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The fatigue characteristic of electromyography, heart rate variability, electroencephalography under physical and mental demands: a review

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Many modern occupations require confronting concurrent mental and physical demands (PWL ×MWL). However, the electromyography (EMG), electrocardiography (ECG), Heart rate variability (HRV), and electroencephalography (EEG) signals might be only discussed under physical fatiguing condition. The main objective of this literature review is to discuss the fatigue characteristic of EEG, HRV, and EMG parameters under physical and/or mental condition. The global famous databases were searched from origination to April 2018. The words “fatigue”, “EEG”, “HRV”, “EMG”, “physical demand”, “mental demand” as well as “ECG”, “exercise”, “sports”, “cognitive task” and “mental stress” were used as keywords for searching. 3,114 original documents were found, but only 67 articles were identified for deep read after two independent reviewers’ assessment. Under fatiguing physical and/or mental task, the amplitude parameter of EMG increased with the frequency decreased. Imbalance in autonomic nerves system (ANS) branch was presented and HRV time domain parameters tended to decrease. The power spectrum of theta in EEG increased, but alpha and beta might be influenced by the type or the difficulty of the task. In conclusion, EEG, HRV, and EMG may be sensitive under physical and/or mental condition. If the intensity of the task was high enough to make other signals highly involved in this process, it may be essential to integrate apply EEG, HRV, and EMG for fatigue mechanism discussion in the future.

Keywords: Electromyography, Heart rate variability, Electroencephalography, Fatigue, Physical demand, Mental demand

INTRODUCTION

Many occupations in modern society including professional sport may consist of physical, mental, or a combination of different demands (Xie and Salvendy, 2000). Physical and /or mental overload may compromise performance or even safety, by the decline in motivation, increase in reaction times and error rates (Xie and Salvendy, 2000), neglect of critical information (Dixon, et al., 2013), or engendering fatigue (Young and Stanton, 2002). Fatigue, generally transitory, refers to a reduced efficiency, disinclination for effort, and deficiency of alertness (Chaffin, 1973; Barofsky and Marcia, 1991). It may have a meaning range from neuromuscular weakness to mental disorder because we may experience “physical fatigue” or “mental fatigue” in daily life. Physical fatigue may be a transient muscle inability to maintain optimal physical performance in the workplace or stadium (Purvis, et al., 2010). The mental fatigue is, also temporary, a dysfunction of maximal cognition or attention performance, which result from the prolonged cognitive task, unbearable mental stressor or even long-term physical exercise (Lorist, et al., 2002). Even though the idea that the central nervous system (CNS) may be highly involved in the feelings of somnolence, lethargy, tiredness, or even mood disturbances, more evidence still needs to be done to support the significant role of the brain in the process of mental fatigue. But the well-known things are that the mechanism of fatigue may be influenced by both CNS and periphery (Abbiss and Laursen, 2005). Central mechanisms may focus on CNS abnormalities besides disorder in supraspinal or spinal (Gandevia, 2001), while the mechanism in the peripheral category may relate to the muscle function involving muscle bioenergetics failure or excitation-contraction abnormalities. Recently, more and more evidence was being illuminated benefit by a widespread application of the psychophysiological monitoring method consists in, for example, electromyography (EMG), electrocardiography (ECG), heart rate variability (HRV), and electroencephalography (EEG), as well as other techniques to measure skin electrodermal activity (EDA) or respiratory rhythm (Millet and Lepers, 2004, Cornelissen, et al., 2010). Those explore had been involved in central and peripheral fatigue, which apply EMG to assess impaired muscle contraction, or HRV to check the balance of ANS, or EEG to measure weakness from the cerebral cortex (Reilly, 2012).Generally, increases in EMG amplitude and decreases in frequency parameter will be shown under well-controlled muscle fatigue contractions (Hakkinen, et al., 1987). Increase in amplitude parameter may mean a higher recruitment in α-motor unit or a higher muscle electrical activation, while a lower or decreased frequency parameter usually refers to lower firing rate originated from central driving (Abbiss and Laursen , 2005). In addition, HRV is the variation over time between consecutive heartbeats, which can be used to detect fatigue (Hjortskov, et al., 2004). It is related to the ongoing interplay between two arms of the ANS, which is the so-called sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). The activity of the cardiac system can be, in general, recognized by the time domain analysis (such as SDNN, rMSSD), while sympathovagal balance can be reflected by the frequency domain analysis (such as LF, HF, LF/HF) (Cygankiewicz and Zareba, 2013). Hence, chronic disease-related fatigue usually will induce a lower value of time domain parameters with a lower PNS and/or increased SNS activity (Mikulski, et al., 2013). More importantly, most original researches and literature reviews have emphasized that acute whole body exercise or muscle strength course will induce an increase in brain electro-cortical activity (Kubitz and Pothakos, 1997). EEG reflects post-synaptic cortical neuronal potentials, which is normally divided into delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-13Hz), and beta (8-30 Hz). Delta waves can be detected in a sleep state or transition stage to drowsiness, while theta has been thought to be associated with low levels of vigilance or inhibition of elicited responses. Alpha is seeming with the purpose of timing inhibitory activity in different locations across the brain, and Beta refers to thinking, focus, high alert, and anxious.

