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REVIEW

Review of exercise-induced physiological control models to explain the development of fatigue to improve sports performance and future trend



Examen des modèles de contrôle physiologique induits par l'exercice pour expliquer le développement de la fatigue afin d'améliorer les performances sportives

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Received 18 October 2017; accepted 5 October 2018

Available online 15 December 2018

KEYWORDS

Sports performance;
Sports physiology;
Physical fatigue;
Mental fatigue;
Mathematical modelling and analysis

Summary

News. – Sports performance is the pursuit of excellence where a sportsman measures his or her performance quantitatively or qualitatively to move towards his or her desired goal. Several physical aspects can influence sport performance. One of these aspects is the neuromuscular factor Tsolakis and Tsolakis (2008) that arises from the relationship between the nervous system, and the musculoskeletal system. Moreover, in many sports (for example, running and cycling), the establishment of an effective rhythm will keep an athlete organised, and physically efficient for an excellent performance. Subsequently, this rhythm will impose a cadence on musculoskeletal activity, mental control as well as psychological factors. These psychological factors can be self-motivation, level of alertness and mental acuity that are the product of a number of integrated factors like physical fatigue or other unrelated sport stresses such as environmental conditions that are not within the athlete's personal control. The athlete is required to have the ability to adapt in these unexpected environmental factors. Another aspect is coaching and external support/assistance for the athlete (in terms of nutrition, sport technique, tactics and training) to the aspiring competitor for success to occur. Amidst all these

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MOTS CLÉS

Performance sportive ;
 Physiologie sportive ;
 Fatigue physique ;
 Fatigue mentale ;
 Modélisation et analyse mathématique

factors which influence sports performance, there is one crucial factor which cannot be overlooked and it is the exercise-induced fatigue which causes a reduction in physical and mental performance.

Conclusion. – Therefore, in this review, we describe and discuss the various physiological theoretical models of exercise-induced fatigue, and the way forward to assess these theories using mathematical models and analysis of biosignals.

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Résumé

Actualités. – La performance sportive est la poursuite de l'excellence du sportif qui mesure sa performance quantitativement ou qualitativement pour aller vers son but désiré. Plusieurs aspects physiques peuvent influencer la performance sportive. L'un de ces aspects est le facteur neuromusculaire entre le système nerveux et le système musculosquelettique. De plus, dans de nombreux sports (par exemple, la course à pied et le cyclisme), l'établissement d'un rythme efficace gardera un athlète organisé et physiquement efficace pour une performance excellente. Par la suite, ce rythme imposera une cadence sur l'activité musculosquelettique, le contrôle mental et les facteurs psychologiques. Ces facteurs psychologiques peuvent être l'auto-motivation, le niveau de la vigilance et l'acuité mentale qui sont le produit d'un certain nombre de facteurs intégrés comme la fatigue physique ou d'autres contraintes telles que les conditions environnementales qui ne sont pas dans le contrôle de l'athlète. L'athlète doit avoir la capacité de s'adapter à ces facteurs environnementaux inattendus. Un autre aspect est le coaching et le soutien ou l'assistance externe pour l'athlète (en termes de nutrition, technique sportive, tactique et entraînement) à l'aspirant concurrent pour que le succès se produise. Parmi tous ces facteurs qui influencent la performance sportive, il y a un facteur crucial qui ne peut pas être négligé et c'est la fatigue induite par l'exercice qui provoque une réduction de la performance physique et mentale.

Conclusion. – Par conséquent, dans cette revue, nous décrivons et discutons les différentes modèles théoriques physiologiques de la fatigue induite par l'exercice et la voie à suivre pour évaluer ces théories en utilisant des modèles mathématiques et l'analyse des biosignaux.

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1. Introduction

Exercise physiology concerns the study of the function and characteristics of the living systems [1]. Therefore, exercise physiologists should not only know how the different parts of an organism work together to achieve a particular function, but also they should have a thorough understanding of how the human body responds to exercise and training [2,3]. Then, these concepts that are developed from exercise physiology can be used to train the athlete, and improve the athlete's sport performance [4]. One detrimental factor that affects sport performance is exercise-induced fatigue which results from excessive exertion leading to a decrease in bodily and mental functions [5]. Therefore, in this context, in order to improve sports performance, there is a need to investigate how to delay the onset of exercise fatigue, or to decrease the rate of development of fatigue during exercise, or how to use efficiently the available metabolic resources in the body to complete a physical activity without catastrophic physiological system failure [6–9].

