Determination of Optimal Pacing Strategy in Track Cycling with an Energy Flow Model

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The purpose of this study was to investigate the effect of pacing strategies on performance times in the 1000 m time trial event and the 4000 m pursuit event in track cycling. For this purpose, we simulated these events with a model based on the flow of energy in cycling. Different strategies in distributing the available anaerobic energy were evaluated and we compared model predictions of split times and final times with values achieved by cyclists during championships. The best result at the 1000 m time trial was obtained when the cyclist had the highest anaerobic peak power output and used an 'all-out' strategy. The fastest time on the 4000 m pursuit was achieved with an 'all-out' start at a high level of initial power output, followed by a constant anaerobic power output after 12 seconds, resulting in an evenly paced race. The results show that even small variations in pacing strategy may have substantial effects on performance. There seems to be an opportunity to gain a competitive advantage when individual athletes experiment with small variations in pacing strategy to find the precise individual strategy that works best under specific conditions.

Introduction

In cycling competition, one may discern two types of races. In the first type, the competitors cycle all together and strive to pass the finish line first. In this type of race, tactics are quite important; success depends on choices made by the cyclist and coach in issues such as leading or following and team strategy. The primary physiological limitations are the availability of muscle glycogen in order to maintain riding pace during the middle of the race and the ability of the rider to produce bursts of muscular power at important tactical moments during the competition. These races, which usually take place over distances of more than 100 km, can be quite strenuous, but the rider does not necessarily exhaust the energy producing capabilities.

In the second type of race, often held on indoor cycling tracks of 200 to 400 m length, individuals or teams try to cover a certain distance in the shortest time possible. In this type of race, the energy producing capacities of the athletes are fully exhausted and there is one dominant tactical consideration: pacing. Pacing refers to the regulation of speed over the race by varying the rate of energy expenditure. In the last decades, considerable effort has been paid to technological innovations aimed at improving performance in time trial cycling.

Many studies have been conducted on the aerodynamics of bicycle and rider (e.g. Zdravkovich et al. 1996; Thompson, 1998) and the physiological responses to training and competition (e.g. Tanaka et al., 1993; Capelli et al., 1993). However, there have been surprisingly few systematic studies on pacing. This is surprising, because both scientists and non-scientific observers feel that pacing has an important effect on the outcome of a competition.

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. When a cyclist is riding at a constant velocity the kinetic energy is constant, so power production and power dissipation by air friction and rolling resistance are balanced. Obviously, all else being equal the higher the velocity, the higher the power dissipation and the higher the power output required to maintain a constant speed. During cycling events such as achieving a maximal distance in one-hour, the steady state rate of power production is a dominant factor in determining average riding velocity, and thus the outcome of the competition. During short time trials such as the 1000m and 4000m contests in the Olympics, a steady state situation will be an exception rather than the rule; during most of the race, the mechanical power generated by the aerobic and anaerobic energy systems will not be in balance with the power dissipated by air friction and rolling resistance. When the power output produced by the athlete is greater than the power needed to overcome air friction and rolling resistance the cyclist will accelerate, and when it is smaller the cyclist will decelerate. The interplay between power production and power dissipation results in a certain velocity profile over the race.

With the help of models including power production and power dissipation, it is possible to simulate a race and predict the velocity profile and performance time. This approach has been applied by van Ingen Schenau et al. (1990, 1991, 1992, 1994), de Koning et al. (1992) and de Koning and van Ingen Schenau (1994) to speed skating, running and cycling. Using these simulations, the effect of pacing strategy on performance was investigated, and optimal pacing strategies leading to maximum performance were found. Very little controlled experimental data on pacing strategies has been published, but the data that is available seems to support model predictions (Foster et al., 1993, 1994). The purpose of the present study was to investigate the effect of pacing strategies on performance times in the 1000 m time trial event and the 4000 m pursuit event in track cycling. For this purpose, we simulated these events with a model based on the flow of energy in cycling, and we compared model predictions of split times and final times with values achieved by cyclists during championships.