Recently more and more evidence try to discuss the fatigue characteristic of EEG, HRV, combined with EMG under physical and mental demand, especially in driving task (Fallahi, et al., 2016, Fronso, et al., 2017). Thus, the aim of this review was to discuss the fatigue characteristic of EEG, HRV, and EMG under physical and/or mental tasks, which include fatigue characteristic under physical, mental or physical concurrent mental task.

EVIDENCE ACQUISITION:

2.1 Search Strategy

The population, demand type (physical, mental or both), and outcome (fatigue characteristic) were applied to define our search strategy. The Web of Science, Google Scholar, PubMed, EMBASE, SPORTDiscus, and Springer were searched from inception to April 2018. A secondary search was conducted by Grey Repository, and Research Gate. Each database was searched by 1 researcher, but another 2 reviewers screened the titles and abstracts independently. The checklists were followed EQUATOR-network reporting guidelines for main study types. In addition, reference lists from the included article and relevant literature review were also researched.

More importantly, an iterative way was carried out in this study: firstly, a global view of the current state in fatigue characteristic under physical concurrent mental demand was searched. The terms applied in this step were: “fatigue”, “EEG”, “HRV”, “EMG” AND “physical concurrent mental demand”. 44 original documents were found, but controlled terms have been used to discard all non-relevant publications. After removing duplicates and rejecting the ones not work with healthy human beings, 26 results were achieved. But only 25 papers were considered for further reading because only linear analysis method of the parameter has been paid attention. Secondly, because the main concepts in current psychophysiological signals and demand were identified and understood again, the search terms were expanded to the several domains and modalities of psychophysiological signals. The identification of the main term will base on the evidence search on website or Khon Kaen University library, which includes the book, thesis and other related documents. Then, the search terms were extended to "physical task" OR "exercise", "sports" AND "mental task", OR "mental stressor", "cognitive task". The first sets of 3,070 documents were retrieved in the case that the bibliographies were also hand-searched. 42 papers were selected in-depth read. Then, the totals of 67 papers (25+42) were selected for fully read. A summary of the methodology used was presented in Figure 1.

