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An Analysis of Pacing Strategies During Men's World-Record Performances in Track Athletics

Ross Tucker, Michael I. Lambert, and Timothy D. Noakes

Purpose: To analyze pacing strategies employed during men's world-record performances for 800-m, 5000-m, and 10,000-m races. ***Methods:*** In the 800-m event, lap times were analyzed for 26 world-record performances from 1912 to 1997. In the 5000-m and 10,000-m events, times for each kilometer were analyzed for 32 (1922 to 2004) and 34 (1921 to 2004) world records. ***Results:*** The second lap in the 800-m event was significantly slower than the first lap (52.0 ± 1.7 vs 54.4 ± 4.9 seconds, $P < .00005$). In only 2 world records was the second lap faster than the first lap. In the 5000-m and 10,000-m events, the first and final kilometers were significantly faster than the middle kilometer intervals, resulting in an overall even pace with an end spurt at the end. ***Conclusion:*** The optimal pacing strategy during world-record performances differs for the 800-m event compared with the 5000-m and 10,000-m events. In the 800-m event, greater running speeds are achieved in the first lap, and the ability to increase running speed on the second lap is limited. In the 5000-m and 10,000-m events, an end spurt occurs because of the maintenance of a reserve during the middle part of the race. In all events, pacing strategy is regulated in a complex system that balances the demand for optimal performance with the requirement to defend homeostasis during exercise.
Key Words: running, self-paced exercise

An optimal pacing strategy is the most efficient use of physiological resources during athletic competition and is essential for optimal exercise performance.[1,2] This optimal pacing strategy depends on factors such as the length of the exercise bout,[3-5] the type of exercise being performed,[1,2] ambient temperature,[6] and altitude.[2] Studies in which the pacing strategy is manipulated by forcing athletes to start either faster or slower than their average speeds for their best performances have found that in shorter events (less than 80 seconds[3]) and in sports such as cycling and speed skating, where resistive drag forces are lower, best performances might occur with a faster start so that kinetic energy is maximized early in the trial.[1,3,4,7,8] Once high velocities are achieved, a reduction in power output would cause only a small reduction in speed compared with running or rowing,[8] where higher drag forces result in a greater reduction in speed if power output decreases.[1]

The authors are with the UCT/MRC Research Unit for Exercise Science and Sports Medicine, Dept of Human Biology, University of Cape Town, Newlands 7700 South Africa.

In contrast, performance during longer-duration events might be optimized by an even or negative pacing strategy,[2,8,9] which is often characterized by an increase in the power output or speed at the end of the event. For example, best performances during a 2000-m cycling trial are achieved when athletes are made to complete the first 1000 m either slightly slower than or at the same pace as the second 1000 m.[2] During self-paced laboratory trials lasting approximately 30 minutes, the pacing strategy is characterized by a significant increase in power output[6,10,11] or running speed[12] at the end of the trial.

It has been proposed that the self-selected pacing strategy plays a key role in a complex regulatory system[13] in which a central governor regulates exercise intensity specifically to ensure that potentially catastrophic derangements to cellular function do not occur.[14-16] In support of this hypothesis, power output and skeletal-muscle motor-unit activation decrease soon after the onset of self-paced cycling trials in hot compared with cool environments, even though body temperature, heart rate, or perceived exertion is not yet different between conditions.[6,11] Similarly, pacing strategy is altered when the oxygen content of the inspired air is either increased (Tucker et al, in review) or decreased,[17] supporting the notion that the observed changes in power output or exercise intensity during self-paced exercise serve a regulatory function.

