PHYSIOLOGICAL RESPONSES AND PERFORMANCE DURING A THREE-MINUTE CYCLE TIME TRIAL: STANDARD PACED VERSUS ALL-OUT PACED

Journal:	*International Journal of Sports Physiology and Performance*
Manuscript ID	IJSPP.2022-0105.R1
Manuscript Type:	Original Investigation
Date Submitted by the Author:	n/a
Complete List of Authors:	Dobler, Florian; Laboratory for Motion Analysis, Department of Paediatric Orthopaedics, Children's Hospital of Eastern Switzerland, St. Gallen, Switzerland Bachl, Philipp; Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden Stoeggl, Thomas; University of Salzburg, Department of Sport Science and Kinesiology Andersson, Erik; Mid Sweden University, Department of Health Sciences
Keywords:	anaerobic capacity, energy system contribution, pacing strategy, oxygen uptake, statistical parametric mapping

PHYSIOLOGICAL RESPONSES AND PERFORMANCE DURING A THREE-MINUTE CYCLE TIME TRIAL: STANDARD PACED VERSUS ALL-OUT PACED

Submission type: Original investigation

Florian Dobler[1,2]

Philipp Bachl[2,3]

Thomas Stöggl[3,4], and

Erik P. Andersson[2,5]

[1]Laboratory for Motion Analysis, Department of Paediatric Orthopaedics, Children's Hospital of Eastern Switzerland, St. Gallen, Switzerland

[2]Swedish Winter Sports Research Centre, Department of Health Sciences, Mid Sweden University, Östersund, Sweden

[3]Department of Sport and Exercise Science, University of Salzburg, Salzburg, Austria

[4]Red Bull Athlete Performance Center, Salzburg, Austria

[5]School of Sport Sciences, Faculty of Health Sciences, UiT The Arctic University of Norway, Tromsø, Norway

Corresponding author:

Dr. Erik Andersson

Department of Health Sciences

Mid Sweden University

831 25 Östersund

Sweden

E-mail: erik.andersson@miun.se

Telephone: +46 10-1428863

Running head: Pacing and performance in cycling

Abstract word count: 250

Text only word count: 3499

Number of tables and figures: 4

ABSTRACT

Purpose: To compare performance and physiological responses between a standard paced 3-min time trial (TT_{SP}, i.e., pacing based on normal intention) and a consistently all-out paced 3-min time trial (TT_{AOP}). *Methods:* Sixteen well-trained male cyclists completed the TT_{SP} and TT_{AOP}, on separate days of testing, on a cycling ergometer with power output and respiratory variables measured. Time trials were preceded by 7×4-min submaximal stages of increasing intensity with the linear relationship between power output and metabolic rate used to estimate the contribution from aerobic and anaerobic energy resources. The time course of anaerobic and aerobic contributions to power output was analyzed using Statistical Parametric Mapping (SPM). *Results:* Mean power output was not different between the two pacing strategies ($TT_{SP} = 417 \pm 43$ W, $TT_{AOP} = 423 \pm 41$ W; $P=0.158$). The TT_{AOP} resulted in higher peak power output ($P<0.001$), mean ventilation rate ($P<0.001$), mean heart rate ($P=0.044$), peak accumulated anaerobically attributable work ($P=0.026$), post time trial blood lactate concentration ($P=0.035$), and RPE ($P=0.036$). SPM revealed a higher anaerobic contribution to power output during the first ~30 s and a lower contribution between ~90-170 s for TT_{AOP} than TT_{SP}. The aerobic contribution to power output was higher between ~55-75 s for TT_{AOP}. *Conclusions:* Although there was no significant difference in performance (i.e., mean power output) between the two pacing strategies, differences were found in the distribution of anaerobically and aerobically attributable power output. This implies that athletes can pace a 3-min maximal effort very differently but achieve the same result.

Keywords: anaerobic capacity, energy system contribution, pacing strategy, oxygen uptake, statistical parametric mapping

INTRODUCTION

Pacing is the method of distributing energy expenditure or velocity throughout an exercise task. It has been recognized to be an important part of overall athletic performance[1]. Different pacing strategies have been previously described in the literature, and their use by athletes appears to be mainly dependent on the duration of the exercise task[2]. For short-distance events (< 60 s) an all-out pacing strategy has been advocated[3,4], whereas for events of longer duration (3-15 min) with a time-trial character, a more even pacing has been suggested[3,5]. In general, in events where aerobic energy provision is close to its maximum throughout the entire race, the pacing pattern depends mainly on the distribution of the finite anaerobic energy reserves during the exercise task[3,6,7]. In head-to-head races athletes must cope with varying pace and breakaways, also making anaerobic energy turnover and race tactics crucial for success[8,9].

