

REVIEW / SYNTHÈSE

Time to move beyond a brainless exercise physiology: the evidence for complex regulation of human exercise performance

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Abstract: In 1923, Nobel Laureate A.V. Hill proposed that maximal exercise performance is limited by the development of anaerobiosis in the exercising skeletal muscles. Variants of this theory have dominated teaching in the exercise sciences ever since, but 90 years later there is little biological evidence to support Hill's belief, and much that disproves it. The cardinal weakness of the Hill model is that it allows no role for the brain in the regulation of exercise performance. As a result, it is unable to explain at least 6 common phenomena, including (i) differential pacing strategies for different exercise durations; (ii) the end spurt; (iii) the presence of fatigue even though homeostasis is maintained; (iv) fewer than 100% of the muscle fibers have been recruited in the exercising limbs; (v) the evidence that a range of interventions that act exclusively on the brain can modify exercise performance; and (vi) the finding that the rating of perceived exertion is a function of the relative exercise duration rather than the exercise intensity. Here I argue that the central governor model (CGM) is better able to explain these phenomena. In the CGM, exercise is seen as a behaviour that is regulated by complex systems in the central nervous system specifically to ensure that exercise terminates before there is a catastrophic biological failure. The complexity of this regulation cannot be appreciated if the body is studied as a collection of disconnected components, as is the usual approach in the modern exercise sciences.

Key words: central governor, A.V. Hill, fatigue, brain, central nervous system, pacing, muscle recruitment, EMG, heart, models.

Résumé : En 1923, A.V. Hill, récipiendaire du prix Nobel, avance que la performance maximale à l'effort est limitée par l'installation de l'anaérobiose dans les muscles sollicités. Depuis, cette théorie et ses variantes font partie des enseignements en sciences de l'exercice. Cependant, 90 ans plus tard, il y a peu de données probantes à l'appui de la thèse de Hill; en fait, il y a en plus à l'opposé. La principale faille du modèle de Hill provient de l'absence de rôle du cerveau dans la régulation de la performance au cours d'un exercice. Tel quel, ce modèle ne peut expliquer les 6 phénomènes suivants : (i) les différences de gradation de l'effort associées aux diverses durées de l'effort, (ii) l'effort terminal, (iii) la manifestation de la fatigue même en présence de l'homéostasie, (iv) le recrutement de moins de 100 % des fibres musculaires dans les muscles sollicités à l'effort, (v) la preuve selon laquelle une série d'interventions s'appliquant exclusivement sur le cerveau peuvent modifier la performance physique et (vi) l'observation selon laquelle la perception de l'intensité de l'effort (RPE) est une fonction de la durée de l'effort plutôt que de son intensité. À mon avis, le modèle du pilote central (CGM) convient mieux pour expliquer ces phénomènes. Le CGM associe l'exercice à un comportement régulé par anticipation grâce à des systèmes complexes dans le système nerveux central qui permettent que l'exercice se termine avant l'arrivée d'une défaillance biologique majeure. On ne peut pas apprécier la complexité de cette régulation si on étudie l'organisme en pièces détachées, ce qui est trop souvent le cas aujourd'hui dans les sciences de l'exercice.

Mots-clés : pilote central, A.V. Hill, fatigue, cerveau, système nerveux central, gradation, recrutement des fibres musculaires, EMG, cœur, modèles.

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Introduction

For my doctoral thesis, I studied the nature of the factors that determine the heart's ability to produce a maximal cardiac output (Resink et al. 1981a, 1981b; van der Werff et al.

1985; Noakes and Opie 1989). Because a large focus of my subsequent career has been to challenge the theory that cardiac output is the principal regulator of human exercise performance (Noakes and St Clair Gibson 2004), only now do I appreciate the irony of that choice.

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Perhaps the single most important physiological principle I learned during that training was described in table 10.1 on page 162 of the 1977 version of the classic textbook of the time, *Physiology of the Heart*, written by Professor Arnold Katz (Katz 1977) of New York (Table 1). That table compared the mechanisms by which the heart and skeletal muscles increase their force production. It explains that skeletal muscle increases its force production almost entirely by increasing the number of motor units (and hence muscle fibers and cross-bridges) that are active (recruited) in the exercising muscles.

In contrast, because all its fibers contract with each beat, the heart cannot boost its force production by increasing muscle fiber recruitment. Instead, this increase can occur only as a result of maximizing (i) the number of actin and myosin cross-bridges formed during contraction (the Frank-Starling effect) and (ii) the contractility of each cross-bridge. The strange paradox is that cardiologists like Professor Katz, who have little if any direct contact with the exercise sciences, never teach that the output of the organ of their specialty, the heart, determines the capacity of the skeletal muscles to produce force (consequent to a large cardiac output and hence a more generous oxygen delivery to the exercising muscles). Rather, they teach that the speed at which we run, or the mass that we can lift, is determined by the number of motor units that are recruited in our exercising limbs (Katz 2010) and presumably by the quality of the muscle fibers producing that force (i.e., their inherent contractility) (Rae et al. 2010). In contrast, a major focus of the exercise sciences has become to prove that how far or how fast we run is determined solely by the magnitude of our maximal cardiac outputs (Levine 2008; Shephard 2009). Most remain vigorously opposed to any suggestion that the extent of skeletal muscle recruitment plays any role. Thus, as another North American cardiologist has written,

The primary distinguishing characteristic of elite endurance athletes that allows them to run fast over prolonged periods of time is a large, compliant heart with a compliant pericardium that can accommodate a lot of blood, very fast, to take advantage of the Starling mechanism to generate a large stroke volume.

