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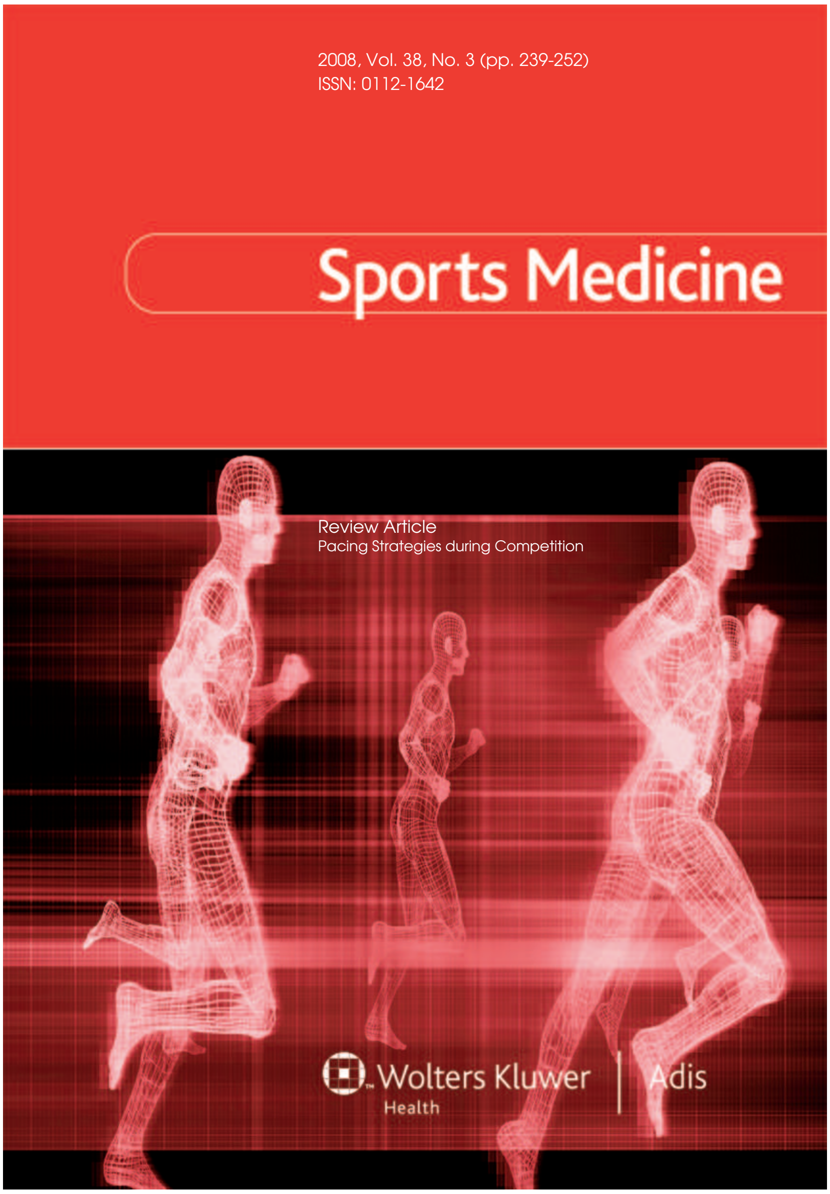
2 authors:

Chris R Abbiss
Edith Cowan University

Paul Laursen
Auckland University of Technology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Describing and Understanding Pacing Strategies during Athletic Competition

Chris R. Abbiss and *Paul B. Laursen*

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

Contents

Abstract

It is widely recognized that an athlete's 'pacing strategy', or how an athlete distributes work and energy throughout an exercise task, can have a significant impact on performance. By applying mathematical modelling (i.e. power/velocity and force/time relationships) to athletic performances, coaches and researchers have observed a variety of pacing strategies. These include the negative, all-out, positive, even, parabolic-shaped and variable pacing strategies. Research suggests that extremely short-duration events (≤30 seconds) may benefit from an explosive 'all-out' strategy, whereas during prolonged events (>2 minutes), performance times may be improved if athletes distribute their pace more evenly. Knowledge pertaining to optimal pacing strategies during middle-distance (1.5–2 minutes) and ultra-endurance (>4 hours) events is currently lacking. However, evidence suggests that during these events well trained athletes tend to adopt a positive pacing strategy, whereby after peak speed is reached, the athlete progressively slows. The underlying mechanisms influencing the regulation of pace during exercise are currently unclear. It has been suggested, however, that self-selected exercise intensity is regulated within the brain based on a complex algorithm involving peripheral sensory feedback and the anticipated workload remaining. Furthermore, it seems that the rate and capacity limitations of anaerobic and aerobic energy supply/utilization are particularly influential in dictating the optimal pacing strategy during exercise. This article outlines the various pacing profiles that have previously been observed and discusses possible factors influencing the self-selection of such strategies.