Methods

For the simulations of cycling events we used the model proposed by van Ingen Schenau et al, 1990). This model is based on the flow of energy, and includes expressions for power production and dissipation:

$$P_0 = P_f + \frac{dE_{cb}}{dt} \qquad (1)$$

where P_0 is the average total power output of the cyclist (the mean mechanical power generated), P_f the average power loss to air friction and rolling resistance and dE_{cb}/dt the average rate of change of the kinetic, rotational and potential energy of the cyclist-bicycle system (CB-system). The rate of change of mechanical energy of the CB-system averaged over multiple revolutions is in cycling predominantly determined by the rate of change of kinetic energy of the mass center of the system:

$$\frac{dE_{cb}}{dt} = \frac{d(\frac{1}{2}mv^2)}{dt} = mv\frac{dv}{dt} \qquad (2)$$

with v the average speed. Thus, the rate of change of kinetic energy equals:

$$\frac{d(\frac{1}{2}mv^2)}{dt} = P_0 - P_f \qquad (3)$$

To perform valid simulations of time trial performance it is necessary to have valid expressions for P_o and P_f. These expressions are derived below.

Power Production (P_0)

The power production (P_o) of the athlete is the sum of the power production by the aerobic (P_{aer}) and anaerobic (P_{an}) energy production systems:

$$P_0 = P_{aer} + P_{an} \qquad (4)$$

The mechanical aerobic power kinetics was modeled as:

$$P_{aer} = P_{aer-max}(1-e^{-\lambda t}) \qquad (5)$$

with $P_{aer-max}$ the maximal mechanical aerobic power contribution and λ a constant. This aerobic contribution was the same in all simulations. At the beginning of a maximal exercise bout, the external power output can be considerably higher than P_{aer} due to P_{an}, representing the contribution of immediately availability of energy rich phosphates and anaerobic glycolysis to the generation of muscle power (e.g. Åstrand & Rodahl, 1986; Serresse et al., 1988; Davies & Sandstrom, 1989). Due to the limited pool of energy rich phosphates and the accumulation of lactate in muscles (the rate of lactate breakdown and removal from the muscle is limited), the anaerobic capacity is limited. Typically, a large decrease in P_{an} is observed during the course of maximally performed exercise bouts. The anaerobic power was modeled as:

$$P_{an} = P_{an-max}e^{-\gamma t} \qquad (6)$$

with P_{an-max} the maximal mechanical anaerobic power at $t = 0$ and γ a constant. Values for $P_{aer-max}$, γ, P_{an-max} and γ were obtained from cycle ergometer tests performed with elite speed skaters (de Koning et al., in preparation) and amounted to 6.35W/kg, 0.1069s^{-1}, 22W/kg and 0.0389s^{-1}, respectively.

Power Dissipation to Friction (P_f)

A cyclist has to overcome rolling resistance and air frictional forces. Air friction has two components, friction drag and pressure drag. Friction drag is caused by friction in the layers of air along the body and is dependent on, for example, the roughness of the clothing. In cycling, friction drag is relatively small compared to pressure drag. According to Bernoulli's law, the pressure in front of the cyclist is higher than the pressure behind the cyclist. A lower velocity of the air in the front and a higher velocity of the air in the back of the CB-system causes this. This pressure difference is mainly determined by the dynamic pressure $0.5\rho v^2$ where ρ is the density of the air at sea level ($1.25\ kg/m^3$) and v velocity of the air relative to the body. Given a cross-sectional area (the surface of a frontal projection of the CB-system) A_p, the pressure drag force, equals $0.5\rho v^2 A_p$. This equation, however, does not account for the influence of streamlining and the contribution of friction drag. Indeed, modifications of racing suits in cycling and speed skating by adding 'strips' are intended to disrupt the accumulation of air in front of the athlete and the formation of a wake in the back of the athlete, thus minimizing the effect of pressure drag. To account for friction drag, a dimensionless coefficient C_d, the drag coefficient, is added to this equation. This drag coefficient can only be determined experimentally. Total air friction force F_{air} thus equals:

$$F_{air} = \tfrac{1}{2} p \cdot v^2 \cdot A_p \cdot C_d \qquad (7)$$

The component A_pC_d is described in literature as the effective frontal area. For the simulations in this study, we used for this effective frontal area values reported by Zdravkovich et al. (1996). These values were $0.23\ m^2$ in the 1000 m time trial (the crouch position) and $0.202\ m^2$ in the 4000 m pursuit (the aerobar position). If there is no wind, as in our simulations, the air frictional power loss (P_{air}) can be described by:

$$P_{air} = \tfrac{1}{2} p \cdot A_p \cdot C_d \cdot v^3 \qquad (8)$$

The power loss to rolling resistance (P_{rol}) is assumed to be equal to:

$$p_{rol} = \mu m g v \qquad (9)$$

with μ the rolling friction coefficient, m the mass of the CB-system and g the gravitational acceleration. The value for μ (0.004) was obtained from literature (de Groot et al. 1995).

Simulations

Simulations were performed for both the 1000 m time trial and the 4000 m pursuit. For each step in the simulation, the rate of change of kinetic energy was calculated as:

$$\frac{d(\tfrac{1}{2} m v^2)}{dt} = P_o(t) - P_{air}(v) - P_{rol}(v) \qquad (10)$$

The time history of the kinetic energy of the mass center of the CB-system, and therewith the velocity, was acquired by integration of this differential equation with a variable step size second-order predictor, third-order corrector integration algorithm using the Runge-Kutta method.

