

Brainwave biomarkers of brain activity, physiology and biomechanics in cycling performance

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Abstract

Generally, in sports performance, the relationship between movement science and physiological function has been conducted integrating neuronal mechanism over the past decades. However, understanding those interaction between neural network and motor performance comprehensively in achieving optimal performance is still lacking, mainly in cycling. The purpose of this study was to discuss the issues in neuroscience related to brain activity, physiology and biomechanics in achieving optimal performance in cycling. As sports technology improves, more objective measurement can be demonstrated in solving specific issue in cycling, with optimization of performance as the main focus. In this review, the focus on brain activity will be based on the evaluation of the alpha and beta brainwaves as well as the alpha/beta ratio since they are biomarkers of EEG specifically related to cycling performance. Further in-depth understanding of the mechanism and interaction between brain activity, physiology and biomechanics in competitive cycling were acquired and discussed. Moreover, the biomarkers of brain activity related to cycling performance from previous studies were clearly identified and discussed and recommendations to be incorporated in future research were proposed.

Keywords: Cycling, brain activity, physiology, biomechanics, EEG, biomarkers

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INTRODUCTION

Technological development has caused innovation to have a major role in bringing about improvement to the cycling industry. This has even led to the integration with different disciplines especially between physiological, neuroscience and mechanical aspects of human and engineering. Recent work by researchers in sports performance found that there is psychological issues involved with the interaction of neuroscience, physiological and biomechanical characteristics (Cheron, 2015; Cheron et al., 2016). These are important to understand that the central nervous system interacts with the musculoskeletal system to physically generate efficient motor behaviour (Enders & Nigg, 2015). Most of the time, this mechanism will occur while implementing tactical strategy during cycling competition. As athletes, coaches, trainers and professionals aim on what makes a difference between winning and losing, the emerging field of sports neuroscience seeks to produce better understanding between brain and behavior (Park et al., 2015). According to Yarrow et al. (2009), apart from physical fitness, elite athletes must develop sport specific cognitive skills that integrate with perception, cognition and action. When talking about competitive cycling, especially during high-pressurized situations, brain function plays an important role in regulating physiological and biomechanical functions (Cheron et al., 2016). These interactions are present in the mechanism involving brain imaging from a neuroscience perspective. Exercise functions in cycling are prominently explored and investigated using variables such as maximum oxygen consumption (VO₂max), power (Ludyga et al., 2016b), and blood lactate (Hottenrott et al., 2013). Since cycling is considered a continuous cyclic movement due to pedalling, researchers have recently started to investigate how brain activity was influenced

and changed with cadence (Ludyga et al. 2016a; Ludyga et al., 2016b; Ludyga et al. 2016). It involved the mechanisms of brain activity as well as physiological and biomechanical functions that have been thought as the activation of motor units signalling from the central nervous system (Ludyga et al., 2016). This area of study was found to be limited in sports applications and thus even more lacking in cycling. This was due to the methodological limitations in solving brain function issues especially in more dynamic movements (Brümmer et al., 2011). It is important for all stakeholders of competitive cycling to understand the function of brain activity in responding and reacting with other elements especially in real time. Previously, it has been known that objective measurements can be attained for physiology and biomechanics variables but not for brain function. Therefore, the focus of this review was to discuss the issues in neuroscience in the context of brain activity interactions with physiological and biomechanical functions in achieving optimal performance in cycling. Additionally, the common methodological issues in dealing with research related to brain activity using electroencephalogram (EEG) in sports application was highlighted. Finally, this review discussed the common EEG biomarkers from previous studies and proposed recommendations for future studies related to cycling performance.