In an attempt to enhance our understanding of athletic performance, sport scientists have examined how work or energy expenditure is distributed during an exercise task.[1-5] This distribution of work, or pattern of energy expenditure, has been termed 'pacing' or 'pacing strategy'.[2,6,7] It is well documented that during athletic competitions, well trained athletes must regulate their rate of work output in order to optimize overall performance.[3,8,9] However, scientific research examining the pacing strategies employed during competition is scarce.[10] Recently, St Clair Gibson et al.[11] have illustrated how communication between the brain and peripheral physiological systems may regulate pace during exercise. However, little is presently known pertaining to the specific physiological, cognitive and/or environmental factors that affect or control the detailed distribution of work during exercise.[11,12] Furthermore, St Clair Gibson et al.[11] recognize that "further research is required to help clarify which of the different possible pacing strategies are optimal for different sports and for different distances performed during athletic events." Therefore, the purpose of this article is to: (i) examine the literature pertaining to the various pacing strategies that have been observed; (ii) provide recommendations for use of such pacing strategies under the varying situations encountered by athletes in the field; and (iii) to determine possible underlying mechanisms responsible for the regulation of pace during varying exercise tasks and conditions.

1. Defining Pacing Strategies

Most individual sporting events, such as running, swimming, cycling, rowing, skiing and speed skating, are considered to be of a 'closed-loop design'.[13] That is, the athlete aims to finish a known distance in the shortest time possible.[8,14] Within these events, athletes are required to compete against others in either direct 'head-to-head' competition or individually against the clock.[8] For success in head-to-head competition, the performance time of the winning athlete need only be marginally lower than that of other competitors in the same race.[8] Thus, the actions of opponents or team members often influence race dynamics, making team, coach and individual tactics important to overall success.[15] Alternatively, events also exist whereby athletes may not race each other in direct head-to-head confrontation, but may instead be 'racing the clock'.[8,15] In this race format, often known as a time trial, results are determined by the time required to complete the given distance.[16] An advantage of the individual time trial is that, in the absence of any direct head-to-head confrontation, laboratory-based trials can somewhat replicate true competition, allowing performance to be accurately modelled.[7,17-19] While the distribution of work (i.e. pace) during a time trial has been shown to be important to overall performance,[3,9] it is still unclear as to the optimal pacing strategies required to ensure the best possible performance outcome under the variable environmental conditions experienced by athletes (e.g. climate, terrain, altitude, wind).[11]

The overall speed of an athlete during a locomotive task is dependent upon a number of factors, including the mechanical power generated, momentum or kinetic energy, and the degree of resistive forces that are experienced (i.e. aerodynamic/hydrodynamic resistance/drag, frictional resistance, gravity).[7,18-21] Although recent technological advancements have allowed scientists to measure the mechanical power produced by an athlete during competition,[22,23] it is important to note that the term 'pacing' more accurately refers to performance times or velocity and not the actual mechanical work or power output produced. Despite this, the regulation of pace is largely dictated by the ability to resist fatigue, making the mechanical power output generated of extreme importance.[7] By modelling power/velocity relationships and observing elite athletic performances, coaches and researchers have been able to gain some insight into understanding optimal pacing strategies during varying competition scenarios.[1,15,20] In particular, it is believed that short-duration sprint events (i.e. ≤30–60 seconds) may benefit from an 'all-out' sprint strategy,[1,8,24] whereas more extended (>2 minutes) endurance performance may be improved if athletes distribute energy resources more evenly.[7] Indeed, a variety of pacing profiles have been observed during different exercise tasks and under differing exercise conditions.[9,11] Such profiles include negative, all-out, positive, even, parabolic-shaped and variable pacing strategies. These pacing profiles are reviewed in the context of determining situations in which each strategy may be most favourable to athletic performance.

1.1 Negative Pacing

An event is considered to have been performed with a negative-split, or through use of a negative pacing strategy, when there is an increase in speed observed over the duration of the event. Adoption of such a pacing strategy is thought to improve prolonged exercise performance by reducing the rate of carbohydrate depletion,[12] lowering excessive oxygen consumption ($\dot{V}O_2$)[25] and/or limiting accumulation of fatigue-related metabolites (i.e. inorganic phosphate, potassium and hydrogen ions) early on in the exercise task.[12,26,27] Supporting this presumption, Mattern et al.[26] showed that compared with self-paced trials, a negative pacing strategy resulted in a significantly lower blood lactate concentration during the initial 9 minutes of a 20-km cycling time trial. Furthermore, the relatively low enforced starting power output (15% lower than self-selected power output) resulted in significant improvements in overall performance.[26]

A negative pacing strategy is often observed, especially during middle-distance events, when power output[2,26,28-30] and velocity[2] are increased towards the end of both simulated and actual time-trial events (figure 1). This final increase in exercise intensity commonly occurs in events when athletes are made aware of the remaining trial distance[13,28] or duration.[31-33] It is believed that this increase in

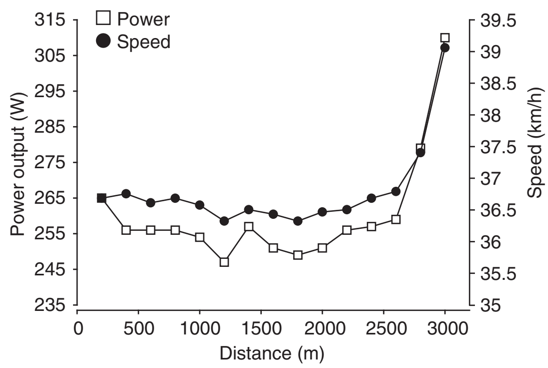

Fig. 1. Speed and power output profiles during 3000-m track cycling events. Note the dramatic increase in speed and power output during the final 13% (400 m) of the event, resulting in the observation of a negative pacing strategy (reproduced from Foster et al.,[2] with permission from Georg Thieme Verlag).