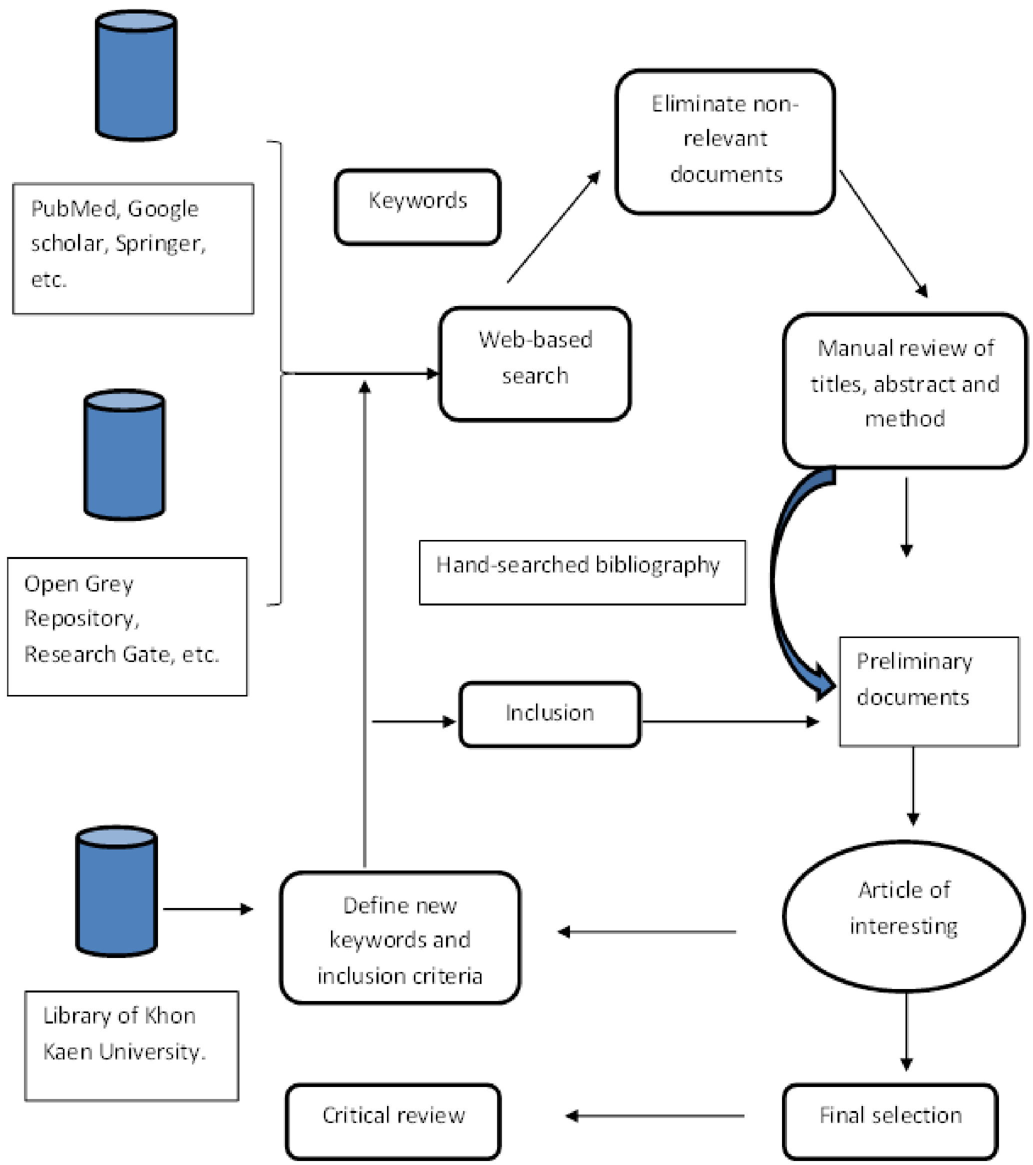

Figure 1. The applied search methodology in the literature review process.

Eligibility Criteria

Only the papers in where discussing fatigue characteristic under physical and/or mental demand for healthy human beings were accepted. However, the healthy human beings in this study included sedentary subjects or the person with a stressful life because those kinds of participants have more chance to confront our target demand condition. Any study populations consist of patients with diagnosed chronic fatigue syndromes, or chronic disease-related fatigue or serious psychological disorders were excluded. The original, empirical, theoretical, and review articles were allowed to assess, but the articles must be written in English and published before April 2018.

EVIDENCE SYNTHESIS:

Fatigue Characteristic of EMG Parameter under Physical and Mental Task

Medical research, rehabilitation, ergonomics, biomechanics, sports science and other bio-related disciplines may find the wide application of EMG signal analysis for muscle fatigue. Since 1987, Hakkinen has illuminated that a 50% isometric loading induced fatigue will lead significant increase in integrated EMG (IEMG) and decrease in mean power frequency (MPF) (Hakkinen, et al., 1987). That also has been proved by Crenshaw in 1997, which found similar results even though the participants joined low and high level isometric maximal voluntary contraction (MVC), separately (Crenshaw and Gerdle, 1997). Moreover, the MPF has been proved to be sensitive under hyperthermia because there may be a linear relationship with the muscle temperature according to Madigan & Pidcoe's research in 2002 (Madigan and Pidcoe, 2002). Recently, Hill, et al. (2016) has paid attention to the sex differences (Hill, et al., 2016). They found the MPF of man will decrease by 20.0%, while female will 25.3%. The only sex difference is how much the parameters will change. Moreover, EMG has been also applied as biological indicators for mental fatigue. Bansevicius, et al., in 1997 found the EMG response will increase after 1-hour cognitive test (Bansevicius, et al., 1997). In 2008, Schleifer, et al. also proved that 1-hour typing task can induce increases in EMG activity and decreases of frequencies (Schleifer, et al., 2008). Recently, Wijsman and his colleagues firmly believe no matter how the workload type change, a higher RMS with lower MPF and MF will appear when fatigue present (Wijsman, et al., 2010). Even though mental and physical fatigue should have a different mechanism, they still share a similar neuromuscular activation in α -motor unit. We may be interested in the pathway of this phenomenon. Someone thought it may be related to control driving switch (Abbiss and Laursen, 2005), then let's pay attention to the brain activation as follows.