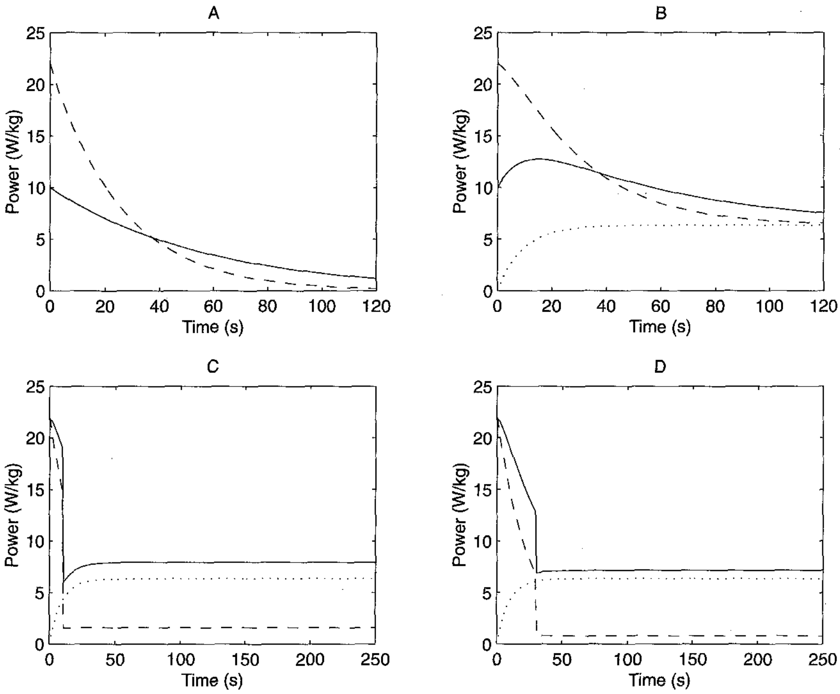

Figure 1: Effects of manipulations in anaerobic kinetics and 'time to constant anaerobic power' TC on power output.
In Figure 1A the anaerobic power output is shown from an anaerobic distribution with $P_{an\text{-}max}$ = 22 W/kg and γ = 0.0389 (broken line) and with $P_{an\text{-}max}$ = 10 W/kg and γ = 0.0177 (solid line). In both cases, the anaerobic capacity is identical (565 J/kg).
In Figure 1B the anaerobic power output as show in figure 1A is added to the aerobic power output (dotted line), giving the total power output for both anaerobic distributions.
In Figure 1C and 1D, the effect of TC on total power output (solid line) is shown. The anaerobic power output (broken line) is following the 'all-out' profile (with $P_{an\text{-}max}$ = 22 W/kg and γ = 0.0389) till the 'time to constant anaerobic power' TC (Figure 1C: TC = 10 s., figure 1D: TC = 30 s). From this point in time, the remaining anaerobic energy is evenly distributed over the rest of the race. The dotted line is the aerobic power output.

As already stated, the aerobic power contribution was the same in all simulations. As explained below, the anaerobic capacity was also kept constant, 565 J/kg (de Koning, in preparation), but we systematically changed (1) the kinetics of the anaerobic power output and (2) the strategy of using the anaerobic capacity, and therewith the velocity profile. The kinetics of the anaerobic power output were changed by altering $P_{an\text{-}max}$ and adapting γ in equation 6 in an iterative way so that the total anaerobic energy contribution was the same in all simulations (see figure 1A and 1B). The strategy of using the anaerobic capacity was changed by introducing a variable henceforth referred to as 'time to constant anaerobic power' (TC), indicating the time at which the cyclist changed from an 'all-out' strategy of anaerobic power distribution to a constant distribution of the remaining anaerobic energy (see Figure 1C and 1D). In these simulations we calculated the remaining anaerobic energy at TC and averaged that amount over the remaining part of the race. Using an iterative procedure, it was ensured that in all simulations the same amount of the anaerobic energy had been used when the cyclist finished the race. All other variables, including the aerobic power production, were kept constant, so the changes in final time obtained from the presented simulations are solely the effect of changes in anaerobic energy distribution.

The simulations were performed for a cyclist of 70 kg with a bicycle mass of 10 kg at sea level in a condition without wind (indoor). Simulation results were compared to times from the medallists at the 1998 Track World Championships held at Bordeaux, France.

Results and Discussions

Figure 2 shows the results of the manipulations of anaerobic kinetics and 'time to constant anaerobic power' (TC) for 1000 m time trial cycling. The best result at the 1000 m time trial (the lowest point of the surface of Figure 2) was obtained when the cyclist had the highest anaerobic peak power output and used a strategy in which the 'time to constant anaerobic power' (TC) was larger than 60 s. In other words, best 1000 m performance is achieved with an 'all-out' strategy regardless of peak power output. Table 1 shows split times and final times for simulation and real cycling results. Although the simulated performance times are faster, the predicted percentages of total time used to complete each successive section of 250 m closely agree with values observed in real cycling.