INTERACTION BETWEEN BRAIN ACTIVITY, PHYSIOLOGICAL FUNCTIONS AND BIOMECHANICAL MECHANISMS

Cycling and brain activity

Research on cycling performance has been widely conducted ranging from recreational subjects to elite athletes. This was shown in a few studies on cycling performance model (Atkinson et al., 2003;

Faria et al., 2005; Mujika & Padilla, 2001; Olds et al., 1995). Most studies claimed that physiological, mechanical and environmental aspects play an important role in determining high performance cycling. However, modelling by Gregor et al. (1991) had focused on the aspects of biomechanics. Later, a model called Multi-Action plan (MAP) was developed by Bortoli et al. (2012) in order to help athletes maintain at optimum performance level especially during fatigue and under stressful situations. In this model, they cultivate the right strategy for specific performance which undergoes a process from mind and body in determining specific required movement that needs to be executed (Lewthwaite & Wulf, 2010). The process involved neuron activities which linked to athletes' success or failure as well as optimized or detrimental performance during competition (Cheron, 2015).

As the nature of cycling includes exposing cyclists upon uncertain environment such as air temperature, wind speed, air resistance, different sceneries and different levels of competitors for long distances, brain activity function serves to regulate information and available physiological capacity as well as responding with strategies in achieving optimal performance (Atkinson et al., 2007). The capability of individuals to produce right decisions in dealing with pacing strategies has been said to be closely related to functions of their central nervous system (Neubauer & Fink, 2009; Yarrow et al., 2009). In cycling performance, brain activity was found to have effects on pacing strategies (Atkinson et al., 2007; Noakes, 2011) as it was a dominant issue discussed especially in the time trial event (Aisbett et al., 2009; Atkinson et al., 2003; Atkinson et al., 2007; Boswell, 2012a, 2012b; Cangle et al., 2011; Dahmen & Saupe, 2015; de Koning et al., 1999; Konings et al., 2016; Mauger et al., 2009; Micklewright et al., 2010; Pinheiro et al., 2016; Schmit et al., 2016; Wells & Marwood, 2016). Brain activity was said to act together with cyclist's experience, pacing strategies and tacticals of a race. These would ultimately help cyclists to win races or achieve optimum individual and team performances (Greg Atkinson et al., 2007). Other than that, brain activity also works with cyclist's physiological capacity to adjust and realign with external forces such as air resistance and other environmental factors as they can cause major pressure on elite cyclists (Barry et al., 2014).

Cycling competition especially road racing requires good pacing strategies as well as experience in order to perform well in the race (Atkinson et al., 2007). These two elements involve specific brain function towards cycling performance as they are obtained from individual insight and attention in retrieving information and knowledge from working memory to be converted into desired sensorimotor tasks (Neubauer & Fink, 2009). In addition, these mechanisms are more or less related to the cyclist's decision making skills as it require specific training and information stored within the brain perceived as their experiences (Atkinson et al., 2007; Yarrow, et al., 2009). Whether it was newly acquired skills, mastery complex skills, correctly executed skills or precise action, it reflect higher order of brain function that ensures success accordingly. Thus, the regulation of brain activity could potentially either limit the cyclist's performance or make some adjustment of work rate to cope with various factors such as the different environmental conditions (Davies et al., 2016), experiences (Mauger et al., 2009) and training (Faria et al., 2005).

Brain activity and physiology

Neurophysiology is the term much utilized in exploring relationship between brain activity and physiology. It expresses the link between multiple signal neurophysiologic from different neural generators at different brain regions. It is often related to the neuron's ability to adapt to training and exercise which consequently leads to neural efficiency (Ludyga et al., 2016b). Individuals who possess neural efficiency are thought to have high cognitive task due to increased proficiency in brain cortical function (Neubauer & Fink, 2009). It was evident that pedalling with high intensity during training can prolong cycling performance and contribute to maximal aerobic power (Hottenrott et al., 2013). Additionally, the different level of athletes' competitiveness, which was affected by their individual training levels and participation in competition, caused variation in

their brain function activity (Nakata et al., 2010). Based on the nature of cycling, physiological variables of a well-trained cyclist with three to five years of training for 60-240 minutes a day should possess 70-75 ml/kg/min or 5.0-5.3 L/min of VO₂max and 300-450 power output (Jeukendrup et al., 2000). In order to obtain optimal physiological function, specific training is required to improve the athlete's performance.

