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Models to Explain Fatigue during Prolonged Endurance Cycling

Chris R. Abbiss and *Paul B. Laursen*

School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia

Contents

Abstract

Much of the previous research into understanding fatigue during prolonged cycling has found that cycling performance may be limited by numerous physiological, biomechanical, environmental, mechanical and psychological factors. From over 2000 manuscripts addressing the topic of fatigue, a number of diverse cause-and-effect models have been developed. These include the following models: (i) cardiovascular/anaerobic; (ii) energy supply/energy depletion; (iii) neuromuscular fatigue; (iv) muscle trauma; (v) biomechanical; (vi) thermoregulatory; (vii) psychological/motivational; and (viii) central governor. More recently, however, a complex systems model of fatigue has been proposed, whereby these aforementioned linear models provide afferent feedback that is integrated by a central governor into our unconscious perception of fatigue. This review outlines the more conventional linear models of fatigue and addresses specifically how these may influence the development of fatigue during cycling. The review concludes by showing how these linear models of fatigue might be integrated into a more recently proposed nonlinear complex systems model of exercise-induced fatigue.

Road cycling is a complex sport. In each professional cycling season there are 90–100 competition days, comprising 1-day races, 1-week tour races, and 3-week tour races.[1,2] Within each of these races, participants may perform a number of competition requirements: (i) flat, long stages; (ii) individual time trials; and (iii) uphill ascents,[1,3] – demanding individual and team strategic approaches.[3,4] Of each of these requirements, the individual time trial is considered vital to the overall standings of a race.[1,5] The time-trial racing format is of a 'closed-loop design', whereby cyclists individually ride a known given distance in the shortest possible time.[5] In this type of race, or component of a race, various physiological systems are pushed to exhaustion,[3] making pacing, by regulation of speed, essential to completion of the event.[3] To date, a vast number of investigations have examined many physiological (maximal oxygen uptake [$\dot{V}O_{2max}$], anaerobic threshold, economy and efficiency of movement),[6-10] environmental (wind, temperature, altitude and humidity),[6,11] and biomechanical (positioning)[3,6,12] factors relating to time-trial performance. During prolonged time trials, all of these variables play a significant role in the eventual outcome, with the most important being maximal maintainable power and aerodynamics.[3,6,13] The ability to maintain a high power output during prolonged cycling is limited by the ability of the cyclist to resist fatigue. What precisely causes this fatigue, however, is controversial. Indeed, understanding fatigue during prolonged endurance exercise has been a major research agenda of exercise scientists for at least the last 50 years.[14] However, despite numerous theories and models, no precise explanation exists.[15] The physiological, biochemical, biomechanical and

cognitive models used to explain fatigue are diverse.[15-18] This may be because precise fatigue mechanisms will vary according to specifics of the task.[19] For example, Tordi et al.[20] recently showed, during two bouts of repeated 6-minute cycling exercise (>85% $\dot{V}O_{2max}$), that performance was limited by the supply of sufficient oxygen to the working muscles. However, Kay et al.[11] have also recently shown that during prolonged cycling (60-minute self-paced time trial), decrements in power production were the result of central and peripheral neuromuscular alterations.

The recent works of Noakes and St Clair Gibson,[21] St Clair Gibson and Noakes,[22] and Lambert et al.[23] have made clear that much of our uncertainty surrounding the understanding of fatigue stems from: (i) scientists having traditionally developed the viewpoint that fatigue is a catastrophic event whereby the termination of exercise occurs as a result of some involuntary peripheral physiological or biochemical event;[21] and (ii) sport scientists from diverse specialist fields having taken a reductionist approach in an attempt to solve the underlying cause of fatigue.[22] As a result, numerous linear cause-and-effect models have been developed to explain this so-called catastrophic event.[15] More recently, however, St Clair Gibson and Noakes,[22] and Lambert et al.[23] have commendably put forward that fatigue might be better explained using a nonlinear complex systems model approach, whereby the perception of fatigue during exercise is a consequence of the complex interaction of multiple peripheral physiological systems acting as afferent signallers to the brain in a dynamic, nonlinear integrative manner.[23]

The purpose of this review, therefore, is to: (i) review the well established linear models of fatigue; (ii) attempt to further develop the nonlinear integration of these models (complex systems approach) recently proposed by St Clair Gibson and Noakes[22] and Lambert et al.;[23] and (iii) explain how these models influence the development of fatigue during cycling.

1. Defining Fatigue

Historically, the numerous divisions of sport science have defined fatigue in order to best suit the individual disciplines. For example, a biomechanist may view fatigue as a decrement in the force output of a muscle,[24,25] a psychologist may see fatigue as a 'sensation' of tiredness,[16,26] whereas a physiologist may define fatigue as the failure of a specific physiological system.[27] For the purpose of this review, the word 'fatigue' is used to define sensations of tiredness and associated decrements in muscular performance and function.[11,16,27-33] It is therefore important to note that exercise is terminated at exhaustion, and not at a point of fatigue.[11,28] Fatigue is considered by some to be a safety mechanism aimed at preventing injury or death from occurring during exercise.[15,28,32,34] As fatigue is considered an inevitable and negative consequence of physical activity,[11,32] there has been much research into its effect on exercise performance.[24,30,31,33,35-40] Understanding fatigue during cycling is an important initiative for coaches and cycling scientists if we are to contribute further to the performances of elite endurance cyclists. Indeed, if factors determining fatigue and cycling performance can be established more definitively, it may help us to determine which training adaptations are most important for increasing cycling performance, or how training should be structured to maximise those adaptations.[15,41]

Research into fatigue-induced decrements in exercise performance spans numerous sport science disciplines. This reductionist approach to understanding fatigue[21] has caused a differentiation in the theories that explain the specific process (i.e. physiological, cognitive, biomechanical) responsible for decrements in exercise performance. As a result, numerous linear models have been developed to explain the fatigue response that inevitably occurs

during prolonged exercise. Some of these models include: (i) cardiovascular/anaerobic; (ii) energy supply/energy depletion; (iii) neuromuscular fatigue; (iv) muscle trauma; (v) biomechanical; (vi) thermoregulatory; (vii) psychological/motivational; and (viii) central governor. These models are reviewed in the context of understanding fatigue during cycling, and shown how they might be integrated into a complex systems model of fatigue.[22,23]

2. Cardiovascular/Anaerobic Model

The cardiovascular/anaerobic model of fatigue states that fatigue occurs during cycling when the heart is no longer able to supply oxygen and remove waste products to and from the working muscles.[15,27,41-45] This model is supported by the observation that concomitant increases in cardiac output and oxygen utilisation of the muscles lead to increases in physical work capacity.[46,47] This ability to process oxygen to do work can be quantified in terms of individual $\dot{V}O_{2max}$.[15,44,48,49] Professional level endurance cyclists possess $\dot{V}O_{2max}$ values of 70–80 mL/kg/min, or 5.0–5.5 L/min.[6,50,51] These high levels of $\dot{V}O_{2max}$ are achieved through increases in oxygen delivery and utilisation at the tissue level,[52,53] which can be modified by changes in cardiac output,[45,52,54] red blood cell mass[54] and potentially plasma volume.[55,56]

2.1 Oxygen Delivery

2.1.1 Cardiac Output

Cardiac output of the heart is increased via an increase in stroke volume and heart rate.[29,44,57,58] There is, however, a limit to the capacity of the heart to pump blood to the working muscles.[45,47] The specific adaptations to endurance training have been well documented whereby cardiac output can be significantly increased following endurance training.[46] Both highly trained and elite cyclists possess greater left ventricular dilation and hypertrophy than untrained individuals, thus permitting a greater stroke volume during exercise.[59,60] These adaptations to training insinuate that performance during cycling may be limited by an insufficient supply of oxygen to the working muscles via cardiac output.[16,27,44,53] Support for this model has been shown by Gonzàlez-Alonso and Calbet,[61] who examined cardiac output, mean arterial pressure, muscle blood flow and muscle oxygen delivery during exhaustive maximal aerobic cycling (356W) in trained subjects. This study found that under both thermally elevated (i.e. skin temperature 10°C and core body temperature 1°C above normal levels) and thermally neutral conditions, cardiac output and mean arterial pressure were reduced, which leads to a reduction in muscle blood flow, oxygen delivery, and oxygen uptake ($\dot{V}O_2$).[61] $\dot{V}O_{2max}$ was also reduced under heat stress; this too was caused by an earlier diminution of cardiac output and mean arterial pressure[61] It was concluded that because leg arterial-venous oxygen difference and extraction progressively increased until the end of the test without reaching maximum (91%), limitations in oxygen diffusion at the muscle level were not the cause of fatigue.[61] Similarly, Calbet et al.[62] showed that during maximal endurance exercise (cross-country skiing), skeletal muscle performance was limited by cardiac output. Through the examination of femoral and subclavian venous blood flow, intra-arterial blood pressure and cardiac output during whole-body exercise, they showed that in order to prevent a potentially dangerous decrease in systemic blood pressure (and thus oxygen delivery to the brain) the sympathetic nervous system constricts more blood vessels in active muscle.[62] It was found in this study that during two modes of skiing using predominantly arms (double pooling) and predominantly legs (leg skiing), the regional (arms and legs) skeletal muscle vascular conductance was related to local $\dot{V}O_2$ in both the arms ($r = 0.99$, $p < 0.001$) and the legs ($r = 0.98$, $p < 0.05$). The combined maximal vascular

conductance of the arms and legs is greater than the maximal achievable cardiac output; thus, during maximal whole body exercise (diagonal stride) it is thought that some degree of vasoconstriction occurs in order to prevent hypotension.[62] To date, specific studies examining limitations to cycling performance caused by inadequate cardiac output are lacking. What is more, future studies need to determine whether cardiac output or perhaps oxygen extraction (see section 2.2) limits cycling performance at exercise intensities similar to those achieved by professional endurance cyclists.

2.1.2 Red Blood Cell Mass and Plasma Volume

The enhancing performance effects of increasing blood volume and/or red blood cell mass on oxygen delivery to working muscles is well documented.[54,55,63] Elite endurance-trained cyclists possess much greater blood volumes (6648mL, 95 mL/kg)[55] compared with untrained individuals (4876mL).[64] Artificial increases in plasma volume irrespective of maintained haemoglobin content should lead to a reduction in the content of oxygen in the blood and cause decrements in maximal exercise performance.[55] However, Warburton et al.[55] showed that an artificial plasma volume expansion of approximately 8% (500mL infusion of 6% dextran) in elite cyclists had no effect on $\dot{V}O_{2max}$. Plasma volume expansion did, however, lead to an increase in cardiac output and stroke volume, signifying that performance at $\dot{V}O_{2max}$ is not limited by the ability of the heart to pump blood (cardiac output) but perhaps by a combination of blood volume and haemoglobin content.[55]

Support for the cardiovascular/anaerobic model of fatigue is strengthened by the fact that cycling performance is improved following increases in red blood cell concentration,[54,55] either through red blood cell reinfusion (blood doping), erythropoietin (EPO) supplementation,[54,65] or altitude acclimatisation.[54,63] The practice of EPO and/or blood doping has been alleged to be used by a number of elite cyclists in order to improve cycling performance;[65] however, this practice is dangerous as it increases the viscosity of the blood resulting in an increased likelihood of stroke, heart attack, heart failure and pulmonary oedema.[66,67] Therefore, the International Cycling Union has set legal levels of haematocrit,[65,68] free plasma haemoglobin and stimulation index (= haemoglobin [g/dL] − 60 √ reticulocytes [%]) at 50% (47% for females), 17 g/dL (10.5 mmol), and 133 (123 for females),[69] respectively. While ≈3% of humans can naturally have a haematocrit exceeding this limit,[65] Saris et al.[68] found that between the years 1980 and 1986 (prior to the introduction of EPO), 353 blood samples collected from 34 professional cyclists had haematocrit levels that were constantly below 50% (43.0 ± 0.02%; range 39–48%). The significant influence that endurance training has on the supply of oxygen to working muscles provides evidence that exercise performance is limited by variables inside the cardiovascular/anaerobic model (figure 1).[54] Further support for the cardiovascular/anaerobic model stems from studies that have examined the occlusion of blood flow to muscles, the utilisation of oxygen by the muscles, and the accumulation of metabolic byproducts.