For cycle ergometry in a laboratory, the performance and effectiveness of a pacing strategy are purely related to a maximal utilization of energetic reserves and its conversion to external work (i.e., the gross efficiency). In contrast, traditional time-trial races additionally impose mechanical factors like kinetic energy and frictional forces, e.g., air drag or rolling resistance, which also influence the effectiveness of a pacing strategy and race outcome[3,4], making tactical pacing decisions more complicated for the athlete. However, for ergometer tests, an optimal pacing strategy results in a maximized performance and would be characterized by maximized utilization of both the anaerobic energy reserve and the aerobic energy provision (i.e., fractional utilization of maximal oxygen uptake [$\dot{V}O_{2max}$]) as well as the gross efficiency[10]. For some pacing patterns/strategies (i.e., negative or even pacing), there is a possible risk of not fully depleting the anaerobic energy reserve, as such strategies show continuous anaerobic contribution throughout the effort, which would differ from an all-out pacing strategy employed during a 3-min time trial where anaerobic energy reserves should be depleted within 2 min[11,12]. This is because humans are always exercising with an energetic reserve and terminate exercise before catastrophic failure of homeostasis occurs, which can be viewed as a protective threshold that may be moved upward when employing an all-out pacing strategy[13]. Therefore, a 3-min all-out strategy may result in slightly higher values of accumulated anaerobic energy expenditure (or accumulated anaerobically attributable work), which would be beneficial from an energetic perspective. In addition, aerobic energy contribution could potentially be improved by faster $\dot{V}O_2$ kinetics at the start of a race with an all-out pacing strategy. For example, Bishop et al.[14] found an increase in mean power output of 3.8% during a 2-min kayak ergometer test when participants adopted a 10-s all-out start strategy followed by even pacing compared to a consistent even pacing strategy. The authors suggested that the faster $\dot{V}O_2$ kinetics at the beginning of the trial, and therefore a higher total oxygen uptake throughout the trial, was a potential explanation for the superior performance. This hypothesis of improved performance due to faster $\dot{V}O_2$ kinetics has also been supported by others[15,16]. However, too aggressive pacing could instead lead to premature fatigue and negatively impaired performance, due to a decrease in aerobic energy contribution and/or efficiency[17,18,26]. Thus, the adoption of a more sustained all-out effort has been suggested to be an unfavorable pacing strategy for middle-distance events[3,5].

Some studies have found better performance outcomes for fast-start strategies than even-paced or slow-start strategies in middle-distance events[15,16,19], whereas other studies have found better outcomes for even[5] or self-paced trials[20]. Furthermore, the realization of a fast-start strategy differs in pacing studies. Some authors conducted fast-start strategies defined as a higher than the mean speed in the early stage of a race[5,15,16,19], whereas others predetermined a maximal effort for 10 s at the start, followed by an even pacing[14]. Although employing a consistent all-out pacing strategy for durations longer than ~90-s has been suggested to result in inferior race performance[3,5], this kind of pacing has seldom been investigated other than in simulation studies. From a testing perspective, short time trials (~3-4 min) may be a preferable alternative as a laboratory-based performance test compared to an incremental $\dot{V}O_{2max}$ test or a time-to-exhaustion test[21,22]. Burnley et al.[12] suggested that a 3-min cycle test with consistent all-out pacing would elicit peak $\dot{V}O_2$ and result in an end-test power output that is equivalent to the maximal steady-state.

To date, little is known about the differences in physiological responses and performance between a standard paced (i.e., pacing based on normal intention) versus a consistently all-out paced 3-min cycle time trial (i.e., a very aggressive pacing strategy). Therefore, this study aimed to compare performance outcomes and physiological responses between a standard paced and a consistently all-out paced 3-min cycle time trial. We hypothesized that both pacing strategies would result in similar mean power output (i.e., performance) and that the major difference would be related to the physiological response, i.e., the distribution of the anaerobic energy reserves throughout the trial.

METHODS

Participants

Sixteen well-trained male cyclists (27.0 ± 4.3 yrs, 1.83 ± 0.07 m, 78.4 ± 7.5 kg), who were competitively active, took part in the study. All participants were fully informed about the study and provided written consent to participate. The ethical board of the University of Salzburg approved the study (GZ 05-2020). Exclusion criteria were a $\dot{V}O_{2max} < 55$ mL·kg^{-1}·min^{-1} and/or no prior experience of laboratory performance testing. Participants were instructed to abstain from alcohol 24 h before testing and from caffeine on the test day. Furthermore, participants were asked to avoid intense exercise on the day before testing. During the tests, drinking water *ad libitum* was allowed, but no intake of carbohydrates.

Study overview

For the present study, participants visited the laboratory twice with a minimum of 48 h between visits. On each visit, the participants performed a standard paced 3-min cycle time trial (TT_{SP}) or an all-out paced 3-min cycle time trial (TT_{AOP}) in a randomized order. The two sessions were conducted at the same time of day for each participant and each testing session had a duration of about 80 min.

Equipment

Participants' body height and body mass were measured before the first test (Seca 764, Hamburg, Germany). The testing was performed on a mechanically braked cycle ergometer (Monark LC7TT, Monark Exercise AB, Vansbro, Sweden) and the participants used their own cycling shoes. The sitting position on the ergometer was individually adjustable and was replicated during the second visit. Cycling power output and cadence were logged continuously as second-by-second data. Expired air was analyzed using a Cosmed Quark CPET mixing chamber system (Cosmed, Rome, Italy) as 10-s mean values. This setup was used to provide valid and reliable metabolic measurements[23]. The gas analyzers were calibrated with a mixture of 15.0% O_2 and 5% CO_2 (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany) and ambient air before each test. The flowmeter was calibrated with a 3-L syringe (M9424; Medikro Oy, Kuopio, Finland). Heart rate was monitored using a Wahoo Kickr HR Belt (Wahoo Fitness, Atlanta, GA, USA). Blood lactate concentration ($[La^-]$) was determined from whole blood earlobe samples (20 µL per sample) with a Biosen S-Line (EKF-diagnostic GmbH, Magdeburg, Germany). The system was calibrated with a standard solution of lactate (12 $mmol \cdot L^{-1}$) before each analysis.