(Levine 2008).

In 1982, I began to write the manuscript that would become *Lore of Running* (Noakes 2003). In researching the book, I came across the following statement by Dr. David Costill:

Since the early work of Hill and Lupton (1923), exercise physiologists have associated the limits of human endurance with the ability to consume larger volumes of oxygen during exhaustive exercise.

(Costill 1979). This led me to the work of the English physiologists Professor A.V. Hill and Dr. Harry Lupton and, through them, to the study by Professor Frederick Gowland Hopkins and W.M. Fletcher (1907) that had a major influence on Hill's understanding.

The study by Fletcher and Hopkins (1907) was particularly interesting because their intent was purely to prove that they were able to measure accurately the real lactic acid concentrations in the skeletal muscles of recently dead creatures, specifically frogs. They showed that lactate concentrations were increased in muscles stimulated to contract

or stored in an atmosphere of nitrogen but fell progressively in muscles stored in oxygen. They also concluded that the instantaneous increase in muscle lactate concentrations in recently killed frogs could be prevented by plunging the muscles into ice-cold alcohol.

Hill, Long, and Lupton (1924) interpreted these findings as proof that skeletal muscles produce lactic acid only when they are "anaerobic", and that it is this production of lactic acid that causes skeletal muscle fatigue. Yet the work of Hopkins and Fletcher had essentially nothing to do with exercise physiology. They studied neither exercise nor "anaerobiosis"; rather, they studied totally ischaemic, anoxic muscle. Nor did they even study mammals, let alone humans.

Ultimately, I discovered the critical statement by Hill, Long, and Lupton:

Considering the case of running... there is clearly some critical speed for each individual... above which, the maximum oxygen intake is inadequate, lactic acid accumulating, a continuously increasing oxygen debt being incurred, fatigue and exhaustion setting in

(Hill et al. 1924). The standard teaching in human physiology, then as now, is that the body has multiple redundant controls to ensure that all bodily systems are homeostatically regulated under all conditions of life (Lambert et al. 2005) but fail catastrophically only at the moment of death. Yet in this single paragraph, A.V. Hill introduced the concept of catastrophic failure into human exercise physiology. Ninety years later, this concept continues to dominate teaching in our discipline.

In 1971, Jerry Mitchell and G. Blomqvist (Mitchell and Blomqvist 1971) produced the classic figure, reproduced here (Fig. 1), which indicated their interpretation of how the failure of oxygen delivery as conceived by Hill limits maximal exercise performance by producing a "plateau" in oxygen consumption. Their depiction of a plateau was specific: the absence of any further increase in oxygen consumption once a maximum value had been achieved. Yet, currently, there are about 13 modern definitions of the criteria used to define the "plateau phenomenon" (Noakes and St Clair Gibson 2004) and none describes the precise and unequivocal event that Mitchell and Blomqvist conceived.

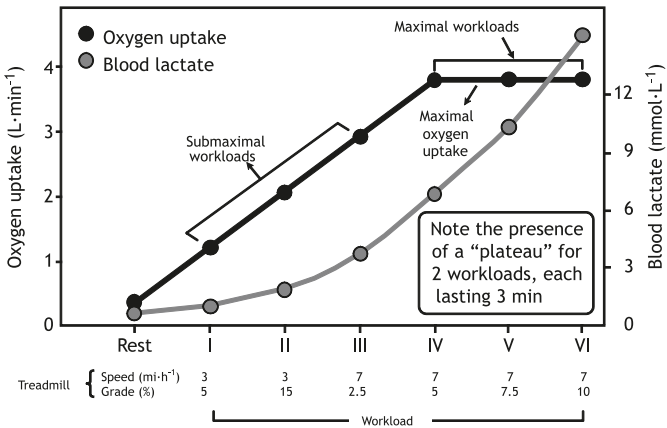
If the plateau phenomenon is caused by the physiological phenomena that Hill described, specifically the onset of myocardial ischaemia leading to skeletal muscle anaerobiosis, then the description of what constitutes a plateau phenomenon is quite simple: it must take the form depicted by Mitchell and Blomqvist. Indeed, according to the Hill model, the real test of a maximal effort must be the development of myocardial ischaemia, a point that is consistently avoided by those seeking to prove that cardiovascular function alone determines maximal oxygen consumption ($\dot{V}O_{2\max}$) (Day et al. 2003; Rossiter et al. 2006; Hawkins et al. 2007; Brink-Elfegoun et al. 2007a, 2007b; Levine 2008).

In a presentation in 1987, I argued for the first time that Hill's original study did not establish that fatigue during maximal exercise is caused by the development of anaerobiosis in the exercising muscles (Noakes 1988) (Fig. 2). This was the start of a decades-long journey to better understand exactly what it was that Hill believed.

Table 1. Mechanisms regulating muscular performance of heart and skeletal muscle. (From Katz 1977, *Physiology of the Heart*, © 1977 Lippincott Williams & Wilkins.)