2.1.3 Muscle Blood Flow Occlusion

Muscle blood flow plays a significant role in the delivery of substrates and is therefore thought to have a significant effect on the development of fatigue.[15,25,41,45] During steady-state submaximal exercise, there tends to be a linear relationship between muscle blood flow and power output,[45,46] quantity of active muscle mass,[46,47] haemoglobin concentration of the blood, and the arterial oxygen content.[46] There is, however, a limited ability of the heart to supply blood to the working muscles. During dynamic knee extension exercise, large ranges in peak muscle perfusion (149–373 mL/min/100g muscle) have been reported,[47] with cyclists reporting values as high as 380 mL/min/100g muscle.[70]

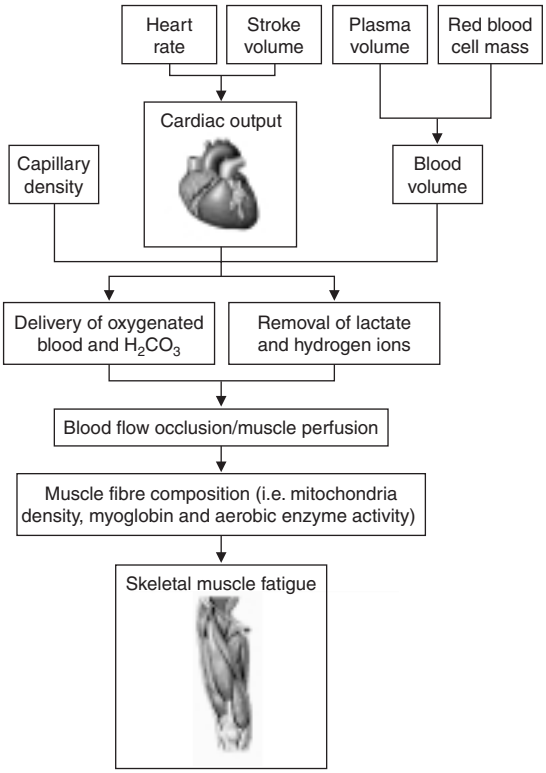

Fig. 1. Cardiovascular/anaerobic model of fatigue. Exercise performance may be limited by the ability of the heart to supply sufficient oxygenated blood to the working muscles. A limited blood supply along with the ability of the muscle to the utilise oxygen (muscle fibre composition) may result in greater anaerobic metabolism. Cycling performance is then inhibited by insufficient oxygen supply or perhaps the build-up of anaerobic metabolites (i.e. hydrogen ions) in the working muscles.

During dynamic single-legged knee extensor exercise, Radegran et al.[47] showed that muscle perfusion of quadriceps femoris did not differ when ≈64% of the muscle mass was active, compared with when 100% of the muscle was active. This finding occurred despite further increases in muscle $\dot{V}O_2$, suggesting that muscle blood flow was limited. Thus, increases in muscle $\dot{V}O_2$ may be due to increases in oxygen extraction by working muscle.[47]

Attenuation of muscle blood flow during cycling could be the result of blood flow occlusion.[25,71,72] During long, slow tetanic muscular contractions, such as during low cadence (low pedal rate) cycling, greater blood flow occlusion occurs in the muscle, which could impact on muscle blood flow.[25,71,72] Increases in blood flow are thought to be due to a greater efficiency of the muscle to act as a pump, thereby facilitating venous blood flow return during high cadence cycling.[71,73] Using near-infrared spectroscopy, Takaishi et al.[71] recently found that vastus lateralis blood flow was significantly reduced during the downward pedal stroke due to intramuscular pressure being greater than blood pressure. Thus, the high cadences inherently chosen by professional cyclists appear to play a role in reducing fatigue-induced decrements in cycling power output.

2.2 Oxygen Utilisation

It is well documented that endurance training increases the aerobic potential or oxidative power (oxidative phosphorylation rate) of muscle.[53] Aerobically trained skeletal muscle contains greater mitochondrial density (size and volume),[66,74-78] aerobic enzyme activity,[37,74-79] capillarisation[79,80] and myoglobin.[37,78] These increases permit greater aerobic adenosine triphosphate (ATP) production by the mitochondria,[66,74,76,77] and are supported by studies showing significant relationships between $\dot{V}O_2$ and mitochondrial density,[54,75,81,82] aerobic enzyme activity,[54,74,75,81,83] and muscle capillarisation.[79,80,82]

2.3 Metabolite Accumulation

2.3.1 Lactate

Well trained cyclists not only tend to report high $\dot{V}O_{2max}$ values,[6,50] but their anaerobic threshold (second ventilatory threshold) occurs at a greater percentage of their $\dot{V}O_{2max}$,[1] suggesting an increased fatigue resistance of type I fibres, and a greater ability to oxidise fat and reduce lactate accumulation at a given workload.[84] Studies examining lactate accumulation during cycling have found

that a strong correlation exists between increases in lactate concentration and reductions in power output above threshold levels.[42,85] Due to high anaerobic and lactate thresholds (≈90% of $\dot{V}O_{2max}$) and maximal aerobic power output (>500W),[1,50] professional cyclists have an ability to maintain significantly high percentages of $\dot{V}O_{2max}$ for prolonged periods of time (>60 minutes).[1,50]

Training an individual's lactate threshold is thought to allow the muscles to work at high intensities for longer periods before the development of skeletal muscle anaerobiosis.[41,44,86,87] To be competitive, endurance cyclists are required to maintain high exercise intensities for prolonged periods.[84] Therefore, higher level cyclists are able to exercise at lower percentages of their $\dot{V}O_{2max}$ for a given submaximal workload.[49,51] It is debatable, however, whether these adaptations directly reduce the onset of fatigue or occur in response to other adaptations.[15,86]

During high-intensity cycling exercise, lactic acid can accumulate because of an imbalance between its production and removal.[1,16,42,48,50,87,88] The generation of lactic acid in the muscles results in a lowering of the pH of the muscle and blood due to the dissociation of lactic acid into lactate and hydrogen ions (H^+).[16,87-89] During a maximal incremental cycling test performed by professional cyclists, lactate response in capillary blood at exhaustion ($\dot{V}O_{2max}$) was found to be significantly higher in hill climbers (≈7.0 mmol/L, 480W) compared with time trialists (≈5.0 mmol/L, 520W).[8] Stepto et al.[90] showed significant increases in muscle lactate (6.2 mmol/kg dry mass to 32.7 mmol/kg dry mass) and significant decreases in pH (7.09 to 7.01) in highly trained cyclists following eight repeated bouts (5 minutes duration) of high-intensity cycling (86% $\dot{V}O_{2max}$). The reduced intramuscular pH may decrease glycolytic flux by inhibiting phosphofructokinase (PFK), interrupting contractions by reducing Ca^{2+} release and removing Ca^{2+} from troponin,[16,91,92] stimulating pain receptors[16,17,91,92] and consequently diminishing performance.[91,93] Furthermore, H^+ ions that are released into the blood may affect performance by influencing pain receptors in the brain,[88] inhibiting oxygen transportation via haemoglobin,[16] and reducing the dissociation of free fatty acids into the blood.[16] Removal of H^+ ions via an increased speed of blood flow, or an increase in skeletal muscle buffering capacity has previously been thought to be crucial in the reduction of fatigue. Indeed, Weston and colleagues[94] have reported significant increases in skeletal muscle buffering capacity following 3 weeks of interval training, and also a significant relationship between 40km cycling time-trial performance and skeletal muscle buffering capacity ($r = 0.82$; $p < 0.05$). While these findings might suggest a negative influence of H^+ ions in skeletal muscle, more recent research suggests that the generation of lactic acid does not impair skeletal muscle function or efficiency,[95-98] but may actually have a beneficial effect on muscular contraction.

In a randomised study involving the ingestion of sodium bicarbonate or placebo, Santalla et al.[95] showed that despite a significant reduction in blood lactate acidosis, the magnitude of the $\dot{V}O_2$ slow component in seven professional cyclists was unaffected. In fact, numerous studies have found that other metabolites/molecules such as inorganic phosphate[96] or potassium[97,98] that accumulate during exercise may have greater effects on skeletal muscle function (see section 4.2.2 on neuromuscular propagation failure theory). Further, increased intracellular acidification of working muscle fibres induced by exercise may actually preserve membrane excitability and therefore protect against the development of neuromuscular fatigue.[98-101] A reduced intracellular pH may counteract the depressing effects of excitation-induced potassium efflux (accumulation in the T system) via decreasing chloride permeability, which would in turn reduce the size of

the sodium current needed to generate action potential propagation.[99-101] Further work is required to clarify whether the presence of excess H^+ ions during exercise plays a negative or positive role in the development of fatigue during cycling.

2.4 Summary of the Cardiovascular/Anaerobic Model

The cardiovascular/anaerobic model of fatigue states that exercise performance is limited by both the ability of the heart to supply sufficient oxygenated blood to the working muscles and the ability of the cardiovascular system to remove accumulated metabolites (figure 1). A model that is related to the cardiovascular/anaerobic model is the energy supply/energy depletion model.

3. Energy Supply/Energy Depletion Model

3.1 Energy Supply/Metabolic Capacity

The energy supply model proposes that fatigue during cycling is a direct consequence of a failure to supply sufficient ATP via the various metabolic pathways (phosphocreatine re-phosphorylation, glycolysis, lipolysis)[15,27,102] to the working muscles.[15,25,93,102] Support for this model stems from the observation of McArdle's disease patients, who are unable to perform muscle glycogenolysis due to a mutation in the gene that encodes myophosphorylase.[103-105] Consequently, patients with McArdle's disease are unable to perform forceful contractions, and suffer muscle cramps, muscle spasms, pain and myoglobinuria during exercise.[103,105,106] Interestingly, however, 10 minutes of exercise usually alleviates the pain and patients find exercise easier to tolerate. This is known as the 'second-wind phenomenon', and is thought to occur due to the improved delivery of blood glucose to working muscle.[103,105] Further support for this model comes from the fact that regular cycle training upregulates the enzymes associated with the energy systems involved with re-phosphorylation,[37,82,107,108] including creatine kinase,[108] succinate dehydrogenase and malate dehydrogenase.[109] It has been suggested that the decrease in glycolytic and oxidative capacity that naturally occurs as we age may be the cause of increased fatigue-onset in aged subjects.[25,82] Again, however, it is uncertain whether these adaptations occur as a result of training/detraining or in response to other adaptations. Indeed, intramuscular ATP stores are highly protected and rarely fall below 40% of resting levels following high-intensity exercise.[27] Levels any lower than this would not be expected, however, as the complete depletion of intramuscular ATP stores would cause rigor mortis to occur.[15] This sheds some doubt as to the direct influence that levels of ATP play in determining fatigue, but it is possible that the perception of fatigue might be influenced by receptors sending afferent information to the brain about abnormal levels of ATP.[110]

3.2 Energy Depletion

The energy depletion model is related to the energy supply model, but differs in that fatigue during prolonged cycling is thought to be a direct result of fuel substrate depletion, namely muscle and liver glycogen,[16] blood glucose and phosphocreatine.[1,111,112] This model is supported by the observation that levels of phosphocreatine are almost completely depleted during fatiguing short-term high-intensity sprint cycling,[16,27,66,112] as are levels of muscle and liver glycogen at the point of exhaustion following prolonged endurance cycling.[16,113] Using an animal model, Gigli and Bussmann[114] showed 60% and 86% reductions in the glycogen content of rat gastrocnemius muscle during 90 minutes running and at exhaustion (≈3 hours), respectively, compared with controls. Significant reductions (51%) in ATP concentration were only found in the exhaus-

tive group.[114] This is an excellent example of a linear fatigue model, whereby the longer one exercises, the more glycogen and ATP is found to be depleted, whereby some level of these substrates (but not necessarily a consistent level in all individuals) will eventually coincide with the subject's point of exhaustion.