Testing protocol

An overview of the testing protocol is given in Figure 1. On each test day, participants performed either the TT_{SP} or TT_{AOP} in a randomized order. For TT_{SP}, participants were instructed to generate the highest mean power output possible throughout the time trial. On the other hand, for TT_{AOP}, participants were advised to adopt an all-out pacing strategy with a maximally fast start and then keep the power output as high as possible until the end of the time trial. For TT_{SP} no verbal encouragement was given during the test, but information about elapsed time was provided every 30 s. For TT_{AOP} participants were verbally encouraged to maintain an all-out effort throughout the trial, with no provided information about elapsed time[12]. Power output during both time trials was regulated individually via a bike shifter and was, therefore, cadence dependent and the power output was not visible to the participant. Each respective time trial was preceded by a 6-min warm-up at 39% of $\dot{V}O_{2peak}$, followed by 7 × 4-min submaximal stages (at 39-73% of $\dot{V}O_{2peak}$ with 5-6% increments from stage-to-stage) followed by a 6-min passive break before the time trial (Figure 1). Data from the submaximal protocol were used to estimate the anaerobically attributable power output during the time trial (for details, see the calculations paragraph). The individual protocols were the same before each respective time trial with power outputs based on previous test results or familiarization trials. Blood for determination of $[La^-]$ was collected 1-min before and 2-min after the respective time trials. Participants reported their rating of perceived exertion (RPE) immediately after completing the time trial. Both respiratory and heart rate data were collected continuously during the submaximal exercise and the time trial as 10-s values.

Processing of respiratory data

To enable a higher resolution of the mixing-chamber respiratory data during the time trials (i.e., to obtain a more realistic dynamic physiological response), raw respiratory data were interpolated second-by-second using piecewise constant interpolation for each 10-s mean and smoothed using a 9-s counterbalanced moving average (i.e., using a ±4-s time-window for smoothing), which was conducted twice according to Lidar et al.[24].

The highest 20-s moving average during the time trial was used to calculate $\dot{V}O_{2peak}$ and peak ventilation rate, while peak heart rate was obtained as the highest 10-s mean value. Peak respiratory exchange ratio (RER) was taken over the same period as the $\dot{V}O_{2peak}$. The $\dot{V}O_2$ mean response time (MRT) was calculated as the total time required to reach 63% of the $\dot{V}O_{2peak}$

during the time trial. Excess post-exercise oxygen consumption (EPOC) was calculated as the total amount of oxygen consumed within 5-min after the time trial as this time frame covers the initial and most rapid regeneration of anaerobic energy stores[25].

Calculations

Submaximal exercise

Energy expenditure was calculated from $\dot{V}O_2$ and RER ($\dot{V}CO_2 \cdot \dot{V}O_2^{-1}$) according to the equation introduced by Weir[26] and then converted into a metabolic rate (MR). MR was based on the average $\dot{V}O_2$ in $L \cdot min^{-1}$ and RER values (≤ 1.00) during the final minute of each stage of the submaximal exercise protocol.

$$MR\ [W] = \frac{4184(\dot{V}O_2(1.1RER + 3.9))}{60} \qquad \text{(Eq. 1)}$$

Gross efficiency (GE) was calculated as:

$$GE = \frac{PO\ [W]}{MR\ [W]} \qquad \text{(Eq. 2)}$$

Time-trial exercise

A linear relationship between PO (W) and metabolic rate (W) during the final minute of each of the 7 × 4-min submaximal stages was derived for each participant and the regression equation was used to estimate the required second-by-second instantaneous metabolic rate (MR_{TT_req}) during each of the time trials. Instantaneous GE (GE_{REG}) was also calculated by dividing PO by the instantaneous MR calculated from the regression equation.

The instantaneous anaerobic metabolic rate (MR_{AN}) at each 1-s time-point (*t*) of the TT could then be expressed as:

$$MR_{AN,t}[W] = MR_{TT\_req,t} - MR_{AE,t} \qquad \text{(Eq. 3)}$$

where MR_{AE} is the aerobic metabolic rate calculated according to Eq. 1 but using a fixed RER value of 1.00 (i.e., assuming 100% carbohydrate utilization during the time trial). The total accumulated anaerobic energy expenditure ($kJ \cdot kg^{-1}$) was calculated by time-integrating MR_{AN} over the 3-min TT. The peak accumulated anaerobic energy expenditure was calculated as the maximum value of the accumulated anaerobic energy expenditure during the 3-min TT.

Aerobic PO contribution (PO_{AE_cont}) (i.e., PO attributable to MR_{AE}) at each 1-s time-point (t) of the TT was calculated as:

$$PO_{AE_{cont},t} = MR_{AE,t} \times GE_{REG,t} \qquad \text{(Eq. 4)}$$

Anaerobic PO contribution (PO_{AN_cont}) (i.e., PO attributable to MR_{AN}) at each 1-s time-point (t) of the TT was calculated as:

$$PO_{AN_{cont},t} = PO_{TT,t}[W] - PO_{AE_{cont},t}[W] \quad \text{(Eq. 5)}$$

where PO_{TT} is the PO during the TT. The total accumulated anaerobically attributable work (i.e., “anaerobic work”) in Joules was calculated by time-integrating the PO_{AN_cont} (W) over the 3-min TT. The peak accumulated anaerobically attributable work was calculated as the maximum value of the accumulated anaerobically attributable work during the 3-min TT.

Statistics

Normality was assessed by using a Shapiro-Wilk test. Mean values between TT_{SP} and TT_{AOP} were compared with paired *t*-tests and the standardized mean differences (Hedges’ g_{av}, effect size [Hg_{av}]) were reported according to Lakens[27]. Differences in RPE and 5-min EPOC were tested with a Wilcoxon *signed-rank* test due to ordinal data or violated normality assumptions. Time courses of external power output, aerobic and anaerobic contribution throughout the time trial were examined using Statistical Parametric Mapping (SPM)[28]. Before applying SPM, time series were smoothed with a 5-s moving average filter. The significance level was set to $\alpha < 0.05$.