Mechanism	Functional role in skeletal muscle	Functional role in cardiac muscle
Ability to summate individual contractile events (partial and complete tetanus)	Minor	None
Ability to vary number of active motor units	Major	None
Ability to undergo length-dependent changes in contractile properties (length–tension or Frank–Starling relationship)	Usually minor	Major in beat-to-beat regulation; minor in sustained circulatory changes
Ability to change intrinsic contractile properties (contractility)	Minor	Major in sustained circulatory changes

Fig. 1. An early graphic depicting the “plateau phenomenon”, according to the interpretation of Mitchell and Blomqvist in 1971. Note that in this diagram, the plateau phenomenon is clearly apparent and is present for 3 consecutive workloads. (From Mitchell and Blomqvist 1971, reproduced with permission of New Engl. J. Med., Vol. 284 © 1971 Massachusetts Medical Society.)

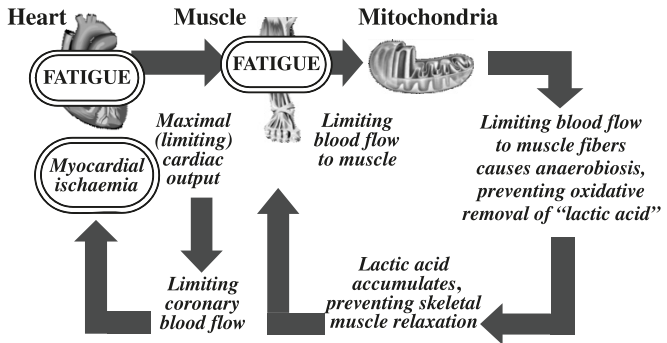


Hill’s original model of the factors limiting human exercise performance

Figure 2 shows Hill’s model of exercise physiology as I understood it before 1996 and as it is usually taught in the majority of modern textbooks of exercise physiology. The key concept is that there is a maximal or limiting cardiac output that cannot be exceeded. As a result, there is a limit to the amount of blood that can be pumped to the exercising muscles. But during maximal exercise, the exercising muscles’ requirement for blood flow exceeds this maximal rate. As a result, the muscles are forced to function “anaerobically” with the production of lactic acid in excess. This lactic acid inhibits muscle contraction, in fact muscle relaxation according to Hill’s original understanding.

When I first concluded that maximal exercise may not be “limited” by a failure of oxygen delivery to the exercising muscle, I postulated incorrectly that fatigue might instead be due to a failure of skeletal muscle contractility (Noakes 1988). This error was based on (i) my training in cardiac physiology; and (ii) my assumption, shared with all exercise scientists who believe in a peripheral regulation of exercise performance either now or in the past, that fatigue in all types of exercise must occur only after all the available motor units in the exercising limbs have been recruited. If exercise is indeed regulated purely by changes in the ability of the exercising skeletal muscles to produce force, the so-called “peripheral fatigue”, then this fatigue can occur only

Fig. 2. The sequence of physiological events that A.V. Hill and colleagues described in 1923 as the cause of fatigue during progressive maximal exercise to exhaustion. Hill based this interpretation on studies in which he and others ran at constant but progressively faster running speeds (Noakes 2008a). Hill did not study subjects running progressively faster until exhaustion, as has become the current model for measuring “maximal” exercise performance.



after all the available motor units have been activated in the exercising limbs and their contractions have been synchronized appropriately. But if exercise terminates without complete skeletal muscle recruitment in the exercising muscles, then the exercise performance must be regulated by the brain and the neural pathways that connect the central nervous system to the muscles. The peripheral fatigue model is unable to explain how exercise can terminate even though there is a population of fresh, unused skeletal muscle fibers in the exercising limbs waiting to be recruited by the brain. I next concluded that the goal of this regulation would be to

prevent the development of organ damage or even death during exercise in both health and disease and under demanding environmental conditions

(Noakes 1997).

The rebuttal to this paper, by Drs. David Bassett and Edward Howley of the University of Tennessee (1997), encouraged me once again to review all of Hill’s writings. I discovered a critical paragraph that had been overlooked by all previous authors, myself included:

The enormous output of the hearts of able-bodied men, maintained for considerable periods during vigorous exercise, requires a large contemporary supply of oxygen to meet the demands for energy... When the oxygen supply becomes inadequate, it is probable that the heart rapidly begins to diminish its output, so avoiding exhaustion.

(Hill et al. 1924).

Hill next suggested a mechanism that would prevent the

development of irreversible heart damage during maximal exercise:

We suggest that... either in the heart muscle itself or in the nervous system, there is some mechanism (a governor) which causes a slowing of the circulation as soon as a serious degree of unsaturation occurs

(Hill et al. 1924).

Remarkably, Hill foresaw that this mechanism acted in an anticipatory manner even though it was activated only after the catastrophe had already begun. The function of this anticipatory control was to ensure that a worse catastrophe, irreversible myocardial damage, was prevented. In his model, the heart and brain are in communication to produce a reduction in myocardial function as soon as myocardial ischaemia begins to develop. Again, this model predicts that fatigue is caused by a catastrophic biological failure. Figure 3 provides a diagram of the real Hill model of exercise performance as he had described it by 1924. Surprisingly, Fig. 2 represents the model that is usually taught; the brain component added in Fig. 3 was not included until I rediscovered Hill's complete theory in 1998 (Noakes 1998).