The metabolic demand of prolonged cycling causes extreme calorie expenditure, requiring significant contributions from carbohydrate, lipid and protein metabolism.[6,115] The ability to oxidise lipids during endurance cycling is one of the most important adaptations to occur following endurance training.[107] The increased rates of fat oxidation at submaximal exercise intensities is clearly of benefit to endurance cyclists, as it permits work to be done without depleting carbohydrate stores.[90] As the oxidation of carbohydrate permits high rates of ATP production,[90,113] while fat and protein do not, our focus in this section will be on the important role that carbohydrate plays in increasing fatigue resistance during prolonged high-intensity cycling.

3.2.1 Carbohydrate

High-intensity exercise performed during time trials (>90% $\dot{V}O_{2max}$) [in the Tour de France],[1,6] requires significant energy contributions (≈85%) from carbohydrate (CHO),[90,116] which supplies about 4.03 kcal/g at a steady rate of 340 μmol/kg/min.[66] These high-intensity time trials (>40 km/hour) require muscle glycogen to be utilised at a rate of 4.6 mmol/kg dry mass/min, and as a result muscle glycogen has been reported to decline by up to 61%.[16,113,117] Due to the limited storage capacity of endogenous carbohydrate, carbohydrate has been recommended to be consumed at rates of 30–60g CHO/hour,[111] in the form of a 5–10% glucose polymer solution[112] at a rate of 15 mL/kg body mass/hour.[112,117] Interestingly, a recent study has shown that the voluntary intake of carbohydrate by ten professional cyclists during the Vuelta Ciclista a España tended to be considerably lower, ranging from 10 to 43 g/hour and averaging 25 g/hour.[1,118] If sufficient carbohydrate is not supplied during prolonged cycling (>2 hours), a greater shift in substrate oxidation from carbohydrate to lipid metabolism occurs.[35,107] Indeed, the ingestion of carbohydrate before and during exercise increases cycling time to fatigue and decreases performance time in cycling time trials.[112,113]

A strong relationship exists between starting glycogen levels and cycling time to exhaustion.[16,28,102,111,113] While, the relationship between glycogen and exercise performance is commonly considered to be causally linked at the point of exhaustion,[113,116] muscle glycogen depletion is not considered to be the sole cause of fatigue in prolonged exercise.[15,112,113] This is because during exhaustive exercise, skeletal muscle glycogen stores remain high (≈60% of resting values).[26,119] What is more, a study performed by Hawley et al.[117] showed that increased muscle glycogen via carbohydrate supplementation had no effect on 1-hour cycling time-trial performance, muscle glycogen utilisation or lipid oxidation. It has been suggested that perhaps muscle glycogen depletion plays a larger influence on the development of fatigue during prolonged exercise (>2–3 hours) but via another mechanism detached from its role in energy production.[15,119] Shulman and Rothman[102] propose a glycogen shunt model, suggesting that as glycogen concentration is lowered, but still non-zero, there is insufficient muscle glycogen to provide the rapid burst of gluconeogenesis required to compensate for the millisecond energy demands of muscle fibres during high-intensity exercise. Thus, many researchers believe that the oxidative capacity of carbohydrate is not limited by the availability of ATP in the blood (blood glucose) but by the rate at which muscle glucose can be oxidised (energy supply model).[15,16,113]

3.3 Summary of the Energy Supply/Energy Depletion Model

The energy supply/energy depletion model is a linear model of fatigue developed using a reductionist approach that involves two mechanisms that may be causal for fatigue during prolonged cycling. This model states that fatigue during cycling is related to either an inadequate supply of ATP to working muscle by the energy systems (energy supply), or that fatigue is the result of a depletion of endogenous substrates (energy depletion) [figure 2].

4. Neuromuscular Fatigue Model

The majority of past research into the development of fatigue during prolonged exercise has assumed that exercise performance is determined by either the ability of the cardiovascular system to provide enough blood, nutrients and oxygen to the working muscles, or the ability of the energy systems to re-phosphorylate ATP inside the muscle.[15,44,50] Although these factors are strongly related to fatigue during cycling, another theory is that the functions involved in muscle excitation, recruitment and contraction are what limit exercise performance.[15,31,110,120,121] Electromyography (EMG) is commonly used as a global indicator of these factors.

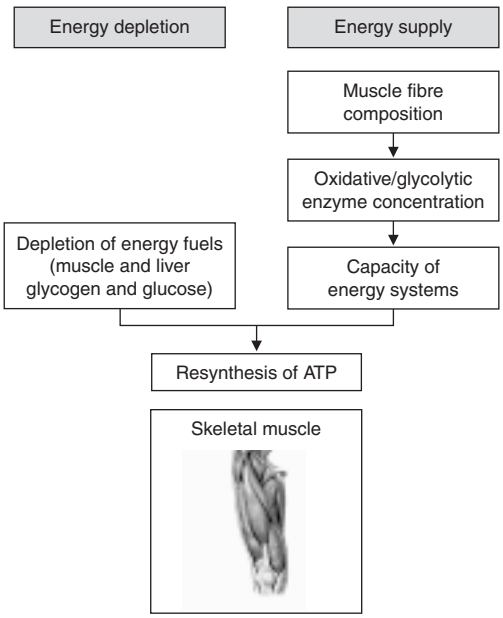

Fig. 2. Energy supply/energy depletion model of fatigue. Cycling performance is limited by the availability of adenosine triphosphate (ATP). The inability of the energy systems (phosphocreatine, anaerobic glycolysis, aerobic glycolysis and lipolysis) to resynthesise ATP may inhibit muscle contractions. The depletion of energy stores and enzymes (i.e. phosphocreatine and creatine kinase) associated with ATP resynthesis may also reduce cycling performance.

4.1 Electromyography and Fatigue

EMG is a measure of both the quality and quantity of electrical activity in the muscle.[11,38,84,122,123] EMG has long been considered as an acceptable method of determining functional and dysfunctional recruitment patterns during dynamic movement.[38,84,122-126] During maximal fatiguing exercise (i.e. maximal voluntary isometric contractions), there tends to be a gradual decrease in EMG activity by the working muscles.[84,125-129] A reduction in the firing frequency of motor neurons along with an increase in the time taken for muscle fibre relaxation, is recognised as a fundamental attributing factor to observed decreases in muscle force production.[32,127] This reduction in motor neuron output during a maximal voluntary contraction (MVC) is considered to be a CNS modification used to optimise force output of a muscle during a maximal fatiguing task – a process known as 'muscle wisdom'.[33,130] Thus, it has been established that analysis of changes in the integrated electromyographic signal (IEMG), or root mean square (RMS), and the compound action potential (M-wave) are effective measures of neuromuscular fatigue.[124,126,131-133] Here, IEMG refers to an EMG signal that has been filtered and smoothed,[134] the RMS is a quantification of the global EMG signal,[123,135] and action potential refers to the electrical impulse sent from the brain.[134] Central activation failure has been

associated with a reduction in the RMS irrespective of maintained M-wave amplitude.[132]

It is debatable as to where on the pathway from the CNS to the peripheral contractile mechanism the neuromuscular fatigue response might be controlled.[35,36,132] In fact, studies that have investigated neuromuscular function during prolonged cycling have suggested that a reduction in leg muscle capacity occurs as a result of alterations to both central and peripheral mechanisms (see table I).[11,24,34-36,131,132,136] This hypothesis holds the basis for the neuromuscular fatigue model.[43,93,112]

4.2 Neuromuscular Fatigue

Models of neuromuscular fatigue have been recently reviewed by Cairns et al.[19] Neuromuscular fatigue refers to a reduction in the force[24,31,33,35-39,121,137] or power production[25,131] of a muscle despite increases in perception of effort.[17,33,38,138] While an abundance of research is available on the effects of exercise on neuromuscular function,[32,33,35,36,39,136,138,139] few studies have examined the relationship between neuromuscular function and prolonged cycling exercise.[35,36,112] Focal to the neuromuscular fatigue model are two reviewed philosophies explaining the resulting decrease in neural drive that occurs during exercise. These ideas are primarily based upon where, in the chain of command, from the motor centres in the brain to the actin-myosin crossbridging, failure or impairment occurs.[37,121,132,140,141] These concepts include, the central activation failure theory[24,25,132] and the neuromuscular propagation failure theory.[25]

4.2.1 Central Activation Failure Theory

Traditionally, studies into neuromuscular fatigue during exercise have focused on alterations in the neuromuscular junction or in the muscles themselves, with little attention paid to the CNS.[93,110,142] The cause of central fatigue, defined as a progressive reduction of muscle activation by the CNS, is still inconclusive.[11,25,27,93,110,121] Following pro-

Table I. Alterations in central activation root mean square (RMS) and M-wave properties in cross-sectional cycling studies[a]

Study (year)	Activity	Reduction in central activation (%)	Muscle	Increase in M-wave duration (%)	Reduction in M-wave amplitude (%)	Reduction in RMS/RMS_M (%)
Hautier et al.[131] (2000)	2 min cycling		VL			13.89
Lepers et al.[35] (2000)	30 min cycling	16.10	VL	Insignificant	Insignificant	30 ± 5
			VM	Insignificant	Insignificant	30 ± 6
Lepers et al.[132] (2001)	2h cycling	24.20	VL	19.60	14.10	
			VM	10.30	18.90	
Lepers et al.[36] (2002)	5h cycling	8.50	VL	5.90	7.80	16
Millet et al.[24] (2003)	140km cycling	Insignificant	Knee extensor muscle			
Nybo and Nielsen[136] (2001)	Cycle to exhaustion at 40°C (≈60% $\dot{V}O_{2max}$)	54	RF			

a Summary of cross-sectional studies that have measured the fatiguability of the quadriceps (VL, VM and RF) during prolonged submaximal cycling. Increases in M-wave duration, showing an increased duration of action potential, along with decrease in M-wave amplitude suggest impairment of neuromuscular propagation and peripheral fatigue.[35,36,40] A reduction in RMS/RMS_M suggests an impairment of central activation.[35,36,40]