Generally, brain activity related to emotions such as enjoyment, mood swings and anxiety has been said to be influenced by individual experience and self-beliefs (Mothes et al., 2017). In long-term, exercise with such emotions can affect blood pressure benefits over a few weeks (Crum and Langer, 2007). It was also mentioned earlier by Jacobs (2001) that expectations and beliefs can affect physiological response. His study using spectral analysis and topographic EEG mapping of the relaxation response demonstrated that by changing mental, changes in the central nervous system activity also occurred. There was effect on motivational stimuli of psychological and neurophysiological reactions during the execution of isometric motor task with high fatigue level through an examination of self-report that measured with other physiological parameters of muscular activity (Bigliassi et al., 2016). This study showed those who executed motor task under the influence of motivational stimuli experienced higher level of motivation instantly after exercise bout and performance of a maximal isometric task. In addition, this study revealed that motivational stimulus to some extent could block the effect of fatigue so that the subject is able to preserve and increase neural activation of the functioning muscle during last bout of exercise.

Another role of brain activity involved in the mechanism of homeostasis is to ensure that when exhaustion develops to some degree, the exercise terminates. As a result, a catastrophic outcome is avoided (Noakes, 2011). According to the same author, before one reaches exhaustion level, fatigue is a condition that people would feel; it is interpreted as a state of sensory perception, in which it may be expressed as a variation within an athlete's pacing strategy. It is the mechanism by which the central nervous system ensures that homeostasis is sustained. It is a complex system where exercise as a behaviour could not be appreciated if the body is studied as a collection of disconnect components. Therefore, the involvement of brain activity during exercise was fundamentally significant in determining total human function.

Brain activity and biomechanics

As far as mechanical efficiency is concern, particularly in cycling, the biomechanical application is critical. The area of neuromechanics, in which it is described as the relationship between movement and brain, is essential in highlighting the response of the central nervous system towards equipment and external environment involved in muscular force production (Tytell et al., 2011). On another note, research by the same author has discovered the link between brain activity and biomechanical mechanism. They found that interaction between the two comprised elements of neural circuits, muscles, environment and body. The body itself represents the motor output in which the movement was executed. Theoretically, the mechanism of neuromechanics comprise cardiovascular function in distributing oxygen and nutrients supply to the working muscles controlled by the central nervous system. In conjunction to this mechanism of neuromuscular function towards environmental demand, understanding in neuromechanics is needed.

According to Li (2004), he discovered that cycling movement controlled by the central nervous system would influence neuromuscular control to regulate the body's postures and pedalling cadence. This connection between the central nervous system and neuromuscular control was due to the presence of signals from the sensory stimulus which is required before the movement could be executed. Furthermore, the same researchers explained that the interactions between neural circuits, body, muscles and environment are crucial to understand despite it being difficult to predict (Tytell et al., 2011).

Scientifically, evidence based on Overton (2013), during a 5-6 min cycling task until failure, cyclists was found to decrease in force or

power in order to increase muscle recruitment and torque production at the hip and knee. Based on this study, as fatigue developed, kinematics and biomechanics are not consistent to the entire exercise as it was supposed to be based on mathematical model. Indeed, performance is reduced when forcing cyclists to adopt a pedaling rate that differs from their self-selected cadences despite being more economical or capable of reducing the onset of neuromuscular fatigue (Abbiss et al., 2009). The reason cyclists are incapable of constantly maintaining in an optimum biomechanical position is presently unclear, however, according to Fujiwara et al. (2013), it might be due to the altering motivation as it restricts self-choice. Thus, understanding the biomechanical of central nervous system, peripheral and brain activity function during exercise is likely to be important in the determination of optimal cycling strategies.

In sports science, biomechanics has become a significant field of study that currently contributes to optimal performance; thus, studies on brain activity using EEG measurement can probably help to identify and link with characteristics of more complex tasks such as movement trajectory and changeability of muscle activation (Enders et al., 2016). It is possible that after such amount of research conducted on it, future research on dynamic movement (Hottenrott et al., 2013) and time to exhaustion exercise will be significantly relevant (Dingwell et al., 2008; Enders et al., 2016).