Fatigue Characteristic of EEG Parameter under Physical and Mental Task

As we all know, EEG is the technology that summates inhibitory and excitatory postsynaptic potentials of cortical nerve cells (CNC) in the cortex. Then, it has been widely used in fatigue detection since 1979. Townsend proved that fatigue may be associated with increased theta activity (Townsend and Johnson, 1979). After that, Toravall successfully verified the theta had a significant positive correlation with deep fatigue (Torsvall, 1987). However, in 1996, Kiroy and his co-worker believed a prolonged mental activity would induce a significant increase of theta, delta and beta activities (Kiroy, et al., 1996). Moreover, a decrease of alpha band power has been displayed after 4 sessions of 30minutes Video Display Terminals task (VDT) (Uetake and Murata, 2000). A decreased alpha activity may reflect a state of increased cortical activation with a stressful and increased anxiety (Petruzzello, et al., 1991). More interesting things are, only one year later, Nielsen found the α/β index will rise with an increased alpha and declined beta under the hot environment (H, 42°C) when the participants did a fatiguing cycling (Nielsen, et al., 2001). In addition, Ng & Raveendra have changed the workload type to resistance exercise in 2011 (Ng and Raveendran, 2011). The results also show the asynchronous increase of alpha, theta, and beta.

Based on the discussion above, the waveform of theta will have the same feature under physical or mental exhaustive task. But the feature of alpha will depend on the type, difficulty of tasks, and environments. The type of task may not influence the characteristic of beta, but environments will make sense. As we know, theta is associated with cognitive complexity and focused attention, while alpha is related to information processing, and beta refers to the level of thinking or vigilance. Focused attention may be the necessary source in a different kind of demand including physical or mental ones. However, the demanding for the capacity of information processing and the level of vigilance activation will contribute to the characteristic of alpha and beta. More importantly, the balance between vigilance and inhibition will be broken in CNS as α/β index changes. As a consequence, it may induce the imbalance in ANS, which push us to pay attention to HRV discussion.

Fatigue Characteristic of HRV Parameter under Physical and Mental Task

Since the HRV has been thought to be associated with ANS activity, the interrelationship between fatigue and HRV parameters has been investigated (Hjortskov, et al., 2004, Cygankiewicz and Zareba, 2013). Riemersma's experiment in 1977 was interpreted the HRV parameters decreased greatly during prolonged night driving (Riemersma, et al., 1977). In 2004, Hjortskov and co-worker found the stressing computer task group would have a lower HF but higher LF/HF ratio (Hjortskov, et al., 2004). More interesting thing is the value of LF has no any differences. The mental stress may mainly influence the PNS activity leading to induce the imbalance in ANS. But, in 2010, other researchers found participants will show a higher LF with lower HF after 90 minutes simulated driving test. The similar results have been found in the same year (Olsson, et al., 2010), which the researchers recruited participants to do a computerized mental task.

Recently, more and more evidence try to discuss the influence of high-intensity exercise on the cardiac response and ANS balance. For example, Mikulski, et al. (2013) have recruited 11 healthy endurance-trained men to do 30 hours of prolonged exercise without any sleep (Mikulski ,et al., 2013). They found all the parameters were going to be lower. Moreover, in 2017, Clemente found almost all time parameter will significantly decrease after high-intensity interval training (HIIT) (Clemente-Suarez, Arroyo-Toledo, 2017). No matter joining which kind of demand time domain parameters will be going to lower, and the balance between SNS and PNS will be broken. This imbalance may be derived from the reinforcement of SNS activity and/or weakness of PNS function from vigilance and inhibition regulation in CNS. A new trend has been seen in fatigue characteristic of those signals.