Various theoretical control models of fatigue have been proposed [7,10–14] with the aim of providing a clearer picture of the underlying mechanisms of fatigue either from

energy or biorhythms perspectives. However, these physiological models cannot explain exactly the cause and effect of fatigue on sports performance. Next, we describe these theoretical models and how they have evolved through time, and we discuss the concepts underlying these models. Then, we propose the development of mathematical models and analysis of physiological signals to help in understanding and assessing the theoretical models of exercise-induced fatigue.

2. Evolution of exercise-induced physiological theoretical models

Currently, the physiological theories to explain the cause and the effect of fatigue on exercise performance include the [6,8,12–16]:

- cardiovascular/anaerobic/catastrophic model;
- energy supply/energy depletion model;
- thermoregulatory model;
- teleoanticipation model;
- integrative central regulator model;

- neuromuscular fatigue model;
- task dependency model;
- psychological/motivational model.

2.1. Cardiovascular/anaerobic/catastrophic model

The cause of the exercise-induced fatigue which is developed during high intensity exercise of short duration is still unknown. From studies of Fletcher and Hopkins (1907) [17] and that of Sir Archibald Vivian Hill, and colleagues [11], it was suggested that this form of exercise is limited by a peripherally-based metabolite that induced failure of the skeletal muscle contractile function independent of the reduction in skeletal muscle activation which is caused by the central nervous system (CNS) [8].

The classical theory, also defined as the cardiovascular/anaerobic/catastrophic (CAC) model of exercise physiology, states that the fatigue associated with high-intensity exercise results from a skeletal muscle "anaerobiosis". This "anaerobiosis" is developed when the increasing oxygen demand of the exercising muscles cannot be supplied by the heart [8,11]. Therefore, this inadequate oxygen supply to the exercising muscles prevented the neutralisation of the progressive accumulation of lactic acid that Hill (1923) believed would prevent skeletal muscle relaxation leading to skeletal muscle rigor [8,11,18]. However, it is known that it is the depletion of adenosine triphosphate (ATP) within the exercising skeletal muscle that causes rigor [19]. According to the CAC model, during maximal exercise, fatigue occurs when the cardiovascular system is unable to provide the required amount of oxygenated blood to the active muscle and the waste products accumulate in the skeletal muscle. Subsequently, an endurance athlete would rely primarily on anaerobic metabolism which would result in a higher blood lactate accumulation during physical activity [20]. It is believed that for endurance time trial exercise lasting more than 30 minutes that the lactate threshold is a crucial factor as it represents a good predictor of endurance performance in various sports such as cycling (Farria et al., 2005) [21].

2.2. Energy supply/energy depletion model

The cardiovascular/anaerobic model is further extended into another model called the energy supply/energy depletion model that associates fatigue during exercise to the failure of the energy metabolic pathways to produce sufficient amount of energy (ATP) to the active muscles, or to the depletion of endogenous substrates such as carbohydrates [22]. This model highlights energy conservation through energy pathways (i.e., the anaerobic system and the aerobic system) and incorporating a strategy to utilise efficiently the available metabolic energy resources during the exercise. Shulman and Rothman [22] (2001) stated that athlete who had greater amount of glycogen in muscles at the start of the physical activity had an extended duration of exercise to fatigue by being more resistant to this exercise-induced fatigue. In the same line of thought, there is a subset of the energy supply and energy depletion model which explains the onset of fatigue by regarding the muscle as elastic energy systems which is called the biomechanics model involving the biomechanics of the human body.

This model states that the role of muscles is regarded as elastic energy systems which work in the same principle as springs and torque producers during physical activity [23]. This model predicts that the more elastic is the muscle, the less torque this particular muscle is required to produce which in turn increases the efficiency of the muscle system. This will eventually enhance sport performance, especially in weight-bearing activities such as running, by decreasing the rate of substrates accumulation that might induce exercise fatigue; and by decreasing the rate of rise of body temperature so as the physical body is delayed in reaching critical core temperature, which is responsible in preventing exercise activity [8].

