The 4000-m team pursuit cycling world record: theoretical and practical aspects

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ABSTRACT

SCHUMACHER, Y. O., and P. MUELLER. The 4000-m team pursuit cycling world record: theoretical and practical aspects. *Med. Sci. Sports Exerc.*, Vol. 34, No. 6, pp. 1029–1036, 2002. Due to constant competition conditions, track cycling can be accurately modeled through physiological and biomechanical means. Mathematical modeling predicts an average workload of 520 W for every team member for a new team pursuit world record. Performance in team pursuit racing is highly dependent on aerobic capacity, anaerobic skills, and aerodynamic factors. The training concept of the 2000 record-breaking team pursuit team was based on unspecific training of these qualities and periodical, short-term recall of previously acquired track specific skills. Aerobic performance was trained through high overall training mileage (29,000–35,000 km$\cdot$yr^{-1}) with workload peaks during road stage races. Before major track events, anaerobic performance, and track-specific technical and motor skills were improved through discipline-specific track training. Training intensities were monitored through heart rate and lactate field tests during defined track-training bouts, based on previously performed laboratory exercise tests. During pursuit competition, analysis of half-lap split times allowed an estimation of the individual contribution of each rider to the team's performance and thereby facilitated modifications in team composition to optimize race speed. The theoretically predicted performance necessary for a new world record was achieved through careful planning of training and competition schedules based on a concise theoretical concept and the high physiological capacities of the participating athletes. **Key Words:** TRACK CYCLING, PURSUIT, MODELING, PERFORMANCE

Only a few Olympic disciplines can be modeled as accurately as track cycling. Due to relatively constant conditions on indoor tracks, minor external disturbances, and precisely measurable variables influencing performance in this discipline, track cycling has been widely investigated. 4000-m individual and team pursuit races, track cycling's time-trial events, require high aerobic and anaerobic skills and have therefore challenged scientists. Furthermore, equipment-related factors resulted in considerable efforts to improve the biomechanical and aerodynamic side of performance. Several authors have described models including physiological, aerodynamic (position), and equipment-related variables contributing to track-cycling performance and subsequently validated these models in practical testing with reasonable accuracy (4,7,8,10,15,18,19,28).

Broker et al. (4) recently presented a model predicting 4000-m individual and team pursuit performance based on direct measurement of cycling power output by using bicycle crank dynamometers (SRM crank, Schoberer Messtechnik, Jülich, Germany). This model was subsequently validated with internationally competitive athletes and theoretical power output for pursuit world record performances was displayed. The authors concluded that for the present individual pursuit world record, an average cycling power of 520 W was required, and for the team pursuit, every team member performed about 480 W over the 4:00.958 min of the record ride.

Although many reports have addressed the theoretical background and physiological requirements of peak performance in track cycling, only a few reports give insight on the practical aspects, such as training systems, the use of competition data to direct team selection, and the practicability and reliability of such models in high-performance athletes. The aim of the present communication is therefore to describe the theoretical background and practical aspects of training and testing in connection with data from the new team pursuit world record set during the 2000 Olympic games by the German national team, and to discuss this issue in connection with the current knowledge on pursuit racing and the most recent theoretical model predicting performance in this cycling discipline. These findings could be useful to further improve training and testing schedules and be a valuable help to coaches and trainers.

THEORETICAL BACKGROUND

Several variables influence the power necessary to propel a bicycle and its rider at a given speed: height, body mass, and seat position of the rider; type and aerodynamic characteristics of the bicycle; and rolling resistance of the surface cycled on are only a few examples. Modeling of these factors has been widely practiced by scientists. Some authors mainly investigated aerodynamic characteristics; other focus on physiological data of the rider (6,7,8,13). To validate these models, field testing with measurement of

0195-9131/02/3406-1029/$3.00/0
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Submitted for publication June 2001.
Accepted for publication November 2001.

metabolic variables and calculation of energy expenditure as indices of power requirement has been used. Because of the introduction of mobile crank dynamometers, direct measurement of power, and thereby workload demands, during cycling has become possible, considerably facilitating such validation processes.