power output commonly seen towards the end of individual time-trial events may be the result of an increase in motor unit recruitment[28] and the use of the anaerobic energy reserve.[2]

1.2 'All-Out' Pacing

During certain locomotive events, the cost associated with acceleration can significantly influence the pacing strategy required for optimal performance.[1] During the 100-m sprint, world-class runners spend ~50–60% of the race in the acceleration phase.[34] Consequently, 20–25% of the overall work demand of a 100-m sprint event may be required merely to alter the body's kinetic energy from rest. Furthermore, due to an increase in kinetic energy as a result of increasing momentum, the energy required to maintain a constant pace is lower than the energy required to accelerate, especially when inertia is high (i.e. greater mass and velocity). Since the energy expenditure required to accelerate is inevitable, it is believed that this energy is best distributed at the start of short events, as any submaximal movement speed ultimately results in slower performance times.[1,7] As this initial acceleration period at submaximal speed is proportionately greater during short-duration sprint events, it is possible that optimal performance during these events may be obtained when athletes start and continue the event in an 'all-out' fashion[1,35] (figure

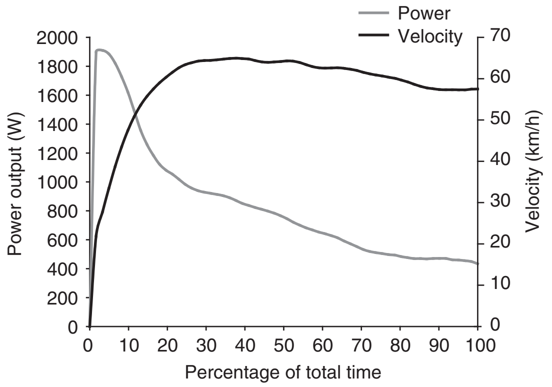

Fig. 2. Example of power output and velocity profiles during a 1000-m track cycling event. Note the high power output needed to alter the kinetic energy from rest, and the gradual decline in velocity beyond 40% (~25 sec) of the overall trial time.

2). Despite adoption of this all-out strategy, the significant percentage of time spent in the acceleration phase (at low relative speeds) during short sprint events often results in 'negative-split' performance times[1,2,7,15] (figure 2). Interestingly, the greater percentage of the event time spent in the acceleration phase during the current men's 100-m world record sprint time has actually resulted in a slower average speed for the 100-m sprint when compared with the 200-m sprint (10.24 vs 10.35 m/sec, respectively).

After an athlete has reached peak velocity using an all-out pacing strategy, speed tends to gradually decrease[15] (figure 2), possibly resulting in suboptimal performance times.[1,7] It should be noted, however, that during a time trial, any velocity/energy that exists when passing the finish line is essentially wasted kinetic energy.[1,7] Thus, compared with a constant pace, the all-out pacing strategy may result in considerably lower kinetic energy losses due to a slower finishing velocity.[1,7] Short-duration sprint performance may therefore benefit from the all-out pacing strategy, despite a comparatively greater amount of energy lost to frictional resistance as a result of the high peak velocity.[1,7] The choice between reducing wasted kinetic energy and/or preserving energy lost to frictional resistance is dependant upon the degree of kinetic energy lost at the end of the race and the magnitude of the resistive forces experienced.[7,20] The longer the event, the less important kinetic energy loss becomes relative to the cost of aerodynamic/hydrodynamic resistance.[2,6,8,18,20,36] With the use of various mathematical models and physiological constants calculated from previous world record times, Keller[24] determined that optimal performance can be achieved during running events of <291 m when athletes adopt the all-out pacing strategy. A limitation of this and other calculations,[34,37] however, is that models are fundamentally based on a number of physiological constants pertaining to the maximal acceleration, velocity and the endurance or rate-of-fatigue in athletes. Thus, the various physiological attributes of an athlete will significantly influence the distance beyond which an all-out strategy is no longer optimal to performance. Despite this, the predictions by Keller[24] seem plausible as research suggests that anaerobic energy resources become significantly reduced following all-out sprinting beyond this distance (i.e. ~30–60 seconds duration).[38]

1.3 Positive Pacing

A positive pacing strategy is one whereby an athlete's speed gradually declines throughout the duration of the event. In both the 100-m and 200-m swimming,[39] as well as the 2000-m rowing events,[40] national and elite calibre athletes have been shown to adopt a positive pacing strategy. In addition, athletes who run within 2% of the world record time in the 800-m running track event have been shown to utilize a positive pacing strategy.[25] Sandals et al.[25] reported that elite 800-m runners typically run the first 200 m, the middle 400 m, and the final 200 m at 107.4%, 98.3% and 97.5% of the average speed for the entire 800 m, respectively. Moreover, compared with an even pacing strategy (see section 1.4), positive pacing resulted in a significantly greater fractional peak $\dot{V}O_2$ during the event (89.3 ± 2.4% vs 92.5 ± 3.1% maximum oxygen consumption [$\dot{V}O_{2max}$], respectively).[25] As previously stated in section 1.2, the relative time spent accelerating may significantly influence pacing strategy, often resulting in the adoption of a negative pacing strategy during short-duration events. However, in certain locomotive events such as swimming and relay athletics, the relative time spent accelerating may be reduced. During swimming, the dive start allows athletes to reach maximal velocity within a relatively short time. Similarly, the ‘flying start’ that occurs during the final three legs of relay athletic races reduces the influence of acceleration on overall pacing strategy. Athletes may, therefore, adopt a positive pacing strategy during such events due, at least in part, to the specific starting procedures.