2.3. Thermoregulatory model

Environmental conditions greatly affect exercise ability [24]. The thermoregulatory fatigue model proposes that when the human body core temperature increases to a critical level of about 40°C, fatigue occurs [25]. This is because the central nervous system (CNS) has a reduced ability to maintain a constant neural drive [24] at or above this critical temperature of 40°C. During prolonged exercise, the beginning of hyperthermia (i.e., body temperature much above normal) is related to a reduction in cerebral circulation that results in a decreased supply of substrates or metabolic resources to and from the brain [24].

2.4. Teleoanticipation model

In contrast to the previous physiological models that focus on the efficiency of expenditure of the energy systems, Ulmer (1996) proposed a totally different hypothesis of the physical fatigue during exercise. He proposed a hypothetical model of a control system which optimised performance especially during heavy physical activity [13]. This model was founded on a standard feedback control loop where efferent signals from the central nervous system (CNS) contain information to determine muscle metabolic rate and exercise intensity. Afferent signals from the muscles or peripheral organs feedback information to change movement and power output to optimise sport performance accordingly. It was also proposed (Ulmer, 1996) that the model was more complex than this simple feedback control loop when taking into consideration the additional presence of endogenous reference signals, and factors such as training, muscle reserve, muscle metabolic rate and past experiences [13]. This subsequently gave rise to the 'teleoanticipation model' which included both feed forward planning and feedback control from afferent changes, which are principally regulated by the known endpoint of an event and the distance still to be covered to complete that event.

2.5. Integrative central regulator model

Working from the teleoanticipation model, another model of integrative central neural regulation of effort and fatigue was proposed [6,12]. In this physiological control model, it was suggested that physical activity is regulated by a central controller in the brain, and that the human body functions

as a complex system during exercise. In this model, a central regulator paces the body during exercise to make sure that the physical activity is completed without homeostatic failure by sending and receiving information to and from central and peripheral sensors and body systems in a deterministic manner [6].

2.6. Neuromuscular fatigue model

The neuromuscular fatigue model or the central fatigue model states that it is not the rate of supply of substrate (i.e., oxygen/fuel) to muscle that limits the performance during physical activity but rather the processes involved in the skeletal muscle recruitment [26]. The nervous system is important in coordinating physiological responses in the human body and the neuromuscular fatigue model also suggests that there is a reduction in force or power output despite the fact that perception of effort increases. This reduction in force or power is suggested to be associated with central activation failure (i.e., a reduction of muscle activation by the CNS) or the neuromuscular propagation failure (i.e., the decreasing response of the muscle to an electrical stimulus). The decreasing ability of the muscle to respond to an electrical stimulus is due to the reduction in the muscle action potential called the *M-Wave*. The reduction in *M-Wave* occurs when there is a decrease in ionic transmembrane gradient such as sodium and potassium ions [27,28]. The studies that supported the idea that fatigue is linked to the CNS have examined and found changes in the CNS neurotransmitter (serotonin and dopamine) concentrations in the brain during prolonged exercise that in turn was suggested to diminish the level of arousal (excitement) and skeletal muscle recruitment [29] which are altogether related to an increase in the perception of effort that eventually affects exercise performance. Therefore, this evidence demonstrates that the central nervous system fatigue model contributes to fatigue during prolonged exercise lasting tens of minutes to hours [30].

2.7. Task dependency model

Following the neuromuscular model and the integrative central controller model, it was argued that various studies [4] indicated that decreases in performance, owing to exercise-induced fatigue, cannot be explained fully by any one of these models [14]. Instead the concept of task dependency model was recommended as a suitable model of fatigue in which mechanisms of fatigue vary depending on the specific exercise and this model includes characteristics of the central and peripheral contributions to fatigue, and their relative importance depends on the type of exercise [14].

2.8. Psychological/motivational model

This model postulates that the capability to maintain exercise performance comes from a conscious effort, and is frequently included as an additional component of the central fatigue model hypothesis [26]. However, this model does not support one principle of the muscle recruitment model which holds that performance during exercise is controlled

at a subconscious level. The psychological/motivational model does not agree that the conscious brain can override fundamental physiological functions and cause irreversible damage to the human body.