Workload Demands in Team Pursuit Racing

Several authors have tried to quantify workload sustained during cycling and pursuit racing by using different approaches (7,18,19). Only recently, Broker et al. (4) presented a model estimating the power requirements in team pursuit racing from a standing start, based on direct power measurement via dynamometric cranks:

$$P = 0.7697\ K\ (0.00953\ M_t V + 0.00775\ V^2 + K_i\ (A_f)\ 0.007551 V^3) \quad [1]$$

P = power (W)
K = constant describing track characteristics and rolling resistance
M_t = mass of rider and bike (kg)
V = speed ($km \cdot h^{-1}$)
K_i = constant describing aerodynamic factors (see equation B)
A_f = frontal area of the rider, calculated as $A_f = 0.0293 \times height^{0.725} \times weight^{0.425} + 0.0604$; and 0.7697 = correction factor for team pursuit.

The constant K ranges usually around 1. The constant K_i quantifies the influence of aerodynamic factors and is calculated as follows (see (1,4) for details):

$$K_i = K_d \times K_{po} \times K_b \times K_c \times K_h \quad [2]$$

K_d = density ratio (1 at sea level, 0.78 at 2500-m altitude)
K_b = bicycle-related factor (1 for standard bike, 0.93 for aerodynamically optimized track bike)
K_c = clothing (1 for aerodynamic skin suit, 1.09 for long sleeve jersey)
K_h = helmet (1 for aero time-trial helmet, 1.025 for conventional bike helmet)
K_{po} = position of the rider on the bike (1.08–1.18 for standard position, 1 for standard aero position).

For team pursuit racing, a regular change of racing positions occurs within the team during the race (usually each lap), and thereby a constant change in the aerodynamic drag on every rider must be considered in theoretical modeling. It has been demonstrated in different investigations (3,12,17) that the rider leading a pursuit team bears 100% of the power required to perform at a given speed, whereas the riders following him benefit from his draft and present thereby reduced power requirements: a rider in position 2 performs at 70%, and riders in positions 3 and 4 cycle at about 64% of the power required for the actual racing speed. In addition, during interchanges (after leading one lap, each rider drops back into last position), the riders are exposed unshielded from their teammates for about one fifth of a lap (distance of the interchange). These factors and the energy required for acceleration have been summed up in a correction factor (0.7697), which adjusts the equation to the specific characteristics of team pursuit racing. For individual pursuit, equation 1 without the correction factor can be used to calculate performance from given race speeds (See reference (4) for a detailed description).

Analyzing equation 1, it is obvious that P, at increasing speed, is mainly dependent on the aerodynamic variable K_i and the frontal area A_f of the rider. To obtain maximal speed from a given performance, it is therefore necessary to aim for optimized aerodynamic characteristics, as this equation shows the importance of such factors for cycling speed. By inputting different values for the variables in equations 1 and 2, the impact of factors influencing aerodynamic drag or environmental conditions on cycling performance can easily be modeled. As an example, it can be calculated that the choice of an aerodynamic helmet alone can decrease power requirement at high speeds by almost 20 W. Presuming the other variables as constant, mathematical regression of equation A toward V allows estimation of race speed (V), when power (P) is known.

Physiological Demands of Pursuit Racing

In addition to the above-mentioned biomechanical variables, physiological indices for successful pursuit performance have been investigated by several authors (7,8,15). There is a general consensus that pursuit racing requires high aerobic and anaerobic skills. Some authors have developed equations using indices of aerobic and anaerobic performance to predict performance in this event. The main predictors of performance in these investigations were aerobic capacity, measured as $\dot{V}O_{2max}$ or power output at anaerobic threshold, and anaerobic capacity, measured as maximal accumulated oxygen deficit (MAOD) during anaerobic testing or peak lactate concentrations after maximal exercise. Nevertheless, physiological testing is highly dependent on test protocol and testing equipment, and for this reason data from different laboratories might not be fully comparable, thus reducing the practicability of prediction of pursuit performance through physiological variables.

Prognosis

In sporting disciplines, where competition ranking is determined by racing times (such as track cycling, swimming, or running), prognosis of future winning times through analysis of past winning times of the same event and their historical progression is possible. This is of crucial importance when planning or modeling top performances in such events, in order to evaluate in advance the own team's capacity and to set goals for future training and competition. Such calculations have been performed for most endurance events (11,16,20,24,27). Retrospective analysis of winning times from team pursuit events at world championships from 1978 to 1999 shows a linear increase of performance of 0.7% per year (22). Regression analysis results in the following equation for the estimation of future team pursuit winning times in major cycling events:

$$y = 0.2833x - 506.6 \quad [3]$$

y = race speed required to win ($km \cdot h^{-1}$) and x = competition year.