The moment I understood Hill's explanation, I realized that the central nervous system can ensure that homeostasis is maintained in all bodily systems, not just the heart, by regulating the number of motor units recruited in the exercising muscles by the brain in a feed-forward manner on a moment-to-moment basis. Thus began the start of the evolution of the central governor model (CGM), so named in honour of A.V. Hill's original ideas.

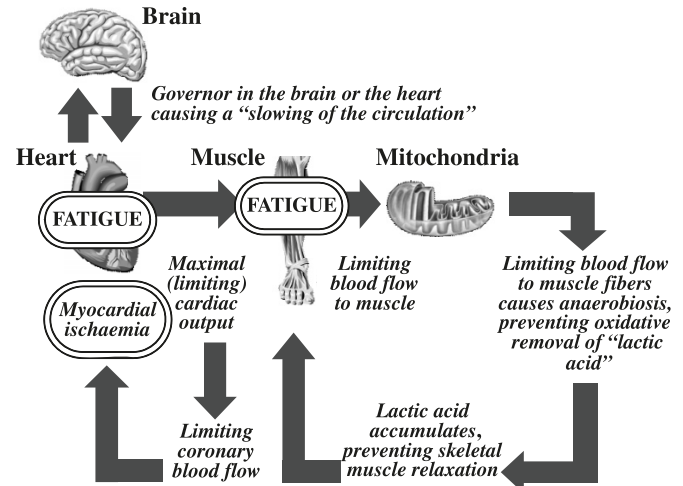
Undoubtedly, the most damaging effect of the Hill model was the exclusion of central command from the brain as a possible factor in exercise performance (Noakes 2008c, 2010b, 2010c). Thus, his specific physiological model of fatigue focused the minds of generations of exercise scientists on maximal exercise to exhaustion in the laboratory as the dominant (and simplest) model for the study of fatigue. Yet, in this model, the experimenter controls the athlete's level of central command by progressively increasing the work rate. But the role of central command in regulating exercise performance cannot be determined if this critical function of the brain is the controlled variable in the experiment. Only if the athlete is allowed to set the pace does the role of central command in the regulation of exercise behaviour become obvious (Tucker et al. 2004, 2006c).

Two competing models to explain either the limitation or the regulation of human exercise performance

Figure 4 shows the main features of the 2 different models that are currently used to explain the factors that either limit or regulate human exercise performance. The Hill model is based on the use of a series of fixed but increasing work rates directed by the experimenter, which continue to increase until the tested subject is no longer able to increase the work rate further (Fig. 1), at which point the brain of the tested subject chooses to terminate the exercise bout. That the brain causes the termination of this test has not always been acknowledged by the advocates for this model.

The first model has encouraged the interpretation that exercise results in linear changes in metabolism, in energy pro-

Fig. 3. The complete A.V. Hill model included the role of the brain as a regulator of heart function. Hill's postulated governor protected the heart from damage by reducing its contractility when myocardial ischaemia developed. Hill understood that myocardial ischaemia must develop if the cardiac output was ever to reach a maximal value (in the absence of anticipatory controls designed to prevent this outcome).

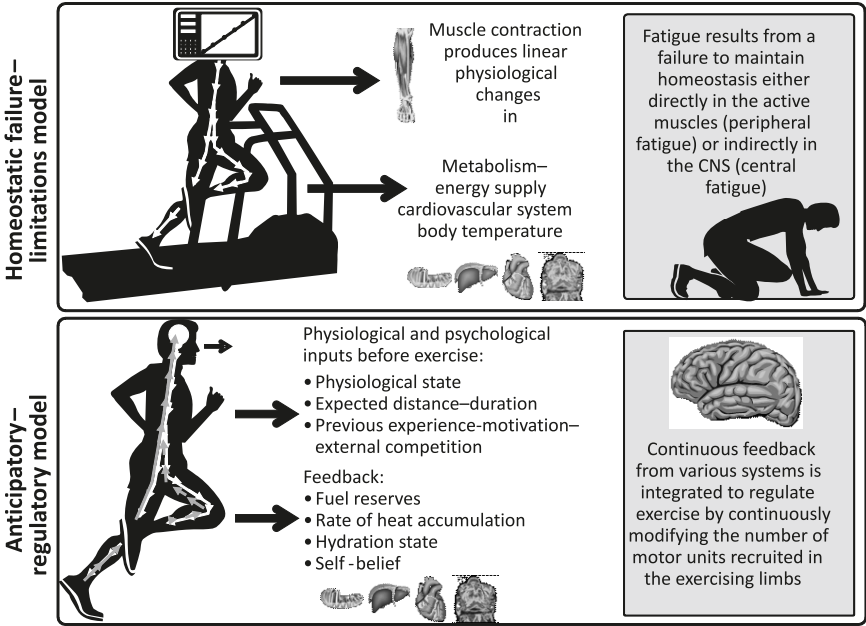


vision, and in the cardiovascular, respiratory, thermoregulatory, and hormonal responses, among many others. Ultimately, demand exceeds capacity in one or more systems, causing them to fail. As a result, this failure to maintain homeostasis either directly in the active muscles (peripheral fatigue) or indirectly in the central nervous system (central fatigue) causes both fatigue and the termination of exercise. Note that this model does not include any role for feedback from the periphery to influence the extent of central motor drive to the exercising muscles. Only more recently and somewhat belatedly have defenders of the Hill model suddenly begun to include peripheral sensory feedback in their models of exercise regulation (Amann et al. 2006, 2007; Amann and Dempsey 2008; Dempsey et al. 2008; Levine 2008; Shephard 2009).