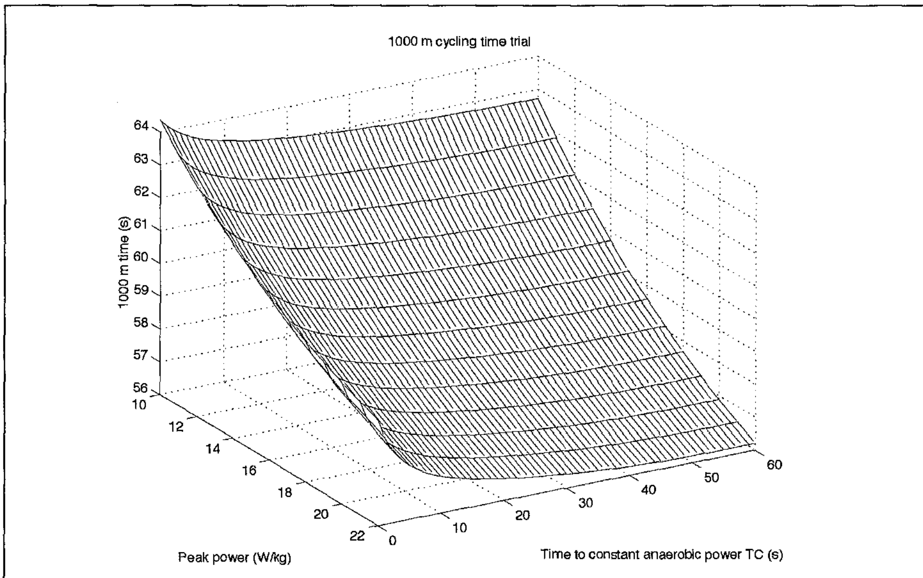

Figure 2: Results of simulations for 1000 m time trial cycling were the anaerobic kinetics and the 'time to constant anaerobic power' (TC) is manipulated. The lowest point of the surface ($P_{an\text{-}max}$ = 22 W/kg, TC = 60 s) indicates the fastest final time and thus the optimal pacing strategy.

	250 m	500 m	750 m	1000 m
real cycling (s)	18.75 (30.1%)	32.50 (52.2%)	46.84 (75.2%)	62.26 (100%)
Simulation (s)	17.23 (29.7%)	30.30 (52.2%)	43.77 (75.4%)	58.09 (100%)

Table 1: Split times and final time for the 1000 m time trial, expressed both as absolute values and as percentage of the final time, for the medallists of the 1998 Track World Championships and for the optimal solution of the model (P_{an-max} = 22 W/kg, TC = >60s.).

P_{an-max} (W/kg)	Final time (s)	Work to friction (J)	Kinetic energy at finish (J)
14	61.52	44698	10693
18	59.51	47058	11384
22	58.0	948874	11438

Table 2: Results of 1000 m time trial simulations obtained with an 'all-out' strategy at the same total anaerobic energy contribution but different values for P_{an-max} (and adjusted γ).

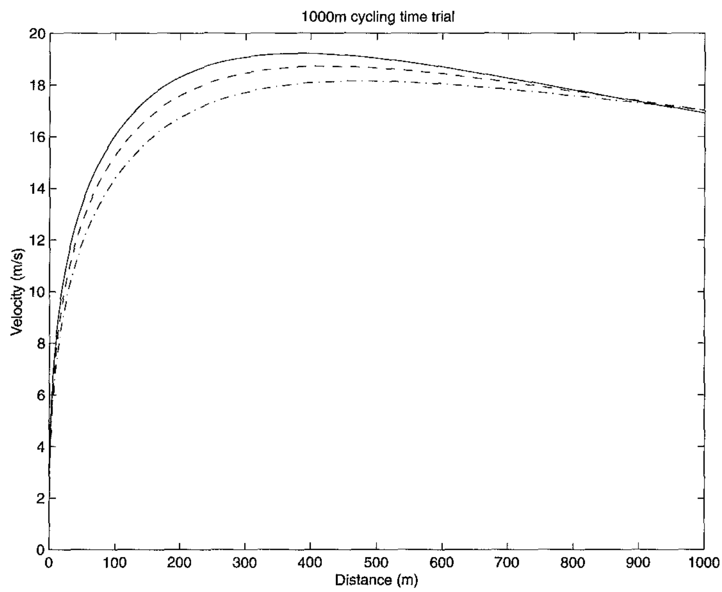

Figure 3: Velocity profile of 1000 m cycling time trials obtained from simulation with the rider using an 'all-out' strategy with an anaerobic energy distribution that is characterized by peak anaerobic power outputs of 14 (dotted line), 18 (broken line) and 22 W/kg (solid line).

To further illustrate the effect of the kinetics of anaerobic power output and the 'time to constant power', we shall present more information on six simulations. Table 2 and Figure 3 show simulation results for an 'all-out' strategy with peak anaerobic power outputs of 14, 18 and 22 W/kg. Table 3 and Figure 4 shows results from simulations where the peak anaerobic power output was 22 W/kg,

TC (s)	Final time (s)	Work to friction (J)	Kinetic energy at finish (J)
0 (constant from start)	61.04	47451	14746
30	58.33	48429	12096
60 ('all-out')	58.09	48874	11438

Table 3: Results of 1000 m time trial simulation obtained with a constant $P_{an\text{-}max}$ of 22 W/kg but different values of TC.