Therefore, understanding the pacing strategies of elite athletes during competitive or maximal exercise might give us insight into the underlying physiological and regulatory processes. We have previously analyzed 32 world-record performances from the mile event (Noakes and Lambert, unpublished observations) and found that the first and final laps were significantly faster than the second and third laps. In contrast, in the sprint events (100, 200, and 400 m) at the 7th IAAF World Athletics Championships, the fastest split times for every single athlete (n = 16 for each event) were recorded early on, and running speed decreased progressively until the finish.[18]

Accordingly, the aim of the present study was to describe the pacing strategy adopted during world-record performances for the 800-m, 5000-m, and 10,000-m events for men. We hypothesized that in the longer-distance events (>110 seconds), the running speed would decline during the middle portion of the race before increasing, with the fastest speeds occurring at the end of the race. In contrast, in the shorter event, the 800-m (<110 seconds), the first lap would be significantly faster than the second lap, resulting in an overall positive pacing strategy.

Methods

Overall performances and split times for men's world-record performances for the 800-m, 5000-m, and 10,000-m events were obtained. In the 800-m event, lap times were analyzed for 26 world-record performances from 1912 to 1997. Data for 200-m intervals were available for 12 of these performances. In the 5000-m and 10,000-m events, times for each kilometer were analyzed for 32 world records from 1922 to 2004 and 34 world records from 1921 to 2004. Although we acknowledge that some world records might be set in competitive races in which tactics might influence the pacing strategy, we consider that, generally, these races use pacemakers in structured, planned world-record attempts and so represent maximal efforts.

An analysis of variance with repeated measures and a Tukey honestly significant difference post hoc test were used to determine differences in lap times for the 800-m event and kilometer times for the 5000-m and 10,000-m events. Statistical significance was accepted as $P < .05$. Values are shown as mean ± SD.

Results

800-m

Figure 1 depicts the time for each lap from 26 world-record performances. The second lap was significantly slower than the first lap (52.0 ± 1.7 vs 54.4 ± 4.9 seconds, $P < .00005$). In only 2 of the 26 world records set since 1912 has the second lap been faster than the first lap, once in 1966 (Jim Ryun) and again in 1972 (Dave Wottle).

The times from the 200-m intervals of 12 world-record performances are shown in Figure 2. The second and fourth 200-m intervals were significantly slower than the first and third 200-m intervals ($P < .05$).

5000-m

The kilometer splits from 32 world-record performances are shown in Figure 3. The first and final kilometers were significantly faster than kilometers 2, 3 and 4 ($P < .005$).

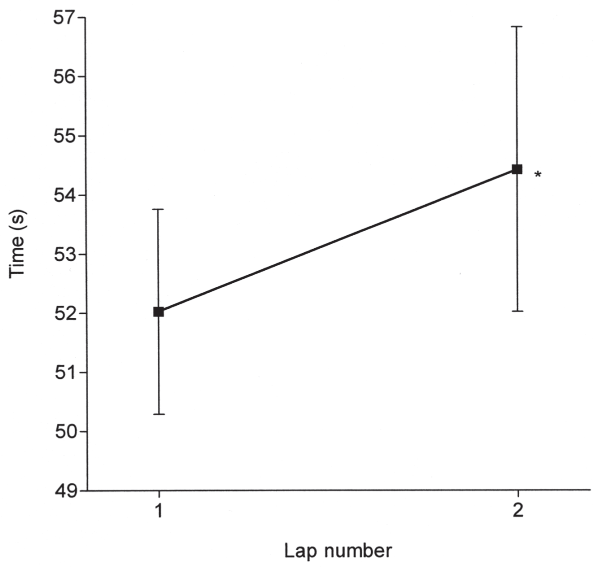

Figure 1 — Lap times from 26 world-record performances in the 800-m event. Values are mean ± SD for 26 performances. *Significantly different from first lap ($P < .0005$).