TABLE 1. Anthropometric and physiological characteristics of the German national pursuit team and personal best times with estimated power requirements over 4000-m individual pursuit racing during the 2000 season.

Rider	Height (cm)	Weight (kg)	IaT ($W \cdot kg^{-1}$)	$\dot{V}O_{2peak}$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	Max. Lac. ($mmol \cdot L^{-1}$)	4000 m time (min)	Power (W)
1	186	82	5.1	65	10.3	4:18.8*	551
2	190	84	4.4	69	21.3	4:19.0	557
3	180	74	4.8	67	13.6	4:26.7	476
4	187	76	4.7	73	14	4:26.0	494
5	185	77	4.4	66	14.5	4:32.2	464
6	188	79	4.8	66	14.8	4:23.4	517
7	189	73	4.4	67	11.9	4:33.6	452

* 1999 season best.

Modeling of the Sydney Olympic Games Winning Performance

Inserting "2000," the year of the Sydney Olympic games into the equation for prognosis (equation 3), results in a speed of 60 $km \cdot h^{-1}$, thus a team pursuit time of 4:00.0 min. This performance ranges beyond the previous world record of 4:00.958 min, set in 1996 in Manchester by the Italian team. This record was set using aerodynamic equipment and aerodynamically optimized rider positions ("Superman"), which have since been forbidden by the international cycling federation. Those new rules made the establishment of a new world record in this discipline more difficult to achieve but nevertheless possible. It must be noted that even other more substantial technical innovations in the past (disk wheel) had no significant impact on the development of peak performance in track cycling. On the other hand, it cannot be predicted from the present data whether the evolution of winning times in team pursuit events is levelling off, although other cycling and running disciplines have shown stagnation in their peak performance for several years (3,17,22,24). Inserting 60 $km \cdot h^{-1}$ and average values for mass (79 kg) and height (186 cm) into equation 1 for the calculation of workload demands, an average team pursuit power of 521 W is required for a 4-min pursuit time, implicating a power of about 670 W in position 1 and around 450 W in positions 3 and 4 to win this discipline at the Sydney Olympic games.

Anthropometric and physiological data of the German pursuit team for the 2000 Olympic games, as well as seasonal best times in individual pursuit with power output calculated from these individual times by using the formula presented by Broker et al. are displayed in Table 1. The participating riders and the German Cycling Federation gave their informed written consent for the publication of these data. All physiological tests were approved by the scientific committee of our department. When modeling these data with the above-mentioned equations 1 and 2 for team pursuit, it was estimated that the hypothetical winning time of 4 min for the 2000 Olympics games was possible with several combinations of these athletes, as the average power output of pursuit teams composed from these riders could with training exceed the 521 W required for the presumed winning time. These theoretical calculations are supported by the observations during precompetition training: 3 d before the event, the team performed 2000-m test rides from a flying start ("peak" training, see Table 2) with (in that order) riders 3, 5, 6, and 4 (without their presumed strongest riders 1 and 2, see Table 1) in 1:58.7 min (gear 53 × 15) and 1:55.9 (gear 53 × 14) min, corresponding to average power outputs of 480 W and 513 W. (It has to be noticed that a flying start considerably reduces the power requirements and that a bigger gear (54 × 14) was used for the record ride 3 d later).

Nevertheless, this theoretical modeling is limited by the fact that every rider has individual preferences concerning his position in the team (1–4), allowing him only to perform at top level at this position, thereby limiting the number of possible combinations. Furthermore, riders 1 and 2 competed in the individual pursuit of the Olympic games and were thereby influenced in their performance for the team pursuit, which was held after the individual event.

Practical Aspects

Physiological and anthropometric data. Table 1 shows physiological and anthropometric data of the German pursuit team competing at the 2000 Olympic games in Sydney. Riders 1–4 rode the Olympic final and established the new world record.

Individual anaerobic threshold (IaT) and $\dot{V}O_{2peak}$ were determined during incremental exercise testing until volitional exhaustion on a SRM-Ergometer (SRM, Schoberer Messtechnik, Jülich, Germany) and using the standardized protocol of the German cycling federation, starting at 100 W

TABLE 2. Training schedule of the German national pursuit team during the last 19 d before the 2000 Olympic games' 4000-m team pursuit event.