An unwise devotion to the concept that the $\dot{V}O_{2\max}$, limited by the cardiovascular system, is the ultimate determinant of human athletic performance (Bassett and Howley 1997, 2000; Bassett 2002; Levine 2008) has produced this "brainless" model of exercise physiology. For in the test to measure the $\dot{V}O_{2\max}$, the brain of the experimenter usurps the usual function of the experimental subject's central nervous system to establish the pacing strategy (Noakes 2008c). Thus, any potential role of the brain in determining the exercise performance cannot be detected during laboratory testing for the measurement of the $\dot{V}O_{2\max}$.

In contrast, the anticipatory CGM model (St Clair Gibson and Noakes 2004; Noakes 2010b, 2010c) allows feedback from the periphery to influence the magnitude of the feed-forward central drive that determines the extent of skeletal muscle recruitment. Thus, this model allows the action of physiological and psychological inputs before exercise to establish the athlete's initial pace. These factors likely include the athlete's physiological state at the start of exercise; the expected distance or duration of the intended exercise bout; the degree of previous experience that the athlete has, especially in the specific activity that is being undertaken; the

Fig. 4. Two different models (the homeostatic failure–limitations (A.V. Hill) model and the anticipatory regulatory model (central governor model)) are currently used to explain human exercise performance. CNS, central nervous system.



athlete’s level of motivation, which will be influenced by the level of external competition and the importance the athlete ascribes to the event; and the athlete’s level of self-belief, among many other possible factors.

Then, during the exercise, there will be continuous feedback from all the organs in the body, which will inform the central command of the state of the fuel reserves, the rate of heat accumulation, and the hydration state, among a host of other variables. As a result, continuous feedback from multiple organs is integrated to regulate the exercise behaviour by continuously modifying the number of motor units recruited in the exercising limbs.

This system allows an anticipatory regulation of the exercise performance and that is the central prediction of the CGM and the single most important prediction distinguishing it from the traditional central fatigue model (Bigland-Ritchie et al. 1995; Gandevia 2001). That central fatigue model postulates that fatigue occurs as a result of a failure of brain function. It is therefore also a linear, catastrophic model (St Clair Gibson and Noakes 2004) and differs from the traditional peripheral fatigue model only in as much as the brain, and not the exercising muscles, is the site of the catastrophic failure. Although the latter model accepts that the brain causes the termination of exercise, this can occur only after there has been some catastrophic failure of brain function. Thus, the central fatigue model does not allow the brain to anticipate a future failure and so to modify that behaviour specifically to ensure that homeostasis is protected and a catastrophic failure prevented (St Clair Gibson and Noakes 2004).

The explanation for 6 common exercise phenomena according to either the limitation (A.V. Hill model) or the regulation (CGM) of human exercise performance

Table 2 lists 6 phenomena that must be obvious to all

who study human exercise physiology (Noakes 2007). It includes the explanation for these phenomena according to either the Hill model or the CGM.

Only the CGM can explain the variable pacing strategy that is observed in all sporting competitions (Tucker et al. 2006b; Noakes et al. 2009) and indeed in the moment-to-moment changes in muscle power output during exercise (Tucker et al. 2006a). In contrast, the Hill model predicts that athletes can only ever follow one pacing strategy, as discussed subsequently.

Our studies (Kay et al. 2001; Marino et al. 2004; Tucker et al. 2004, 2006c) were among the first (Tattersson et al. 2000) to rediscover the presence of anticipatory pacing (Ulmer 1996), the specific goal of which is to ensure that a thermoregulatory or other failure does not occur during demanding exercise.

Amann and colleagues (2006) extended this to the study of the effects of different levels of hypoxia on pacing, although they may have missed the true physiological relevance of their findings (Noakes and Marino 2007; Noakes 2009). They showed that subjects altered their pacing strategies within less than 60 s of exposure, without their knowledge, to gas mixtures with different inspired oxygen fractions. The effect was dose dependent. Importantly, electromyographic (EMG) activity was reduced in proportion to the reductions in power output, indicating that (i) the reduction in power output on exposure to hypoxia was associated with a reduced central motor drive, as predicted by the CGM; and (ii) this effect was anticipatory and did not occur only after there had already been a catastrophic failure of oxygen delivery to one or more vital organs.

The second phenomenon, and perhaps one of the most interesting in exercise physiology, is the “end spurt”, in which athletes speed up at the end of the race, running the fastest when they should be the most tired (Tucker et al. 2006b). Subjects in the study by Amann and colleagues (2006) pro-

Table 2. The explanation for some common phenomena observed in athletes according to either the A.V. Hill or central governor model.