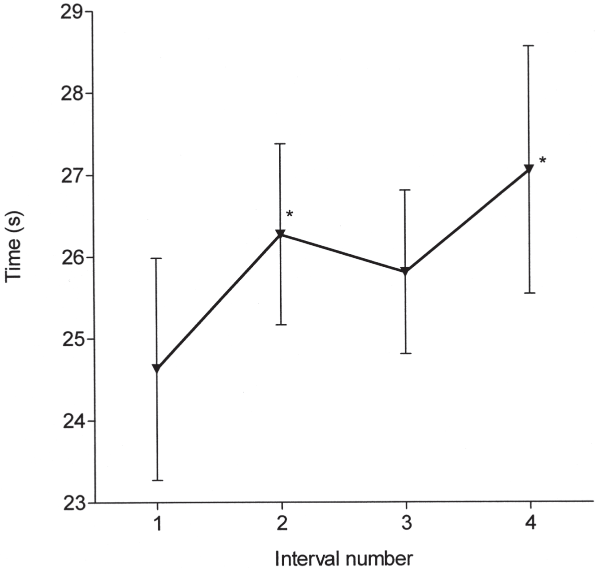

Figure 2 — 200-m interval times from 12 world-record performances in the 800-m. Values are mean ± SD for 12 performances. *Significantly different from intervals 1 and 3 ($P < .05$).

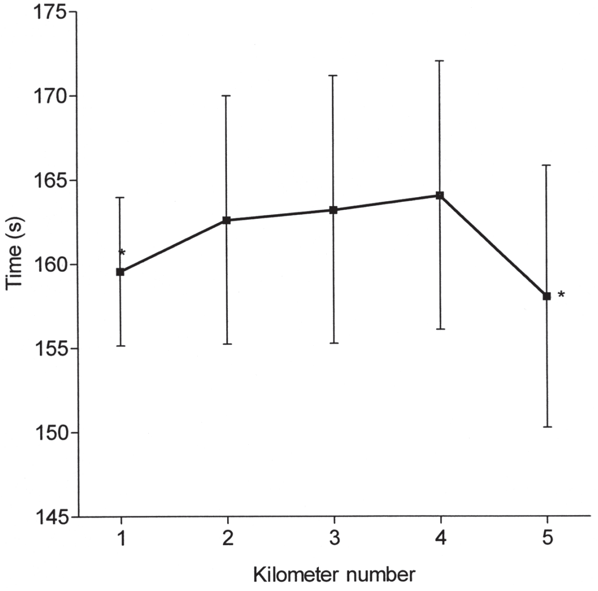

Figure 3 — Kilometer times from 32 world-record performances in the 5000-m event. Values are mean ± SD for 32 performances. *Significantly different from kilometers 2, 3, and 4 ($P < .005$).

10,000-m

Figure 4 depicts the kilometer times from 34 world-record performances in the 10,000-m event. The kilometer times increased progressively after the start and became significantly greater than at the start from 3 km onward, before decreasing significantly in the final kilometer, resulting in the final kilometer being the fastest of the race ($P < .005$).

The average running speeds for each event are shown in Figure 5. For the 800-m event, the interval refers to each lap, whereas for the 5000-m and 10,000-m events, running speeds are plotted for each kilometer. In the 800-m event, the overall pacing strategy is positive, with a reduction in running speed in the final interval, compared with the 5000-m and 10,000-m events, where running speed increases significantly at the end of the race. We have also included the average data from the mile event (Noakes and Lambert, unpublished observations) because it represents a "transitional duration" event.

Figure 6 shows the first and second lap times during world-record performances in the 800-m event. The fastest second-lap time ever recorded during a world record was 51.6 seconds in 1972 (Figure 6, bottom panel), following a first lap of 52.9 seconds.