Days to Competition	Training
15–19	Stage race
14	Rest day
13	115-km basic training
12	120-km basic training
11	115-km basic training
10	120-km basic training
9	Rest day
8	Track training: 3 × 5000-m "Evolution" Training
7	Morning: 3 × 5000-m "Evolution" Training Afternoon: 4 × 5000-m "Evolution" Training
6	2 × 5000-m "evolution" training 1 × 2000-m, 1 × 1000-m "peak" training
5	75-km basic training/recovery (road)
4	Morning: 2 × 5000-m "evolution" training Afternoon: 1-h basic training (road)
3	3 × 5000-m "evolution" training 2 × 2000-m "peak" training
2	75-km basic training/recovery (road)
1	2 × 5000-m "evolution" training

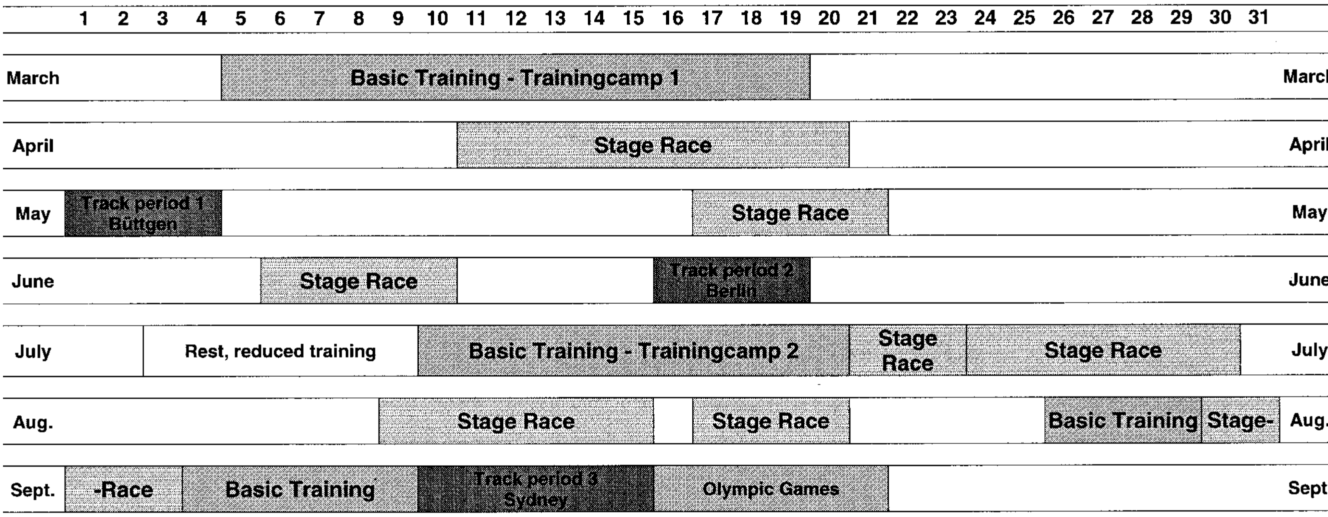


FIGURE 1—General training and competition schedule of the German national pursuit team during the Olympic season.

with 20-W increases every 3 min. The test was performed 6 wk before the Olympic games. Oxygen uptake was measured with an automated analyzer (Oxycon Delta, Jaeger GmbH, Hoechberg, Germany). $\dot{V}O_{2peak}$ was determined as the highest $\dot{V}O_2$ reached during the last stage of exercise. IaT was determined through lactate sampling by using the method described by Berg et al. (2). To characterize anaerobic mobilization, the highest lactate reached during 2000-m individual track testing is displayed.

Riders 1 and 2 placed first and second in the individual pursuit competition in the Olympics and present a similar level of performance (personal best over 4000-m individual pursuit racing: rider 1: 4:18 min; rider 2: 4:19 min). It is interesting to notice that these two riders deliver their performance in two distinctive, different ways: whereas rider 1 presents high aerobic capacity with 5.1 $W \cdot kg^{-1}$ at IaT and only limited anaerobic mobilization when compared with his teammates, rider 2 is capable of considerable anaerobic mobilization, represented by his peak lactate of 21.3 $mmol \cdot L^{-1}$, although his aerobic capacity is only team-average.