It has been shown that the adoption of a positive pacing strategy results in an increased $\dot{V}O_2$,[25,41] greater accumulation of fatigue-related metabolites[41,42] as well as an increase in the rating of perceived exertion[41] during the early stages of an exercise task. As a result, a reduction in the exercise intensity and the observed positive pacing profile likely evolves in response to these signals so that catastrophic failure of any one physiological system does not occur.[4,42,43] In support of this hypothesis, well trained endurance cyclists (peak power output ≥370W) have been shown to commence cycling time trials in the heat (35ºC) at relatively high power outputs.[5,28] Following this initial high exercise intensity, Tucker et al.[5] showed that power output declined at a significantly greater rate in hot (35°C) compared with cool (15ºC) conditions (2.35 ± 0.7 vs 1.61 ± 0.8 W/min). In this study, subjects were required to cycle at a set perceived exertion (16 on the Borg’s rating of perceived exertion scale) until power output fell below 70% of initial power output.[5] As the rate of decline in power output was correlated (r = 0.92) to preceding rates of heat storage, the authors’ hypothesized that work rate is continuously manipulated to limit the rate of rise in heat accrual and avoid the development of critically high core temperatures (~39.5–40.5ºC).[5,44,45] The reason athletes self-select such relatively high power outputs during an endurance exercise task in the heat is unclear,[5,28] but may be related to the lack of thermal stress at the commencement of the trial. Further research is required to better understand the influence of environmental heat and thermoregulation on self-selected pacing strategies.

It is possible that a relatively fast starting strategy during competition may be the result of unrealistic ambitious perceptions regarding personal athletic ability, whereby athletes begin their race at a pace designed to finish within the medallists or at a personal best pace.[2] The adoption of this race tactic may be seen during a number of high-level competition events. Cyclists are often seen attempting to breakaway from the main group of riders during numerous road cycling events (such as Le Tour de France, Giro d’Italia and La Vuelta a España), presumably for the purpose of winning the race or days’ stage. Such breakaways do not usually succeed unless either allowed to or misjudged by the peloton. Despite few of these breakaways being successful, it is possible that this strategy may succeed often enough to be considered as a viable tactic to employ during high-level competitions. Indeed, in 2001, Ben Kimondiu, a pacesetter employed to set a high pace at the start of the LaSalle Bank Chicago Marathon, continued beyond what was expected and ultimately won the race in 2:08:52. However, such a tactic is seldom successful and instead often results in a progressive reduction in exercise intensity due to disturbances in physiological homeostasis (i.e. fatigue).[2] To illustrate this point, Thompson et al.[42] asked swimmers to swim at 102% of their maximal 200-m time-trial speed, and found that they slowed significantly during the latter half of the event. Furthermore, this positive pacing strategy was associated with higher post-blood lactate concentrations, respiratory gas exchange ratios and perceived exertions compared with even split pacing trials.[42]

Evidence suggests that self-selected exercise intensity during an ultra-endurance event (>4 hours) also tends to progressively decrease (figure 3).[46-52] For example, it has been found that heart rate declines at an average rate of 1–2% per hour during cycling and triathlon events lasting 6–24 hours, in both recreational[46,52] and elite[51] athletes. Similarly, power output and speed have also been found to significantly decline during the 180-km cycle phase of an Ironman triathlon.[47] It is believed that this progressive reduction in exercise intensity may be

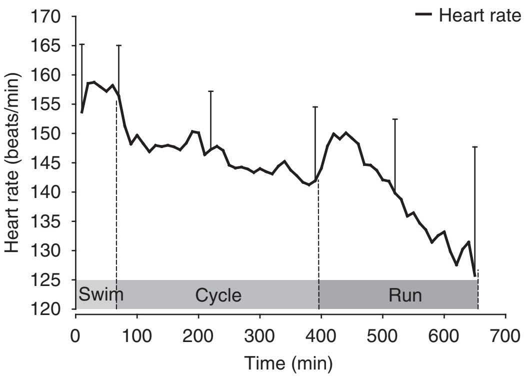

Fig. 3. Example of a positive pacing strategy shown by a decline in heart rate during the swim, cycle and run phases of the Ironman triathlon; n = 27 (adapted from combined data of Laursen et al.[46,58]).

the result of increased glycogen depletion,[33,53] resulting in altered substrate utilization,[50,51,54] neuromuscular fatigue[12,54-56] and/or psychological factors associated with the perception of fatigue.[12,51,57] Thus, the ability to resist fatigue may play a significant role in the regulation of pace during ultra-endurance events. The optimal pacing strategies to employ during such prolonged exercise, however, are unknown and require further investigation.

