25**</td>
<td>118.65 ± 8.57**</td>
</tr>
<tr>
<td>Rest</td>
<td></td>
<td>-</td>
<td>-</td>
<td>1.02 ± 0.34**</td>
<td>62.55 ± 8.77</td>
</tr>
</tbody>
</table>

Measurement point \( p<0.01 **; S.D: standard deviation; RPE: Rating of perceived exertion; rpm: revolutions per minute; BL: Blood Lactate; HR: Heart Rate.
Table 2. Variables; percent (%) of EEG spectra power (Alpha, Beta, and Theta waves) during Pedaling states; REST, Warm-up, six states of changing cadences and Cool-down and then REST. All data are shown via Mean ± S.D.

<table>
<thead>
<tr>
<th>Pedaling states</th>
<th>Cadence [rpm]</th>
<th>Theta [%]</th>
<th>Beta [%]</th>
<th>Alpha [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REST</td>
<td>-</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Warm-up</td>
<td>90</td>
<td>350 ± 160**</td>
<td>230 ± 130**</td>
<td>282 ± 200**</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>317 ± 201</td>
<td>255 ± 145</td>
<td>361 ± 395</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>200 ± 133**</td>
<td>145 ± 82**</td>
<td>171 ± 112**</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>260 ± 175</td>
<td>210 ± 166</td>
<td>335 ± 455</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>165 ± 90**</td>
<td>112 ± 57**</td>
<td>143 ± 80</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>170 ± 85**</td>
<td>152 ± 111**</td>
<td>150 ± 85</td>
</tr>
<tr>
<td>Cool-down</td>
<td>60</td>
<td>147 ± 114**</td>
<td>103 ± 75**</td>
<td>114 ± 78</td>
</tr>
<tr>
<td>REST</td>
<td>-</td>
<td>35 ± 22**</td>
<td>38 ± 21**</td>
<td>41 ± 22**</td>
</tr>
</tbody>
</table>

Figure 1. Blood Lactate [mmol. l⁻¹] variability during the 8 steps of workload Pedaling states; Warm-up, 6 states of changing cadences and Cool-down.
The spectral EEG power was significantly (p<0.01) for the entire rest-to-warm-up frequency ranges (Theta: +251%, alpha: +182%, beta: +131%). The cadence changes are reflected in the spectral power of the EEG (see Table 2), Fig.1. By comparing the different cadences, the spectral power of the EEG (p<0.01), in theta, beta. The brain activity at the resting stage was decreased significantly (Theta: -67%, alpha: -58%, beta: -63%) in all cadences (p<0.01) compared to the beginning (90 rpm). According to the EEG brain map in the cadence of 120 rpm theta-waves, clear in all the brain (Figure 3).

**Figure 2.** RPE variability during workload Pedaling states; Warm-up, 6 states of changing cadences and Cool-down.

**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 cadence to 120 rpm and decreasing of the spectral power (gray) or dark gray after diminishing the cadence to 60 rpm. Lower spectral EEG power at the end of the workload (90 rpm).