3. Discussion based on the concepts of physiological control models

Following the various postulations of these physiological control models, it is clear that there is an uncertainty of these biological theories in successfully explaining the real cause of fatigue during physical activity. By taking into account the different factors that influence sports performance based on the theories of these exercise physiological models, we will discuss the following important concepts:

- energy system pathways that are aerobic and anaerobic systems;
- exercise-related central fatigue and nutrition metabolism;
- pacing in competition and the relationship between pacing and ratings of perceived exertion (RPE);
- effect of biorhythms on sports performance;
- homeostasis in physiological systems;
- arousal state for optimum performance (cognitive load and information processing);
- mathematical modelling and analysis of biological signals in exercise physiology.

3.1. Energy system pathways and physical activity (anaerobic and aerobic)

Fatigue is a common feeling which is experienced by everyone daily such as during long vigorous physical activity. In the sporting competitive events context, athletes' performance is influenced by fatigue. Generally speaking, the moment at which physical activity ceases is termed as the point of exhaustion in human studies. The feeling of fatigue occurs before any damage to the human body systems, and it is termed the "volitional fatigue" which indicates that the human beings made the decision to stop exercising. Therefore, exhaustion can be defined as the extreme fatigue which is a state in which a human being may exceed his or her physiological capacity and then they experience the homeostasis catastrophic failure [31,32].

To perform a marathon run or sprint, skeletal muscle is fuelled by one compound [33], the adenosine triphosphate (ATP). ATP is an organic compound (with chemical formula $C_{10}H_{16}N_5O_{13}P_3$) which consists of high-energy bonds, and is utilized to transport energy to cells for biochemical activities such as muscle contraction through its hydrolysis (i.e., reaction with water) to ADP (adenosine diphosphate) [34]. The human body stores a small amount of this energy currency which is sufficient to meet the energy demands of an all-out explosive exercise for a few seconds [4]. Firstly, the ATP-PCr (Adenosine Triphosphate-Phosphocreatine) system will produce about 5 to 8 seconds worth of energy in an all-out activity such as sprinting after the initial storage of ATP in the muscles is used up [4,35].

Then, for longer duration or activity, the lactic system predominates whereby carbohydrate is broken down and

used to produce ATP in a metabolic process called the anaerobic glycolysis. The chemical reactions, during anaerobic glycolysis, take place without the presence of oxygen, and the by-product of anaerobic exercise is lactic acid [20]. This lactic acid system can be the source of fuel to an athlete for about 45 seconds, and for exercise duration greater than this, the aerobic system will begin to predominate [35]. During the aerobic exercise, the human body has enough time to use oxygen in the biochemical reactions [20]. Therefore, the availability of energy resources and the rate of production of energy resources differ for different type of exercise-bout physical activity and an athlete should be able to use efficiently these resources in a running/sprinting competition for instance. One possible way of determining the proper allocation of energy resources through time is the use of mathematical modelling in determining the rate of energy production through these two energy system pathways.

3.2. Exercise-related central fatigue and nutrition metabolism

The definition of exercise fatigue could be as an interruption of muscular activity due to substrate depletion which provides energy for muscular contraction, and metabolite accumulation in the body [36]. However, exercise fatigue can originate from both on the peripherally (skeletal muscle) or centrally (central nervous system-CNS) [37]. On the other hand, above definition of exercise fatigue mostly defines peripheral fatigue but as to the central fatigue, there are a huge body of evidence which implicates CNS role producing fatigue during exercise. And simply central fatigue (CF) is described as the impairment of the CNS to induce skeletal muscle to produce force during exercise [38]. Some metabolites, which are produced in the brain like neurotransmitters and monoamines, which include serotonin (5-hydroxytryptamine, 5-HT), dopamine and noradrenaline have been known to play a crucial part in the development of the central fatigue [39]. Secondly, it was first mentioned that plasma amino acid level could affect brain serotonin level during exercise particularly [40]. As a result, the level of metabolites' changes in the brain could affect perception of fatigue and exercise performance individually. Cognitive function plays an important role in sports performance and as a consequence there are specific dietary products that affect our cognitive function such as caffeine which can enhance performance as well as reduce the perception of effort during prolonged physical activity and also influence specific reward centers in the brain. There are also plant products and herbal extracts that are ginseng, ginkgo biloba and polyphenols that are marketed as supplements in order to boost sports performance [41]. Moreover, two metabolic explanations over central fatigue bring up new nutritional issues such as: carbohydrate and amino acids (BCAAs, tyrosine), to manipulate fatigue perception centrally.