RESULTS

Performance, physiological, and subjective rating data for the TT_{SP} and TT_{AOP} are depicted in Table 1. As shown in Table 1, the mean power output was not different between TT_{AOP} versus TT_{SP}. However, higher values were observed for peak power output, mean ventilation rate, mean heart rate, peak accumulated anaerobically attributable work, post TT [La^-], and RPE during TT_{AOP} than TT_{SP}. Figure 2 shows the mean time courses of external power output and the aerobic contribution throughout the time trial for TT_{SP} and TT_{AOP}. As shown in Figure 3A-B, SPM showed a significantly higher external power output and anaerobic power contribution during the first ~30 s of the time trial for TT_{AOP} than TT_{SP}, whereas between ~90-170 s the external power output and anaerobic power contribution were significantly lower for TT_{AOP} than TT_{SP}. Between ~50-70 s of the time trial, the aerobic power contribution was significantly higher for TT_{AOP} than TT_{SP} (Figure 3C).

DISCUSSION

The results of the current study suggest that in well-trained cyclists mean power output is not significantly different between 3-min cycling time trials that are standard paced (i.e., TT_{SP}) and all-out paced (i.e., TT_{AOP}). The differences in power output profiles between the two pacing strategies were mainly due to differences in the distribution of anaerobically attributable power output (or work). In addition, the TT_{AOP} generated higher values of mean ventilation rate, mean heart rate, peak accumulated anaerobically attributable work, post TT [La^-], and RPE than TT_{SP} (see Table 1).

In the current study, athletes were forced to employ an all-out pacing strategy over a 3-min duration as well as their self-selected pacing strategy. Interestingly, the time-trial performance did not differ significantly between the two pacing strategies. Therefore, it is likely that potential beneficial effects counteracted detrimental physiological effects of employing an all-out pacing strategy. The TT_{AOP} demonstrated, compared to TT_{SP}, a higher aerobic contribution between 55-75s of the trial and a moderate effect (but not significant) for a shorter $\dot{V}O_2$ MRT in TT_{AOP} was found. However, the mean power output was not different between the two pacing strategies. This suggests, that the potentially faster $\dot{V}O_2$ kinetics could be compensated by some disadvantageous physiological effect with an all-out pacing strategy. Faster $\dot{V}O_2$ kinetics are also supported by other studies that employed fast start[19] or all-out[14,29] pacing. The TT_{AOP} showed a higher mean heart rate, mean ventilation, RPE, peak accumulated anaerobically attributable work, and post-TT [La^-] compared to TT_{SP}. Although the perceived effort was higher during TT_{AOP}, the mean power output was not significantly higher. This implicates a potential disadvantage of employing an all-out pacing strategy in an event with repeated races on the same day when recovery between races is crucial.

The participants generated a positive anaerobic power contribution throughout TT_{SP}, whereas a slightly negative anaerobic power contribution (i.e., a recharge of the anaerobic work capacity) could be observed for TT_{AOP} during the final half of the time trial (see Figure 2). Thus, the peak accumulation of anaerobically attributable work was reached already after ~80 s during the TT_{AOP}, whereas during TT_{SP} the accumulation of anaerobically attributable work reached its peak value approximately at the end of the time trial. These results highlight that the anaerobic work capacity can be distributed very differently during a 3-min maximal effort on a cycle ergometer without imposing any differences in performance. However, the early depletion of the anaerobic work capacity could result in premature fatigue during TT_{AOP}[13] as the depletion of the anaerobic work-capacity reserve is directly related to perceived exertion and fatigue[30,31]. Also, gross efficiency may decline as ventilation and fatigue increase during high-intensity exercise[32]. The higher mean ventilation observed for TT_{AOP} could also be unfavorable, as the work of breathing increases exponentially with higher ventilation rates[33], which in turn would influence the gross efficiency negatively[18] and constitutes a potential limitation of the methodological approach that was used in the current study to determine the anaerobic work capacity.

All these physiological data suggest that neither TT_{SP} nor TT_{AOP} were optimal pacing strategies for achieving a maximal utilization of both the aerobic and anaerobic energy systems. Based on previous research, and the results presented in the current study, it is likely that the metabolic requirements to defend homeostasis and optimize performance conflict with one another[13]. The even pacing strategy employed during TT_{SP} was arguably too conservative, while the TT_{AOP} was potentially too aggressively paced with an excessively fast depletion of the anaerobic reserve[5], which possibly induced a greater threat to the maintenance of homeostasis[13]. From a practical point of view and despite the absence of a significant difference between the two pacing strategies, the 1.5% (6 W) higher mean power output during TT_{AOP} may still provide a meaningful effect for athletes in a race situation. This suggests that some athletes could benefit from a more positive pacing strategy than the even strategy that was employed during TT_{SP}, which also is in agreement with previous studies[14–16,19,34,35]. However, optimization of pacing strategies should occur at an individual level with the metabolic profile considered. For instance, one could assume a larger variation between TT_{AOP} and TT_{SP} for athletes with higher compared to lower anaerobic work capacity. It is also possible that athletes with a very high anaerobic work capacity could suffer more negatively from premature fatigue during TT_{AOP} than TT_{SP} compared to athletes with a more modest anaerobic work capacity, this because "more anaerobic" athletes probably also would have a higher fraction of less fatigue-resistant muscle fibers[36].