1.4 Even Pacing

As previously mentioned in section 1.3, one's chosen starting strategy can significantly influence the overall performance time, especially during short-duration events. During more prolonged events, however, starting strategy appears to have less of an effect on overall performance times[2,9] because of the lower percentage of time spent in the acceleration phase. Consequently, it has been suggested that under stable external conditions (i.e. environmental and geographic), a constant pace is 'optimal' for prolonged (>2 minutes) locomotive events such as running, swimming, rowing, skiing, speed skating and cycling.[7,41,42] Wilberg and Pratt[15] showed that more successful Canadian national and international calibre pursuit (3000–4000-m) and 1000-m track cyclists used more constant/even pace race profiles, whereas less successful riders did not. Further evidence supporting an even distribution of pace has been shown in a study by Padilla et al.,[59] who examined the speed of a cyclist during a successful 1-hour track world record attempt. From this study, it can be seen that the cyclist was able to maintain a steady velocity during the entire duration of the trial and that the speed of the cyclist per lap deviated very little from the target speed (53.0 km/hour) or the actual mean of 53.040 km/hour (figure 4).[59] The theoretical support for an even pacing strategy is primarily based on critical power models and mathematical laws of motion, which indicate that velocity is dictated by the maximal constant force that an athlete can exert along with the resistive forces experienced.[17,60-62] By using mathematical modelling, Fukuba and Whipp[62] have shown that performance will be compromised if an athletes' velocity or power drops below their physiological limits (i.e. 'fatigue threshold' or 'critical power') at any point during an endurance event, even if athletes attempt to make up for lost time with a final increase in speed towards the end of an event. Furthermore, as an athlete increases velocity, a greater percentage of the power generated is used to overcome fluid (i.e. air or water) resistance rather than producing forward motion. Minimizing such variations in pace may be especially important during events that incur a high degree of fluid resistance. For example, the higher velocities reached during cycling compared with running result in sig-

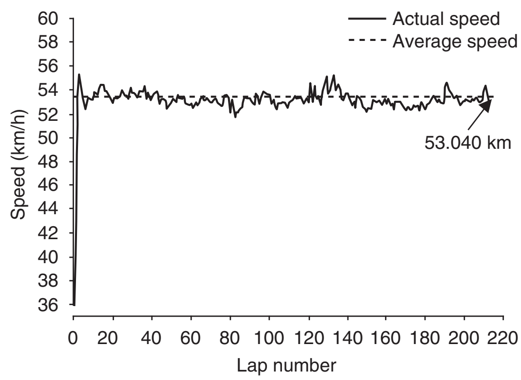

Fig. 4. Average speed of a cyclist during progressive laps and the entire 1-hour track cycling world record. Note that the speed of the cyclist deviated very little from the trial mean resulting in the adoption of an even pacing strategy (reproduced from Padilla et al.,[59] with permission).

nificantly greater aerodynamic resistance. Furthermore, as a result of differences in fluid viscosity, fluid resistance is greater during water-based sports such as swimming and rowing compared with land-based sports. As even minor fluctuations in speed can result in a greater energy cost,[63] it is possible that overall performance times during prolonged events may be optimized when acceleration and deceleration is minimized.[18] Further research is need to understand the influence of improved skill and technique on energy cost and pacing strategy, especially during repetitive stroke/stride exercises such as running, swimming and rowing.

1.5 Parabolic-Shaped Pacing

Historically, research into the regulation and distribution of energy expenditure during an exercise task has examined the distribution of work over relatively long time periods or distances. In particular, studies focusing on pacing strategies have examined differences in performance during the first and second halves of a race (i.e. split times).[1,10] However analysis of these split performance times is a relatively simple or gross analysis of one's overall pacing strategy (i.e. positive, negative or even splits), and does not provide great insight into the distribution of work throughout the event. The recent development of more accurate and reliable power and time meters has allowed scientists to specifically examine performance profiles during

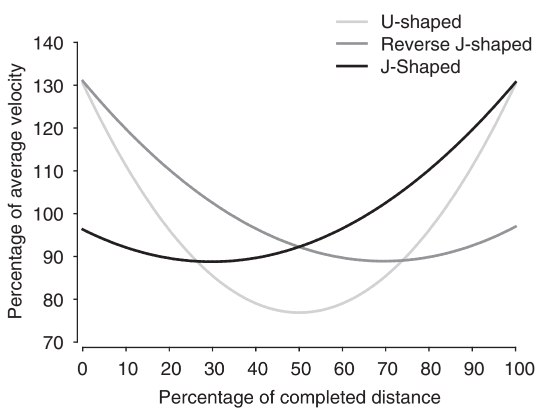

Fig. 5. Example of U-shaped, reverse J-shaped and J-shaped pacing profiles during exercise.