3.3. Carbohydrate

Substrate provision, particularly CHO, must be maintained both peripherally and in the CNS during exercise. Moreover, it has been shown that muscle fatigue due to CF was related to directly hypoglycaemia existence [42]. Beside, 1 hour high

intensity endurance exercise performance was improved with CHO feeding with minimal muscle glucose uptake [43]. Interestingly, it was recently shown that the brain glycogen stores might be important during long duration exercises [44]. Another interesting topic is CHO rinse during exercise. There have been shown exercise performance benefit with CHO rinsing by several time trial and endurance exercise studies [45–47]. These studies are implied that brain CHO metabolism has become an integral part of exercise fatigue. As to CHO supplementation dosage in the recent review, it was advised minimum level 2.67 g/kg BW CHO intake in order to decrease CF and improve exercise performance [48].

3.4. Amino acids

BCAAs: the key roles of BCAAs leucine, isoleucine, and valine in the brain metabolism were reviewed by Fernstrom in detail [49]. They have an important mission over protein, 5-HT, dopamine, noradrenaline synthesis and energy production [49]. BCAAs supplementation has been thought a smart way to reduce central fatigue but studies over this issue provided limited evidence and remained inconclusive [50–52]. There is one metabolic explanation over the failure of BCAAs supplementation to improve exercise performance could be rise in ammonia production which might reduce tyrosine uptake across the blood-brain barrier [37].

Tyrosine: tyrosine (4-hydroxyphenylalanine) containing some foods are yogurt, cheese, milk, chicken, soy based products, turkey and almond. Some animal studies indicated that tyrosine decreases negative effects of acute stress on cognitive performance, it has been also shown similar results in sleep-deprived and chronically stress exposed humans [37,53]. However, tyrosine supplementation studies during exercise remained inconclusive to show clear effect of tyrosine on exercise performance and central fatigue [50,54].

Here, a linear mathematical simulation model could be devised for any particular physical activity to integrate input factors such as metabolites, and plasma amino acid level and the output of such mathematical model being the perception of mental fatigue.

3.5. Pacing in sporting activities

The changes in the pattern of speed or velocity during a time-trial race (e.g. running), has drawn the attention of sport scientists and exercise physiologists to examine the concept of pacing [15,55]. The three well-known types of pacing are negative, positive and even pacing that depend greatly on the event duration and the consequences of slowing down because of power output reduction [56]. It was posited that pacing during physical activity is developed as a preventive measure to optimize sports performance according to the limit of the individual physical or physiological abilities, and hence preventing their physiological systems from large fluctuations in homeostatic disturbances during an exercise bout [12,57]. It was suggested that changes in the concentration of intramuscular metabolites, body core or brain temperature and other physiological factors determine the power output during shorter competitions of 1 to 30 minutes duration. Then, subsequently the conscious brain integrates all these factors together

creating a conscious fatigue which can be measured using the ratings of perceived exertion scale (RPE) [6,13,58], a psychological instrument, to measure sensations of fatigue. Next, we will discuss the influence of the biological rhythms that govern the human behaviour and physical activity. The only way to assess pacing is to analyse mathematically the speed (acceleration/deceleration) of a runner or cyclist through time and the effect of pacing on his perceived fatigue and his overall performance.

3.6. Effect of biorhythms on sports performance

The psychomotor, physiological, cognitive and psycho-emotional processes are all influenced by biorhythms [59,60]. Within the sports performance context, by understanding the patterns of the biorhythms and the energy flow within the human body, the factors that may deter an athlete's optimal performance can be identified.

Now, we look at some common biological rhythms associated with human performance. Firstly, the psychomotor rhythms may affect sport performance through the synchronization of neurotransmitters and motor neuron synthesis for both coordination and reaction time [60,61]. Secondly, the physiological rhythms may also influence performance owing to the synchronization process of neurotransmitters, the ability to generate ATP, the ability to develop lactic acid tolerance for speed as well as strength and power [62] (Nielsen et al., 2001) and the elasticity of muscle fibers for flexibility [23]. Moreover, the physiological rhythms stress the heart to pump as efficiently as possible during endurance exercise [59]. Thirdly, there are also cognitive rhythms which affect performance through memory and attention followed by psycho-emotional rhythms which affect sports performance such as pressures in a competition [59–61].