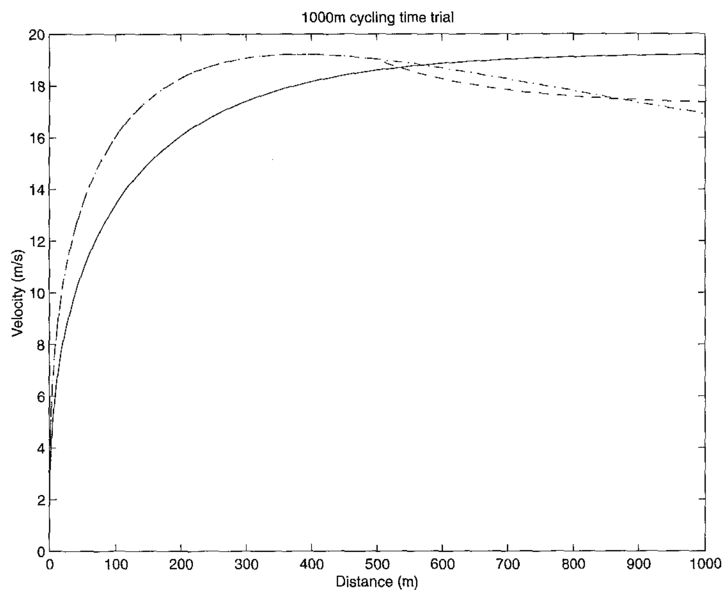

Figure 4: Velocity profile of 1000 m cycling time trials obtained from simulation with the rider using an anaerobic energy distribution that is characterized by a peak anaerobic power output of 22 W/kg and a 'time to constant anaerobic power' TC = 60 s ('all-out') (dotted line), TC = 30 s (broken line) and TC = 0 s (constant anaerobic power) (solid line).

but with three different TC's of 0 s, 30 s and 60 s. The results show that with the same amount of anaerobic energy the cyclist performs considerably better when he releases a large amount of anaerobic energy early in the race. In the strategy with the highest initial power output, considerably more energy is lost to friction than in the other strategies, but the amount of energy present as kinetic energy at the end of the race (which can be considered as useless energy) is lower. Apparently, the advantage of a higher acceleration in the first part of the race and the lower amount of kinetic energy left at the end of the race, outweigh the unavoidable disadvantage of higher frictional losses associated with the higher mean velocity.

Table 4 shows for the results of the top 8 riders at the 1998 Track World Championships that there is a relatively high correlation between time on the first lap and final time, but no correlation between time on the final lap and final time.

	r
Time 0-250 m - final time 1000 m	0.71
Time 0-250 m - time 750-1000 m	-0.67
Time 750-1000 m - final time 1000 m	-0.06

Table 4: Coefficients of correlation (r) between times on different sections (250 m laps) of 1000 m time trials of the top 8 cyclists participating in the 1998 Track World Championships.