Training Concept

With the theoretical requirements and physiological demands for pursuit racing explained above in mind, the training concept of the German track cycling pursuit program focused on the improvement of aerobic power and increase in anaerobic capacity. Training was based on the following concepts: establishment of a high aerobic performance level through high total training mileage (29,000–35,000 $km \cdot yr^{-1}$); improvement of the thereby gained aerobic level through repetitive workload peaks in road stage races; and recall of discipline-specific workloads and anaerobic mobilization through periodical track training.

To succeed with this concept of mostly discipline-unspecific training, riders must present a high level of discipline (track)-specific technical and motor skills, which can be recalled whenever necessary, so that the main focus in training can be directed on the performance determining physiological adaptations. All members of the Olympic pursuit team have been on the national track-cycling program since their junior year and were therefore familiar with the technical requirements of team pursuit racing. For this reason, no special pursuit line training was performed, as it seemed unlikely that a further gain in performance would be possible from this side.

General Training Plan

Figure 1 shows the general structure of the training year in preparation for the Olympic games. Important features are the division in three macrocycles with similar build-up through "low-intensity, high-mileage" road training (training monitored through heart rate at 50–60% $\dot{V}O_{2peak}$, exercise duration from 3 to 8 h or 100–240 $km \cdot d^{-1}$), road stage racing, and discipline-specific track testing. The road stage races were carefully chosen in increasing order of intensity and difficulty over the macrocycles, starting with mostly flat profiles during the first macrocycle and mostly hilly, mountainous races during the second and third macrocycles. One period of relative rest was observed before the last macrocycle. Track training was limited to 1 wk at the end of each macrocycle. We display only training camps and stage races performed with the national track-cycling team. The rest of the time, the riders performed mainly basic, low-intensity training at home. Overall distribution of training intensities showed that, out of track competition or stage racing, 94% of the training was performed at levels below the anaerobic threshold (IaT), 4% around IaT, and 2% above IaT. These numbers might seem low, but during road stage races, a main part of the presented training program, higher intensities are reached, as demonstrated recently by Fernandez-Garcia et al. (9).

Precompetition Training

In addition to the mostly low-intensity, high-mileage training during the periods preceding the stage races, the short-term preparation of track competitions is of major importance, because previous training achievements can be secured or even improved by appropriate precompetition training. Road training and racing focused mainly on the establishment of physiological adaptations such as improved aerobic an anaerobic capacity, whereas precompetition track training was aimed at securing these achievements, boosting anaerobic capacity, and recalling track- and discipline-specific technical and motor skills. For these purposes, only a very short amount of track time appeared to be necessary; before the 2000 Olympic games, the team performed only eight discipline-specific track-training units on six distinctive days. Physiological adaptation to high-intensity anaerobic training has been subject of several investigations (5,14,25,26). The results of Weston et al. (26) support our empirical observation of fast adaptation, as they showed that only very few repetitions of submaximal exercise bouts (80% of peak power output) are necessary to significantly improve cycling time trial performance in highly trained cyclists. The authors attributed these findings to increased buffering capacity of the working muscle, which was highly correlated with the increase in exercise performance.

It is known that during pursuit racing, high levels of blood lactate occur (see Table 1), resulting in high hydrogen ion circulation and a subsequent fall in pH. Decreased pH considerably inhibits skeletal muscle contractility and, thereby, performance. An increased buffering capacity could therefore limit the exercise-induced decrease in pH and maintain muscle function for a longer period of time during exhaustive cycling exercise. The fast anaerobic adaptation of the athletes of our program might be due to this same mechanism. Other reports showed (21,23) altered capacity of oxidative enzymes after interval training. Nevertheless, these changes occurred only after longer periods of interval training and are therefore less likely to have influenced the adaptation in the studied riders.

Table 2 displays the last 15 d of training before the 2000 Olympic team pursuit event. In the following section, the role and the names of the track specific training units are explained.

