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Research paper

Quantifying mental arousal levels in daily living using additional heart rate

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ABSTRACT

Monitoring the mental arousal level is an effective way of mental health assessment. Additional heart rate has been proved highly correlated with mental arousal level, which presents the changes of heart rate that caused by mental activities. A mathematical heart rate model is introduced to predict the heart rate in response to body movement, and then to calculate the additional heart rate and mental arousal level. The effectiveness of the proposed model was verified on the physical activity monitoring dataset, which contains ten kinds of daily activities of ten subjects. The proposed model was then applied to the data of one subject in daily living, and the mental activities are indicated clearly from the mental arousal level. The proposed heart rate model provides an efficient way to calculate the additional heart rate and then quantify the mental arousal level, which can serve as a powerful tool in the mental health assessment.

1. Introduction

Arousal is the state of being awake, both physically and mentally [1]. Physical arousal occurs when we are engaged in sports and other physical exertions. Mental arousal includes cognitive arousal and affective arousal. Cognitive arousal happens when we are exploring, learning and discovering interesting things. Affective arousal is the state when we are emotionally charged up and feel passionate about something. The mental arousal reveals great information about our mental health [2]. Most mental health problems, anxiety or depression for instance, are accompanied with symptoms such as prolonged sadness or irritability, constant or severe mood swings and increased depression, anger, hostility etc. Therefore, continuously monitor the mental arousal level facilitate the assessment of our mental health.

Researchers [3–6] have done many work on mental arousal in laboratory, shows the strong relation between mental arousal and the heart rate. In these studies, the subjects were typically sitting during various mental task and the physical arousal was controlled and ignored. In daily living, however, both physical arousal and mental arousal lead to similar physical reactions, increased heart rate, blood pressure or alertness for instance. In addition, the physical and mental arousals are interactive and we may experience any combination of arousal states at any time. For example, the cognitive arousal can lead to affective arousal, such as we get excited about a new discovery. On the contrary, the affective arousal can suppress cognitive arousal [7], such as the anger state may leads to unwise decisions. The affective arousal can also trigger physical arousal [3], such as the Fight-or-Flight reaction. Due to the similar physical reaction of mental and physical arousal, it is hard to separate mental arousal from physical arousal only from peripheral physiological reactions. Fortunately, studies [8] indicate that the heart rate increase induced by multiple stressors is nearly additive combination of the increase induced by each stressor. Therefore, additional information can be used to calibrate the heart rate increases due to physical activities, so as to quantify the mental arousal in daily living.

This research contributes a practical way to measure the mental arousal levels in daily living which facilitate the assessment of our mental health. The increases of heart rate induced by body movements are separated from the measured heart rate according to the acceleration of body trunk. Then, the remains are called additional heart rate and assumed induced by mental activities. Thus, the mental arousal level can be quantified by the additional heart rate. The rest of the article is organized as follows. In the next

Abbreviations: AHR, additional heart rate; AV node, atrioventricular node; HR, hart rate; MAL, mental arousal level; PAMAP2, Physical Activity Monitoring Data Set; SA node, sinoatrial node; VO2, oxygen consumption.

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section, the background of additional heart rate are introduced and related works on dynamic models of heart rate are discussed. After that, we propose a mathematic model of heart rate during low to moderate physical movement intensities and then map the additional heart rate to mental arousal level. Next, the heart rate model is verified on the physical activity monitoring dataset [9] and the mental arousal levels during three daily fragments of one subject are showed. In the last section, we discuss the limitation of the proposed mental arousal level quantifying method and conclude its applicable environment.

2. Background and related works

2.1. Control of the heart rate

The intrinsic rhythm of the heart rate is determined by specialized cells of the SA node, which generates action potentials at a rate of 100–110 beats/min if left unmodified by neurohumoral factors. This action potentials keep the heart pumping and keep blood flowing to the lungs and body. The intrinsic heart rate is strongly influenced by autonomic nerves [10]. Normally, the heart rate at rest is between 60 and 80 beats/min with the vagus nerve being dominant over sympathetic influences. When the body needs more energy, the heart rate will increase and thus the increased blood flow will deliver more oxygen to the tissues.

Factors that affect the heart rate are various, including exercise, physical state, mental state, and environment etc. Physical exercise increases the heart rate to transport adequate oxygen to the muscles when working out. Besides exercise, the transition of body postures [11], sitting to standing for instance, may also cause the heart rate goes up directly after the transition and then remains elevated for about 10 s. Systemic illness like fever can increase the heart rate. The body's metabolism is increased to fight off the disease which require the heart to beat faster to provide body increased oxygenation and nutrients. Body size has a direct effect on the heart rate. Higher body weight needs more oxygen which makes the heart has to work harder. Emotions and stress can influence the heart rate. A peaceful mind slows down the heart rate while stressful situations turn on the fight or flight system in the brain which increases the heart rate. The environment also affect the heart rate. For example, the heart need to beat more rapidly in an attempt to drive more oxygen to the body in circumstances of low oxygen in the environment.