Tucker[37] proposed that an anticipatory feedback model may regulate pacing through feedback integration and anticipation. The anticipatory component is based on exercise duration and a pre-set RPE template at different stages of the effort, which is compared to the conscious/actual RPE during the effort to regulate the effort and ensure that the exercise intensity is at an acceptable RPE level. Even though the athletes in the current study did not receive any time-related feedback during the TT_{AOP}, they were aware of the total exercise duration and, thus, likely to pace the maximal all-out effort[30]. This was likely due to the following observations of a relatively low peak power output and a slight increase in power output at the end of the TT_{AOP}. Moreover, the pre-set RPE template was likely to be more challenging during the TT_{AOP} than TT_{SP}. This could explain, at least to some extent, the early depletion of the anaerobic work capacity reserve, the higher mean ventilation rate and heart rate, the higher post-trial RPE, as well as the higher post TT $[La^-]$ during TT_{AOP}.

The choice of using verbal encouragement and not providing time feedback during TT_{AOP} was to encourage athletes to employ an all-out pacing strategy (i.e., an aggressive pacing strategy that normally would not be used). In addition, only time feedback was provided in TT_{SP} with no verbal encouragement as this could have influenced their self-selected pacing strategies. However, the difference in verbal encouragement between TT_{AOP} and TT_{SP} could contribute to differences in performance and could thus be a limitation.

The current study was conducted on a bicycle ergometer with the performance being the mean power output. Therefore, the investigated differences in pacing strategies were only related to physiological variables and not external factors such as wind resistance. However, in-field competitions also external factors must be considered. Namely, these are mechanical factors like air drag, slope, or kinetic energy. Therefore, in an outdoor situation, the effectiveness of a specific pacing strategy is related to the complex interplay between both physiological and external factors.

PRACTICAL APPLICATIONS

The results of the current study indicate that performance and total physiological response during a 3-min time trial can be similar, though the pacing strategies are very different. However, as “optimal” pacing on a cycle ergometer is related to a maximized utilization of both aerobic and anaerobic energy reserves, neither TT_{SP} nor TT_{AOP} can be considered truly “optimal”. Our data indicate that TT_{SP} was likely to be too conservatively paced, while the opposite was true for TT_{AOP}. Therefore, a theoretically optimal pacing strategy would probably lie somewhere in between the TT_{SP} and TT_{AOP}

strategies. Thus, athletes and coaches should evaluate the impact of different pacing strategies on performance and physiological responses regularly to maximize sports performance over middle-distance events (~3 min).

CONCLUSION

The results of this study suggest that there is no significant difference in mean power output between all-out paced and standard paced 3-min cycling time trials in well-trained cyclists. However, differences were found in the time-course of the aerobic and anaerobic power contributions and the peak accumulated anaerobically attributable work during the time trial.

ACKNOWLEDGMENTS

The authors thank the athletes for their participation, enthusiasm, and cooperation in this study. We also thank Anna Schmuttermair for assisting with the data collection.

FUNDING

This study was supported financially by the Swedish National Centre for Research in Sports (CIF, P2020-0157) and part-financed by the Mid Sweden University and Östersund City Council financial agreement.

REFERENCES

1. Foster C, Schrager M, Snyder AC, Thompson NN. Pacing strategy and athletic performance. *Sports Med.*

1994;17(2):77-85. doi:10.2165/00007256-199417020-00001

2. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med*. 2008;38(3):239-252. doi:10.2165/00007256-200838030-00004

3. de Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy flow model. *J Sci Med Sport*. 1999;2(3):266-277. doi:10.1016/S1440-2440(99)80178-9

4. Van Ingen Schenau GJ, de Koning JJ, de Groot G. A simulation of speed skating performances based on a power equation. *Med Sci Sports Exerc*. 1990;22(5):718-728. doi:10.1249/00005768-199010000-00026

5. Foster C, Snyder AC, Thompson NN, Green MA, Foley M, Schrager M. Effect of pacing strategy on cycle time trial performance. *Med Sci Sports Exerc*. 1993;25(3):383-388

6. Gastin P, Costill D, Lawson D, Krzeminski K, McConell G. Accumulated oxygen deficit during supramaximal all-out and constant intensity exercise. *Med Sci Sports Exerc*. 1995;27(2):255-263

7. Hettinga FJ, de Koning JJ, Meijer E, Teunissen L, Foster C. Effect of pacing strategy on energy expenditure during a 1500-m cycling time trial. *Med Sci Sports Exerc*. 2007;39(12):2212-2218. doi:10.1249/mss.0b013e318156e8d4

8. Sanders D, van Erp T. The physical demands and power profile of professional men's cycling races: an updated review. *Int J Sports Physiol Perform*. 2021;16(1):3-12. doi:10.1123/ijspp.2020-0508

9. Hettinga FJ, Edwards AM, Hanley B. The science behind competition and winning in athletics: using world-level competition data to explore pacing and tactics. *Front Sports Act Living*. 2019;1:11. doi:10.3389/fspor.2019.00011

10. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol*. 2008;586(1):35-44. doi:10.1113/jphysiol.2007.143834

11. Medbø J, Mohn A, Tabata I, Bahr R, Vaage O, Sejersted O. Anaerobic capacity determined by maximal accumulated O2 deficit. *J Appl Physiol*. 1988;64:50-60. doi:10.1152/jappl.1988.64.1.50

12. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Med Sci Sports Exerc*. 2006;38(11):1995-2003. doi:10.1249/01.mss.0000232024.06114.a6

13. Tucker R, Noakes TD. The physiological regulation of pacing strategy during exercise: a critical review. *Br J Sports Med*. 2009;43(6):1-9. doi:10.1136/bjsm.2009.057562

14. Bishop D, Bonetti D, Dawson B. The influence of pacing strategy on VO2 and supramaximal kayak performance. *Med Sci Sports Exerc*. 2002;34(6):1041-1047. doi:10.1097/00005768-200206000-00022