RF = rectus femoris; **RMS_M** = root mean square (M-wave); **VL** = vastus lateralis; **VM** = vastus medialis; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

longed ultramarathon exercise, MVC of the quadriceps muscles has been shown to decrease by 32 ± 18%,[31] which is thought by some to be due to a reduction in neural input[28,31,38,127] resulting from control of some 'central governor' (see section 9) located in the brain,[33,41] associated with a build-up of intracortical inhibition in response to the development of pain.[37]

As fatigue develops during prolonged exercise, there is an increase in intracortical inhibition.[24,37] Increases in serotonin and perhaps dopamine and acetylcholine concentrations in the brain may reduce the rate of central neural drive, which negatively influences the excitement and recruitment of skeletal muscle.[28,93,110,140] It is thought that these neurotransmitters have an important effect on arousal, lethargy, sleepiness and mood state, which in turn may influence perception of effort during exercise.[93] Indeed, it has been shown that an artificial increase of both dopamine[93] and serotonin[93,110] in the brain reduces exercise performance. Somewhat in contrast, however, Bailey and colleagues[143] showed that during prolonged exercise in rats, fatigue was associated with increases in serotonin and decreases in dopamine concentrations in the brain. It has since been hypothesised that a low serotonin/dopamine ratio may improve muscle activation (via increasing arousal, motivation and optimal neuromuscular coordination) and therefore improve prolonged exercise performance.[110] What is more, it has been suggested that nutritional status (especially that of carbohydrates) may affect neurotransmitters via attenuating increases in serotonin.[110] More research is necessary to distinguish between the specific effects of carbohydrate ingestion on central activation as opposed to its well known advantageous peripheral effects.[110]

Few studies that have assessed EMG during cycling have looked specifically at central fatigue.[35,132] The involvement of the CNS in fatigue is often implied through default.[93,110,140] In these studies, muscle twitch interpolation (where stimuli [single, double or tetanic] are sent to the motor axons, thus removing the CNS from the contraction) is compared with voluntary contractions.[25,35,120,121,132] If no difference is found, then it is assumed that no central fatigue has occurred.[25,37,93,110] A major flaw in this method of determining central fatigue is that many other factors (including psychological,[11,17,28,144-147] environmental[28,136,147] and hydration level[35,37,142]) all influence neural drive and thus exercise performance. An extension upon previous methods of determining central activation failure was developed by Schillings et al.[142] who compared the superimposed force (via 5-pulse-train twitch interpolation every 15 seconds) with estimated force decline due to peripheral factors (muscle fibre conduction velocity). Under these circumstances, a decline in muscle fibre conduction velocity is thought to be reflective of transformations within the muscle (i.e. the accumulation of metabolic byproducts) and therefore peripheral fatigue.[142] Using twitch interpolation (12-pulse electrical train), Stackhouse et al.[148] found a lower central activation ratio (ratio of voluntary force production to total force production using superimposition) in an isometric exercise-induced fatigued state (0.90, 0.74) compared with a non-fatigued state (0.98, 0.94), in young and elderly subjects, respectively. The lower central activation ratio in elderly subjects under both conditions suggests a greater central activation failure, which may be related to age-related weakness.[148] Clearly, the ability to separate central fatigue from other possible causes of fatigue (i.e. neuromuscular propagation failure theory) is complicated by the fact that both supraspinal and spinal mechanisms may be involved, where spinal factors include the involvement of both positive and negative influences of afferent sensory feedback (see sections 7.2 and 8).[141,149] Millet and Lepers[141] have shown that central fatigue tends to be greater following pro-

longed running compared with cycling, when duration and intensity are similar. It was suggested that neurally arbitrated afferent sensory feedback resulting from significantly greater muscle damage, as seen in running, show the possible involvement of greater spinal modulation during running compared with cycling.[141]

In summary, as neural drive must surely influence cycling performance, determination of central activation failure may allow the separation of cerebral alterations (i.e. neurotransmitters and/or cognitive alterations) and peripheral changes that lead to fatigue during cycling.

4.2.2 Neuromuscular Propagation Failure Theory

An alternative notion explaining a decrease in force production is that peripheral mechanisms could be involved.[25,27,84,128,150] Millet et al.[24] have shown that after a prolonged cycling race (140km at 31 km/hour), a 10% reduction in leg extensor MVC was unrelated to central fatigue. This theory holds that the ability of the muscle to produce force is limited by the response of the muscle to an electrical stimulus.[36,86,127,151] Thus, alterations in the muscle action potential (M-wave) may reflect a decrease in membrane excitability.[16,31,126,151] It is important to note that short periods of repetitive muscle stimulation may in fact result in an improved contractile response (potentiation) whereas continued stimulation may result in a reduced contractile response (fatigue).[24,152] In relation to neuromuscular fatigue, it is thought that both fatigue and potentiation coexist during exercise performance.[152] An inhibition is thought to occur at the sarcolemma[27,31,127,138,151] or α-motor neuron,[86,121,127,153] whereby a peripheral reflex response originates in the functioning muscles causing a reduction in neural activation.[28,121,127,151] Interestingly, whilst performing a positioning task compared with a force task, it was found that a greater motor unit activity occurred during submaximal isometric contractions (15% of MVC) causing greater variation in motor output, mean arterial pressure, heart rate and ratings of perceived exertion.[154] The position task requires a subject to maintain a given elbow angle whilst supporting a submaximal load and the force task required the subject to apply a submaximal force (equal to that of the position task) against an immovable object.[153,154] It has since been suggested that the reduced time to failure in the position task (50% of the force trial), despite similar rates of increases in EMG, resulted from greater excitatory and inhibitory input to the motor neuron pool.[153,154] This then highlights the task-specific nature of fatigue and that differing mechanisms are responsible for 'task failure' under varying exercise conditions.[19,153]

During prolonged cycling, reductions in ionic (Na^+ and K^+) transmembrane gradients may occur, resulting in a decreased muscle action potential (M-wave).[27,150,151,155] In short, a reduction in conduction velocity of action potentials, alterations to M-wave amplitude and/or a decrease in pH have all been found to be related to reduced EMG activity during prolonged cycling exercise.[25,27,33,38,126,151] Furthermore, increases in intracellular lactate and extracellular K^+ results in a decrease in membrane excitability and a reduction in central activation.[27,156] The increased intracellular Na^+[150] and reduced intracellular K^+ has been attributed to insufficient activation of the Na^+/K^+ muscle pumps.[27,86,150,151,157] Evidence suggesting that neuromuscular propagation failure may be a limiting factor in prolonged cycling performance stems from the fact that submaximal cycle training (5–6 times per week, 68% peak oxygen uptake [$\dot{V}O_{2peak}$]) resulted in a 35% increase in Na^+/K^+ pump concentration of the vastus lateralis.[158]

As group III and IV muscle receptors have been found to react to fatigue-related changes (i.e. anoxia, increased H^+ or K^+ and/or the production of neuropeptides) within the muscle, these receptors are thought to be influential on the peripheral fatigue reflex response.[33,35,36,86,159] However, Walton et

al.[86] found that during submaximal isometric plantarflexion contractions (30% of MVC), reductions in reflex amplitude were not exclusively the result of group III and group IV chemical sensitivity to fatigue-related muscular metabolites. This is supported by Ray and Gracey,[159] who showed that under thermally elevated conditions, muscular sympathetic activity can increase due to an increase in the firing rate of group III and IV afferents. A decrement in M-wave peak-to-peak amplitude has been found in a study of well trained male cyclists who performed 2 hours of cycling at 65% maximal aerobic power.[35] However, no significant changes in M-wave amplitude were found during fatiguing submaximal cycling protocols lasting 30 minutes.[35,160] This suggests that there may be a relationship between the specific task performed and the fatigue response during cycling.

In summary, neuromuscular propagation failure theory states that neuromuscular fatigue during cycling occurs due to a diminished response of the muscle to an electrical stimulus at the level of the sarcolemma or α-motor neuron.

4.2.3 Muscle Power Model/Peripheral Failure Theory

Fatigue is also thought to occur directly at the muscle level, whereby alterations in the coupling mechanism between action potential and contractile proteins[16,92,128,156] or calcium release, calcium regulation at actin-myosin contractile level, cross-bridge cycling[11,15,16,37,92,142] or depletion of energy stores occurs.[28] Much of the research into peripheral failure has looked at reductions in maximal voluntary contractions.[9,33-35,122,124,125,138,144,160,161] However, it has been suggested that prolonged cycling exercise may have a greater initial impact upon muscular endurance than on muscular strength.[38,84] In fact, it has been found that during both maximal and submaximal cycling, central activation (EMG firing rate) may be increased in order to achieve the same torque or power.[25,84,162] This disproportional relationship between motor unit recruitment and force production (known as the fatigue or EMG threshold) reflects a compensation for the diminishing peripheral force production caused by fatiguing motor units.[84,163] Interestingly, through the use of fine-wire and surface electrodes, Westgaard and de Luca[164] found that during a number of contractions (static, manipulation and operational task) lasting 10 minutes, low-threshold motor units had periods of inactivity after the first few minutes of the contraction. During these periods, higher-threshold motor units were recruited and surface EMG (action potentials) remained constant. This 'substitution' process is thought to reflect a protective mechanism used to defend the individual motor units against 'catastrophic' failure.[164] This finding lends support to the existence of muscle power/peripheral failure, as it suggests individual motor units may be susceptible to fatigue during prolonged muscular activity. In theory then, the strength or resistance to fatigue of each individual actin-myosin cross-bridge (intrinsic strength) is a major determinant of the force-generating capacity of a muscle as a whole.[165]

Low-frequency fatigue, defined as a decrease in force output following stimulation with low-frequency stimuli, and with little or no decrease in force when stimulated with high-frequency stimuli,[141] has been shown to be related to a reduction in calcium (Ca^{2+}) release to a given stimulus.[27,35,36,43,92,132,142] Ca^{2+} release from the sarcoplasmic reticulum is vital for muscle contraction.[157] It is thought that a reduction in Ca^{2+} release from the sarcoplasmic reticulum, caused by increases in lactate anion and/or inorganic phosphate concentration, may negatively influence the excitation-contraction coupling process.[16,27,91,151,157,166] During fatiguing exercise there may also be a reduction in Ca^{2+} return from contractile proteins to the sarcoplasmic reticulum, which may be responsible for an increase in the muscle relaxation time.[92,157] The response of contractile

elements to free calcium may also be delayed.[27,167] During excitation-contraction coupling, the calcium released by the sarcoplasmic reticulum may also be taken up by the mitochondria, which may interfere with mitochondrial function.[16,93] An increase in mitochondrial Ca^{2+} causes greater $\dot{V}O_2$ and reduces the phosphorylation ability of adenosine diphosphate (ADP) to ATP.[16] It is also important to note that researchers often fail to address alterations in muscle power mechanics, and therefore view peripheral fatigue as the combination of neuromuscular propagation failure and changes at the level of the muscle.[11,29,38,122,128]

As previously stated, electrical stimulation (trains of five stimuli every 15 seconds) was used by Schillings et al.[142] who found that during a 2-minute maximal contraction of the biceps brachii, the decrease in voluntary force (38%) in the first minute was largely the result of peripheral factors (89%), after which further decrements in force were a result of mainly central fatigue. This pattern makes sense, as demands are initially placed upon the muscle, with the latter sequence resulting from a number of alterations occurring in the CNS. This suggests that there are likely multiple fatigue sites, depending on the peripheral physiological systems involved with the task. It has also been hypothesised that this relationship between neural and peripheral fatigue is a safety mechanism,[32-34] whereby motor unit firing rate is reduced by the CNS in order to protect Na^+, ATP concentration,[11,112] and to avoid excessive damage of the muscle fibres.[15,33] Thus, central fatigue could be the response to afferent input from peripheral organs in order to prevent injury or death by causing a reduction or termination of activity.[11,25,28,33,35,37,112] To date, however, it is inconclusive whether the same patterns of fatigue occur during prolonged submaximal cycling.