Brain activity, physiology and biomechanics

According to Noakes (2011), the explanation on how athletes terminate from exercise seems to contradict itself when there is an absence of brain function influence. This is due to the existence of 'end spurt' phenomenon where athletes can push or speed up at the end of the race although they are already tired (Tucker, Lambert, & Noakes, 2006). There is much influence that brain activity would regulate or maintain athletes' homeostasis so that they could delay fatigue and eventually reach optimal performance during competition (Noakes, 2011). In competitive cycling, power output becomes an indicator of mechanical efficiency to determine cyclist performance during training which finally predicts their physiological performance (Reed et al., 2016). Therefore, recent issues on how these functions can influence brain activity is highly in demand. In a high-pressurized situation especially during competition, athletes require high central activation to maintain and sustain high loads (Bailey et al., 2008). Consequently, a decrease of central activation often leads to fatigue and subsequently poor performance since it is related to brain function central mechanism (Noakes, 2012). Previous findings have confirmed that in endurance competitions, the maintenance of a high central activation is required to prevent the reduction of power output and the termination of exercise resulting from central fatigue (Shober & Schumann, 1991) as cited in Ludyga et al. (2016a).

In cycling, as pacing is important especially in time trial and road event, research conducted on it has dramatically increased as stated in the review by Skorski & Abbiss (2017). In their review, previous studies had examined interaction of pacing with physiological, brain activity and biomechanics as these elements were applied and directly contributed towards total cycling performance during competition. As biomechanics involve dealing with variables such as power output, resistance and force to some extent, researchers have come out with theoretical models that highlighted brain activity and physiological characteristics as main variables that command the regulation of pacing during exercise and race (Gibson et al., 2006; Pageaux, 2014; Renfree et al., 2014).

Fig 1 shows the interaction between brain function, physiological capability, biomechanical function and performance. Sensory feedback in this figure represents sensory information through afferent pathways in order for brain to monitor further action. The sensory receptors would respond from auditory and visual feedback integrated with information stored within the brain as well as reflection from recognized or uncertain environment. The elements of cognitive, attention, perception, visualization and action refer to brain activity function in regulating homeostasis activity and controlling physiological demand during high intensity exercise. The interaction of cardiovascular function, muscular force production and afferent

sensory feedback were highlighted partially in the model of Abbiss & Laursen (2005). The contribution of their model provided a fundamental guideline for endurance sports to prevent them from early fatigue. Although there is discussion of neural activity with motor unit strategies, the authors' review had summarized that the interactions during prolonged constant load and submaximal cycling exercise is unknown. Thus, it shows that even with all of the theoretical framework or model, research on how brain activity interacts with other body function still needs to be proven through scientific work.

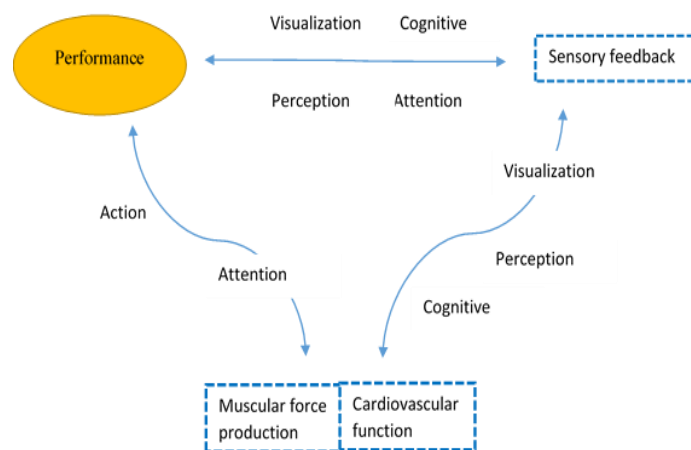


Fig. 1 Interaction between brain activity, physiology, biomechanics and performance