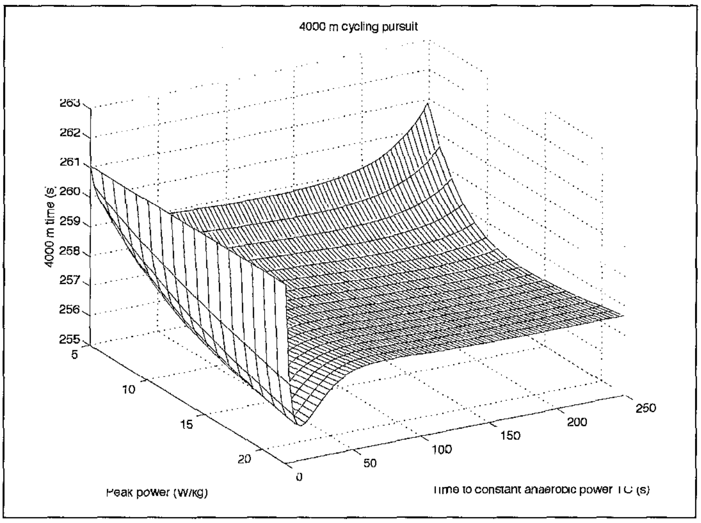

Figure 5a: Results of simulations for 4000 m pursuit cycling were the anaerobic kinetics and the 'time to constant anaerobic power' (TC) is manipulated. The lowest point of the surface ($P_{an\text{-}max}$ = 22 W/kg, TC = 12 s) indicates the fastest final time and thus the optimal pacing strategy.

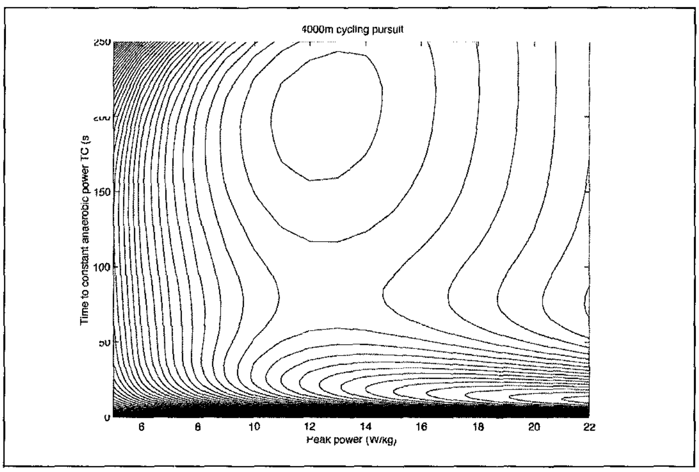

Figure 5b: Contour plot of the results presented in figure 5a (4000 m pursuit cycling). Each contourline represents a difference in time of 0.1 s. The lowest point of the surface ($P_{an\text{-}max}$ = 22 W/kg, TC = 12 s) indicates the fastest final time (256.15 s.) and thus the optimal pacing strategy.

	1000 m	2000 m	3000 m	4000 m
Real cycling (s)	69.02 (26.2%)	133.73 (50.9%)	196.25 (74.6%)	263.00 (100%)
Simulation (s)	65.72 (25.7%)	129.82 (50.7%)	193.19 (75.4%)	256.15 (100%)

Table 5: Split times and final time for the 4000 m pursuit, expressed both in absolute values and as percentage of the final time, for the medallists of the 1998 Track World Championships and for the optimal solution of the model (P_{an-max} = 22 W/kg, TC = 12 s.).

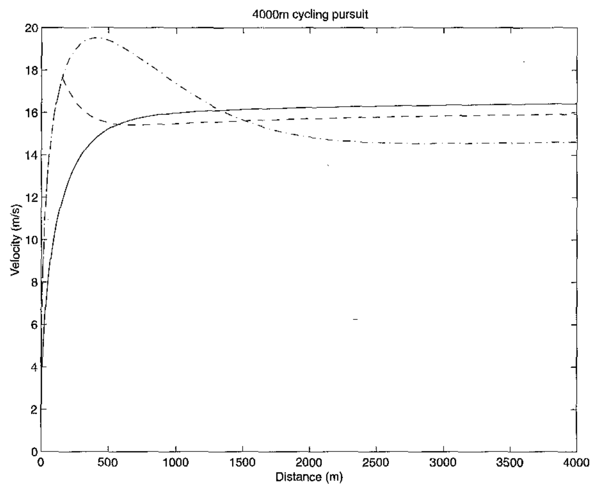

Figure 6: Velocity profile of 4000 m pursuit cycling obtained from simulation with the rider using an anaerobic energy distribution that is characterized by a peak anaerobic power output of 22 W/kg and a 'time to constant anaerobic power' TC = ~ ('all-out') (dotted line), TC = 12 s (optimal) (broken line) and TC = 0 s (constant anaerobic power) (solid line).