4.3 Summary of the Neuromuscular Fatigue Model

In relation to the muscle recruitment fatigue model, there are three viewpoints that explain the resulting decrease in muscle activation and contraction during prolonged cycling. These models have been developed to explain where, along the neuromuscular pathway, inhibition occurs (figure 3). While the central activation failure theory involves a reduction in the neural drive, the neuromuscular propagation failure theory sees fatigue as a result of reduced responsiveness of the muscle to an electrical stimulus. Finally, the muscle power/peripheral failure theory states that fatigue occurs within the muscle and involves excitation-contraction coupling mechanisms.

5. Muscle Trauma Model of Fatigue

The stress of exercise-induced muscle damage can have numerous detrimental effects on muscle function, ranging from disruption of the sarcolemma or sarcomere, to complete tear of myofibrils,[138,168-170] thus causing alterations in body homeostasis.[166,170,171] Scientists classify muscle damage into three distinct categories based on specific clinical changes:

- a type I injury refers to exercise-induced muscle damage that is associated with muscle swelling, stiffness and delayed onset of muscle soreness (DOMS), occurring 24–48 hours after exercise;[166]
- a type II injury includes the specific tearing of muscle fibres;[166]
- a type III muscle injury refers to muscle soreness and/or cramps that occur during or immediately after exercise.[27,166-168,170,171]

As professional cyclists push high gears (i.e. 53 × 12–11) for prolonged durations, some degree of muscle damage would be expected.[1,172] It has been suggested that damage to muscle cells may cause a

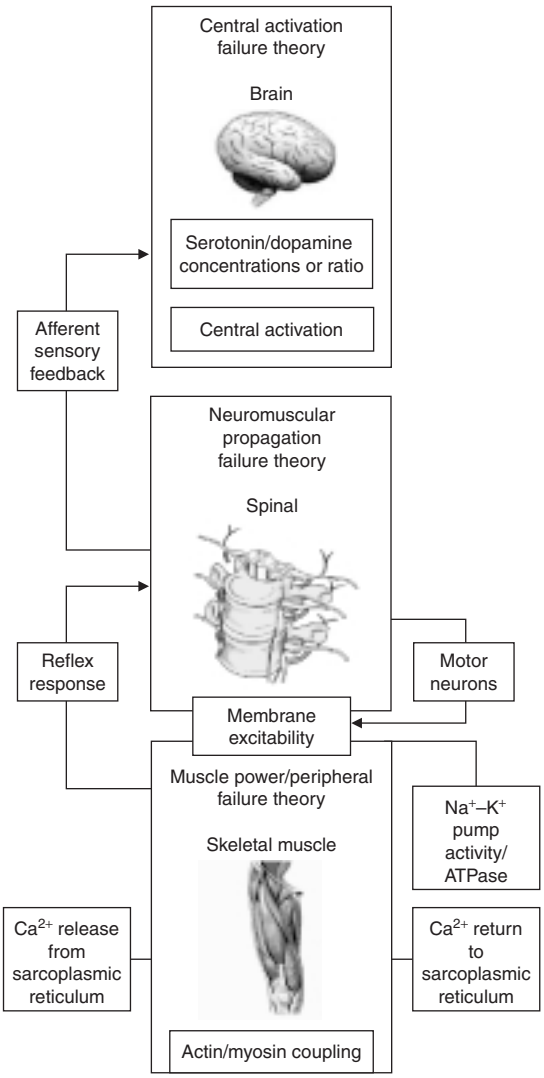

Fig. 3. Neuromuscular fatigue model. Exercise performance may be limited due to a reduced central activation, caused by alterations in neurotransmitter concentrations or in response to afferent sensory feedback. Alternatively, reduced cycling performance may be caused by reduced membrane excitability due to alterations in ionic pump activation and/or the motor neuron pool. Finally, inhibition may occur in the muscle as calcium status may affect actin/myosin function. **ATPase** = adenosine triphosphatase.

significant increase in plasma aminotransferase, alanine aminotransferase, and lactate dehydrogenase during prolonged cycling.[173] During both the Vuelta Ciclista a Valencia and Vuelta Ciclista a España cycle races, Mena et al.[174] found that there was a rise in aspartate aminotransferase, alanine aminotransferase, lactate dehydrogenase and alkaline phosphatase plasma activity, likely caused by both acute and chronic mechanical damage to muscle cells resulting in the contents leaking into the interstitial fluid. The effect that these particular enzymes have on power output and fatigue is unclear; however, structural and chemical imbalances caused by exercise-induced muscle damage are thought to have an influence on the neuromuscular/afferent sensory pathways (EMG/force ratios).[17] Through EMG analysis, it has been found that increased muscle pain, caused by the injection of hypertonic saline, resulted in a reduced activation of the muscle agonist, and ultimately increased the activity of the muscle antagonist during sustained submaximal (30% and 80%) isometric contractions.[173] This also led to a reduction in endurance time in the pain-induced trials.[173] This muscular fatigue is associated with a decreased RMS of pain-induced muscle (lowered EMG/force ratio) and a reduced EMG amplitude of the non-pain synergistic muscles,[173] suggesting that induced pain reduces muscular activation, causing fatigue of compensatory synergistic muscles.[173] The precise mechanisms responsible for a decrease in performance of pain-induced muscle are unknown, but may be due to the relationship between pain receptors and the CNS (central governor) or an increase in type II fibre recruitment.[17,170,171]

Much of the research into tissue damage during exercise has looked at the physiological responses to eccentric exercise.[27,162,166,167,175] For example, Gibala et al.[176] showed that after a single bout of resistance exercise (eight sets, eight repetitions, 80% of one repetition maximum) untrained males exhibited greater myofibrillar disruption of the elbow flexors resulting from eccentric (>80%) compared with concentric (>30%) exercise. However, in a later study using the same protocol on trained

individuals, the damage following eccentric exercise was found to be significantly lower (eccentric 45%; concentric 27%).[177] Thus, the increase in fatigue resistance that occurs with exercise training also appears to coincide with reduced muscle damage.

In relation to damaged muscle, it is thought that reductions in force production may be the result of alterations to the excitation-contraction coupling system, sarcomeres[27,151,166,175] and/or intracellular calcium homeostasis.[16,27,175] As the use of oxygen increases during prolonged exercise, so too does the production of reactive oxygen species (ROS).[41,108,178] Reports suggest that this accumulation of ROS may be damaging to mitochondria, resulting in a reduced ability to utilise oxygen, which could in theory reduce cycling performance.[27,151] Some evidence also suggests that damage to ROS may also reduce the activity of Na^+-K^+-ATPase (adenosine triphosphatase), a membrane protein that maintains homeostatic ionic gradients at the sarcolemma.[166,168,171,173,174,178]

It has been found that after exercise-induced soft tissue damage, there is an increase in insulin secretion and a temporary systemic insulin resistance[16] accompanied by reduced creatine kinase activity.[27,41] As insulin affects the rate at which glucose is utilised and creatine kinase affects the rate at which ATP is produced, it is thought that these changes may have a significant influence upon cycling performance and the development of fatigue. To date, the cellular mechanisms responsible for whole body insulin resistance following exercise-induced skeletal muscle damage are unclear, but may possibly be due to alterations in the insulin signalling pathways.[2,11,26,27,112]

5.1 Summary of the Muscle Trauma Model of Fatigue

In summary, the muscle trauma model of fatigue suggests that muscle damage resulting from prolonged cycling may influence a reduction in the power-producing capacity of the active muscles. This is because prolonged cycling may cause significant disruption to the muscle, resulting in alterations to intramuscular chemical homeostasis and activation of pain receptors, which, in turn, may cause a reduction in neuromuscular activation and/or reduced force production of the muscle (figure 4).

6. Biomechanical Model of Fatigue

The biomechanical model of fatigue suggests that fatigue is governed by the efficiency of movement patterns during cycling,[179] and that an improvement in cycling efficiency will lead to: (i) a reduction in the $\dot{V}O_2$ required to handle a given workload;[49,54,139,180,181] (ii) a reduced depletion of energy stores;[54] (iii) a delayed accumulation of metabolites; and (iv) an attenuated rise in core body temperature.[13]

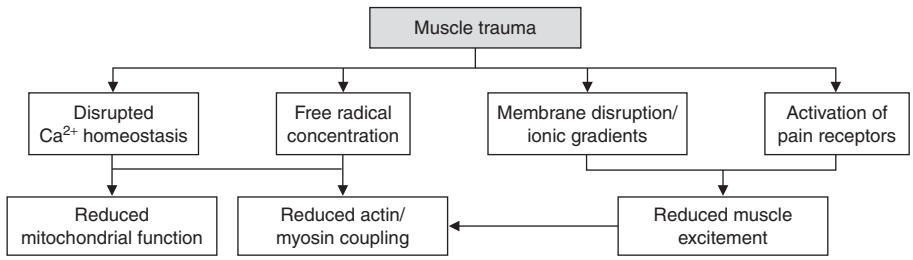

Fig. 4. Muscle trauma model. Exercise-induced muscle damage causes alterations that may limit prolonged cycling performance. Such alterations include disturbances to ionic pumps leading to disrupted chemical homeostasis. This may, in turn, lead to activation of pain receptors, and ultimately a reduction in actin/myosin coupling.