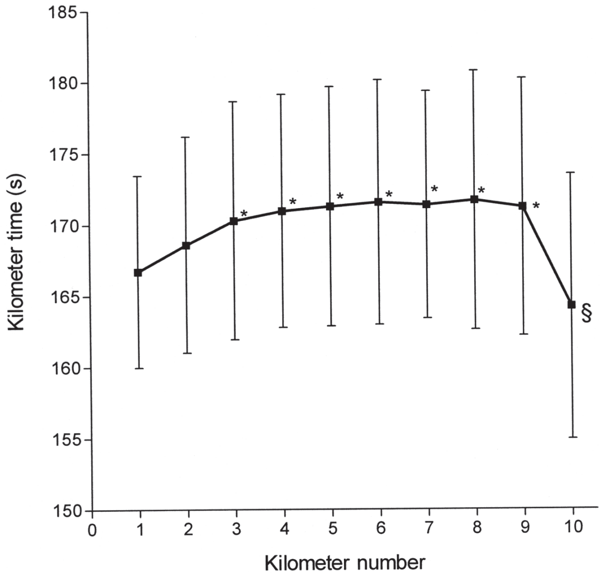

Figure 4 — Kilometer times from 34 world-record performances in the 10,000-m event. Values are mean ± SD for 34 performances. *Significantly slower than kilometers 1, 2, and 10 ($P < .05$). §Significantly faster than the preceding 9 km ($P < .005$).

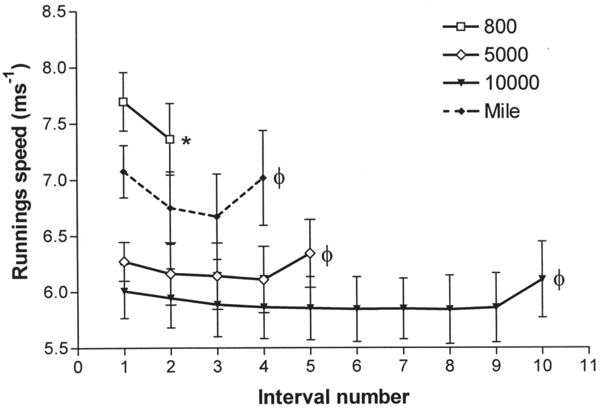

Figure 5 — Average running speed for each interval during world-record performances in 800-m, 1-mile, 5000-m, and 10,000-m events. The running speeds for the mile event are shown with a dashed line (from Noakes and Lambert, in review). *Significantly slower than the first lap ($P < .005$). ΦSignificantly faster than preceding intervals.

Discussion

A key factor determining the optimal pacing strategy is the duration of the exercise bout.[2-5] Thus, a maximal start followed by a progressive slowing down has been proposed to be optimal for shorter events,[3,4,7] whereas an even pace is suggested to be more beneficial during exercise of longer duration.[2,3] Accordingly, the first significant finding of this study was that during the 800-m event, world records are mostly achieved with a second lap that is significantly slower than the first lap (Figures 1 and 2). Indeed, in only 2 world records has the second lap been run at a faster pace than the first lap. This supports the notion that performance in shorter events (<110 seconds) is improved by a faster start, even if the running pace declines toward the end of the race.

It is noteworthy that the 2 fastest second-lap times ever achieved in 800-m world-record performances were run in 1972 and 1966 (Figure 6, bottom panel). The second-lap time has therefore not improved in over 30 years, since Jim Ryun broke the world record with a time of 1:44.3 (min:s) and a second lap of 51.60 seconds in 1966. The current world-record holder, Wilson Kipketer, has broken the world record on 3 occasions, with second-lap times of 52.12, 52.90 and 51.80 seconds. Therefore, the 3.2-second reduction in the world record in the 800-m between 1966 and 1997, from 1:44.3 to 1:41.11, has been achieved by running the first lap significantly faster, rather than an improved ability to increase running speed on the second lap (Figure 6, top panel). Collectively, these findings suggest that the ability to run faster during the second lap of an 800-m is limited, and so the optimal pacing strategy might consist of a faster start followed by a slower second lap.