Fatigue Characteristic of EEG, HRV and/or EMG Parameter under Physical and Mental Task

Recently, more and more researchers trend to apply EEG combine with ECG (HRV) (Zhao, et al., 2012) or HRV combine with EMG (Mehta and Agnew, 2012), or even EEG combine with EMG (Ushiyama, et al., 2011) in fatigue feature assessment to illuminate the mechanism that CNS influence α -motor unit firing or ANS imbalance. As table 1 shown, the magnitude of EEG-EMG coherence was significantly increased after muscle fatigue (Masakado, et al. 2011). As their discussion presented, this phenomenon may be related that an increase in the sensorimotor cortex of the descending command to the excitation of spinal motor neurons happened and an increase in the tendency of the corticospinal cell population to discharge in synchrony was also presented under fatigue. In 2012, Zhao and his colleagues also proved that driving fatigue (mental) impacted the CNS function, and then consequently influence the cardiovascular system (Zhao, et al., 2012). In the same year, Mehta and Agnew found PWL significantly affected the percent changes in power frequency of EMG, but MWL and PWL ×MWL conditions can't make any difference (Mehta and Agnew, 2012). In addition, either PWL or MWL or PWL ×MWL can't influence amplitude parameters as well. However, both PWL and MWL can significantly affect HRV response. A lower HRV can be induced in PWL ×MWL condition. The results support that the CNS function will play the important role under PWL ×MWL condition, and EMG may be not so sensitive in PWL ×MWL conditions, but EEG and HRV may be a good choice under this condition. More importantly, under PWL ×MWL condition mental workload presentation may make an interaction on physical workload executed, which the mental workload (stress) may make subject hardly to perform enough physical workload as they do PWL task only. If the task transfer to high-intensity PWL ×MWL task, it may be interesting that how the fatigue characteristic of EEG, ECG (HRV) and EMG will be presented. Unfortunately, little studies pay attention to this issue.

Table 1. Fatigue variation of EMG under physical and/or mental task

Author (year)	Number of participants (age)	Demand	Main Parameter	Outcome Feature
Ushiyama, J., Katsu, et al., 2011.	7 healthy mal e volunteers (age: 22.7± 1.6 year)	(1). Pre-fatiguing and post-fatiguing task: 30% of isometric MVC dorsiflexion. (2). Fatiguing task: 50% of isometric MVC dorsiflexion	(1). EMG: MPF,RMS (2).EEG-EMG coherence	RMS ↑ MPF ↓ EEG-EMG coherence ↑ when both RMS and MPF reached a plateau.
Zhao, C, et al., 2012.	13 male volunteers (mean age: 25.8 years; range: 22–27 years)	(1). Oddball task(Gentask, Neuroscan Stim2, El Paso, TX, USA) (2). A simulated driving task	(1). EEG: delta, theta, alpha, and beta. (2). ECG: 1). ApEn; 2) HF, LF	(1). theta ↑ alpha ↑, but beta ↓, delta — (2). ApEn ↑, LF ↑, HF ↓
Mehta, R. K., & Agnew, M. J., 2012.	12 participants (22.3 ±1.86years)	(1). Intermittent static shoulder abduction at 1).low: 15% MVC, 2). moderate: 35% MVC, and 3).high: 55% MVC (2). Control condition (absence), 2). Concurrent condition(presence of a mental arithmetic task)	(1). EMG: amplitude , MnPF (2). HRV: R–R intervals	(1). EMG: 1). PWL significantly affected in EMG MnPF. No difference found in MWL and PWL×MWL conditions.2). EMG amplitude was not affected by either PWL or MWL or PWL ×MWL. (2). Both PWL and MWL can significantly affect HRV. PWL ×MWL will induce a lower HRV.

CONCLUSION

The fatigue characteristics of EEG, HRV, and EMG have been widely illuminated within decades. No matter the subjects performing physical and/or mental activity, the amplitude parameter of EMG will increase with the frequency decrease. Moreover, HRV parameters tend to be a decrease in the time domain with an imbalance present in ANS branches. Lastly, the power spectrum of theta waveform in EEG was found increase after physical or mental fatiguing task, but alpha and beta may be influenced by type or difficulty of the task as the literature review above show. EEG may be the most important signals under PWL ×MWL conditions. As results shown, EEG and HRV also seem to be more sensitive than EMG under concurrent condition. More importantly, the high-intensity PWL ×MWL task may be usual in sports match or training (Clemente-Suarez, Arroyo-Toledo, 2017). If this intensity was high enough to make other bio-signals involved in the fatigue process, integrate applying EEG, HRV, and EMG for fatigue mechanism discussion will be essential in the future.

CONFLICT OF INTEREST

The authors declared that present study was performed in absence of any conflict of interest.

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AUTHOR CONTRIBUTIONS

Shuxun Chi contributes to acquisition of reference, interpretation of reference, and drafting of manuscript. Orawan Buranruk contributes to critical revision.

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