15. Jones AM, Wilkerson DP, Vanhatalo A, Burnley M. Influence of pacing strategy on O_2 uptake and exercise tolerance. *Scand J Med Sci Sports*. 2008;18(5):615-626. doi:https://doi.org/10.1111/j.1600-0838.2007.00725.x

16. Bailey SJ, Vanhatalo A, Dimenna FJ, Wilkerson DP, Jones AM. Fast-start strategy improves VO_2 kinetics and high-intensity exercise performance. *Med Sci Sports Exerc*. 2011;43(3):457-467. doi:10.1249/MSS.0b013e3181ef3dce

17. Hanon C, Thomas C. Effects of optimal pacing strategies for 400-, 800-, and 1500-m races on the VO_2 response. *J Sports Sci*. 2011;29(9):905-912. doi:10.1080/02640414.2011.562232

18. de Koning JJ, Noordhof DA, Uitslag TP, Galiart RE, Dodge C, Foster C. An approach to estimating gross efficiency during high-intensity exercise. *Int J Sports Physiol Perform*. 2013;8(6):682-684. doi:10.1123/ijspp.8.6.682

19. Aisbett B, Le Rossignol P, McConell GK, Abbiss CR, Snow R. Effects of starting strategy on 5-min cycling time-trial performance. *J Sports Sci*. 2009;27(11):1201-1209. doi:10.1080/02640410903114372

20. Hettinga FJ, de Koning JJ, Schmidt LJI, Wind NAC, MacIntosh BR, Foster C. Optimal pacing strategy: from

theoretical modelling to reality in 1500-m speed skating. *Br J Sports Med*. 2011;45(1):30-35. doi:10.1136/bjsm.2009.064774

21. Losnegard T, Myklebust H, Hallén J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc*. 2012;44(4):673-681. doi:10.1249/MSS.0b013e3182388684

22. Jeukendrup A, Saris WHM, Brouns F, Kester ADM. A new validated endurance performance test. *Med Sci Sports Exerc*. 1996;28(2):266-270. doi:10.1097/00005768-199602000-00017

23. Nieman DC, Austin MD, Dew D, Utter AC. Validity of COSMED's quark CPET mixing chamber system in evaluating energy metabolism during aerobic exercise in healthy male adults. *Res Sports Med*. 2013;21(2):136-145. doi:10.1080/15438627.2012.757227

24. Lidar J, Andersson E, Sundström D. Validity and reliability of hydraulic-analogy bioenergetic models in sprint roller skiing. *Front Physiol*. Published online 2021. doi:10.3389/fphys.2021.726414

25. Piiper J, Spiller P. Repayment of O_2 debt and resynthesis of high-energy phosphates in gastrocnemius muscle of the dog. *J Appl Physiol*. 1970;28(5):657-662. doi:10.1152/jappl.1970.28.5.657

26. Weir JB de V. New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol*. 1949;109(1-2):1-9.

27. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol*. 2013;4:863. doi:10.3389/fpsyg.2013.00863

28. Pataky T. One-dimensional statistical parametric mapping in Python. *Comput Methods Biomech Biomed Engin*. 2011;15:295-301. doi:10.1080/10255842.2010.527837

29. Aisbett B, Lerossignol P, Mcconell GK, Abbiss CR, Snow R. Influence of all-out and fast start on 5-min cycling time trial performance: *Med Sci Sports Exerc*. 2009;41(10):1965-1971. doi:10.1249/MSS.0b013e3181a2aa78

30. de Koning JJ, Foster C, Bakkum A, et al. Regulation of pacing strategy during athletic competition. *PLoS ONE*. 2011;6(1):e15863. doi:10.1371/journal.pone.0015863

31. Stone MR, Thomas K, Wilkinson M, St Clair Gibson A, Thompson KG. Consistency of perceptual and metabolic responses to a laboratory-based simulated 4,000-m cycling time trial. *Eur J Appl Physiol*. 2011;111(8):1807-1813. doi:10.1007/s00421-010-1818-7

32. Jones AM, Grassi B, Christensen PM, Krustrup P, Bangsbo J, Poole DC. Slow component of VO_2 kinetics: mechanistic bases and practical applications. *Med Sci Sports Exerc*. 2011;43(11):2046-2062. doi:10.1249/MSS.0b013e31821fcfc1

33. Aaron EA, Seow KC, Johnson BD, Dempsey JA. Oxygen cost of exercise hyperpnea: implications for performance. *J Appl Physiol*. 1992;72(5):1818-1825. doi:10.1152/jappl.1992.72.5.1818

34. Andersson E, Holmberg HC, Ørtenblad N, Björklund G. Metabolic responses and pacing strategies during successive sprint skiing time trials: *Med Sci Sports Exerc*. 2016;48(12):2544-2554. doi:10.1249/MSS.0000000000001037

35. Foster C, de Koning JJ, Hettinga F, et al. Pattern of energy expenditure during simulated competition: *Med Sci Sports Exerc*. 2003;35(5):826-831. doi:10.1249/01.MSS.0000065001.17658.68

36. Bar-Or O, Dotan R, Inbar O, Rothstein A, Karlsson J, Tesch P. Anaerobic capacity and muscle fiber type distribution in man. *Int J Sports Med*. 1980;01(02):82-85. doi:10.1055/s-2008-1034636

37. Tucker R. The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *Br J Sports Med*. 2009;43(6):392-400. doi:10.1136/bjsm.2008.050799

FIGURE CAPTIONS

Figure 1. A schematic overview of the protocol used during the two laboratory visits where participants either performed a standard paced 3-min cycle time trial (TT_{SP}) or an all-out paced 3-min cycle time trial (TT_{AOP}) in a randomized order. After a 6-min warm-up, 7 × 4-min submaximal exercise bouts were performed followed by a 6-min passive break, with the intensities being similar for the two separate test days. Capillary blood samples for the determination of blood lactate concentration (lactate) were collected two times. Abbreviations: @, at; $\dot{V}O_{2peak}$, peak oxygen uptake; TT, time trial; RPE, rating of perceived exertion.

