An Analysis of the Pacing Strategies Adopted by Elite Athletes During Track Cycling

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Purpose: To investigate pacing strategy during the 1-km time trial (TT) and 3- and 4-km individual pursuit (IP), in elite cyclists. Methods: Total times and intermediate times were obtained from the 2007 and 2008 cycling World Championships in the 1-km TT and 2006, 2007, and 2008 World Championships in the 3- and 4-km IP. Data were analyzed to examine the pacing-profiles employed and pacing strategies of “slow” and “fast” performances. Results: Similar pacing-profiles were evident in each event, which were characterized by an initial acceleration followed by a progressive decay in split times. In the 1-km TT, the first 250-m split time was a primary determinant of total time, whereas the rate of fatigue over the remainder of the race did not discriminate between performances. The first 250-m split time was also related to total time in the 3- and 4-km IP, although to a lesser extent than in the 1-km TT, whereas the ability to maintain a consistent pacing-profile was of increased importance. There were differences in the pacing strategies of slow and fast performances in the 3- and 4-km IP, with slow performances characterized by an overly quick start with a concomitant slowing at the finish. Conclusion: The pacing profiles adopted were similar to the optimal pacing strategies proposed in simulation models of cycling performance. However, in the 3-km and 4-km IP small alterations in pacing strategy appear to be important, at the elite level.

Keywords: performance, fatigue, energy expenditure

In cycling, the power produced by the athlete is primarily used to overcome the air friction and rolling resistance, and to increase the kinetic energy of the rider. However, during high-intensity exercise the capacity to produce and maintain power output is rapidly diminished. Consequently, to enable a sustained high power output during exercise lasting longer than several seconds athletes must adopt a pacing strategy. Pacing strategy has been defined as the conscious or subconscious regulation of work output according to a predetermined plan. It has been suggested that the optimal pacing strategy is one that makes the most efficient use of physical resources during athletic competition, and is essential for optimal exercise performance. However, the pacing strategy might be influenced
by a number of factors including the exercise mode, exercise duration, ambient temperature, and altitude.

Analysis of the pacing strategies employed during running events has shown a clear profile. In the 100-m, 200-m, 400-m, and 800-m events, the pacing strategy is generally characterized by a rapid start, with a progressive decrease in velocity until the finish. This is in contrast to the pacing strategy evident in the mile, 5,000-m and 10,000-m running events, which are characterized by a rapid start, a period of slower running during the middle of the race, and a fast finish (often termed end-spurt). A similar pacing-profile is also adopted by elite rowers during 2000-m rowing races and time trials (TTs). However, the pacing strategies adopted during track cycling events are less clear.

In contrast to rowing and running, where high drag forces result in a large reduction in speed if power output is decreased, once a high velocity has been attained during cycling a reduction in power output will have a smaller effect on the cycling speed. As a consequence, modeling studies have advocated the use of a fast start to reduce the time taken to overcome the inertia associated with accelerating from a standing start and to maximize the kinetic energy, particularly during shorter events such as the 1-km TT. However, the extent to which these pacing strategies are supported practically is unclear. Although the proposed models demonstrate good agreement with the split times recorded during the 1990 and 1998 World Championships, other research suggests that athletes who accelerated too rapidly during the first portion of a 1-km TT were out performed by riders with a more consistent race profile. Indeed, during a 1500-m laboratory TT an even paced strategy resulted in a greater total amount of work being completed than when the first 750 m was performed at a slower or faster pace, while an even paced strategy, or even a slower starting pace, has been shown to yield quicker 2000-m laboratory cycling TT performances than a fast starting pace. For longer races, such as the 4-km individual pursuit (IP), it has been suggested that once a maximal start has been performed a quick transition to an even pacing strategy is necessary to minimize metabolic disturbances. However, similar to the 1-km TT, athletes who covered the first portion of the 4-km IP too rapidly were invariably beaten by athletes adopting a more even pacing strategy. Moreover, in contrast to optimal pacing models, in some studies athletes appear to retain a reserve, allowing for an end-spurt, even when the initial pacing strategy might have included a fast start. This is particularly interesting as kinetic energy which is present when the athlete crosses the finish line can be judged as useless energy since it cannot be used to improve performance.