METHODOLOGICAL ISSUES IN STUDIES ON BRAIN ACTIVITY

The methodological issues in studies on brain activity in sports application have been highlighted since a decade ago (Thompson et al., 2008). Investigations of brain activity have transformed from using high cost equipment with limited feasibility in resolving rapid variations of activity (Enders et al., 2016), such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) (Brümmner et al., 2011), to the use of electroencephalographic (EEG) recording which is cheaper, easy to wear, lightweight and has high temporal resolution (Reis et al., 2014). The EEG is also known for its non-invasive nature of high density recording in providing quantitative feedback to practitioners and coaches (Chapman et al., 2008; Cheron et al., 2016; Lopes da Silva, 2010; Reis et al., 2014; Thompson et al., 2008). However, for application in sports setting, there is still a need for improved hardware and software that are able to minimize artifacts. The artifacts that potentially occur are muscle artifact, skin artifact, electrode movement, eye movement, ECG artifact, respiration artifact, tongue movement, electrical interference, and restriction of mobility (De Pauw et al., 2013; Thompson et al., 2008). This was supported by Enders et al. (2016); they indicated that EEG was rarely used in dynamic situations as it is commonly known to have artifacts. However, in recent years, researchers, especially in the field of neuroscience, engineering, physiology and biomechanics have identified the need of EEG recordings in research related brain function during activities such as walking, running, jumping and cycling. Due to this need, there have been two major development to ensure that it is more feasible to be used in experimental settings. The first development was that EEG sensors have been made to become smaller, amplified at the source and more noise robust (Reis et al., 2014). The second major development was on the data analysis techniques used to deal with noise, cable and movement artifacts, sweating and muscle activity (Enders & Nigg, 2015).

The use of EEG in sporting research, either in the context of exercise or for competitive purposes, has always been more dominant among less dynamic sports. In the methodological issue highlighted when acquiring signal from EEG during exercise was that perspiration

rate potentially increases the risk of electrode bridging which results in a distortion of signal. Some of the researcher designed reading the signal during pre and post exercise; however, this will contribute to the loss of information due to time delay between the post measurement and at the end of the first exercise bout (De Pauw et al., 2013). Due to these issues, less dynamic movement during locomotion, such as static or cyclic motion, was found to be able to minimize artifacts. In fact, these type of movements enable research to be conducted in the lab setting. However, recent development in mobile EEG technology provides an opportunity in tackling many issues related to neuroscience and sporting behavior despite having challenges to move out from the lab (Park et al., 2015).

THE BIOMARKERS OF EEG RELATED TO CYCLING PERFORMANCE

Table 1 The biomarkers of EEG related to cycling

Brainwaves	Previous study	Variables	Corresponding function
Alpha/beta ratio	(Ludyga et al., 2016)	Effects of high cadence	Vigilance
Alpha/beta ratio	(Ludyga et al., 2016b)	High vs low aerobic power	Neural efficiency
Alpha, beta	(Ludyga, et al., 2016a)	High versus low cadence upon aerobic performance	Sensorimotor processing, arousal
Alpha, beta, gamma	(Enders et al., 2016)	High intensity cycling exercise	Fatigue, motor control
Beta	(Jain et al., 2013)	Pedaling	Sensorimotor processing
Alpha, beta	(Hottenrott et al., 2013)	Cadence and relationship with heart rate, blood lactate and RPE	Fatigue
Alpha, beta	(Comani et al., 2014)	Attentional focus, optimal performance	Arousal, attentional focus, motor commands
Beta	(De Pauw et al., 2013)	Prolong cycling, recovery	Sensorimotor processing, fatigue,
Alpha	(Robertson & Marino, 2015)	Exhaustion	Arousal, attention

In this part, it is the author's intention to discuss the issues of EEG biomarkers related to cycling performance. As previously mentioned, studies on application of sports neuroscience in more dynamic natured sports are still rare. A previous study had summarized five major EEG biomarkers based on type of brainwaves which are delta, theta, alpha, beta, gamma (Cheron et al., 2016). For the purpose of this review, only biomarkers of EEG specifically for cycling performance was highlighted. Based on Table 1, most studies conducted on brain activity in cycling context are based on alpha and beta waves as well as alpha/beta ratio. Therefore, the discussion will emphasize on these two brainwaves and their ratio. These brainwaves mostly focused on basic movement in cycling in which cyclists have to pedal to move the bicycle. When a cyclist is pedalling, all reactions and mechanisms from the human physiological and biomechanical aspects as well as brain activity are involved.