Figure 2. Mean time-course data of external power and aerobic attributable power contribution throughout the 3-min standard paced time trial ($TT_{SP)}$ (*blue color*) and the all-out paced time trial (TT_{AOP}) (*red color*). The difference between external power and aerobic power contribution represents the anaerobic power contribution. The anaerobic power contribution integrated over time represents the accumulated anaerobically attributable work (i.e., the *light blue area* for TT_{SP} and the *light red area* for TT_{AOP}).

Figure 3. Time course for mean ± SD and statistical parametric map (SPM) for external power (A), anaerobic power contribution (B), and aerobic power contribution (C) throughout the 3-min standard paced time trial ($TT_{SP)}$ (*blue color*) and the all-out paced time trial (TT_{AOP}) (*red color*).

Table 1. Performance, physiological, and subjective rating data for the 3-min standard paced time trial (TT$_{SP}$) and the all-out paced time trial (TT$_{AOP}$).

	TT$_{SP}$	TT$_{AOP}$	P-value	CI (95%)	ES (Hg_{av})
Mean power output (W)	417 ± 43	423 ± 41	$P = 0.158$	[-15.2; 2.7]	0.14
Aerobic power contribution (W)	306 ± 42	305 ± 25	$P = 0.931$	[-15.5; 16.9]	0.02
Anaerobic power contribution (W)	111 ± 27	118 ± 31	$P = 0.418$	[-24.6; 10.8]	0.23
Peak power output (W)	459 ± 49	729 ± 79	$P < 0.001$	[-306; -234]	3.91
Cadence (rev·min^{-1})	97 ± 6	91 ± 9	$P = 0.073$	[-0.6; 12.9]	0.75
Mean $\dot{V}O_2$ (L·min^{-1})	3.98 ± 0.43	4.01 ± 0.43	$P = 0.730$	[-0.24; 0.18]	0.08
Mean ventilation rate (L·min^{-1})	137 ± 20	158 ± 23	$P < 0.001$	[-31.5; -11.5]	0.95
Mean heart rate (beats·min^{-1})	161 ± 10	165 ± 8	$P = 0.044$	[-7.8; -0.1]	0.41
GE$_{REG}$ (%)	22.0 ± 1.5	21.9 ± 1.3	$P = 0.897$	[-0.8; 0.9]	0.04
Total AnW$_{ACC}$ (kJ·kg^{-1})	0.25 ± 0.06	0.27 ± 0.05	$P = 0.494$	[-0.05; 0.03]	0.08
Peak AnW$_{ACC}$ (kJ·kg^{-1})	0.26 ± 0.06	0.30 ± 0.04	$P = 0.026$	[-0.08; -0.01]	0.78
Total AnEE$_{ACC}$ (kJ·kg^{-1})	1.17 ± 0.33	1.18 ± 0.24	$P = 0.914$	[-0.21; 0.19]	0.39
Peak AnEE$_{ACC}$ (kJ·kg^{-1})	1.19 ± 0.32	1.33 ± 0.21	$P = 0.131$	[-0.34; 0.05]	0.51
$\dot{V}O_2$ MRT (s)	46 ± 10	42 ± 6	$P = 0.079$	[-0.6; 10.1]	0.54
$\dot{V}O_{2peak}$ (L·min^{-1})	5.13 ± 0.51	5.01 ± 0.56	$P = 0.144$	[-0.05; 0.29]	0.21
RER at $\dot{V}O_{2peak}$ ($VCO_2 \cdot VO_2^{-1}$)	1.12 ± 0.08	1.10 ± 0.10	$P = 0.374$	[-0.04; 0.09]	0.30
Peak ventilation rate (L·min^{-1})	195 ± 23	200 ± 26	$P = 0.193$	[-12.4; 2.7]	0.19
Peak heart rate (beats·min^{-1})	182 ± 9	182 ± 8	$P = 0.815$	[-1.6; 2.0]	0.02
Pre TT [La$^-$] (mmol·L^{-1})	2.1 ± 0.6	2.1 ± 0.5	$P = 0.812$	[-0.3; 0.4]	0.06
Post TT [La$^-$] (mmol·L^{-1})	10.2 ± 2.3	11.4 ± 2.6	$P = 0.035$	[-2.2; -0.1]	0.45
5-min EPOC (L) (n=15)	9.23 ± 1.19	9.54 ± 1.46	$P = 0.359$		
Post TT RPE (Borg, 6-20)	19 (18-20)	19.5 (19-20)	$P = 0.036$		

The values are presented as mean ± SD (RPE and EPOC as median and interquartile range).
Abbreviations: CI, confidence interval for the difference between the time trials; ES, Hedges' g_{av} effect size; GE$_{REG}$, mean instantaneous gross efficiency calculated based on the linear regression between power output and metabolic rate; AnW$_{ACC}$, accumulated anaerobically attributable work; AnEE$_{ACC}$, accumulated anaerobic energy expenditure; $\dot{V}O_{2peak}$, peak oxygen uptake; RER, respiratory exchange ratio; [La], blood lactate concentration; TT, time trial; $\dot{V}O_2$ MRT, oxygen uptake mean response time; $\dot{V}O_2$, oxygen uptake; EPOC, excess post-exercise oxygen consumption; RPE, rating of perceived exertion.