In addition to important performance implications, it has been suggested that the pacing strategy adopted has physiological significance, and is likely representative of underlying physiological and regulatory processes. It has been argued that the presence of an end-spurt is supportive of the central governor hypothesis, a complex anticipatory regulatory system in which work output is dictated primarily by motor unit recruitment as determined by a central governor (the brain). In contrast, it has been suggested that a catastrophe model of fatigue, in which pacing strategy is dictated by metabolite accumulation and peripheral fatigue, is more compatible with a pacing strategy characterized by a progressive reduction in power output or speed.
Accordingly, understanding the pacing strategies of elite athletes during competition might give insight into the underlying physiological and regulatory processes. Moreover, analysis of the pacing strategies employed by successful athletes might lend insight into the most desirable pacing strategy for a given event, and offer scope for performance enhancement. Therefore, the aim of this study was to investigate the pacing strategy adopted during the 1-km TT as well as the 3-km and 4-km IP events, in elite athletes.

Method

Total times and 250-m split times (measured to 0.001 s) were obtained from the 2007 and 2008 world championships in the men’s 1-km TT and from the 2006, 2007, and 2008 world track cycling championships for the women’s 3-km and men’s 4-km IP. Data were provided by Tissot S.A., with permission.

Forty-two performances were analyzed from the 1-km TT, and 68 performances were analyzed from the 3-km IP and 4-km IP events. Where an athlete from an IP event competed in the subsequent podium races, their fastest pursuit time from that world championships was included for analysis, with the exception that if an athlete was passed (thus stopping the race at that point), the data from their first round ride was used for analysis.

For ease of analysis 1-km split times were calculated (from 250-m split times), for the 3-km and 4-km IP events. Analysis of variance with repeated measures was used to examine differences in 1-km split times during IP events and differences in 250-m split times during the 1-km TT. Where a significant effect was evident post hoc analysis was performed using Student’s \( t \) test for pair data, with alpha adjusted by the Bonferroni method. To check for the presence of an end spurt, Student’s \( t \) test for paired data was used to compare the split times for the penultimate 250-m split and the final 250-m split in the 3-km and 4-km IP events.

To investigate the importance of a fast start in determining total time the relationship between the first 250-m split time and total time was examined, for each event, using Pearson’s correlation coefficient. Where a significant correlation was identified 95% confidence intervals (CI) have been reported. In addition, to provide a gauge of the decline in cycling velocity over the course of an event a fatigue index was calculated for each performance. This was determined by expressing the difference between the fastest and slowest lap time as a percentage of the fastest lap time, although first lap times were excluded from this calculation due to the time taken to accelerate from a standing start. Pearson’s correlation coefficient was then calculated to determine the strength of relationship between the fatigue index and the total time for each event, with 95% CI reported where a correlation was significant.

Finally, to investigate if there were any differences in the pacing strategies between the “slow” and “fast” performances, in each event, the performance data from each world championships was split into slow and fast groups via a median split. Where there were an uneven number of performances for a given event the median performance was removed from analysis. Subsequently, the slow and fast performances from each championship were pooled. To eliminate the effect that the differences in total race times would have on the analysis of pacing strategy the split times were expressed as a percentage of the total race time (250-m splits.
for the 1-km TT and 1-km splits for the 3- and 4-km IP). A two-way analysis of variance (performance level \( \times \) split time), with split time as a repeated measure, was used to investigate differences in the pacing strategies between the slow and fast performances for each event. Where a significant effect of performance level on pacing strategy was evident, planned independent samples \( t \) tests were performed comparing the first and final splits of the slow and fast groups, with alpha adjusted by the Bonferroni correction. Statistical significance was accepted as \( P < .05 \). Values are shown as mean ± SD.

**Results**

**1-km TT**

The mean total time for the 1-km TT was 63.35 ± 1.19 s. The mean 250-m split times from the 1-km TT are shown in Figure 1. After a slow first 250-m split (18.86 ± 0.45 s), due to the acceleration from a standing start, the second 250-m split was the fastest (13.88 ± 0.31 s), after which there was a progressive decrease in split times. Differences between successive split times were significant in each instance. However, while the first 250-m split was the slowest, the time taken for

**Figure 1** — 50-m split times during 1-km time trial. *Denotes significant difference between split times.
this opening lap was correlated with total time \((r = 0.73 \text{ (CI 0.55 to 0.85), } P < .01)\). The mean fatigue index was 14.79 ± 2.98%, although this was not related to total time in the 1-km TT \((r = 0.12, P = .94)\).