6.1 Efficiency of Motion (Cycling Economy)

It has been suggested that reductions in performance during prolonged submaximal cycling are consistent with fatigue-related decrements in gross efficiency.[179] A decrease in efficiency during repeated submaximal exercise coincides with significant increases in $\dot{V}O_2$,[13,180] which accompanies a reduction in maximal voluntary force production and the power-producing capacity of a muscle.[51] Thus, a comparatively greater economy/efficiency of motion, as reported in professional world-class cyclists,[50,51] may decrease the percentage of $\dot{V}O_{2max}$ and anaerobic threshold needed to sustain a given power output,[8,31,132,156,182,183] allowing improved performance during prolonged cycling. Lucia and associates[51] showed that the cycling economy and gross mechanical efficiency of 11 elite male cyclists averaged 85.2 W/L(O_2)/min and 24.5%, respectively. Although, these high values of gross efficiency have been questioned,[184] values of gross mechanical efficiency of >22% have since been reported for a number of world-class professional cyclists.[172,185,186] Similarly, large differences in the running economy of Kenyan runners and their Caucasian counterparts have been reported to explain comparable differences in running performance despite similar values of $\dot{V}O_{2max}$.[187]

The factors influencing gross efficiency and thus fatigue during exercise are strongly dependant upon both the specific exercise task performed (i.e. voluntary vs electrical stimulation, isometric vs concentric vs eccentric, sustained vs intermittent, maximal vs submaximal force generation and duration)[12,31,37,129,132,144,156,182,183] and muscle properties.[27,34,37,51,132,155,188] Researchers have also found that the pedal rate (cadence) strongly affects the rate at which fatigue occurs during cycling.[132,139,172,181,182,189] Takaishi et al.[139] showed during cycling (85% $\dot{V}O_{2max}$ for 15 minutes) that trained cyclists tend to select an optimal cadence (80–90 rev/min) associated with reduced neuromuscular fatigue. As non-cyclists show a reduction in neuromuscular fatigue at 70 rev/min, it was suggested that optimal pedalling rate would gradually increase in relation to training status[139,181] due to enhanced pedalling biomechanics.[181] At high power outputs, the increased cadence utilised by professional cyclists improves cycling economy and gross mechanical efficiency.[172] An increased cadence is associated with increases in blood flow due to lower blood flow occlusion,[73,181] as well as cardiac output.[73] Gotshall et al.[73] found that a cadence of 110 rev/min, as opposed to 70 or 90 rev/min (200W), in trained cyclists resulted in a drop in the arterial-venous oxygen difference, suggesting that the cardiac output was in excess of $\dot{V}O_2$ requirements. It has been suggested that this increase in blood flow may assist in a greater removal of lactic acid (cardiovascular/anaerobic model), which could be why elite cyclists intuitively choose high pedalling cadences.[73] Force output per pedal stroke is also reduced at higher cycling cadences, resulting in a reduction in the activation of fast twitch muscle fibres,[132,139,155,172,181,189] which have a reduced mechanical efficiency and economy compared with slow twitch fibres.[181,190]

Increases in muscle activation measured via IEMG or RMS during incremental and constant-load exercise are associated with progressive increases in $\dot{V}O_2$,[133,191] and are considered to result from the activation of additional muscle fibre recruitment required to compensate for decrements in force capacity caused by fatiguing fibres.[133,191,192] EMG can also disproportionately increase when compared with the increase in $\dot{V}O_2$ during an incremental cycling test;[123,133] this is thought to coincide with either the second[123,193] or both[194] ventilatory thresholds. Indeed, Hug et al.[133] demonstrated that endurance-trained subjects show a faster decline in the RMS/$\dot{V}O_2$ ratio when compared with untrained subjects, which may be due to the greater percentage of slow-twitch fibres likely possessed by the well

trained cyclists.[181,190,195] Whilst IEMG and RMS indicate overall motor unit recruitment, they fail to provide information regarding the type of fibre recruitment (i.e. type I or type II fibres).[123,192] Further studies of professional road cyclists[123,194] have shown that for all muscles recorded (with differing fibre composition), the second EMG threshold and the second ventilatory threshold occur simultaneously during incremental exercise. This suggests that in professional cyclists there are similar changes in neural activity and motor unit recruitment strategies in the differing leg muscles despite varying muscle fibre composition.[123,194] How well this relates to prolonged constant-load or submaximal cycling exercise is unknown.

The use of magnetic resonance imaging (MRI) has shown that during constant-load cycling above threshold levels (60% of difference between lactate threshold and $\dot{V}O_{2max}$), a greater muscle mass is utilised compared with below threshold intensities.[196] This suggests a greater activation of fast-twitch muscle fibres and consequently a progressively greater $\dot{V}O_2$ and lactate accumulation.[27,125,166,196] However, when subjects cycled at submaximal intensities (either at or below ventilatory threshold) for prolonged periods (>1 hour), no significant relationship was shown between Δ whole body $\dot{V}O_2$ and ΔEMG of the vastus lateralis,[133,191] or MRI transverse relaxation times of the lower extremities during 15 minutes of cycling.[196] It is possible that synergistic and antagonistic muscles may have been recruited to compensate for decrements in force from the fatiguing agonistic muscles.[122,131]

6.2 Stretch/Shortening Cycle

Cycling has long been considered to be an exercise involving solely concentric contractions, whereby patterns of eccentric contractions are though to be minimal. However, recent research has found that eccentric muscle contractions do take place in both gastrocnemius and soleus muscles during fast pedalling velocity.[138,161,169,171] This eccentric muscle action that occurs during the lengthening phase is then followed by a concentric (shortening) action.[138,169,171] This combination of lengthening and shortening is known as the stretch-shortening cycle.[138,169] Komi[169] has stated that during hopping, running and jumping exercises (where a majority of the research into the stretch-shortening cycle has been focused), muscle-tendon lengthening can increase by 6–8%. It has been found that a portion of the stored 'elastic' energy in ligaments and tendons can be recovered during the shortening phase of motion, producing an enhancement of force and power production,[15,124,138,169] thus improving the potential economy of cycling. Stretch-shortening fatigue may also occur in response to muscle contractile capacity failure occurring in response to muscle damage caused during the stretch-shortening cycle.[138,161] Furthermore, the stretch-shortening cycle influences muscle mechanics, joint and muscle stiffness and reflex involvement, thus causing a diminution in the tolerance to muscle stretching and an increase in time to shift from muscle stretch to muscle contraction.[16,28,93] The increased contraction times during both eccentric and concentric phases, and the resultant reduction in force production during repetitive submaximal stretch-shortening cycles, are considered to be a result of a decrease in reflex components, which are interpreted as a protection mechanism of the CNS.[93] It is generally acknowledged that afferent feedback resulting from muscle tension is provided by the Golgi tendon organs,[197-199] and that these may be causal for generalised sensations of muscular fatigue.[17,197] However, a study involving eccentric exercises performed on the gastrocnemius muscle of an anaesthetised cat found that there were insignificant increases in tendon organ sensitivity.[197] It was then concluded that even when the muscles are fatigued, central factors relating to per-

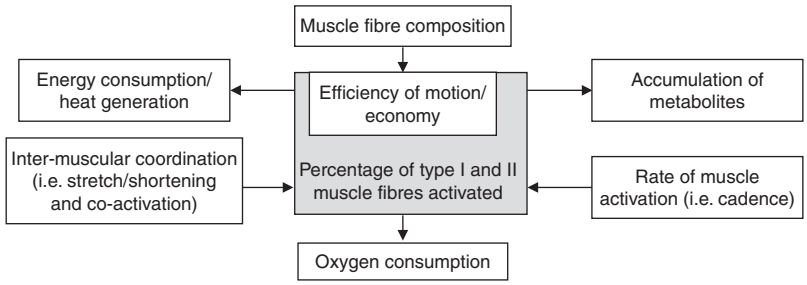

Fig. 5. Biomechanical model of fatigue. Improved mechanical efficiency and economy during cycling leads to a greater activation of slow twitch muscle fibres at a given workload. Improved efficiency and economy then reduces the demands placed on energy consumption and heat generation.

ception of effort play a significantly larger role than peripheral alterations in perception of force development.

6.3 Summary of the Biomechanical Model

The biomechanical model of fatigue (figure 5) is predominantly based upon the idea that an enhanced efficiency of motion results in better economy. Thus, less demand is placed on other physiological mechanisms that may be responsible for fatigue; less oxygen and energy consumption is required (energy supply/energy depletion model; section 3), fewer intramuscular metabolites are produced (cardiovascular/anaerobic model; section 2) and the rise in core body temperature is attenuated (see section 7).

7. Thermoregulatory Model of Fatigue

The negative effects of environmental heat and resulting hyperthermia on exercise performance have been well documented.[200-208] An increase in environmental temperature beyond a thermally neutral environment (e.g. from 21°C to 26°C)[28,111,201,209-212] places a greater physiological demand on the body when exercising.[29,205,207,209,213] Under such conditions, exercise performance in relation to work output or time to exhaustion is compromised.[29,111,200,201,207,213,214] For instance, Tatterson et al.[210] showed during a 30-minute time trial performed by well trained cyclists that mean power output was reduced by 6.5% under hyperthermic (32°C) conditions compared with a thermally neutral (23°C) environment.

Heat created in the body during exercise is transferred to the environment via a number of differing methods.[29,214,215] Rises in core body temperature are affected by the rate of metabolic heat production (muscle metabolism) and heat removal/dissipation (convection, conduction, radiation and evaporation).[200,216] Without adequate heat removal/dissipation, exercising muscle producing heat results in a progressive increase in core body temperature.[201,214] Metabolic heat production during exercise can increase core body temperature by 1°C every 5–7 minutes.[15,111,209,217,218] However, core body temperatures of >40°C cannot be tolerated for prolonged periods.[15,209,219] Thus, it is theorised that as the body reaches critical core body temperatures (i.e. ≈40°C), exercise is limited by the production and dissipation of heat.[205,217,219]

7.1 Central Thermoregulation Fatigue Theory

The hypothalamus receives afferent signals from peripheral thermal receptors, which in turn regulates central neural drive and sympathetic stimulation processes responsible for heat removal (i.e. sweat rate, peripheral blood flow) during exercise.[1,205,220] In a recent study, Nybo and Nielsen[136] electrically stimulated the femoral nerve of endurance-trained cyclists during sustained (2-minute) isometric contractions in a hyperthermic state (40°C) and found

that reductions in maximal isometric force were related more to central than peripheral factors. This suggests that hyperthermic-induced fatigue may cause alterations that affect the ability of the CNS to supply a constant neural drive.[136,206,217,221] It has been hypothesised, therefore, that increases in core body temperature to 'critical' levels may cause a reduction in the rate of central activation.[28,29,66,136,206,209]

Evidence for the central thermoregulatory fatigue model stems from a classic study performed by Nielsen et al.,[208] who found that when well trained cyclists cycled to exhaustion (60% $\dot{V}O_{2max}$) in hot 40–42°C conditions, exercise was terminated when core body temperature (oesophageal) reached approximately 39.5°C. Reductions in muscle or skin blood flow, accumulation of metabolites (i.e. K+, lactate), or a lack of substrates (blood glucose and free fatty acids) were not observed. Thus, increases in core body temperature to 'critical levels' were ruled to be the cause of fatigue.[208] Gonzalez-Alonso et al.[222] also showed that cycling at 60% $\dot{V}O_{2max}$ to exhaustion in the heat (40°C, 60% relative humidity) resulted in consistent core body temperature (oesophageal) and muscle temperatures of 40.1–40.3°C and 40.7–40.9°C, respectively. These finishing core temperatures occurred despite alteration of subjects' initial core temperatures (≈36°C, 37°C, 38°C) via immersion in a cold plunge pool prior to exercise. More recently, however, Tucker et al.[206] have shown that rectal temperatures during a 20km cycling time trial in amateur cyclists was not significantly different between hot (35°C) and cool (15°C) conditions, except in the final recording (20km), where rectal temperatures were 39.2°C and 38.8°C, for hot and cool conditions, respectively. Nevertheless, power output began to decline in the hot climate after only 30% of the total duration (6km) and was significantly different from the cool environment after 80% of the total duration (≈219 vs 260W, for hot vs cool conditions, respectively), suggesting that decrements in power output were not solely the result of an increase in core body temperature. In fact, the highest power output achieved in both trials occurred when core body temperature was the greatest (39.2°C and 38.8°C; during the final 5% of the time trial), a finding that does not support the existence of a critical core temperature as a limiter to exercise performance. Furthermore, reductions in IEMG were shown to occur in the hot conditions at 10km of the trial when core body temperatures were not significantly different. It was therefore proposed that reductions in IEMG and power output were the result of a 'cerebral anticipatory response', used to maintain a homeostatic body temperature.[206] Thus, hyperthermia is certainly a contributor to reductions in power output (i.e. fatigue), but does not appear to be the sole cause of fatigue during cycling, even during cycling in the heat.