There are other individual variables that may affect biorhythms including chronological age, eating habits, genetic predisposition, lifestyle, and overtraining [63]. Most athletes who get exhausted during training sessions are experiencing the effect of the body and mind wanting to go back to rest [63]. This affects ultimately their quality of psychomotor, physiological and cognitive rhythms which influences the athlete's potential for optimal performance. Thus, practice and training need to be held at multiple different times throughout the day for elite athletes to gain maximal recovery and high level of training efficiency on a continual basis [63]. These biorhythms can be monitored easily nowadays using high resolution EEG/ECG/EMG equipment and then these biosignals can be quantified to interpret holistically the amount of neural drive and the amount of effort exerted by an athlete while completing a particular physical task.

3.7. Importance of homeostasis within the human body system

An undesirable change in the internal conditions of the human organism could result in disease or death owing to the failure of homeostasis of the physiological systems. Homeostasis refers to the living system ability to maintain a stable set of internal conditions subjected to changes in the external or internal environment [64]. Examples of internal

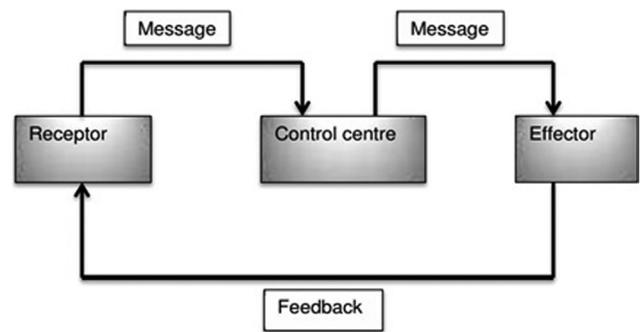


Figure 1 An illustration of the basic processes that happen during homeostasis [65–67].^{63–65}.

conditions are body temperature, blood pressure, and the composition of body fluids which must remain relatively stable for the correct functioning of the human body system. Therefore, to maintain homeostasis, an organism must react to its external environment by making internal adjustments which are activated by homeostatic reflexes [65,66]. For instance, a simple example of homeostatic reflexes occurs when we stay outside on a hot day. Homeostatic reflexes help sustain a constant internal body temperature. Therefore, when the solar heat strikes the skin, nerve endings acting as receptors sense this heat, and send a message to the brain (control centre) which then sends nerve impulses (efferent signals) that cause the blood vessels (effector), in the skin, to expand. The resulting increase in blood flow to the skin produces greater heat loss from the skin surface. The brain also instructs the sweat glands (effectors) to increase production, because evaporation of sweat cools the skin [67]. Fig. 1 summarises all these processes in a simple feedback and feed-forward loop and can be formulated as simulation mathematical model [65–67].

3.8. Arousal state and sports performance (inverted-U model)

From certain physiological control models of exercise-induced fatigue and physiological studies, it was found that changes in the neurotransmitter concentration affect the level of arousal which subsequently affects the skeletal muscle recruitment during physical activity [26–28,30]. The studies [29] that supported the idea that fatigue is linked to the central nervous system found in fact an increase in the dopamine and serotonin concentration in the brain during prolonged exercise. This, in turn, diminishes the level of arousal and skeletal muscle recruitment [29] that eventually impoverishes exercise performance. Cutsem et al. (2017) investigated 11 research articles in this particular topic of the effect of mental fatigue on physical performance. They found that the intensity and the duration of the physical activity seem to be crucial factors in the decline of physical performance owing to mental fatigue. They found that the decline in endurance performance was due to reduced time to exhaustion and also self-selected velocity and power output or owing to an increase in completion time because of mental fatigue which is related to higher than normal perceived exertion [68].