Comparison of the pacing strategies between the “slow” and “fast” 1-km TT performances showed that the pacing strategies employed were not significantly different between the groups \((P = .95\), see Table 1).}

### 3-km IP

The mean total time for the 3-km IP was 221.83 ± 4.02 s. The 250-m split times are shown in Figure 2. After a slow first 250-m split \((22.95 ± 0.76 s)\), due to the acceleration from a standing start, the quickest split times were recorded on the second lap \((17.08 ± 0.56 s)\). Thereafter a progressive reduction in mean split times was evident until the end of the event. The split time for the final lap was significantly slower than the penultimate lap \((18.73 ± 0.72 s \text{ vs. } 18.67 ± 0.69 s, P = .03)\), showing that an end-spurt was not present in the pacing-profile for this event. When expressed as 1-km splits the second kilometer was significantly quicker than the first and third kilometer splits, while the first and third kilometer splits were not significantly different \((P = .95\text{, see Table 1})\). The time taken for the first 250 m split was significantly related to total time \((r = 0.46 \text{ (CI 0.25 to 0.64), } P < .01)\). In addition, the fatigue index \((10.46 ± 4.02\%)\) was also related to total time \((r = 0.26 \text{ (CI 0.02 to 0.47), } P = .04)\).

Comparison of the pacing strategies between the slow and fast 3-km IP performances showed that the pacing strategies employed were significantly different between the slow and fast groups \((P = .01\), see Table 1). The percentage of total race time spent covering the first kilometer was significantly less in the slow group \((P = .01)\), indicating that slower athletes were overly ambitious with their pacing strategy. However, the percentage of total race time spent

<table>
<thead>
<tr>
<th>Event</th>
<th>Split</th>
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<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
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<td>1-km TT</td>
<td>Slow</td>
<td>29.79 ± 0.57</td>
<td>21.89 ± 0.21</td>
<td>23.17 ± 0.23</td>
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<td></td>
<td>Fast</td>
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<td>21.92 ± 0.31</td>
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<td>32.76 ± 0.37</td>
<td>33.66 ± 0.60</td>
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<tr>
<td></td>
<td>Fast</td>
<td>33.98 ± 0.55*</td>
<td>32.61 ± 0.24</td>
<td>33.42 ± 0.49</td>
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<td>4-km IP</td>
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</tr>
<tr>
<td></td>
<td>Fast</td>
<td>26.34 ± 0.31*</td>
<td>24.33 ± 0.25</td>
<td>24.55 ± 0.24</td>
<td>24.78 ± 0.35*</td>
</tr>
</tbody>
</table>

*Denotes significant difference between “slow” and “fast” performances.

### Table 1 Split times, expressed as a percentage of total performance time, for “slow” and “fast” performances. Data for the 1-km TT were calculated from 250-m split times. Data for the 3-km and 4-km IP were calculated from 1-km split times.
covering the final kilometer was not significantly different between slow and fast groups ($P = .15$).

### 4-km IP

The mean total time for the 4-km IP was 267.93 ± 3.36 s. The 250 m split times are shown in Figure 2. The pacing pattern evident in the 4-km IP was similar to that displayed in the 3-km IP, in that after a slow first 250-m split (21.86 ± 0.55 s), the quickest split times were recorded on the second and third laps (16.06 ± 0.45 s and 16.06 ± 0.46 s, respectively), following which a progressive reduction in mean split times was evident until the end of the event. Split times for the penultimate and final 250-m split were 16.74 ± 0.59 s and 16.78 ± 0.62 s, respectively, although these differences were not significant ($P = .11$). When expressed as 1-km splits the first kilometer was slowest, and the second kilometer was quickest, after which there was a progressive slowing in 1-km split times until the finish (Figure 3). Differences between successive 1-km split times were significant, while the final kilometer split time remained significantly quicker than the first kilometer split. The time taken for the first 250-m split was significantly related to total time ($r = 0.38$ (CI 0.16 to 0.57), $P < .01$), although to a lesser extent than in the 1-km TT and 3-km IP. However, fatigue index (7.21 ± 3.36%) was more strongly related to total time in the 4-km event ($r = 0.48$ (CI 0.28 to 0.65), $P < .01$) than in the 1-km TT or 3-km IP.  

**Figure 2** — 250-m split times during women’s 3-km individual pursuit and men’s 4-km individual time trial. *Denotes significant difference between split times.
Comparison of the pacing strategies between the slow and fast 4-km IP performances showed that the pacing strategies employed were significantly different between the slow and fast performances ($P = .01$, see Table 1). The percentage of total race time spent covering the first kilometer was significantly less in the slow group than in the fast group ($P = .02$), while the percentage of total race time spent covering the final kilometer was significantly greater in slow performances than in fast performances ($P = .03$). Taken together, these findings indicate that slow performances were characterized by an overly ambitious start, with a resultant slowing toward the finish. Conversely, fast performances were characterized by a more realistic starting pace which enabled speed to be better maintained during the closing stages of the 4-km IP.