During prolonged submaximal cycling, the onset of hyperthermia has been shown to be associated with reductions in cerebral circulation[223] due to increases in ventilation (hyperventilation) under hyperthermic conditions. This causes a decrease in arterial carbon dioxide pressure,[26,223] which in turn has a significant effect on blood flow to the brain.[224] This reduction in brain blood flow may consequently result in a decreased substrate (oxygen and ATP) supply and waste product removal, to and from the brain.[11,216] The central thermoregulatory fatigue model therefore states that prolonged exercise performance is limited by hyperthermic-induced alterations in brain activity as opposed to peripheral factors associated with muscle activation. An extension of this model was postulated by Tatterson et al.,[210] who stated that brain activity is sensitive to increased arterial blood temperatures, and is thus related to core body temperature. Indeed, it has also been shown that increases in core body temperature, and especially muscle temperature, results in an increased contraction velocity and con-

tractile speed, leading to an earlier and more pronounced neuromuscular fatigue.[29,205,217]

7.2 Peripheral Thermoregulation Fatigue Theory

Increases in skin temperature and the onset of hyperthermia are suggested to be responsible for a reduction in the 'will' or 'drive' to perform exercise.[205,221,223,225] During prolonged exercise in elevated thermal environments, increases in rating of perceived exertion parallel increases in core body temperature.[205,223,224] On the other hand, Tucker et al.[206] showed no significant difference between ratings of perceived exertion and power output or IEMG in hot versus cool climates. This implies that the reduced neural drive (EMG) is in fact the result of centrally controlled alterations to muscle recruitment, which might be influenced by elevated skin and muscle temperatures.[159,206] However, limitations exist in much of the recent research involving thermoregulation and EMG, in that other psychological markers that have the potential to influence performance (i.e. thermal sensation and muscle pain) are often not measured.[220] Interestingly, Armada-da-Silva et al.[220] found that after passive heating during a fatiguing cycle protocol, face cooling (via a mist fan) significantly reduced the ratings of perceived exertion of participants compared with a control group, irrespective of similar perceptions of thermal comfort.

It is considered that the more efficient an individual can be at a given power output or speed, the lower the $\dot{V}O_2$ and heat production there will be, which should in theory increase fatigue-resistance.[206] This is supported by Marino and colleagues,[207] who showed a positive relationship ($r = 0.74$, $p < 0.001$) between heat storage and body mass during an 8km run in thermally elevated conditions (35°C); no relationship was found at 25°C or 15°C.

An increase in the body temperature is sensed by the thermoreceptors located in the hypothalamus,[29,147,201,209,213,216] causing a reflex response initiating an increase in skin blood flow and sweating rate.[27,208,213,223] This increases the demand placed upon the cardiovascular system as it must not only supply blood to working muscles, but it must also shunt systemic blood flow to the skin to dissipate heat.[205,226] Thus, it is believed that during exercise under thermally elevated conditions, cardiac output may remain constant or in fact be reduced[223] due to the onset of hyperthermia and dehydration.[205,216] Increases in skin blood flow may also cause a reduction in splanchnic, renal[223,226] and, in some conditions, muscle blood flow.[205,227] Interestingly, Nielsen et al.[219] showed that when cycling at 45% $\dot{V}O_{2max}$, a plateau in skin blood flow (determined via venous occlusion plethysmography and laser Doppler flowmetry) occurred despite continuing rises in core body temperature. If skin blood flow reaches a limit during exercise, due to the demands of working muscle and vital organs (i.e. heart and brain), this may have a significant effect on core body temperature and thus fatigue. Therefore, thermoregulatory fatigue during cycling appears to be directly linked to the cardiovascular/anaerobic model of fatigue.[16,29,66,205,216,228]

Increases in core body and skeletal muscle temperatures have also been associated with an increase in carbohydrate utilisation,[28,216,220] highlighted by increased muscle lactate accumulation, gluconeogenesis, increased liver glucose output, and increased blood and glycogen oxidation.[168,220] Parkin et al.[229] showed that vastus lateralis glycogen utilisation of endurance-trained men was higher under thermally elevated (40°C) compared with normal (20°C) or cold temperatures (3°C) following cycling at 70% $\dot{V}O_{2peak}$ until exhaustion. This increase in carbohydrate utilisation during exercise in the heat is considered to be the result of a heat-induced stimulus for muscle gluconeogenesis, consequently placing greater demands on glycogen stores.[27,230]

7.3 Summary of the Thermoregulatory Model

The thermoregulatory model of fatigue suggests that a critical core body temperature may exist whereby upon attainment of this temperature, exercise is reduced or terminated. The increase in core body, muscle and skin temperature also causes increased demands to be placed on other physiological systems/models that may be responsible for fatigue during prolonged cycling (figure 6). These include the cardiovascular/anaerobic model, the neuromuscular model, the energy supply/energy depletion model, and the psychological model.

8. Psychological/Motivational Model

The psychological/motivational model of fatigue can be defined as a lack of enthusiasm or interest in exercise performance,[16,136,201,210,214] and is often incorporated as a part of the neuromuscular model of fatigue.[16,26,199,210,217] As addressed by Noakes et al.,[41] the central governor model (see section 9) suggests that a reduction in cycling performance, and thus fatigue, occurs on a subconscious level to avoid damage or death occurring during exercise. However, the psychological/motivational model holds that neuromuscular function is intentionally altered, thus causing a decrease in motor control activation.[26,210,213,231,232]

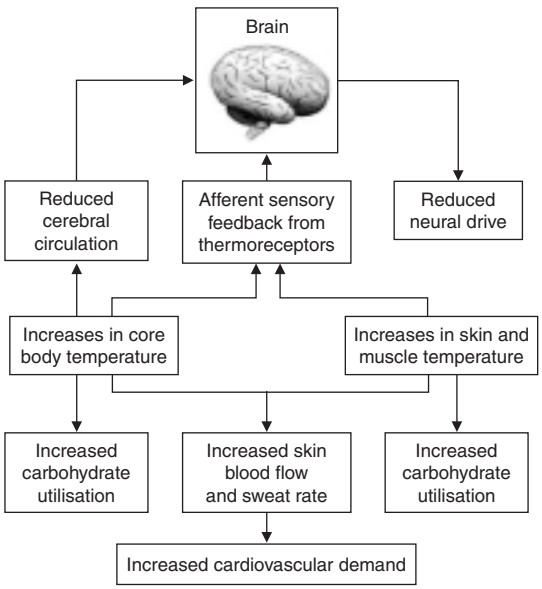

Fig. 6. Thermoregulatory model of fatigue. Fatigue is a result of the body reaching critical levels of temperature in either the core, muscle and/or skin. This creates an increase in skin blood flow and a resulting increase in cardiovascular demand. Heightened temperatures may also lead to a reduced neural drive due to afferent sensory feedback from both central and peripheral thermoreceptors.

To date, it is unclear as to the precise mechanism that affects the brain's response to afferent feedback during cycling exercise.[17,220] It is thought that numerous factors, including muscle trauma, skin temperature, blood lactate,[17] heart rate, respiratory rate, exercise task, minute ventilation, $\dot{V}O_2$,[17,233] and mode of exercise[10,16,17] (i.e. cadence[73,234]) may have a psychological influence on cycling performance. Yet, it is unclear what the specific effect each one of these variables has on physiological fatigue. To better understand the relationship between psychological influences and exercise performance, a number of models have been created, with the most widely accepted being Borg's 15-point rating of perceived exertion (RPE) scale.[231] From research using this, and other scales, it has been suggested that the onset of acute and chronic fatigue is associated with increases in RPE.[235,236] It has been found that RPE has a greater relationship with skin temperature and heart rate, as opposed to changes in core body temperature.[16,220] Alternatively, a greater RPE has been associated with increases in ventilation rate and minute ventilation.[17] In an attempt to better understand the effects of perceived exertion on central command, Williamson et al.[237] hypnotically manipulated effort sense in six highly hypnotisable individuals in order to determine alterations in cerebral activation. From this study it was found that hypnotically increased effort sense during constant-load exercise could increase blood pressure, heart rate, as well as activation of the right insular cortex and right thalamic regions of the

brain.[237] As hypnotically reducing sense of effort failed to reduce heart rate or blood pressure, it was then suggested that afferent sensory information from skeletal muscle must play a role in the magnitude of cardiac activation during exercise.[237] This study is, however, limited in as much as neither muscle activation nor afferent firing rates were determined.[237]

When exercise involves a 'closed-loop' design, where subjects are aware of the overall distance to be completed, subjects appear to markedly reduce their trial by trial repeatability,[10,238] compared with an open-loop time to exhaustion test.[27,217,238] It has been suggested by Ulmer[236] that subjects will anticipate the work required for a task and alter power output so as to complete the activity with the best possible performance, while at the same time avoid fatigue. This is supported by recent observations in professional cyclists showing that the shorter the duration of the competition, the greater the exercise intensity tends to be.[2]

8.1 Summary of the Psychological/ Motivational Model

Collectively, the literature has shown that there is no apparent single physiological variable responsible for motor output alteration from afferent signals (figure 7). From this it is assumed that numerous mechanisms are responsible for psychological alterations in central activation and perceived exertion,[17] which in turn determine the unconscious perception of fatigue, leading to reductions in cycling power output, and sometimes a point of exhaustion during prolonged cycling.

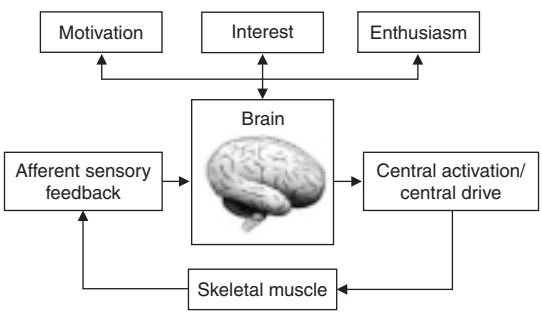

Fig. 7. Psychological/motivational model. Central drive is reduced due to lower motivation, interest and/or enthusiasm for the exercise task. The reduced enthusiasm may or may not be related to afferent sensory feedback.

9. Central Governor Model

In 1996, Ulmer[236] suggested that exercise performance might be controlled by a governor located somewhere in the CNS. In this central governor model, alterations in exercise intensity were thought to be controlled by a continuous feedback system where efferent signals that contain information on force, displacement, time and muscular metabolism are fed back to a central controller via afferent somatosensory pathways. Based on motor learning and the anticipated exercise task in hand, the central regulator is able to use afferent signals from the muscles, as well as feedback from other organs (including metabolic reference signals), in order to alter movement patterns and optimise exercise performance.[236] Noakes et al.[41] have since expanded on Ulmer's[236] theory by suggesting that central skeletal muscle activation is controlled by a regulator located either in the heart, the brain, or along the neuromuscular pathway, in order to protect vital organs from injury or damage.[2,17] Relationships have been found between cardiac output and skeletal muscle performance.[16,44,52,57] However, as recognised by Noakes,[15] if cardiac output does in fact limit performance, then activation of skeletal muscle must be reduced prior to the heart reaching its maximum output, in order to protect blood flow and the integrity of vital organs (heart, brain and respiratory muscles).[15,17,41] Evidence of such a protective mechanism may explain why during maximal exercise, cardiac output, muscle recruitment, and thus exercise performance are reduced in hypoxic conditions (i.e. altitude).[15,17,54] Recent research into the effects of an hypoxic environment on the heart during submaximal exercise has found that an 80km

cycle time trial did not produce any exercise-induced cardiac fatigue or significant cardiac damage (no significant increase in troponin-T).[239] Moreover, no marked differences existed in relation to heart rate and performance times between hypoxic and normoxic environments.[239] The fact that cardiac damage was not found in this study could suggest that some central regulator might have reduced neural drive in order to protect the heart. However, this cannot be confirmed, as performance times were similar and muscle activation was not determined.