Together with the negative correlation between time on the first lap and time on the last lap, this is a strong indication that elite cyclists tend to use an 'all-out' strategy in cycling the 1000 m time trial.

Figures 5a and 5b show the results for simulations of the 4000 m pursuit for different anaerobic kinetics and values of the time at which the model switched from an 'all-out' to a constant anaerobic power output strategy. The fastest time is achieved with an 'all-out' start at a high level of initial power output, followed by a constant anaerobic power output after 12 seconds (TC = 12 s). Table 5 shows split and final times for simulated and real cycling 4000 m pursuits. Again, there is a good similarity. From figure 5a and 5b it is clear that the time at which the rider had to switch from an 'all-out' to a constant power strategy is very critical and that the optimal value of TC depends on the anaerobic energy kinetics.

Figure 6 shows velocity profiles of simulations where the model used either an 'all-out' strategy (TC = ~), a constant anaerobic power strategy (TC = 0 s), or the optimal strategy (TC=12 s). It can be seen in the figure that with the optimal strategy, the rider has a high acceleration early in the race, and soon achieves a more or less constant velocity. The split times presented in Table 6, especially when expressed as percentages of the total time used to cover the distance, show that the constant power strategy (TC = 0) and the 'all-out' strategy (TC = ~) deviate from the values of the cyclists participating in the 1998 Track World Championships (table 5). In the optimal solution (TC = 12 s) the first half of the 4000 m pursuit was completed in 50.7% of the final time. This result is similar to the 50.9% of the 1998 Track World Championships. It is also similar to results from Foster et al. (1993), who had well-trained subjects performing five 2000 m time trials with different pacing strategies, on an ergometer. Although no systematic differences were found among the strategies in physiological measures (O_2 uptake, O_2 deficit, post exercise lactate), significantly better times were realized at the most evenly paced strategy where the first half of the race was completed in 50.9% of the final time.

TC (s)	1000 m (s)		2000 m (s)		3000 m (s)		4000 m (s)		finish velocity (m/s)
0	76.66	(29.4%)	138.64	(53.1%)	200.02	(76.6%)	261.05	(100%)	16.42
12	65.72	(25.7%)	129.82	(50.7%)	193.19	(75.4%)	256.15	(100%)	15.92
~	57.21	(22.2%)	120.64	(46.8%)	189.06	(73.4%)	257.69	(100%)	4.61

Table 6: Split times and final time for the 4000 m pursuit, expressed in absolute values and as percentage of the final time, for the simulations with a constant $P_{an\text{-}max}$ of 22 W/kg but different values for TC. A TC value of 0 s corresponds to a constant anaerobic power strategy, a value of ~ to an 'all-out' strategy, and the optimal value of 12 s.

Conclusion

The results of the simulations performed in this study show the potential effect of variations in pacing strategy on performance in the 1000m and 4000m track cycling events. It turns out that even small variations in pacing strategy may have substantial effects of the order of 1%. Clearly, these effects are not of negligible importance for competing athletes. Typically, the performances of the gold, silver and bronze medallists are within 1% of each other, so only small variations in pacing strategy can dictate competitive results as effectively as extensively studied issues such as the aerodynamics of the cycle and clothing, and the presence vs. absence of altitude training prior to competition. As noted earlier, the results of simulations generally agree with those of experimental studies (Foster et al., 1993). Moreover, experimental studies have clearly demonstrated that individual athletes must experiment with small variations in pacing strategy around the theoretical optima provided by the models to find the precise individual strategy that works best under specific conditions. Surprisingly, athletes and their coaches rarely do this. For those who are ready to experiment there seems to be an opportunity to gain a competitive advantage! Experimentation is possible on the track with the help of portable power output monitors that can be attached to the cycle in the field. The technology is waiting to be used by cyclists for fairly specific field experiments with starting strategies.

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