### Discussion

The aim of this study was to examine the pacing strategies adopted during the 1-km TT as well as the 3-km and 4-km IP events, in elite athletes.

In the 1-km TT, the strong relationship between first lap time and total time demonstrates the importance of a fast start in determining total time. Moreover, although there was a significant increase in lap time after the opening 250 m, indicating an inability to maintain work output over the duration of the event, the fatigue index was not related to the total time. These observations are in good agreement
with previous modeling studies,\textsuperscript{1,7} which suggest that an “all-out” strategy will yield the optimum performance in the 1-km TT event. Indeed, a strong relationship has previously been demonstrated between the time taken for the first 250 m, and total time in the 1-km TT ($r = 0.71$),\textsuperscript{1} albeit in a much smaller subject group than in the current study ($n = 8$). The importance of a fast start in the 1-km TT is likely related to the minimization of the time taken for the acceleration phase, which allows for maximization of the generated kinetic energy for the remainder of the event.\textsuperscript{7} The finding that the fatigue index was not related to total time might, in part, be explained by the fact that in short distance events, such as the 1-km TT, any kinetic energy that remains once the athlete has crossed the finishing line will be wasted, in terms of performance. Interestingly, there were no significant differences between the pacing strategies of “slow” and “fast” performances in this event. Taken together these findings contrast somewhat with those of Wilberg and Pratt,\textsuperscript{14} who suggest that in comparison with faster athletes, the slower athletes in the 1-km TT started too rapidly (relative to their performance level), with the consequence that they had a greater level of fatigue, and finished more slowly. However, it is likely that the performances analyzed in the current study were more homogenous than those analyzed by Wilberg and Pratt,\textsuperscript{14} being at world championship level rather than national/international level, which may explain these divergent findings. Furthermore, it is interesting to note that in the 100-m, 200-m and 400-m running events at the 1999 World Championships in Athletics, the pacing strategies of the winners were similar to those athletes who finished last, but they were faster throughout the race.\textsuperscript{11}

The pacing strategies adopted in the 3-km IP and 4-km IP differed from the 1-km TT in that there was a lower fatigue index, indicating that a more even pacing strategy was adopted in these events. Indeed, it has been suggested that an all-out strategy would be unrealistic in events of this duration due to the premature accumulation of deleterious metabolites in the working muscles.\textsuperscript{7} Nevertheless, a progressive decay in split times was apparent over the course of the event, with the fastest mean split times generally recorded on the second lap and the slowest split times recorded on the final lap. In contrast to the 1-km TT, the fatigue index was significantly related to the total time in the IP events, although to a greater degree in the 4-km IP than in the 3-km event. In addition, while the split time for the first 250 m was related to total time, this was to a much lesser degree than in the 1-km TT. Thus, while a fast start appears to remain a significant aspect of the pacing strategy adopted in the IP events, the ability to maintain a consistent pace appears to be of increased importance. These “real-life” data are again in good agreement with simulation models\textsuperscript{1,7} in which it is suggested that optimal times in the 4-km IP will be yielded by a rapid start followed by a more uniform velocity,\textsuperscript{1} or with a rapid start followed by slightly higher initial energy outlay and a subsequent slight linear decrease in power output.\textsuperscript{7} It has been suggested that the rapid start is still an important component at these longer distance events because a fixed amount of kinetic energy is required to obtain a certain velocity, which can best be delivered at the start of the event since movement at slower velocities will take up a relatively greater amount of time.\textsuperscript{7} A fast start may also increase the supply of energy from oxidative sources over the course of an event.\textsuperscript{19} However, from a mechanical perspective, because the energy lost to air friction increases as the cube of velocity,\textsuperscript{4,20} an evenly paced race is believed to be more appropriate for longer race distances.\textsuperscript{1} Moreover, as the race distance is increased any kinetic energy remaining at the finish will become of pro-
gressively less importance, relative to frictional energy losses. Thus, the most favorable pacing strategy for a given event will be the one that optimizes the balance between the frictional energy losses and kinetic energy remaining at the finish.\textsuperscript{1,20}

Despite similarity between the “real life” data and simulation models,\textsuperscript{1,7} significant differences were evident between the pacing-profiles of slow and fast performances in the IP events. In both the 3-km and 4-km IP the first 1000 m split time of the slow performances was significantly quicker, when expressed as percentage of total race time, than that of the fast performances. In addition, the percentage of the total race time taken during the final 1000 m split during the 4-km IP was significantly longer in the slow performances than in the fast performances. This finding is interesting for two reasons. First, in spite of the apparent importance of a fast start in the IP events, an overly fast start appears to be detrimental to performance in the latter portion of the event. This may result from an increase in frictional energy losses early on, and is in good agreement with previous research showing that individual 4-km pursuit riders who accelerated too rapidly and/or to too high a speed were consistently beaten by athletes adopting a more even pacing strategy.\textsuperscript{14} Second, it appears that even small differences in pacing strategy may be important at the elite level.