Discussion

These results show that the brain neural response decreased in a fatigue condition during pedaling. EEG's recordings in different intensities, unless at the same workload showed at a higher cadence pedaling frequency which is associated with increased brain activity, heart rate, blood lactate, and RPE. Recruiting muscle fibers are increased, muscular coordination, and higher cardiovascular function is needed to maintain a higher cadence (Enoka & Stuart, 1992; Taylor & Gandevia, 2008; Del Percio et al., 2009). Blood lactate increased in the state of high cadence (120 rpm) and decreased at a low cadence (60 rpm). These results support past investigations on how the training's intensity changes affect the energy supply (Del Percio et al., 2009; CE, Rampichini, & Veicsteinas, 2009). In a steady-state workload, blood lactate rises further at cadences from 100 to 120 rpm (CE, Rampichini, & Veicsteinas, 2009), because of the enhanced heart rate caused by enhancing the cadence. Some investigators suggest that blood flow and therefore, blood lactate accumulation increases in the involved muscles. (CE, Rampichini, & Veicsteinas, 2009). The consciousness of higher cadence exertion enhanced with an increased heart rate and blood lactate accumulation (CE, Rampichini, & Veicsteinas, 2009; Del Percio et al., 2009). Bailey confirmed that there is a correlation between brain activity oscillations and physiological aspects of
performance (Bailey et al., 2008). The power spectral increasing of the EEG has been clear in 120 rpm intensities. The brain activity should be adapting with the performance intensity and power output in sports. Fatigue reduces brain activity. Noakes (Noakes, 2011; Weavil et al., 2016) also showed brain wave oscillations reduced after a prolonged exhaustive exercise protocol displayed in the theta and alpha frequencies. Gronwald et al. 2018 have done the same research in cardiovascular regulations in exercise-induced fatigue with emphasizing on the changes of cadences (Gronwald, Hoos, Ludyga, & Hottenrottd, 2018). The "neural efficiency" hypothesis had approved in related to the adaptation of the brain with the frequency of cycling with a lower level of beta activity in cyclists (Ludyga, Gronwald, & Hottenrottd, 2016). Ludyga also showed a reduction in brain activity after intensive ergometer cycling training. It was approved as a mechanism of fatigue to sustain homeostasis, which had explained in the central governor theory. To describe the fatigue mechanism, Noakes has proposed the central governor model for over two decades. This model introduces the unconscious mind of the brain in regulating the power output by modulating the force and applying the motor units to maintain homeostasis, which keeps the body from disastrous physiological disorders. In contrast, there is the neural efficacy assumption depends on task demand and conscious awareness, that the better adaptation of the brain activation product is because of the face to the challenges (Noakes T, 2012). The neural efficiency hypothesis had characterized by adapting brain activation with functions. There is a correlation between high cardiac output and increased blood lactate accumulation during high intensities, and then the perception of force exertion increased (Hagberg, Mullin, Giese, & Spitznagel, 1981). Referring to the results, the variables such as blood lactate and heart rate changed with the intermittent changes, both central governor theory, and the neural efficiency hypothesis is clear with the findings of this study. Meanwhile, any change in cadence observed significant changes in all variables, and homeostasis maintains according to the central governor model. These changes occurred because it was to be adaptive; it has changed by the constant workload. A more complex cognitive task is not inconsistent with this task, so need to remain carried out to a long, intense exercise, to reduce the energy reserves of the individual; Inzlicht & Marcora (Inzlicht & Marcora, 2016) that it mentioned as self-control or inhibitory control, a term borrowed from psychology. Self-control is the ability to regulate one's body necessities, emotions, thoughts, and behavior in the face of internal or external stimulations to achieve specific goals (Delisi, 2014). The beta brainwave is a 'fast' activity, present when we are attentive, alert, engaged in decision making, judgment, problem-solving, or focused mental activity. This band presented in the frontal, occipital, and temporal lobe in 120 rpm. The frontal lobe includes dopamine neurons. The dopaminergic pathways are related to attention, motivation, reward, planning, and short-run memory duties. Dopamine limits sensory information that arrived from the thalamus to the forebrain. The motivation was paid attention to sports and exercises. The theta brain state, where it is realized, everyone can create everything and change reality immediately. The
theta band displayed in the entire area of the brain in 120 rpm approximately. Theta band is powerful. Theta band should be considered the subconscious (mind condition between the conscious and the unconscious). Fatigue-induced by high intensity intermittent pedaling disables the brain, but at high intensities (cadence of 120 rpm), even though limited to the theta band only. The results were obtained at one session, with repeatability in the eight interval steps of the high-intensity workload following a behavioral pattern. With the onset of fatigue, the activity of the brain decreases, but with increasing intensity, the activity of the brain increases. Fatigue concerning HIIT creates new behavioral patterns in response to various situations according to the spectral power % of alpha, beta, and theta with attention to involving areas of the cortical brain.

So, the pattern of brain activity oscillations depends on exercise intensity, and individually preferred cadence contributes to the positive response of the cognitive process (Brümmer, Schneider, Strüder, & Askew, 2011). The activity of the brain cortex is crucial to achieving performance and power output in exercises. The higher part of the cortex processes, cognitive and responsible for tolerating pain and delay the pleasure by self-control. HIIT improves cognitive processes in elderly people also (Coetsee & Terblanche, 2017; Samuel et al., 2017). In conclusion, Fatigue-induced by high-intensity intermittent training leads to a strategy to maintain homeostasis, not a mechanism to survive as such mentioned central governor model.

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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Reference


Noakes, T. (2000). "Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance". *Scandinavian journal of medicine & science in sports, 10*(3), 123–145. PMID: 10843507