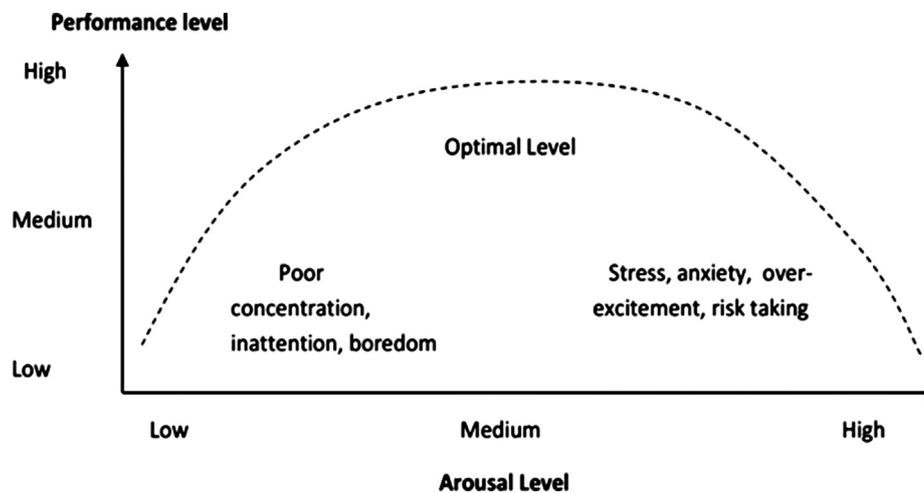


Figure 2 Level of performance as influenced by level of arousal [69].⁶⁶.

Furthermore, Yerkes and Dodson [69] observed that as the arousal level increases, the physical and mental performance of an individual also increases accordingly but only up to a critical point called the optimal level (Figs. 2 and 3) [66], where performance is highest where ideally, an elite athlete is expected to reach. However, too much arousal will cause mental and physical performance to decrease like in cases of a stressful environment. This arousal level can be employed effectively in a computational model which can be used and customised as a biofeedback for a particular athlete to improve his or her performance and feels more confident in his or her endeavours to sports excellence.

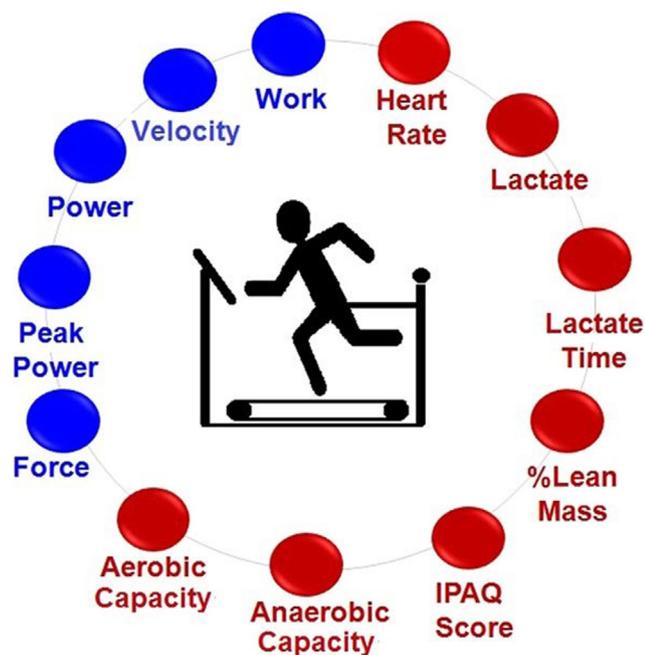


Figure 3

3.9. Importance of mathematics in biological systems

Following the descriptions of the various exercise physiological model of exercise-induced fatigue and the key underlying concepts, we emphasize the importance of mathematics in biology or physiology as it aims at the mathematical representation and modelling of biological processes. From this review, we have noticed that there are a lot of theoretical models which endeavour to explain the exercise-induced fatigue. However, in order to investigate these human exercise-induced fatigue models which comprise of various types of endogenous and exogenous parameters (physiological, physical and environmental) while undertaking a particular physical exercise activity in a particular environment, this complex system requires the use of mathematical models to investigate the influence of those parameters on the human performance.

In the same line of thought, Burnley and Jones (2018) demonstrated that the failure to continue very high intensity physical activity is a physiological phenomenon which involves various mechanisms that interact altogether and thus this indicates that there is a difference between the instantaneous power supply and neuromuscular power demand. They also stated that there should be valid integrative models of fatigue to validate these statements and these models should account for the Power duration relationships and its physiological basis [70].