It has been suggested that the pacing strategies adopted for a given event are likely to be indicative of underlying physiological and regulatory processes.\textsuperscript{8,12} In particular, pacing strategies in which an end-spurt is evident are purported to support the central governor hypothesis.\textsuperscript{8,12} Nevertheless, the data from the current study show no evidence of an end-spurt, in any of the events examined. The finding that an end-spurt was not evident in the 1-km TT was not unexpected, as previous work has suggested that an end-spurt is not evident in maximal exercise lasting less than 2 min.\textsuperscript{3,8,11} However, the finding that an end-spurt was not present in the 3-km and 4-km IP is an interesting feature of the data presented, particularly as the existence of an end-spurt has recently been shown to be a recurrent feature of 1 mile running world record performances,\textsuperscript{12} an event with a similar duration to the 3- and 4-km IP, as well as during repeated 4-km cycling TTs in the laboratory.\textsuperscript{5} The reason for these divergent findings is unclear, but may be due to differences in the tactical nature of these running and cycling events. Most running events require that the time of the winning athlete be only marginally quicker than that of other competitors in the same race. Thus, the pacing strategy may be influenced by other athletes, and might favor an end-spurt to ensure that an athlete crosses the finishing line ahead of other competitors. In contrast, in the track cycling events described in the current study, the optimal pacing strategy will generally be the one that results in the fastest performance time. Due to the low drag forces during velodrome cycling, as well as the assertion that any kinetic energy remaining at the end of an event represents a source of useless energy in performance terms,\textsuperscript{7} the production of an end-spurt would represent an inefficient use of resources in this exercise model. As a consequence track cyclists may consciously, or subconsciously, select a pacing strategy that does not allow for an end-spurt.

It has been suggested that a pacing strategy in which there is a progressive decay in split times might be indicative of a catastrophe model of pacing regulation, in which the work output is dictated by the development of peripheral fatigue.\textsuperscript{12} This suggestion is supported by a recent study in which integrated electromyography activity during a 4000-m laboratory cycling TT increased in the presence of a falling
power output; a finding which was interpreted as being more consistent with peripheral fatigue rather than central down-regulation of power output. However, it has been suggested that a progressively diminishing pacing-profile does not necessarily exclude the possibility of a more complex form of central regulation in which intracellular changes in metabolite accumulation or phosphagen depletion might be centrally monitored, via afferent feedback, in advance of these changes becoming critical or harmful, and that the pacing strategy is regulated in the presence of a falling work output. This strategy would allow for a higher work output during the early stages of exercise, but might cause a certain degree of metabolite accumulation to occur and a subsequent increase in the perception of effort, with a resultant decrease in work output. Nevertheless, as mentioned previously, a high initial work output followed by a slight progressive reduction in work output may represent the optimal pacing strategy during IP cycling and certain levels of noncatastrophic derangements may be tolerated to optimize kinetic energy and performance.

Finally, this study was not without limitation. It was not possible to directly measure power output, thus inferences were made with regard to the relationship between split times and power output. It is probable that the highest power output would have been recorded during the acceleration phase at the start of each event, which coincided with the slowest lap times. However, once a relatively constant velocity was achieved then a change in split time should have been reasonably reflective of a change in power output. Moreover, a number of assumptions were made with respect to the aerodynamic profile adopted by the rider and the distance traveled during each lap. A change in either of these parameters might account for a reduction in cycling velocity, although following the initial acceleration phase it is likely that these parameters would remain fairly constant.

In conclusion, the track cycling events examined showed a similar pacing profile, characterized by an initial acceleration to a high speed, followed by a progressive decay in lap times. A fast first 250 m split time is paramount for quick performance times in the 1-km TT, whereas the rate of fatigue does not discriminate between performances. Moreover, there were no differences in the pacing strategies of slow and fast performers in this event. In the 3-km and 4-km IP events a fast first 250 m split time is also important (although to a lesser extent than in the 1-km TT), but the ability to maintain a consistent pacing profile is also a key determinant of performance. In addition, there was a small but significant difference in the pacing strategies of slow and fast performances, with slow performances characterized by an overly quick start with a concomitant slowing at the finish. Thus, in the 3-km and 4-km IP events small alterations in pacing strategy appear to be important, at the elite level.

Acknowledgments

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References