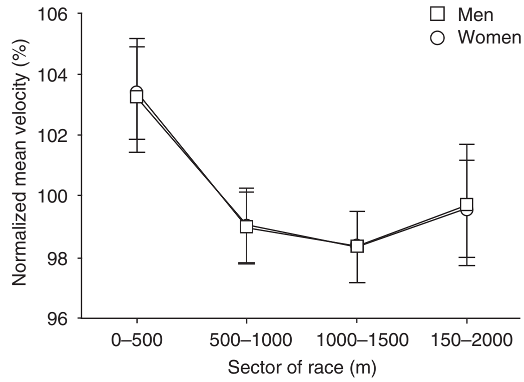

Fig. 6. Example of a reverse J-shaped pacing profile observed during the 2000-m on-water rowing championships (reproduced from Garland,[40] with permission).

field competitions.[36,40,47] Using this technology, researchers have shown that athletes may progressively reduce speed during an endurance trial but tend to increase speed during the latter portion of the event.[28,40] This tactic ultimately results in U, J or reverse J-shaped pacing strategies (figure 5). Evidence for such a pacing profile was shown by Garland[40] who examined the velocity of elite rowers during the 2000 Olympic Games, 2001 and 2002 World Championships and the 2001 and 2002 British Indoor Rowing Championships. In each of these 2000-m races, rowers completed the first 500 m in the fastest time (5.1 seconds faster than subsequent sections of the race), slowed during the middle 1000 m, but increased speed during the final 500 m of the race; this resulted in the adoption of a reverse J-shaped pacing strategy (figure 6).[40]

Little research is available describing these U, J or reverse J-shaped pacing strategies,[40,64] but such strategies may be the result of athletes adopting both a positive and negative pacing strategy during an event. For example, when Tucker et al.[28] had well trained cyclists perform 20-km cycling time trials in the heat, they showed that cyclists reduced power output in an anticipatory fashion, likely in an attempt to prevent the development of excessive exercise-induced hyperthermia. This study also reported that power output was increased during the final 5% of the 20-km time trial despite core body temperatures being at their highest (39.2 ± 0.6ºC).[28] It is believed that this increase in power output is the result of an increase in motor unit recruitment[28] relating to an anaerobic energy reserve.[2] Consequently, the choice of pacing strategy does not appear to be dictated by changes in any one physiological system, but instead may be influenced via a complex system of integrated feedback from a number of sources, including prior experience and anticipated duration.[12] Furthermore, as cross-sectional studies cannot ever determine a cause-and-effect relationship, it is difficult to examine factors influencing pacing strategies with the use of such study designs. Future research should therefore take a holistic and multidimensional approach in examining factors that may influence the regulation of work rate during exercise.

1.6 Variable Pacing

Research into effective pacing strategies has been complicated by a number of external factors, including race duration,[2] course geography[18] and environmental conditions, such as wind[7,59] and environmental temperature.[5,28] As a result, the majority of research into pacing has been performed in controlled[2,26,36,65] or simulated[36,66] environmental conditions. However, it is uncommon for athletes to experience constant external conditions during actual outdoor competition.[36] Under the varying external conditions associated with field race conditions, it has been suggested that a variable pacing strategy may be optimal.[36,66] Variable pacing strategy is a term that has been used to define the fluctuations in exercise intensity or work rate (i.e. power output) observed during exercise.[36,66,67] It should be noted that research investigating variable pacing strategies has examined changes in power output profiles rather than changes in velocity or split performance times.[36,66,67] Indeed, as a variable pacing strategy is usually adopted in an attempt to counteract variations in external conditions,[18] it seems likely that alterations in power output seen during exercise (i.e. variable pacing strategy) are an attempt at maintaining a constant distribution of pace/velocity (i.e. even pacing strategy). However, in order to coincide with previous research, such variations in power output have been referred to as a variable pacing strategy within this article.

Using the modelled motion of a cyclist,[60] Swain[18] showed that despite identical mean 10-km time-trial power outputs, overall cycling performance times were improved when cyclists increased power output on uphill sections, and reduced power output on downhill sections of a race, compared to when the entire trial was conducted at a constant power output (22.8 vs 24.3 minutes, respectively). This model was based upon the notion that during a race, more of the overall time is spent cycling in the uphill/headwind sections compared with the downhill/tailwind sections.[18] By producing greater power output on the uphill/headwind section of a race and less during the downhill/tailwind section, athletes are able to maintain a more constant speed, resulting in improvements in overall performance time.[18,68] Support for this model has been provided by Atkinson and Brunskill[36] who examined the effects of a simulated headwind (first 8.05 km) and tailwind (second 8.05 km) on self-selected and enforced (constant and variable [5% ± mean]) pacing strategies during a 16.1-km laboratory-based time trial. It was found that when compared with a constant or self-paced strategy, performance times were improved when power output was increased into a headwind (5% above average of self-paced trial) and reduced with a tailwind (5% below self-paced trial).[36] Furthermore, during the women's British national time trial championships, cyclists who spent less time (compared with their overall race times) in the headwind section of the race produced the fastest overall times.[10] However, this race was held on a 16-km out-and-back course, where the cyclists experienced a tailwind for the initial 8 km followed by a headwind for the latter 8 km.[10] As a result, the fastest overall performance times may have been due to the cyclists adopting a negative-split pacing strategy rather than a variable pacing strategy. It is also possible that the riders with faster performance times may have had better aerodynamic positioning resulting in a relatively faster time into the headwind section of the race.[36] Despite this possibility, few researchers have examined the influence of technique and athletic skill on pacing strategy.[15,40] Technique may be especially important to pacing strategy during events that experience high resistive forces such as swimming, rowing and cycling.