It is important to note that if exercise performance is limited in order to protect the heart, then this model of fatigue would not apply to patients with chronic cardiac disease, otherwise there would be no cases of sudden cardiac death or episodes of angina and myocardial infarction during exercise. Research examining the specific cause of fatigue in chronic cardiac heart failure patients is limited but is perhaps more closely related to severe left ventricular dysfunction limiting the ability of the heart to increase blood flow to both respiratory and skeletal muscles during exercise (cardiovascular/anaerobic model).[240,241] However, as with the trained cyclist population, a more nonlinear approach is needed when researching the possible causes limiting exercise performance in chronic heart failure patients in order to determine whether physiological differences between the patient population and the normal population (i.e. reduced cardiac output) are causal for fatigue or a result of the training/detraining effect of physical activity.[242]

Intuitively, it would make more sense for such a central regulator to reside in the brain, and there is some evidence for this. Ide et al.[227] have shown that along with muscle blood flow, cerebral circulation velocity is compromised by insufficient cardiac output during exercise involving a large muscle mass (as in cycling). This suggests that if exercise performance is controlled via a central governor (figure 8), as suggested by Noakes et al.,[41] then reductions in cardiac output may influence the activity of such a governor resulting in a reduction in central activation. It has also been suggested that a central regulator is active during the pacing of submaximal exercise, regulating power output based on anticipated exercise requirements.[2,17,22,206,236,243] It has thus been hypothesised that during 3-week tour races (i.e. Tour de France and Vuelta Ciclista a España) the inverse relationship that exists between exercise volume and intensity reflects a 'teleoanticipatory' response activated via the CNS,[2,236] whereby a subconscious increase in intensity occurs when volume (i.e. distance) is less. The activation of this teleoanticipatory response is considered to be due to afferent sensory input, causing a reduced central activation in order to maintain physiological homeostasis.[17,22] Further support for the existence of a teleoanticipatory system can be seen in a recent study by Kay and colleagues,[11] who found that

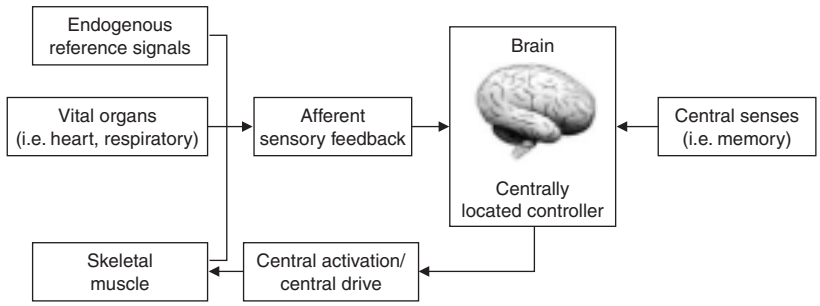

Fig. 8. Central governor model. Efferent drive is controlled in response to both afferent sensory feedback and centrally located senses. Central activation is then limited in order to protect homeostasis of all physiological systems with the endpoint of the exercise bout acting as a controlling variable by which pacing strategies can be continuously set.

during a 60-minute cycle protocol, where 1-minute all-out sprints were held every 10 minutes, subjects were able to increase neural drive (EMG) to restore power output in the final sprint back to values obtained in the first sprint, indicating the presence of a neural reserve. This increase in EMG activity may represent psychological factors in exercise performance (i.e. pacing strategies), as subjects were able to monitor the course profile, observing the occurrence of sprints.[11,243]

10. Complex Systems Model of Fatigue

Lambert et al.[23] and St Clair Gibson and Noakes[22] have since extended the central governor model by introducing the 'complex systems model of fatigue' whereby skeletal muscle fatigue is not dictated by any one of the single or absolute linear models outlined herein. Rather, these authors have put forward the notion that exercise performance is continuously manipulated in response to the interaction of numerous physiological systems monitored via constant feed-forward and feedback loops.[22,23] In this complex model of fatigue, the endpoint of the exercise bout offers a controlling variable so that the central governor can continually manipulate pacing strategies in order to assure the cyclist can complete the exercise bout at the highest work rate, or in as short a time as possible, without pushing any one peripheral system beyond homeostasis. In this complex systems model, fatigue is actually a subconscious sensation, representing the underlying neural integrative processes.

In this complex systems model of fatigue (figure 9), peripheral feedback originating from numerous linear models of fatigue (figures 1–8) are integrated by the brain, along with centrally located senses (i.e. memory, internal clock and teleoanticipation).[22] Consequently, power output during cycling is not solely dependant upon the homeostasis of just one of these linear fatigue models, but is constantly varying due to interaction of all fatigue models. A practical example that the cyclist might relate to is the fatigue experienced during a prolonged period of cycling 'in the saddle' at a relatively constant cadence and power output. Local 'fatigue' or pain is experienced in quadriceps, where required continuation of exercise in that position (i.e. typical laboratory cycling procedure) results in the cessation of exercise. However, 'out of the saddle' standing for only a brief period can relieve this local sensation of peripheral fatigue or pain, and the cyclist reassumes their pace and intensity for another prolonged period (personal observations). As a result of this adjustment, homeostasis of the peripheral area is maintained, and the perception of fatigue is delayed.

11. Conclusions

Much of the previous research into exercise-induced fatigue has taken a reductionist, or a cause-and-effect approach, into understanding fatigue. As a result, numerous linear models have been developed to explain what was thought to be 'catastrophic' fatigue (figures 1–8). These models include the cardiovascular/anaerobic model, energy supply/energy depletion model, the neuromuscular fatigue model, the muscle trauma model, the biomechanical model, the thermoregulatory model, psychological/motivational model, and the central governor model. Accordingly, scientists have discovered that cycling performance can be limited by a number of differing mechanisms that have been proposed in numerous fatigue models. For example, at maximal aerobic power output, cycling performance may be limited largely by the ability of the cardiovascular system to supply sufficient oxygen to the working muscle. However, at submaximal levels, fatigue may be due to neurological alterations causing a reduction in central drive. Indeed, the nonlinear complex systems model of fatigue is an improved model of fatigue, whereby fatigue is understood to be the unconscious perception of the afferent feedback received through the various linear models outlined

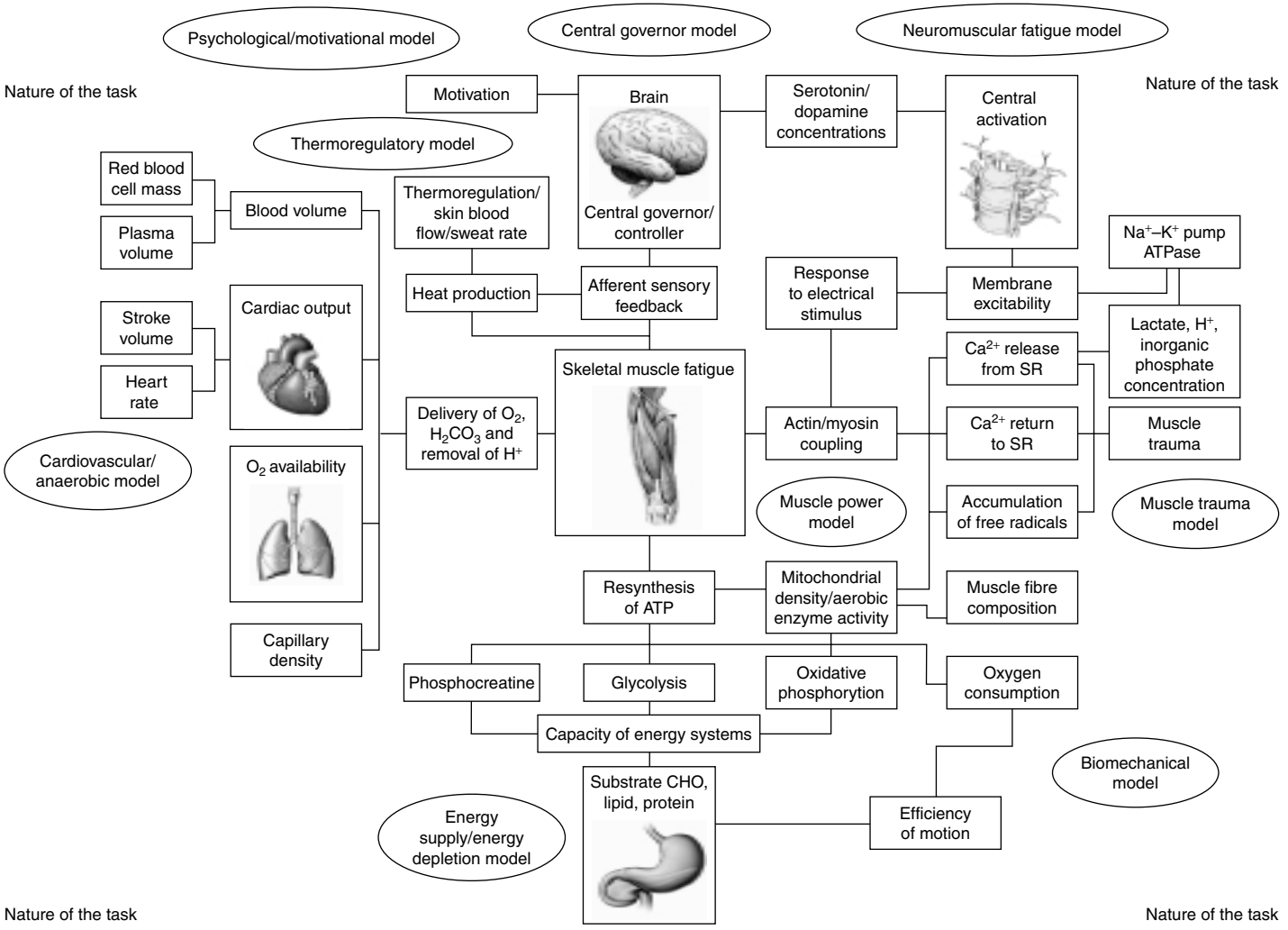

Fig. 9. Complex systems model of fatigue applied to prolonged cycling – interaction of developed fatigue models. **ATP** = adenosine triphosphate; **ATPase** = adenosine triphosphatase; **CHO** = carbohydrate; **SR** = sarcoplasmic reticulum.

(figures 1–8), and the brain integrates these afferent signals in order to protect the organism from death or injury it might receive from straining too far from homeostasis (figure 9).

Further research examining more than one of these linear fatigue models concurrently is required to clarify the numerous interrelating factors. This type of research will lead sport scientists to an improved understanding of the precise mechanisms that are associated with fatigue during cycling, and provide coaches and cyclists with a greater insight of how to further improve cycling performance.

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Correspondence and offprints: *Chris R. Abbiss*, School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, Building 19, Room 159, 100 Joondalup Drive, WA 6027, Australia.
E-mail: c.abbiss@ecu.edu.au