This finding agrees with results of a previous study on pacing strategies adopted during competitive sprinting competitions.[18] That research showed that during 100-m, 200-m, and 400-m races, athletes reached peak running speeds before reaching

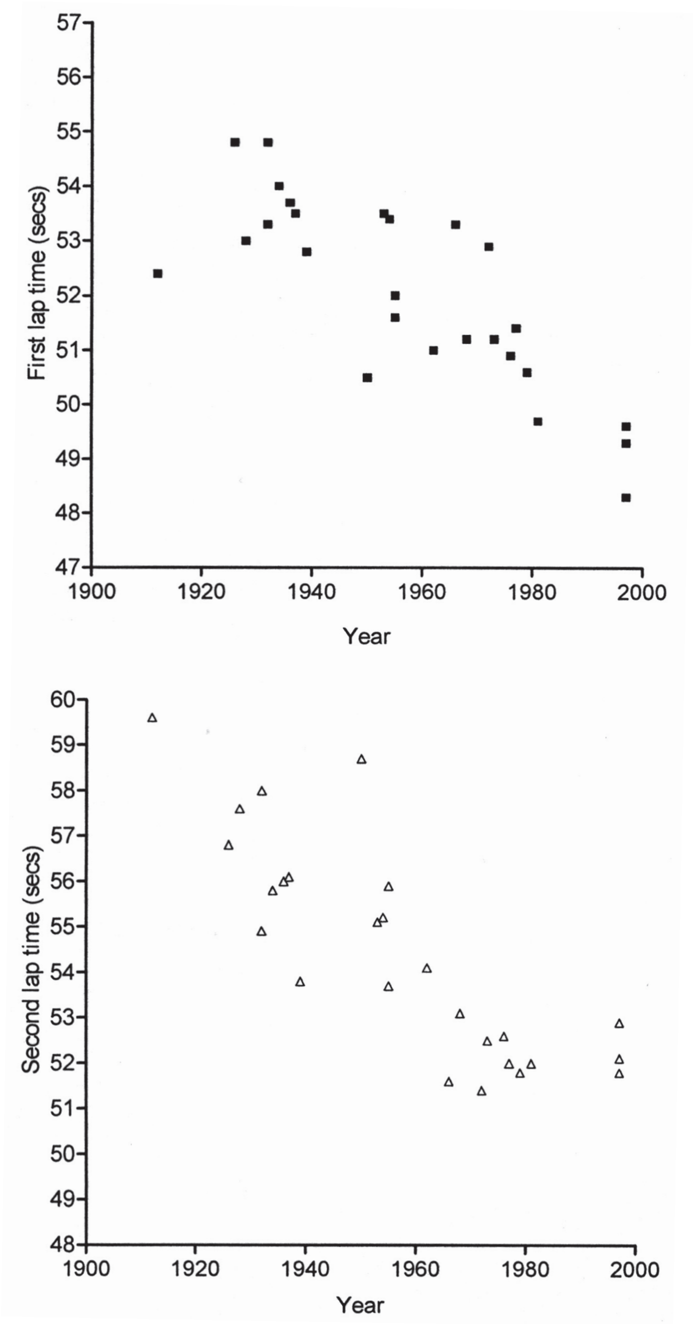

Figure 6 — Times recorded during (top) the first lap and (bottom) the second lap of 800-m world-record performances since 1912.

the halfway mark and then slowed down progressively until the finish.[18] This was the case for every single athlete in both men's and women's sprint events at the IAAF World Championships, suggesting that an underlying physiological process is responsible for the reduction in running speed and that optimal performance in these relatively short-duration events requires the faster start, even at the cost of a progressive reduction in running speed toward the end of the race.

Furthermore, in that study,[18] the athletes who won were not necessarily the ones who began races conservatively and then slowed down the least during the final part of the race. Rather, the athletes who won the races adopted pacing strategies similar to those of the athletes who finished last, but they were faster throughout the race. Similarly, in the 800-m event in the present study, the strategy has not changed since the first documented record in 1912, and improvements in the time in the past 30 years have been achieved by increasing the speed on the first lap and maintaining the same overall pacing strategy. We suggest that if running an even-paced race with a more conservative first lap were the optimal strategy, the improvements in the world record would be expected to occur with a faster second lap, but this is clearly not the case (Figure 6).