The physiological implications of a variable pacing strategy are of interest to sports scientists, as an increase in exercise intensity can significantly increase the physiological demands of the exercise task.[18,25,39,41] Atkinson et al.[67] have recently shown that two of seven subjects were unable to maintain a variable pacing strategy when power output varied within ±5% of the mean trial power output. Currently, studies examining the physiological mechanisms responsible for this inability to perform a variable pacing strategy are inconclusive. Atkinson et al.[67] and Liedl et al.[66] have collectively shown that altering power output within ±5% of the mean trial power output does not significantly alter the mean heart rate, $\dot{V}O_2$, blood lactate, perceived exertion or pedal rate during either a 1-hour or 800-kJ cycling time trial (~75% $\dot{V}O_{2max}$). Despite this, Palmer et al.[69] showed that despite similar heart rate, $\dot{V}O_2$, and perceived exertion, variable intensity exercise (~40–80% $\dot{V}O_{2max}$) resulted in significantly greater plasma lactate concentration and greater plasma glucose oxidation compared with a similar constant pace cycling trial (140 minutes at ~65% $\dot{V}O_{2max}$). Further research is required to better understand the physiological implications of varying power output in order to determine the possible effects and limitations of a variable pacing strategy.

2. Regulation of Pace

In 1965, Monod and Scherrer[70] first reported a hyperbolic relationship between constant power output and time to fatigue. This work was later expanded on[71] and developed into the whole-body critical power concept,[72] suggesting that fatigue and subsequent reductions in exercise intensity will occur if any contributing physiological system (i.e. anaerobic energy supply) arises above its critical power. Similarly, it has been suggested that muscle activation and thus exercise intensity is centrally regulated in response to intrinsic (i.e. physiological, biomechanical and cognitive) and extrinsic (i.e. environmental) sensory signals necessary to preserve physiological homeostasis.[11,43,73] Within this ‘central governor’ hypothesis,[73] it is also believed that the end of an exercise task offers a reference point to which athletes adjust work rate in order to ensure optimal performance.[11,74,75] This concept was originally proposed by Ulmer[76] and suggests that the self-selection of exercise intensity may be controlled in a ‘teleoanticipatory’ manner, whereby athletes anticipate the work required to complete a given exercise task. St Clair Gibson et al.[11] have since expanded upon this theory, suggesting that self-selected exercise intensity may be regulated continuously within the brain based on a complex algorithm involving peripheral sensory feedback and the anticipated workload remaining. In accordance with the anticipatory regulation of pace hypothesis, Nikolopoulos et al.[30] showed that self-selected exercise intensity (i.e. power and heart rate) was unaffected by the deception of correct distance feedback (between 34 and 46 km), suggesting that the regulation of pace may be more influenced by the anticipated workload rather than actual distance performed.[29,30,65]

In support of a central regulation of exercise intensity, numerous studies have shown that variations in power output, such as those often observed during prolonged self-paced competition,[47] are paralleled by changes in integrated surface electromyography (iEMG).[28,77] In particular, St Clair Gibson et al.[77] found that reductions in iEMG paralleled a decline in power output during repeated 1- and 4-km high-intensity bouts performed during a 100-km cycling trial. However, contrary to these findings, Hettinga et al.[78] recently showed that iEMG may increase or remain unchanged despite a decline in power output towards the end of middle-distance (4000 m) cycling time trials. In this study, iEMG of vastus lateralis and biceps femoris progressively increased throughout the trial irrespective of an evoked positive, negative or even pacing strategy.[78] Similarly, Hunter et al.[79] found that iEMG of rectus femoris remain constant during a 30-second Wingate anaerobic cycling test despite a 45% reduction in power output. Collectively, these results suggest that fatigue during exercise is not necessarily dictated by a centrally controlled downregulation of muscle activation. Instead, it appears that physiological changes within the muscle itself (i.e. peripheral fatigue) are also responsible for reductions in power output and subsequent variations in pacing strategies during short- and middle-distance events.[78] However, the relative contributions and influence of peripheral and central fatigue on the regulation of exercise intensity is poorly understood. Further research is needed to ascertain whether inconsistencies with regard to the relationship between iEMG and power output are associated with methodological differences between studies. Indeed, iEMG has been found to parallel changes in power output during prolonged self-paced exercise,[28,77] but not necessarily during short- and middle-distance events.[78,79]

As mentioned in section 1, the pacing strategy employed during an event plays an important role in ensuring the best possible performance outcome. During events of less than ~30 seconds in duration, it seems that performance times will benefit from a relatively fast starting strategy. During more prolonged events (>2 minutes), however, it appears that athletes generally benefit from a more constant pace.[2,8,29,30,46,65,80] During ultra-endurance events (>4 hours), athletes tend to adopt a positive pacing strategy (see table I).[46-52] It is likely that differences in pacing strategy observed under varying exercise conditions and durations may be related to the rate and capacity limits of various physiological systems. Indeed, it has been suggested that exercise intensity is controlled in a way that ensures that various physiological systems are maintained within certain critical limits.[81,82] Supporting this, Tucker et al.[5] showed that power output might be controlled in a way that regulates the rate of heat storage and prevents the development of hyperthermia during prolonged cycling. Furthermore, Amann et al.[82] recently found that the manipulation of arterial oxygen levels (17.6–24.4 mL/O_2/dL) resulted in parallel increases to central neural drive (43%) and power output (30%) during 5-km cycling time trials. Evidence also suggests that pacing strategies may be influenced by the rate and capacity limitations of different anaerobic and aerobic energy pathways to supply the energy for sustained high-intensity muscular contractions.[2,17,78] In support of this, Hettinga et al.[78] recently showed during 4000-m cycling time trials that the power output originating from anaerobic energy resources accurately traced the pacing profile observed, whereas calculated aerobic power output progressively increased throughout the trial. This finding occurred irrespective of whether a positive, negative or even pacing strategy was chosen. Correspondingly, mathematical models aimed at determining optimal performance throughout a variety of exercise durations often incorporate mathematical constants pertaining to the contribution of anaerobic (i.e. adenosine triphosphate-phosphocreatine, glycolysis) and aerobic (oxidation of carbohydrates and lipids) energy supplies.[61,83] To date, however, few studies have examined the use of such modelling along with individually measured indicators of anaerobic and/or aerobic capacity so as to accurately predict performance and/or determine the optimal pacing strategy to employ during an exercise task.[59]