There is contradicting finding on the effect between low cadence training and high cadence training among cyclist. The brain cortical activity showed changes in the frontal area for low cadence training at baseline and after the intervention. On the other hand, for high cadence training, the alph/beta ratio did not show changes after the intervention period. This demonstrated that exercising at high pedalling frequencies

allowed cyclists to complete similar load with less brain cortical activity. Consequently, this leads to neural efficiency which ensures reservation of cortical resources for prolong workloads (Ludyga et al., 2016). In fact, neural efficiency during resting state was suggested to predict performance as it simultaneously measures cognitive and motor performance (Klimesch, 1999). Most of the time, neural efficiency was often used to compare between trained and untrained athletes. Other previous studies showed that trained subjects performed visual, cognitive and motor performance with less brain cortical activity compared to untrained subjects (Claudio et al., 2010; Del Percio et al., 2009)

It has been supported by the other study which stated that reducing alpha and overall spectral power will produce similar improvements in aerobic power for low and high cadence training. However, high cadence training could prepare cyclists to maintain high performance in endurance. In addition, it can also improve the central and peripheral adaptations delaying fatigue among cyclists (Ludyga et al., 2016a).

Compared to resting state, the alpha/beta ratio decreases during cycling exercise as beta power increases more than alpha power (Ludyga et al., 2016b). Increased beta activity reflects higher cortical activation which might be the result of greater processing demands during exercise and the tendency of the sensorimotor system to maintain the network (Engel & Fries, 2010). As alpha power serve as an inverse indicator of mental alertness or arousal, it can be assumed that a lower level of arousal at rest is due to greater relaxation ability in subjects with higher maximal oxygen consumption (VO₂max) (Nielsen et al., 2001). It was supported by Jacobs (2001) who further explained about beta power with high cadence training will decrease as a response of EEG to relaxation.

High cortical activation is necessary to provide high performance and power output in cycling. As explained by Noakes (2011), cycling performance is controlled by the central nervous system regulatory mechanism. This control mechanism does not restrict the functions of the heart or skeletal muscles but it regulates the power output by controlling the number of recruited muscle fibres or motor units involved in the working muscles. Training at different cadences seems to be the key to respond to different requirement during a race. In order to increase power output at higher cadences, higher cortical brain activation is necessary (Hottenrott et al., 2013).

De Pauw et al. (2013) observed decrease in beta waves activity especially in the higher ranged frequency (18.5-21 and 21.5-30Hz) across the entire brain area. Consequently, performance are more probably diminished because of inhibitory signals from the thalamus-hypothalamus to different brain areas that are involved in sensory and motor processing. Another possible reason that led to this result was that it involved emotional processing resulted by frequently training at high intensity in preferred sport. It could create a sense of well-being, calmness and positive emotions. These occurred in regular cyclists as they were involved in proper and consistent training programs. However, this study may need further analysis and discussion on how alpha waves contributed to the performance decrements. It is important as the alpha wave is recognized as mainly responsible for relaxation in contrast to arousal (Gutmann et al., 2015). In fact alpha waves could express cortical function of arousal, attention, motivational state and correlating information processing across brain regions (Robertson & Marino, 2015). Furthermore, in the same study, they proved that during incremental exercise test, there was decrease in alpha waves activity specifically on respiratory compensation point especially within ventrolateral prefrontal cortex. Based on the previous studies shown in Table 1, only this particular study highlighted the significance of brain region function. In sports, it is necessary to look into the interaction of mental relaxation and musculoskeletal work demand where both leads to either negative or positive performance outcome.