Another instance where the use of quantitative values are needed to compute sports performance or monitor exercise fatigue is the rate of force of development. Rodriguez-Rosell et al. (2017) reviewed the rate of force of development in the aims to help coaches and sports scientist in the field to improve sports performance in high intensity exercise. The rate of force development (RFD) is the ability of the neuromuscular system to augment contractile force from a low or resting level when muscle activation is performed as fast as possible. The RFD is an important parameter for those athletes who require high-speed actions. The RFD estimates the amount of fatigue and recovery after acute exhausting exercise [71].

Furthermore, by describing the biological systems in a quantitative way, their biological behaviour can be simulated and their properties can be predicted which may not be an easy task to the biologist or physiologist [72]. Also recent development of mathematical tools can help understand the complex, nonlinear mechanisms in living systems as well as an increase in computing power can help perform lengthy or difficult calculations and simulations quicker [73,74]. Currently, there are various mathematical tools that are currently being used in medicine and biology and these mathematical methods could be applied in this sports science and sports physiology research to probe into the functioning of the various physiological systems to investigate the cause and control of fatigue during physical exercise. For instance, to understand the regulation of physiological systems, it is necessary to differentiate between deterministic and stochastic signal as the common characteristics of biological activities [75]. A signal is said to be deterministic if its future values can be produced according to a set of known parameters and rules [76].

Another mathematical tool is the use of Shannon entropy. Certain physiological control of exercise fatigue [8,26] states that there is a conscious neural effort that maintains physical performance. The entropy of a signal is becoming an emerging and promising mathematical method in quantifying the amount of information flow especially in the electroencephalogram (EEG) signals [77]. The information entropy was initially developed by Shannon [78] (1948) to measure and evaluate the information content of a transmitted communication signal. Therefore, the entropy (H) is defined as the average amount of information per source output. From the entropy measures as well as with electroencephalography (EEG) and event related potential (ERP) metrics, one is able to observe any changes or make associations in the brain activities with cognitive performance. This can help in favouring or refuting some of the concepts of the proposed exercised-induced theoretical models. By analysing physiological signals that are encephalography (EEG), electromyography (EMG) and electrocardiography (ECG) data, one can quantify the amount of cognitive and physical neural effort employed by an athlete while undertaking a particular physical activity.

Moreover, linear and nonlinear mathematical simulation models can be used to model the various physiological theories that endeavoured to explain the onset of exercise fatigue. By using mathematical models, one can focus or isolate certain factors of the model and vary this factor and observe the effect of this factor or variable on the output of the simulated model. In so doing, one can have a more concrete perception of the exercise-induced physiological control model of fatigue in favouring or refuting some of the proposed models. By using mathematical modelling and analysis, we can slim down the number of proposed models rather than more and more theoretical models being created.

Furthermore, the control and measurement of fatigue and recovery in competition and training contexts comprises a complicated task, generally speaking, one needs expertise in physiology, psychology as well as sports science in order to contribute to a successful implementation of a monitoring routine. Therefore through the development of mathematical models in each discipline can alleviate this tedious task

and hence can provide useful recommendations to the coach and athletes and to individualised athletes. Individualisation process is a pivotal and challenging task in the monitoring of research and practical environments. Kellmann et al. (2018) stated that future recovery studies should develop holistic models in order to create practical procedures for diagnostic, intervention, evaluation purposes [79].

4. Conclusions and future research

The fatigue which is developed during exercise seems to be a 'blackbox' phenomenon which exercise physiologists are trying to solve by creating physiological control models based on various physical and physiological observations or factors. Some of these models have some common principles while other models totally conflict with the principles of the cause and control of fatigue during physical activity. Therefore, future research should focus on quantifying the models and also analyse the biosignals or data from the various physiological systems in the hope to observe the nature and characteristics of the system control mechanisms that are responsible for human behaviour and control physical activity during exercise. Through mathematical modelling and analysis, one could attempt to unlock the nature and cause of fatigue by investigating the energy system pathways and the system control mechanisms responsible for homeostatic regulation of the physiological systems. In so doing, mathematical theories as well as physiological theories can be developed or extrapolated from the existing biological control theories to understand better the control of fatigue during exercise so as to boost athletic performance.

Disclosure of interest

The authors declare that they have no competing interest.

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