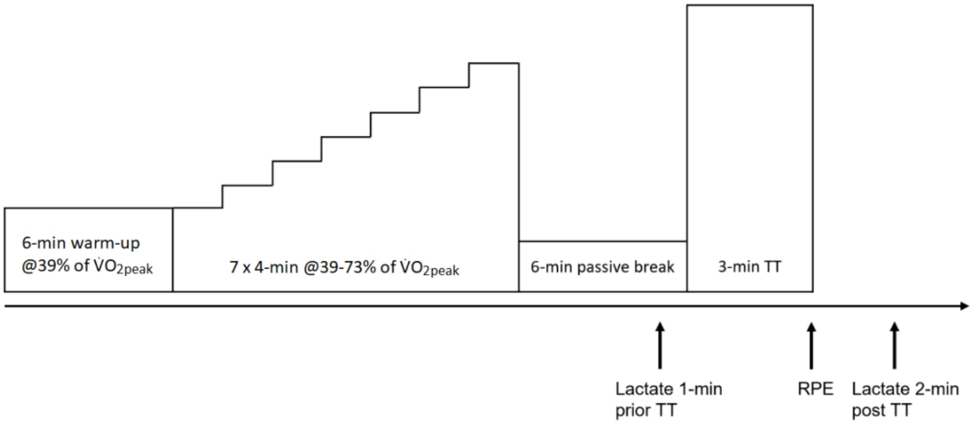

Figure 1. A schematic overview of the protocol used during the two laboratory visits where participants either performed a standard paced 3-min cycle time trial (TTSP) or an all-out paced 3-min cycle time trial (TTAOP) in a randomized order. After a 6-min warm-up, 7 × 4-min submaximal exercise bouts were performed followed by a 6-min passive break, with the intensities being similar for the two separate test days. Capillary blood samples for the determination of blood lactate concentration (lactate) were collected two times. Abbreviations: @, at; V O2peak, peak oxygen uptake; TT, time trial; RPE, rating of perceived exertion.

107x48mm (300 x 300 DPI)

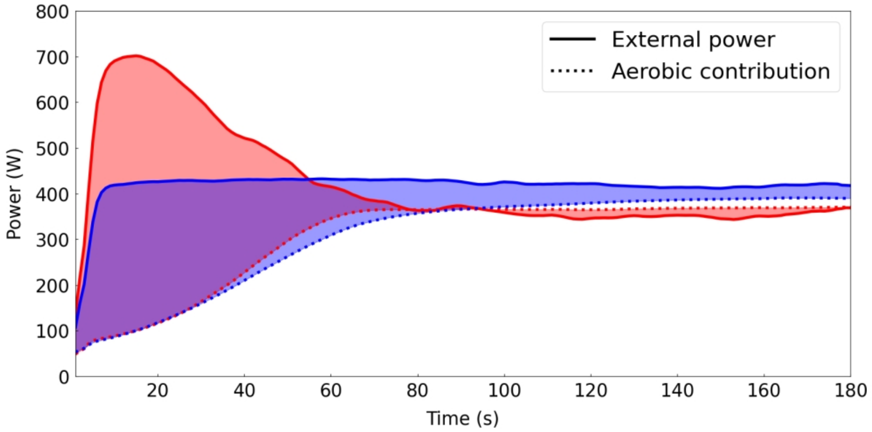

Figure 2. Time course of external power and aerobic attributable power contribution throughout the 3-min standard paced time trial (TTSP) (blue colour) and the all-out paced time trial (TTAOP) (red colour). The difference between external power and aerobic power contribution represents the anaerobic power contribution. The anaerobic power contribution integrated over time represents the accumulated anaerobically attributable work (i.e., the light blue area for TTSP and the light red area for TTAOP).

162x77mm (300 x 300 DPI)

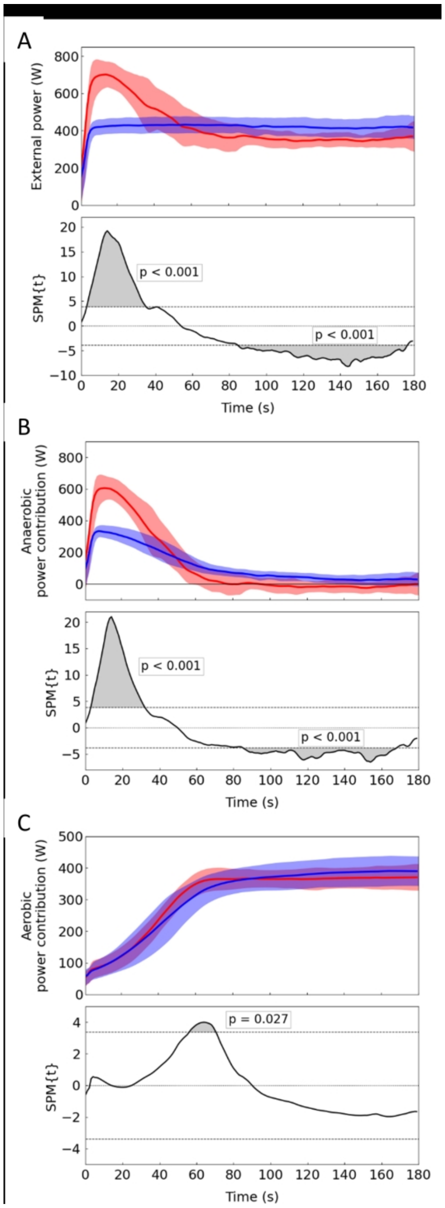

Figure 3. Time course for mean ± SD and statistical parametric map (SPM) for external power (A), anaerobic power contribution (B) and aerobic power contribution (C) throughout the 3-min standard paced time trial (TTSP) (blue colour) and the all-out paced time trial (TTAOP) (red colour).

84x230mm (330 x 330 DPI)