While most researchers focused on changes in brain activity caused by movement in cycling, one group of researchers conducted a study on how different attention could change cyclist's brain activity (Comani et al., 2014). The study proved that the right attentional focus can determine optimal performance during high-fatigue or stressful situation. They claimed that when cyclists focused on the external

environment, it would lead to superior performance. Other than that, altering brain activity function also can be employed by inserting or mind setting the right attentional strategies which could lead to optimal performance (Bertollo et al., 2015). In fact different tasks or desired outcomes require different attentional strategies (Comani et al., 2014). However, individual level of competitiveness may produce different result of performance. They may need different attentional strategy due to the difference in brain activity which resulted from genetic and training (Yarrow et al., 2009).

The results of EEG coherence of the alpha beta band showed that the alpha band indicates lower arousal state and are accompanied with higher alpha power eventually required in goal-directed behavior. It was further explained that it is related to attentional focus on the components of action and the feeling of muscle fatigue. On the other hand, the beta band from this study indicates that there is an involvement with sensorimotor processing that is associated with resistance to movement, voluntary action as well as emotional capacity in coping with fatigue. Thus, future researchers may look into different sports as they may require different attentional focus during competition. Apart from that, there is also a need to study the physiological and biomechanical influence towards a cyclist's attentional focus that may potentially lead to neural efficiency.

FRAMEWORK OF EEG BIOMARKERS

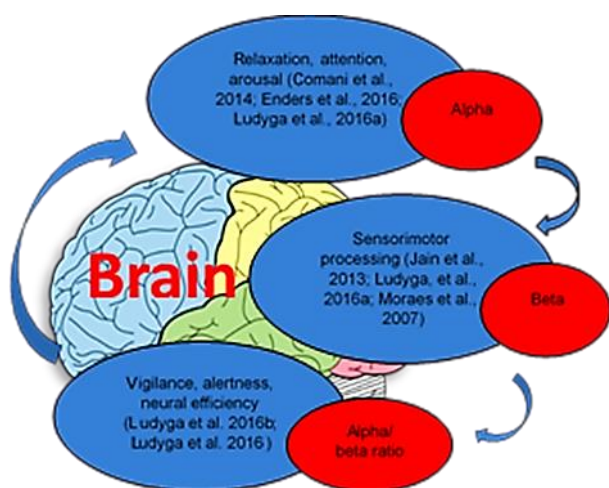


Fig. 2 A theoretical framework of EEG Biomarkers and its corresponding function of cycling

Based on previous studies, this review came out with a simple framework to present potential EEG biomarkers and its corresponding function with regards to cycling performance and exercise. According to Fig. 2, the alpha and beta brainwaves along with the alpha/beta ratio play important roles in identifying the mechanism of cyclists' physiological functions and required movement to achieve optimal performance. Nevertheless, this framework is limited to studies shown in Table 1. Therefore, it is essential to form such adaptation from theoretical aspects in determining mutually defined terms towards specific physiological and biomechanical perspectives. Furthermore, identification from specific brain region is also critical as it differs from each other in terms of its function.

GAMMA WAVES IN CURRENT AND FUTURE BIOMARKERS

Based on the review from Cheron et al. (2016), study of gamma brain activity with EEG has started to gain interest from researchers especially in relation to sensorimotor task, perception, attention, working memory and associative memory. Other scholars found gamma brain activity to be relevant to assessing sensory and cognitive brain function (Reis et al., 2014), complex activities of information processing (Colgin et al., 2009), visual motor processing and facial feature (Muthukumaraswamy, 2010; Tang et al., 2011). In regards with

the limitations of artifact in EEG, study conducted by Yuval-Greenberg et al. (2008) does not raise any doubt about the processing from intracranial signal. However, it highlighted a few things that need to be controlled in analysing any type of sports behaviour. Previously, cognitive performance has been conducted via global IQ test in which it is not practical to assess specific cognitive functioning associated with exercise and fitness level (Hillman et al., 2005).