Phenomenon	A.V. Hill model	Central governor model
Pacing	One pace for all distances	Variable pacing
End spurt	Impossible	Possible
Homeostasis	Fatigue due to loss of homeostasis	Homeostasis maintained under all conditions as a result of behaviour modification
Skeletal muscle activation	Exercise terminates with 100% muscle activation	Never 100% muscle activation during exercise
Drug effects	Act on heart, lungs, muscles, but not brain	Explains effects of drugs acting on brain
RPE	A measure of the exercise intensity	A measure of the relative exercise duration

Note: RPE, rating of perceived exertion.

duced an end spurt associated with an increase in EMG activity in the active skeletal muscles (Tucker et al. 2004, 2007; Ansley et al. 2004*b*), confirming that the end spurt is due to an increased central motor drive (as predicted by the CGM). Interestingly, the end spurt in running is associated with an increase in both the length of each stride and the stride frequency (Enomoto et al. 2008). This can be regulated only by the central nervous system. It is difficult to understand how the end spurt, which determines the race winner in running events, can be initiated by

a large, compliant heart with a compliant pericardium that can accommodate a lot of blood, very fast, to take advantage of the Starling mechanism to generate a large stroke volume

(Levine 2008).

Indeed, the end spurt phenomenon poses significant theoretical problems for our current understanding of fatigue (Marino et al. 2009), which is most simply defined as an inability to maintain the present or required work rate. Yet athletes who develop an end spurt cannot be fatigued according to this definition if they are able to increase their power outputs at the end of exercise when they should be the most tired. This simple analysis of a common real-world phenomenon cannot continue to be ignored simply because it is inconvenient.

According to the CGM, the moment-to-moment (Tucker et al. 2006*a*) changes in pacing strategies that occur during exercise are due to changes in the extent of skeletal muscle recruitment, either increasing or decreasing, depending on whether the athlete either speeds up or slows down. But the Hill model can explain neither a pacing strategy that is set at the start of exercise nor the end-spurt phenomenon (Noakes 2007, 2010*b*, 2010*c*). If the pace is set by the accumulation of a “poisonous metabolite” (e.g., lactic acid or potassium in the exercising muscles), then in the absence of such regulators athletes would begin all forms of exercise at unsustainable paces. Their paces would then slow inexorably as the inhibitory pacing molecules accumulated, causing a progressive reduction in pace.

Thus, according to this model, there can be only one pace in all sporting events, regardless of distance: an initial fast pace that falls progressively until the metabolites reach a constant, equilibrium concentration. Thereafter, it should be possible to sustain a constant pace until the exercise terminates. The presence of such metabolites must also prevent any sudden increase in pace immediately prior to the end of exercise (the end spurt).

The third phenomenon is the protection of homeostasis

(Baron et al. 2008; Pires et al. 2010), which, according to the Hill model, does not occur. Rather, according to that model, it is the failure of homeostasis that causes fatigue and exhaustion. In contrast, the key prediction of the CGM is that behaviour modification ensures that homeostasis is protected under all conditions (Tucker et al. 2004, 2006*c*; Noakes 2009).

The fourth phenomenon is the difference in the extent of skeletal muscle activation that either model requires to be present at the point of fatigue. The Hill model must predict that exercise terminates when there is 100% activation of all the motor units in the exercising limbs (Noakes and St Clair Gibson 2004), for if the periphery alone determines the exercise performance, then the activity can only stop after all the muscle fibers have been recruited and used to the point of their individual exhaustion. In contrast, the CGM predicts that exercise must always terminate before there is 100% muscle activation because complete skeletal muscle activation would cause bodily harm and a failure of homeostasis (St Clair Gibson and Noakes 2004; Lambert et al. 2005).

There is convincing evidence that complete skeletal muscle recruitment does not occur during exercise in humans (Sloniger et al. 1997*a*, 1997*b*; Amann et al. 2006, 2007; Albertus 2008). In fact, it occurs rarely in humans, perhaps only in medical conditions such as infection with the tetanus bacillus, which causes tetanic muscle contractions that may lead to bony fractures (Baisch 1917; Wilhelm 1923; Roberg 1937). Similarly, treatment of patients with schizophrenia with the analeptic (convulsion-producing) drug metrazol (Bennett and Fitzpatrick 1939; Polatin et al. 1939), or of those with depression with convulsive shock therapy (Hamsa and Bennett 1939), was associated with bony fractures before these forms of inhumane treatment were finally terminated. These examples show that unregulated skeletal muscle contraction can produce sufficient force to cause bony fractures. It makes sense that complete skeletal muscle recruitment must be prevented by some central control mechanism if these complications are to be avoided.

The fifth phenomenon is the manner in which certain drugs that act only on the central nervous system can improve exercise performance. According to the “brainless” Hill model, only drugs that act on the heart, lungs, and muscles, but not on the brain, can improve exercise performance. In contrast, the CGM is able to explain why certain drugs that act exclusively on the brain can improve exercise performance. Our own studies show that amphetamines act by modifying the extent of skeletal muscle reserve and allow exercise to continue for longer at a higher intensity (Swart et al. 2009).

The sixth phenomenon is the true meaning of the rating of perceived exertion (RPE). According to the classic interpretation of its originator, Dr. Gunnar Borg, the RPE is a measure exclusively of exercise intensity (Borg 1998). In contrast, in the process of developing the CGM, we discovered that the RPE is a measure of the duration of exercise that has been completed or that still remains (Noakes 2004, 2008*b*; Crewe et al. 2008).

We have since shown that the RPE is different from the start of exercise in the heat even though the rectal temperatures of the subjects were not then different (Crewe et al. 2008). Therefore, the brain had calculated the projected rate of heat retention in different environmental conditions and had planned, in anticipation, the exercise duration that could be safely sustained without the risk that heat stroke would develop.