"Evolution" training. Cadence-orientated track training with intensities around the anaerobic threshold aiming at securing aerobic performance gained through road training and racing and recalling track-specific motor skills (cadence). The method of repetitive exercise is used: training bouts of 5000 m, cycled in 5:30–6 min on the track are performed in groups of three to six riders, interrupted by 20-min breaks. The gear choice of the bike (track cycling is performed with fixed gears) ranges around 7 m/pedal turn. Intensity is monitored through heart rate (goal: approximately at the anaerobic threshold ($\pm$5 beats$\cdot$min^{-1})) and controlled with postexercise lactate sampling (goal: postexercise lactate between 2 and 4 mmol$\cdot$L^{-1}).

"Peak" training. Peak training is track training at maximal intensity (racing speed) over distances below racing distance (usually 2000 m in approximately 2:00 min), interrupted by 20-min breaks. The competition gear is used

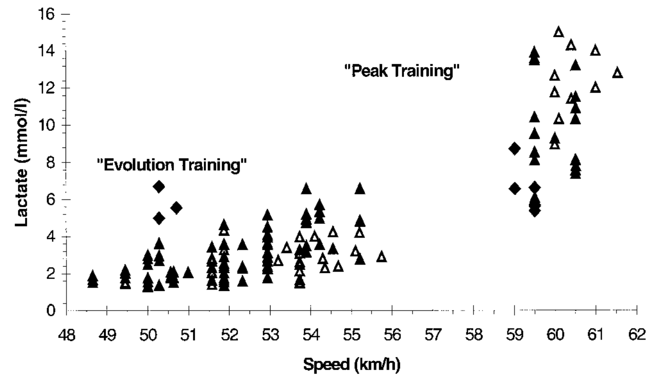


FIGURE 2—Lactate values plotted against race speed after evolution and peak track training during the three precompetition track periods of the 2000 season. (◇ Büttgen, ▲ Berlin, Δ Sydney).

(usually around 8 m per pedal turn). This training form aims at improving anaerobic capacity and lactate mobilization, monitored by postexercise lactate sampling (goal: maximal lactate mobilization).

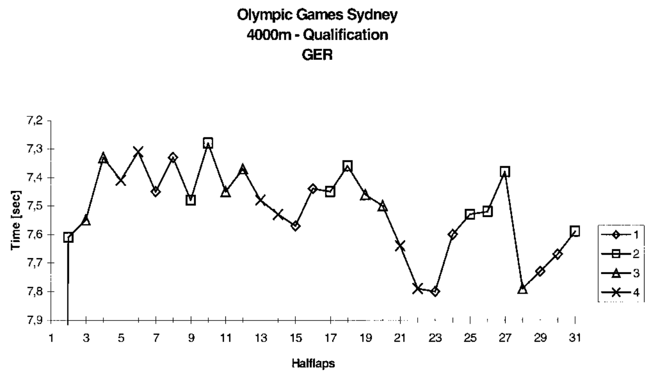
"Basic" training. Basic training is low-intensity road training (50% $\dot{V}O_{2peak}$) aimed at compensating the discipline specific track training and activate recovery. Exercise duration varies between 2 and 4 h.

Lactate Testing during Precompetition Track Training

During precompetition track training, lactate sampling was performed after defined training bouts (Lactate Analyzer LP 20, Dr. Lange Medizinische Systeme, Berlin, Germany). From these data and in comparison with data from previous track events, aerobic capacity and anaerobic mobilization was estimated. Figure 2 shows the lactate values of the German pursuit team after standardized evolution and peak training units from the three distinctive track periods of the 2000 season plotted against race speed. (Büttgen track: first track period, Berlin track: second track period, Sydney: third track period). Before all track events, a similar training schedule was followed. The tracks were all 250-m indoor wooden tracks and thereby comparable in their characteristics. The Sydney variables showed the highest aerobic capacity (riders were able to perform the 5000-m bouts of evolution training at higher speeds with similar lactate) and the highest anaerobic mobilization (highest lactate values after 2000-m all-out track cycling), when compared with previous track periods of the season (statistically significant, Wilcoxon test, $P < 0.05$).