Therefore, although we do acknowledge that world-record performances are not necessarily achieved with "optimal" pacing strategies, this observation does suggest that optimal performance in shorter-duration exercise, such as the 800-m event in the present study, requires the attainment of peak speeds early during the bout, with a progressive reduction in the second half of exercise. Similar findings have resulted from laboratory studies of performance and pacing strategy. For example, Foster et al[1] showed that during self-paced 1500-m cycling time trials (130 to 135 seconds), power output and velocity peaked within the first 100 and 300 m, respectively, and then decreased progressively, with the lowest power outputs being recorded in the final 400 m, a pattern similar to that of the 800-m (Figure 1). In a subsequent study, Foster et al[5] showed that even when power output decreased during cycling time trials ranging in length from 500 to 3000 m, the subjects maintained an ability to increase anaerobic energy production for a terminal acceleration. It was suggested that athletes monitor and then regulate their energetic output over time in order to optimize performance.

Finally, Fukuba and Whipp[19] have demonstrated an inability to make up lost time during the second half of middle- and long-distance running events. They showed that if the initial running velocity were slower than the running speed at a predefined fatigue threshold,[19] the athlete would be unable to make up for the lost time with a final spurt. The fatigue-threshold running speed was conjectured to represent the running speed for each event at which a steady state could be maintained for pulmonary gas exchange, blood acid-base status, and blood lactate concentration.[19] In the 800-m event, however, it appears that the running speed required on the first lap is even greater than a "steady-state threshold speed," because athletes actually slow down on the second lap. Therefore, the present results support the notion that athletes cannot recover lost time from a slow start[19] but also appear to indicate that in the 800-m, the first lap must be run at a speed that forces the athlete to slow down on the second lap, without any ability to accelerate.

In contrast, world records in the 5000-m and 10,000-m events are characterized by fast starts and a period of slower running during the middle of the race, followed by a significant increase in speed toward the end (Figures 4 and 5). This is similar to the pacing strategies adopted by elite rowers during 2000-m rowing races and time trials.[20] That study found that the first 500 m of a 2000-m time trial were completed at an average speed of 103.3% of the average speed for the whole race, with a progressive decrease in speed for the second and third 500-m sectors, before the speed increased slightly in the final 500 m. These 2000-m rowing events typically last between 6 and 8 minutes and therefore lie midway between the 800-m and the 5000-m and 10,000-m events in the present study. This could account for the relatively slower final sector in the rowing trials, because in our study, the fastest kilometer sector occurred at the end of exercise rather than at the beginning.

Laboratory studies have also found that events longer than 120 seconds are optimized by a more even pacing strategy. For example, optimal performances during a 2000-m cycling time trial (150 seconds) were achieved with an imposed even pacing strategy, which was in fact not different from the self-selected pacing strategy. Overall performance was impaired, however, by 7.2 seconds (4.3%) when the imposed speed for the first kilometer was significantly slower. When the first kilometer was significantly faster, overall performance was impaired by 4.9 seconds (2.9%).[2]

The pacing strategy adopted in the 5000-m and 10,000-m world records has been remarkably consistent. For example, in the 5000-m event, the final kilometer of the race has been the fastest of the race in 21 out of 32 world records, whereas it has been the second-fastest kilometer of the race (behind the opening kilometer) in the other 11 world-record performances. Therefore, the middle part of the race, from 2 to 4 km, has never been faster than either the first or the final kilometer in any world-record performance at 5000 m. Similarly, in the 10,000-m event, the first or final kilometer has been the fastest of the race in 33 out of 34 world records. Only during the world-record performance of Paul Tergat in 1997 (26:27.85) was any kilometer other than the first or final kilometer the fastest—the ninth kilometer was run 1 second faster than the final kilometer. In 25 out of the 34 world-record performances at 10,000 m, the final kilometer has been the fastest of the race.