2.2. Additional heart rate

Blix et al. [12] first introduced additional heart rate as the indicator of psychological activation, and it is defined as the heart rate acceleration without corresponding increase of physical activity indicated by oxygen consumption (VO2). In the study, the linear regression coefficients between heart rate and VO2 were trained for each subject, and then the VO2 was used to predict heart rate, and additional heart rate is the difference between measured heart rate and predicted heart rate. Wilhelm et al. [13] used minute ventilation as the substitute of VO2 to calculate additional heart rate for the minute ventilation is closely correlates with VO2 at low and moderate levels of aerobic exercise and can be ambulatory measured. However, the body responds to emotional stress much as it does to exercise stress [14]. The affective arousal can also trigger the fight-or-flight reaction and a series of sympathetically mediated physiological responses. This reaction [14], which prepares the body for fight or flight, includes an increase in circulating stress hormones, heart rate, breathing rate, blood pressure, muscle strength, etc. Therefore, the mental arousal level may be underestimate while eliminating the increase in VO2 or minute ventilation caused by affective arousal. Since accelerometer signal is generally regarded as a reliable index of physical activity, and emotions has much lower effect on body movement than on VO2, Michael et al. [8,15] presented an algorithm for additional heart rate by using accelerometer signal to calibrate the increase of heart rate in the presence of physical activities. Martin et al. [11] indicated that posture transitions may increase the heart rate, however, the additional heart rate algorithm fails to attribute this increase to physical arousal. They provided an activity-aware activations filter to identify arousal that influenced by physical activity transitions, and incorporated the filter with additional heart rate algorithm to estimate mental arousal onset and duration. The additional heart rate algorithm measures additional heart rate minute by minute [15], which decrease the temporal resolution of mental arousal measurement. Based on the relation between exercise intensity and the heart rate dynamics [16–18], this study introduces a mathematic model of heart rate dynamics in low and moderate exercise intensity to get the continuous additional heart rate.

2.3. Model of heart rate dynamics

The mathematic model of heart rate dynamics focus on the relationship between exercise intensity represent by accelerometer signal and the heart rate, assuming that all other factors are kept constant. A large body of literature in exercise physiology show certain rules about the exercise intensity and the heart rate.

Zakynthinaki etc. [17] improved the nonlinear heart rate model presented by Stirling [19]. Their model reduced the number of parameters to one which represents the overall cardiovascular condition λ, $0 < \lambda \leq 1$, and $\lambda \approx 1$ refers to an excellent cardiovascular condition that can maintain an exercise session of approximately 3–4 min at intensities as high as $\nu = 20$Km/hr. Having noticed the slow increase of heart rate during heavy/severe exercise after an exponential increase of heart rate from the onset of the exercise, their model also considered the accumulation of blood lactate which causes this slow component. The concentration of lactate in arterial blood when the body is at rest is around 1 mM, and increases slightly at moderate exercise intensity and rapidly with the intense of exercise. The accumulation of blood lactate levels off after approximately 10–20 min at heavy exercise intensities, and thus causes a slow increase of heart rate which delays the achievement of a steady heart rate. The severe exercise intensity causes a continuous steep increase in the blood lactate until the body becomes exhausted and therefore slows down or simply stops. Considering the slow component of heart rate makes the heart rate model more accurate under various exercise intensities. The heart rate model provided by Zakynthinaki, however, predict heart rate dynamics during constant exercise intensities but are unable to account for dynamic fluctuations in heart rate related to transient exercise intensities.

Michael etc. [16] employ a second-order multi-variable Taylor series expansion as the drive function to capture the nonlinear effects of heart rate dynamics and produced good results in laboratory cycling tests under transient exercise intensities. When applied this model to the experimental heart rate data, however, there are elven parameters need to be estimate. Actually, the heart rate dynamics are affect only by one parameter, the overall cardiovascular condition of an individual. Besides the nonlinear model, the Karvonen formula [20] is widely used to determine the target heart rate training zone in physical exercise, and it establishes a simple mathematic model between exercise intensity and the heart rate demand. Based on the Karvonen formula [20] and the work of Zakynthinaki [17], this study builds a model of heart rate dynamics under low to moderate exercise intensities, and then use the additional heart rate to quantify the mental arousal in daily living.