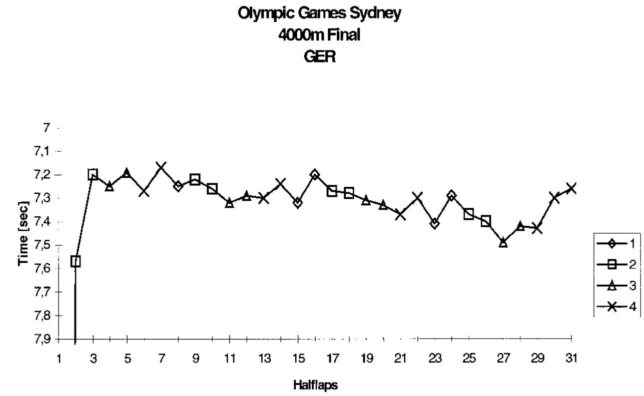
Warm-up Program

Before each pursuit heat, a standardized warm-up program was followed by every rider. It consisted of 20 min of riding at basic-training intensity on the bike used during competition and two 5-min intervals at evolution-training intensity. Between the intervals, a 20-min active recovery (pedalling at own, self-set pace) was observed. After the intervals, 10 min of basic training was added. The warm-up was targeted to be completed exactly 20 min before the start



	1000 m	2000 m	3000 m	4000 m
Time (total) (min)	01:04.8	02:04.4	03:04.9	**04:05.7**
Split	00:00.0	00:59.6	01:00.5	01:00.8

FIGURE 3—Split-time analysis of the qualification heat of the German team pursuit team during the Olympic pursuit competition. Half-lap times (vertical axis) of the leading rider (◇ Rider 1, □ Rider 2, Δ Rider 3, × Rider 4) are plotted against race distance (horizontal axis); 1000-m splits and cumulated race time are indicated below the figure.



	1000 m	2000 m	3000 m	4000 m
Time (total) (min)	01:04.1	02:02.3	03:00.8	**03:59.7**
Split	00:00.0	00:58.1	00:58.5	00:58.8

FIGURE 4—Split-time analysis of the German team pursuit team during the Olympic final. Half-lap times (vertical axis) of the leading rider (◇ Rider 1, □ Rider 2, Δ Rider 3, × Rider 4) are plotted against race distance (horizontal axis); 1000-m splits and cumulated race time are indicated below the figure.

of the pursuit heat. The athletes spent the remaining time mostly resting or pedalling "easy" on a road bike. If possible, warm-up was performed on the track, if not, unbraked roller trainers were used. Intensity was monitored individually through heart-rate monitors. This warm-up program has been in use for many years in the German track team for endurance events, such as individual and team pursuit.

Competition Data

Team pursuit competition is based on a time qualification and subsequent eliminatory heats. Every team first performs a timed single 4000-m team pursuit. According to the respective times, a classification is established, and the first eight teams enter the eliminatory heats with the fastest team competing against the eighth placed, the second fastest against the seventh, etc., until two teams are left over for the final. The best tactical option for team pursuit is to perform a strong timed qualification to obtain less strong opponents in the eliminatory heats to save energy for a potential semifinal or final. To achieve maximum performance in this discipline, a continuous acceleration and subsequent steady speed of all riders to the finish is needed, as additional efforts are necessary for intermittent accelerations and decelerations. In international racing, every rider usually leads one lap (=2 half-laps). As every team is free to choose their four riders from a pool of seven until 1 h before the start of each heat, optimal team composition and analysis of the individual contribution of every cyclist to the team's performance after every heat is crucial to obtain top results and adjust a team to peak performance. For this purpose, a simple, manually operated computer-based chronometric system (FES, Berlin, Germany) measured half-lap times of the leading rider of the team and plotted the results against race distance of 4000 m, corresponding to 32 half-laps on a 250-m track. With the results, the performance of every rider in the team (represented by his half-lap or lap time) can be estimated, and weak riders can be replaced. In addition, monitoring of opponent teams can identify their pacing strategy and might thereby help in optimizing tactical options against these teams. Figure 3 shows the qualification splits of the German team, identifying rider 4 (rider 5 in Table 1) as the weak point of the team. In subsequent heats, this rider was replaced (by rider 1 from Table 1, riding in position 2), resulting in more homogenous performance, finally leading to world record performance. The record ride splits are pictured in Figure 4. Analyzing the individual contribution of every rider to the teams performance during the record ride, it becomes apparent, that the riders in position 1 and 4 (riders 3 and 4 from Table 1) were the strongest performers on that occasion. Compared with the riders in positions 2 and 3 (riders 1 and 2 from Table 1), they were not only capable of maintaining a given pace but were still able to increase racing speed (most visible in half-laps 13–16, 21–23, and 29–31). From a theoretical point of view, this might be somehow surprising, as both riders are 7 s slower in the individual pursuit (Table 1) than their teammates in position 2 and 3. From a practical aspect, this could be explained by the fact that the cyclists in position 2 and 3 competed in the individual pursuit already and were tired. Furthermore, team pursuit racing requires specific motor skills that might be more developed in riders 1 and 4, thereby allowing them to lift their team ride performance to the level of their presumed more powerful teammates. Exchange times (data not demonstrated, measured as time from the beginning of the exchange to the reformation of a straight line within the 4 cyclists) during the record ride averaged 2.7 ± 0.3 s with no significant difference between the riders. Nevertheless, the exchanges of riders 1 and 4 appeared slightly, but not significantly, faster than those of rider 2 and 3, supporting the above mentioned argument of