The characteristic pacing strategy during these longer-duration events has physiological significance. In particular, the presence of an end spurt at the end of the 5000-m and 10000-m races is important, because it suggests that a reserve capacity is maintained during the exercise bout, and whatever factors are responsible for the initial reduction in running speed can be overridden in the final part of the event when the athlete uses this reserve. Clearly, the athlete cannot run at a faster speed early on, for this would result in premature fatigue, but the mechanism by which a submaximal running speed is "selected" during the race and how the optimal pace is regulated during such longer-duration exercise is not yet understood. It cannot be explained by the direct effects of any physiological variable, such as metabolites[21] or high body temperatures,[22] on the ability of the muscle to produce force, because these would prevent any increases in running speed at the end of the trial.

Previous experience and training are important factors that must influence an athlete's decision to either slow down or speed up during an event. Tactics are also important, and in the present study we cannot account for changes in running speed based on tactical situations. Unfortunately, data regarding race tactics do not exist for all world-record performances. The majority of world records are set in planned record attempts, however, with race tactics playing a relatively minor role. Also, in only 1 out of 66 world records in the 5000-m and 10,000-m events has the fastest kilometer split occurred outside of the first or final kilometer. If race tactics affected world-record performances, it might be expected that there would be occasions when the middle kilometers would be fastest, yet this is not the case. It might also be argued that tactically motivated adjustments in work rate would tend to manifest toward the end of the race, as athletes alter their pace in response to athletes around them, and so the reductions in running speed that occur early on are less likely to be influenced by tactics than increases in speed later on during races.

The reasons for the difference in pacing strategy between the 800-m event and the longer 5000-m and 10,000-m events are not clear. The mile event, which lasts approximately 4 minutes, is characterized by a fast first lap, 2 significantly slower laps, and a fast final lap, for an overall even pacing strategy (Figure 5). It is thus similar to the 5000-m and 10,000-m events, although in the longer events, changes in running speed do not appear to be as great as for the mile event (Figure 5). This might suggest that the transition between an optimal negative pacing strategy and an even pacing strategy occurs in events that are shorter than the mile (that is, less than 4 minutes). This is supported by the results of laboratory-based studies, which have shown that 2000-m cycling events, lasting approximately 3 minutes, are optimized by an even pacing strategy,[2] whereas a 1500-m event is optimized by a faster start.[23]

Shorter, higher-intensity exercise is traditionally considered anaerobic, resulting in metabolite accumulation[24,25] and depletion,[26,27] which are presumed to impair muscle contractility and result in a progressive decline in force output.[27] For example, Nummela et al[21] found that drop-jump performance was impaired by 39% after a maximal 400-m sprint, and the impairment was correlated with increases in blood lactate concentration. The EMG activity in the active sprinting muscles increased significantly over the course of the run, and it was concluded that additional motor units were being activated to compensate for the progressive reduction in muscle force production as a result of metabolic acidosis in the muscle.[21] It was concluded that fatigue in the 400-m sprint was mainly a result of processes within skeletal muscle rather than the central nervous system.[21]

Nonetheless, studies of the pattern of energy-system contributions to power output during high-intensity cycling lasting less than 2 minutes suggest a more complex form of regulation. It has been shown that energetic resources are distributed over the duration of the event in such a way as to preserve the contribution of nonoxidative energy production to power output until the end of the exercise bout.[1,5] It was suggested[1] that the intracellular changes occurring during exercise, such as metabolite accumulation[24-26,28] or phosphagen depletion,[27] were being monitored continually and that power output was reduced in advance of these changes becoming critical or harmful, a notion that supports the existence of a pacing strategy, even in the presence of a falling power output. This regulation of energetic resources would allow athletes to expend energy anaerobically for a terminal acceleration[5] and suggests that pacing strategy is not "all-out" but regulated, even in the presence of a falling power output or running speed, as might occur in the 800-m event in the present study.