3. Conclusion

It is understood that exercise performance can be significantly influenced by the distribution of work during an exercise task. However, the precise pacing strategies that ensure the best possible performance outcome under the variety of existing athletic competitions are not clear. It is possible that such uncertainty arises from the fact that an 'optimal' distribution of work will be influenced by numerous external factors; including the specific activity being performed, the race duration, course geography and environmental conditions. Research generally suggests that during extremely short-duration (≤30 seconds) events, athletes will benefit from an explosive 'all-out' pacing strategy. During middle-distance events (1.5–2 minutes) athletes tend to adopt a 'positive' pacing strategy, whereby after peak speed is reached the athlete progressively slows. However,

Table I. Summary of cross-sectional studies that have reported either self-selected or optimal pacing strategies during exercise of varying duration

Study	Duration (min)	Activity	Distance (m)	Athlete/model	Pacing strategy	Observed or optimal
Tibshirani[34]	0.16	Running	100	Elite runner	Negative (all out)	Observed
	0.32	Running	200	Elite runner	Negative (all out)	Observed
van Ingen Schenau et al.[84]	0.62	Speed skating	500	Mathematical model	Negative (all out)	Optimal
Foster et al.[2]	0.67	Cycling	500	Trained cyclists	Negative	Observed
Keller[24]	~0.75–0.83	Running	<391	Mathematical model	Negative (all out)	Optimal
van Ingen Schenau et al.[1]	0.97	Cycling	1 000	Mathematical model	Negative (all out)	Optimal
de Koning et al.[7]	0.97	Cycling	1 000	Mathematical model	Negative (all out)	Optimal
van Ingen Schenau et al.[84]	1.13	Speed skating	1 000	Mathematical model	Negative (all out)	Optimal
Foster et al.[2]	1.45	Cycling	1 000	Trained cyclists	Negative	Observed
Sandals et al.[25]	1.72	Running	800	Elite runners	Positive	Observed
Foster et al.[2]	2.23	Cycling	1 500	Trained cyclists	Positive	Observed
Thompson et al.[41]	2.64	Swimming	200	Trained – elite swimmers	Positive	Observed
Foster et al.[8]	2.8	Cycling	2 000	Well trained cyclists	Even	Optimal
van Ingen Schenau et al.[1]	4.27	Cycling	4 000	Mathematical model	All out (<0.14 min) then even	Optimal
Foster et al.[2]	4.93	Cycling	3 000	Trained cyclists	Even	Observed
Garland[40]	6.03–7.15	Rowing	2 000	Elite rowers	Positive (reverse J-shaped)	Observed
van Ingen Schenau et al.[84]	7.04	Speed skating	5 000	Mathematical model	All out (<0.13 min) then even	Optimal
	14.34	Speed skating	10 000	Mathematical model	All out (<0.13 min) then even	Optimal
Atkinson and Brunskill[36]	27.68	Cycling	16 100	Trained – elite cyclists	Even	Optimal
Perrey et al.[85]	30	Cycling		Trained triathletes	Even	Observed
Padilla et al.[59]	60	Cycling	53 000	Elite cyclist	Even	Observed
Laursen et al.[46]	640	Swim/cycle/run	228 000	Well trained triathletes	Positive	Observed
Neumayr et al.[51]	1 645	Cycling	525 000	Elite cyclist	Positive	Observed

during more prolonged events (>2 minutes) it seems that athletes tend to adopt a more ‘even’ or varied pacing strategy based upon influencing external factors (i.e. course geography or environmental conditions). During ultra-endurance events (>4 hours) evidence also suggests that athletes may progressively reduce speed, resulting in the adoption of a positive pace. Whether these descriptive findings represent optimal scenarios requires further research.

The regulation of pace is thought to be primarily dictated by the ability of an athlete to resist fatigue; however, the precise mechanisms responsible are currently unclear. It seems that one of the more influential factors dictating self-selected exercise intensity and optimal pacing strategy during varying exercise tasks is the rate and capacity limitations of various physiological systems (i.e. anaerobic and aerobic supply). Furthermore, it has also been suggested that exercise intensity may be centrally controlled in order to preserve and protect physiological homeostasis. Further research is needed in order to ascertain contributions of central and peripheral fatigue to the regulation of pace during a variety of exercise tasks, conditions and durations.

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