FIGURE 5—The German national team pursuit team during the 2000 Olympic games pursuit final; rider 3 in the lead, followed by 1, 2, and 4 (Table 1).

their superior technical team pursuit skills. The wheel gap hold by the riders was not specifically trained or measured but is estimated to have ranged between 5 and 30 cm, dependent on the race situation (exchange, start, or finish) and comparable to most international team pursuit teams.

Technical Features and the World Record Ride

During the record ride, which took place on September 19, 2000, at 19:17 local time on the wooden 250-m indoor track of the Duncan Gray velodrome in Sydney, Australia, ambient temperature inside the velodrome was 23°C; 4000 m were covered in 3:59.710 min. All riders rode aerodynamically adapted and individually fitted carbon bicycles (FES, Berlin, Germany) equipped with specially adapted front and rear disk wheels (Mavic, France) on 19-mm tubeless tires (Olympic, Continental AG, Hannover, Germany) inflated to 12 bars in the standard aero position. The weight of the bicycle averaged 8.0 $\pm$ 0.1 kg, depending on individual frame size. The riding position was optimized during track testing using the SRM device several months before the 2000 games. Riders rode individually several repetitions at given speeds (40 km$\cdot$h^{-1}, 45 km$\cdot$h^{-1}) for 8 laps on a 250-m indoor track. The position of the rider on the bike was then modified between the repetitions within the margins set by the regulations of the International Cycling Union (UCI). The position with the lowest power reading at the given speeds was adopted. For the record ride, **a**erodynamic helmets (KED Aero, KED Hemsysteme, Stuttgart, Germany for rider 1; Krono, Rudy Project, Treviso, Italy, for rider 2–4), and Elastolen skinsuits (Aitos Deutschland GmbH, Bergheim, Germany) were worn by each team member. The equipment conformed to the regulations of the UCI and had been previously approved (Fig. 5).

As previously mentioned, pursuit racing is performed with one, fixed gear. For many years, identical gears were ridden by every team member to increase the team's pedalling harmony. However, for higher speeds and to respect individual motor skills, it seemed necessary to adapt the gear choice to the individual preferences of each rider. In the record ride, cyclists 1–3 (Table 1) rode with a gear ratio of 54 $\times$ 14 (8.3 m per pedal revolution), resulting in an average cadence of 120 pedal revolutions per minute (rpm) for the 4 min. Cyclist 4 (Table 1) chose a gear ratio of 53 $\times$ 14 (8.1 m per pedal revolution), requiring a slightly higher cadence of 124 rpm but more suitable to his individual motor skills.

CONCLUSION

The 4000-m track-cycling team pursuit requires high aerobic and anaerobic skills. Due to constant conditions on cycling tracks, pursuit performance can be predicted with reasonable accuracy from physiological and biomechanical measurements. Training for this Olympic event is based on the discipline-unspecific development of aerobic and anaerobic qualities. Before major competitions, discipline-specific motor and technical abilities are recalled during a short period of track training. Monitoring physiological variables and competition data can help to adjust team pursuit performance. The presented exemplary data from the team pursuit world record might help trainers and scientist in the development of future training programs for this cycling discipline.

We thank Guido Fulst, Robert Bartko, Jens Lehmann, Daniel Becke, Olaf Pollack, Christian Lademann, and Thorsten Rund for their outstanding effort and the cooperation during their years on the national team.

In memoriam for Pia Sundstedt.

Parts of these data were presented on the annual meeting of the German Sporting Federation (DSB) in Mannheim, Germany, November 2000.

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