In summary, the biological basis of 6 phenomena, well known to all who observe or study exercise, cannot be explained adequately by the traditional Hill model. Instead, all are compatible with the predictions of the CGM. When added to the compelling body of evidence that disproves the biological basis for the Hill model (Noakes and St Clair Gibson 2004), it becomes quite difficult to understand (Noakes 2010*a*) how some continue to argue that the CGM is “improbable” (Hopkins 2009; Shephard 2009).

Some historical and current studies that confirm that exercise is regulated by central motor command, which also responds to the presence of feedback from a variety of different organs

Figure 5 shows some of the key predictions of the CGM. These are that (i) the ultimate regulation of the exercise performance resides in the central nervous system, the function of which is potentially modifiable by interventions that act exclusively on central (brain) mechanisms; (ii) the exercise pace is set “in anticipation”; (iii) the protection of homeostasis requires that there is always a skeletal muscle reserve during all forms of exercise; (iv) the exercise intensity may increase near the end of exercise (the end spurt), even in the face of significant “fatigue”; and (v) afferent sensory feedback can modify the exercise performance.

Figure 5 includes at least 30 studies that show that exercise performance can be modified by interventions such as music (Barwood et al. 2009; Lim et al. 2009); the use of placebos (Beedie et al. 2006, 2007; Foad et al. 2008; Trojan and Beedie 2008); self-belief (Micklewright et al. 2010); prior experience (Mauger et al. 2009); time deception (Morton 2009); knowledge of the endpoint (Wittekind et al. 2009); the presence of other competitors (Wilmore 1968); psychological skills training (Barwood et al. 2008); monetary reward (Cabanac 1986); mental fatigue (Mancora et al. 2009); sleep deprivation (Martin 1981); glucose ingestion (Chambers et al. 2009; Rollo et al. 2010; Gant et al. 2010); cooling of the palms (Kwon et al. 2010); cerebral oxygenation (Nybo and Rasmussen 2007; Rupp et al. 2008; Seifert et al. 2009; Billaut et al. 2010; Rasmussen et al. 2010*a*, 2010*b*); centrally acting drugs or chemicals such as the amphetamines (Swart et al. 2009) modafinil (Jacobs and Bell 2004), caffeine (Kalmr 2005), pseudoephedrine (Pritchard-Peschek et al. 2010), naloxone (Sgherza et al. 2002), and

acetaminophen (Mauger et al. 2010); and the cytokines interleukin (IL)-6 (Robson-Ansley et al. 2004) and IL-1 β (Carmichael et al. 2006), and bupropion (Watson et al. 2005; Roelands et al. 2008, 2009; Roelands and Meeusen 2010), all of which can reasonably be assumed to act exclusively or predominantly on the central nervous system. More recently, it has been shown that even superstition (Damisch et al. 2010) can influence performance in skilled sporting activities.

In contrast, the “brainless” Hill model (Noakes 2008*c*) cannot explain how interventions that act exclusively on the brain can influence athletic performance.

Similarly, a number of other studies (Fig. 5) support the predictions of the CGM, specifically the presence of anticipatory feed-forward control of skeletal muscle recruitment during exercise (Marino et al. 2004; Marino 2004; Ansley et al. 2004*a*, 2004*b*; Castle et al. 2006; Joseph et al. 2008; Tucker 2009; Tucker and Noakes 2009); the presence of skeletal muscle recruitment reserve during exhaustive exercise (Amann et al. 2006; Albertus 2008; Swart et al. 2009; Mancora and Staiano 2010; Ross et al. 2010), especially at high altitude (Kayser et al. 1994; Noakes 2009); afferent sensory feedback that influences exercise performance (Marino et al. 2004; Noakes et al. 2004*a*; Tucker et al. 2004, 2006*c*, 2007; Rauch et al. 2005; Amann et al. 2006; Clark et al. 2007; Edwards et al. 2007; Eston et al. 2007; Mancora and Bosio 2007; Noakes and Marino 2007; Morante and Brotherhood 2008; Racinais et al. 2008; Altareki et al. 2009; Baron et al. 2009; Flouris and Cheung 2009; Johnson et al. 2009; Lima-Silva et al. 2010); and the presence of the end spurt (Kay et al. 2001; Tucker et al. 2004, 2006*b*, 2007; Amann et al. 2006; Noakes et al. 2009). The end spurt proves that our current understanding of fatigue is incomplete (Noakes and St Clair Gibson 2004) because athletes are able to produce their greatest power outputs when they are supposedly the most fatigued.

My conclusion is that the evidence supporting a central control of exercise performance is rather more secure than is the questionable evidence on which the Hill model is founded (Noakes and St Clair Gibson 2004).