Nevertheless, recently, there is study conducted to measure relative gamma in which it describes as a power ratio between gamma (25-45 Hz) and slow rhythm (4-13 Hz) among healthy subjects (Minguillon et al., 2016). This result showed a positive correlation with expected stress level and heart rate at the prefrontal brain region. As relative gamma was explained upon stress and relaxation components, it is best that to be addressed as a marker to quantify stress level during relaxation/stress situations. The previous work done on relative gamma were limited to meditation states among experts and novices (Lutz et al., 2004; Steinhubl et al., 2015).

Previous review from Gruzelier (2014) particularly on neurofeedback expressed that gamma training (36-44 Hz) improves recollection in long-term memory and perceptual binding. In addition, the earlier study of gamma waves revealed that by inducing gamma activity, it showed human emotional intelligence capacity (Jaušovec & Jaušovec, 2005). In their research, they described that individuals with capability in solving problems was the result of having superior verbal/performance intelligence in their cognitive skills. Later, this study was supported by Herrmann et al. (2010), who found that gamma waves reflected cognitive processes that could be a foundation for attention, binding, object representation and language. It is possible to study gamma waves as biomarkers to indicate cognitive and high mental processing in athletes, as each of them should be able to respond accordingly when facing uncertain situations in which it may not be a usual process during training.

A CONCEPTUAL FRAMEWORK OF OPTIMAL CYCLING PERFORMANCE

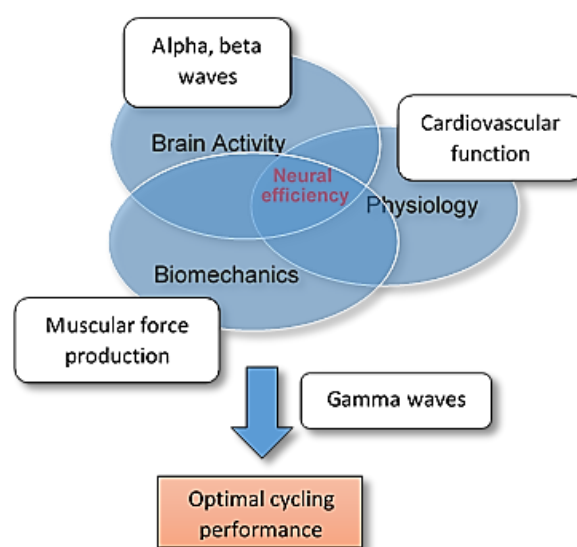


Fig. 3 A conceptual framework of optimal cycling performance.

From the discussion of interaction between brain activity, physiology and biomechanics, Fig. 3 showed a conceptual framework that could potentially be used for future practices and research with regards to optimal cycling performance. All main variables and elements in cycling performance included in this conceptual framework has been scientifically proven in previous studies (refer to table 1). In the framework, neural efficiency is a product of integration of alpha, beta waves, cardiovascular function as well as muscular force production. It has been proven to be the centre of optimal cycling performance despite inconsistency in gamma waves studies to link specific mental capacity with human physiological function and

biomechanics. Nevertheless, few studies on justification of gamma waves in cognitive and high mental processing could be a forerunner in finding the interaction between brain activity function and motor performance.

CONCLUSION

There is a lot of areas in relation to brain activity that can significantly contribute to improvement of cycling performance as well as in reaching peak performance. At resting state, different EEG rhythms among trained and untrained athletes (Del Percio et al., 2009), consequently suggest that each individual has different potential. Generally, despite all the effort in developing feasible methods of EEG measurement, the endless work on methodology used in future studies should be continuously studied. Specifically to cycling performance, current researches have highlighted the interaction of brain activity with physiological function and basic movements in cycling. However, whether it is critical to the outcome of a race, there is a great need to identify what makes a difference between a winner and a loser. Identifying the specific mechanism of solution on this matter may vary from one situation to another of specific task in sports or an event. Therefore, the future in these area will involved multidisciplinary field to ensure it is fundamentally established and progressed.

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