In addition, in the study of Nummela et al,[21] running speed during a maximal 400-m time trial decreased progressively even though motor-unit activation (measured as EMG activity) was able to increase to compensate for the apparent failure of muscle contractility. Early reductions in running speed therefore occurred despite a capacity to increase motor-unit activation, which indicates that a neural control strategy exists even during maximal sprint exercise. Such a complex neural strategy, which ensures the maintenance of a motor-unit reserve, would also explain the finding that when short-duration exercise is undertaken, the initial power output is lower than would be possible if the athlete is instructed to perform an all-out effort with no regard for overall performance.[23] This is observable in the pacing strategies of 400-m sprinters,[18] who run the first 50 m of the race at speeds slower than they can achieve for the first 50 m during a 200-m race. Running speed still decreases progressively, however, in the 400-m event.[18] Therefore, pacing strategies are evident even in the presence of a reduction in running speed.

These factors implicate an anticipatory pacing strategy during even supramaximal exercise, a finding that is supported by Ansley et al,[29] who found evidence for a preprogrammed, centrally regulated pacing strategy during supramaximal exercise lasting only 36 seconds. These observations challenge the notion that fatigue during short-duration exercise is "mainly due to processes within skeletal muscle rather than the central nervous system."[21] Instead, the progressive reduction in running speed or power output in these studies[21] and in the 800-m event in the present study must be a result of a combination of changes occurring in the muscle and a complex regulation by the central nervous system.

Thus, even though a possible contribution of metabolic derangements to fatigue cannot be discounted, reductions in power output and, presumably, running speed during the 800-m event would occur as part of a centrally regulated control mechanism based on afferent feedback[14,16,30,31] to protect against harmful disturbances to homeostasis while still optimizing performance. The balance between preventing catastrophic disturbances to homeostasis and optimizing performance might allow greater running speeds early on during shorter-duration exercise, even though this might cause a certain degree of metabolite accumulation and depletion to occur and might increase the perception of effort according to the proposed model. Because the 800-m event is short, however, both the metabolic changes and the elevated rating of perceived exertion might be tolerable over the anticipated time of exercise, with the result that higher running speeds occur early before a progressive reduction toward the end. In longer-duration exercise, the pacing strategy is regulated to ensure that a reserve is present at the end, with the result that running speed can be increased consequent to a proposed increase in skeletal-muscle recruitment.

The precise reasons for the fact that the second lap in 800-m world records has not improved in 30 years are not clear. According to the current discussion, the apparent inability to increase the running speed in the second lap might be the result of a combination of metabolic changes in the muscle and a centrally regulated pacing strategy, which monitors the use of energetic resources and the degree of metabolic derangement during high-intensity exercise. It might thus be that advances in training and technology of shoes and track surfaces have improved athletes' ability to run faster with similar levels of metabolic derangements. As a result, the brain "allows" faster running speeds before a perceived level of metabolite accumulation or depletion is reached, causing a slowing down in speed over the second lap. Furthermore, the increased contribution of runners of African descent to world-record performances since the mid-1960s cannot be discounted, because it has been shown that these runners have better running economy than White runners. Therefore, it is possible that physiological differences, including improved running economy, that manifest as reduced rates of metabolite accumulation at a given running intensity are responsible for different pacing strategies in recent years.

In conclusion, the optimal pacing strategy during world-record performances differs for the 800-m event compared with the 5000-m and 10,000-m events. In the 800-m, greater running speeds are achieved in the first lap, and it appears that time that might be lost on the first lap cannot be recovered by a faster second lap, because the ability to run the second lap faster than the first appears limited. In longer-duration events, pacing strategy is regulated to ensure that a reserve is maintained, which allows significant increases in running speed at the end of the event. We propose that these findings support the concept that pacing strategy is regulated in an anticipatory manner by a central governor that ensures that physiological reserves are maintained. During both longer- and shorter-duration maximal-effort events, certain levels of noncatastrophic derangements might be tolerated in order to optimize kinetic energy and performance. This suggests that exercise might be regulated by a complex, intelligent system.[15]

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