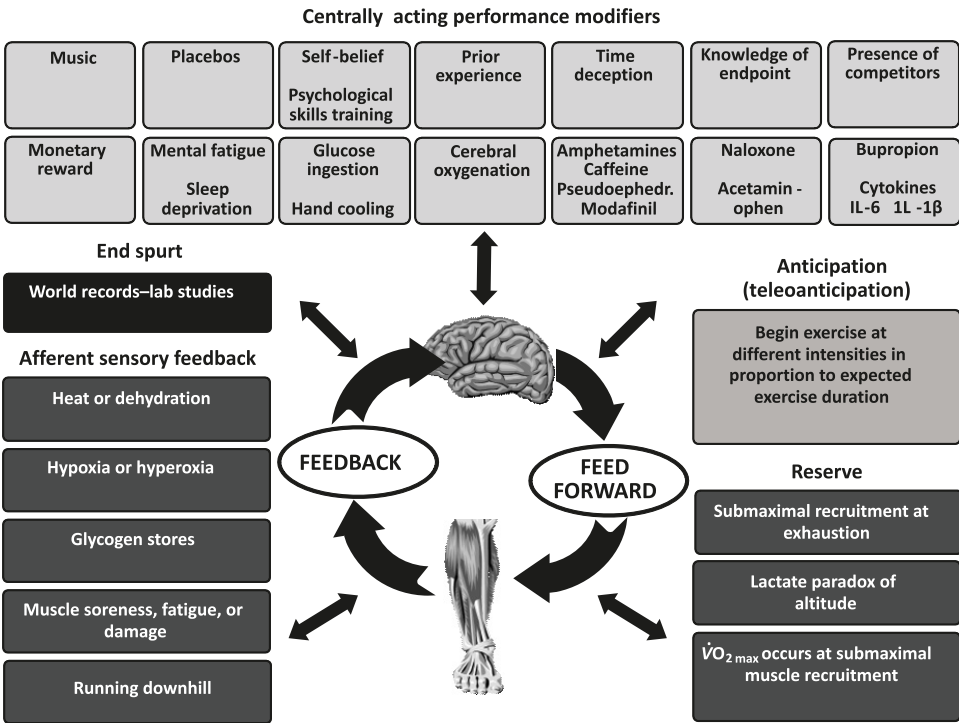
Conclusions

The CGM describes exercise as a behaviour that is regulated in anticipation by complex intelligent systems, the function of which is to ensure that whole-body homeostasis is protected under all conditions. This complexity cannot be appreciated if the body is studied as a collection of disconnected components, as is the usual practice in the modern exercise sciences.

Indeed, on the basis of their work with United States military conscripts during the Second World War, Bean and Eichna warned as early as 1943 that

... physical fitness cannot be defined nor can differences be detected by means of a few simple physiological measurements... obtained during limited tests... To do so results in focusing attention on some erroneous concept. Man is not a pulse rate, a rectal temperature, but a complex array of many phenomena... Into performance enters the baffling yet extremely important factor of motivation, the will-to-do. This cannot be measured and remains an uncontrollable, quickly fluctuating, disturbing

Fig. 5. A collection of historic and modern studies that are compatible with the central governor model but most of which cannot be explained by the A.V. Hill model. The cited studies are fully referenced in the text. IL, interleukin; $\dot{V}O_{2\max}$, maximal oxygen consumption.



variable which may at any time completely alter the performance regardless of physical or physiologic state. (Bean and Eichna 1943).

Similarly, Dr. Roger Bannister wrote in 1956 that

The human body is centuries in advance of the physiologist, and can perform an integration of heart, lungs and muscles which is too complex for the scientist to analyse (Bannister 1956). Later he continued, “It is the brain not the heart or lungs, that is the critical organ, it’s the brain” (Entine 2000). Future generations of exercise scientists would be well advised to heed the words of these most observant scientists.

The novel concepts predicted by the CGM (Noakes et al. 2004b, 2005; Noakes 2010b, 2010c), which are the opposite of those flowing from Hill’s model, are the following:

1. Discovering the biological basis of pacing, not of fatigue, is the most important challenge for those studying exercise performance. The goal of pacing is to maintain homeostasis and to prevent a catastrophic physiological failure.
2. Multiple, independent systems in the periphery provide sensory feedback that influences central motor drive from the brain to the exercising muscles. The outcome of this information is the pacing strategy that develops during exercise.
3. Fatigue is purely a sensory perception, which may be expressed physically as an alteration in the pacing strategy. Fatigue is the mechanism by which the central nervous system ensures that homeostasis is maintained.
4. The role of the brain is to ensure that exhaustion devel-

ops and exercise terminates even though homeostasis is maintained. As a result, a catastrophic outcome is prevented. This interpretation conflicts absolutely with the traditional Hill model, which requires that exercise terminate only after there has been a failure of homeostasis in one or more biological systems.

Like all theories that challenge an entrenched dogma that has been accepted for nearly a century, the CGM has evoked a wave of distrust and even some suggestions that it should be suppressed (Shephard 2009). But the task of real science is to discover that which is true and to advance our knowledge, not to attempt to suppress information that is inconvenient. The value of this debate is that it can encourage the rigorous and open discussion of an idea that challenges the very core of what is currently handed down as the “truth” to succeeding generations of exercise scientists.

In his trilogy devoted to the study of the scientific process and those who produce new knowledge, Daniel J. Boorstein (1983) wrote, “The barrier to knowledge is not ignorance. It is the illusion of knowledge.”

It is improbable that, on the basis of the few simple experiments that he conducted, Professor Archibald Vivian Hill could have developed a model of exercise (Bassett 2002; McLaughlin et al. 2010) for which over the past 90 years “only relatively minor refinements to his theories have been needed” (Bassett and Howley 1997). Instead, the argument can be made that now may be an appropriate time to replace the “brainless” Hill model with a more modern successor in which the controlling role of the central nervous system is appropriately acknowledged (Noakes 2010a).

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