

Optimal Mass Scaling of Power Output for Complex Courses and its Relationship to Time-Trial Performance in Cycling

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Abstract

The allometric scaling of power output is a long-standing topic of debate in cycling research concerning performance prediction. In contrast to previously used test-based approaches, this study employed a numerical method to determine how external forces influence the conversion of power output into race velocity. Time-trial performances of typical elite-level road cyclist models were estimated utilizing the power-duration relationship and normative power data for two recent Grand Tour individual time-trial courses. Optimal body mass exponents were determined based on the estimated average speed of typical cyclists over the respective course sections, their morphological characteristics, and external factors such as incline and wind velocity. Estimated power output expressed in terms of optimally scaled power metrics - namely $W/kg^{0.6068}$ and $W/kg^{0.4891}$ - accurately predicted the estimated performance of five typical elite-level cyclists on two recent Grand Tour individual time-trial courses ($R^2 = 0.99$ for both). The study's findings suggest that optimal mass exponents are course-specific and primarily influenced by the magnitude of headwind relative to the cyclist and the road gradient. Further field-based research is needed to validate the proposed method for determining these optimal mass exponents.

Keywords

allometric scaling; critical power; performance prediction; performance analysis; power-duration relationship



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1 Introduction

According to the cycling performance model proposed by Atkinson and colleagues, one of the primary factors influencing the conversion of power output into race velocity is the presence of race-specific retarding forces (Atkinson et al., 2003). Despite the significance of these forces, there remains no established method for quantifying their impact on the power-to-mass ratio most accurately predicting cycling performance over a given course. As a result, the interpretation of estimated mean maximal power output and power profiles in relation to performance potential remains limited (Pinot & Grappe, 2011). Previous studies have developed allometrically scaled power metrics to support cycling performance prediction based on power output capacity, with varying degrees of success (Jobson et al., 2008; Nevill et al., 2016; Swain, 1994; Heil, 2005; Leo et al., 2023; Lamberts et al., 2014). Nevertheless, no study to date has proposed a power output scaling method specifically designed to predict performance on complex courses that include varied terrain and/or windy sections.

This study aimed to develop a method for determining optimal body mass exponents of the power-to-mass ratio, enabling accurate performance prediction based on power output across complex time-trial courses.

2 Material and Methods

The estimated performance of elite-level cyclist models (i.e., typical cyclists) on complex, real-world time-trial courses was derived using their representative morphological characteristics and normative power data. Five cyclist types were defined — all-rounder, climber, sprinter, time trialist, and general classification (GC) contender — based on data from Valenzuela et al. (2022). This was accomplished through numerically solving the equation of the three-parameter critical power

model and the power-balance equation for road cycling for speed (Martin et al. 1998, Papakonstantinou and Tapia 2013). Subsequently, power law scaling was applied to the derived mean estimated power output (P) of typical cyclists over the time trial courses. This involved iteratively calculating the body mass exponent (x) in the equation $P_{scaled} = P / m^x$, aiming to minimize the absolute slope $|a|$ of the regression line, $P_{scaled} = am + b$, defined by the optimally scaled power output (P_{scaled}), body mass (m) and y-intercept (b). The exponent x that minimized $|a|$ was defined as the optimal mass exponent (x_{opt}).

To address the analysis of complex courses that feature varying terrain and fluctuating wind conditions, we defined the duration-weighted optimal mass exponent. Each race course can be divided into a discrete number of arbitrary sections (n) and the overall performance of typical cyclists over these sections can be characterized by mean section durations $\{\bar{t}_i\}_{i=1,2,\dots,n}$. Through determining optimal mass exponents $\{\bar{x}_{opt,i}\}_{i=1,2,\dots,n}$ corresponding to each defined section, the duration-weighted arithmetic mean of these exponents was derived as:

$$\bar{x}_{opt} = \frac{\sum_{i=1}^n \bar{x}_{opt,i} \times \bar{t}_i}{\sum_{i=1}^n \bar{t}_i}$$

Equation (1)

where the denominator represents the estimated mean total finishing time of typical cyclists.

To demonstrate how external forces define the conversion of power output into speed, the course profiles of distinctly different Grand Tour individual time trial (ITT) races were analyzed, namely Stage 7 of Giro d'Italia 2024 (Foligno – Perugia, 10th May) and Stage 21 of Tour de France 2024 (Monaco – Nice, 21th July).

3 Results

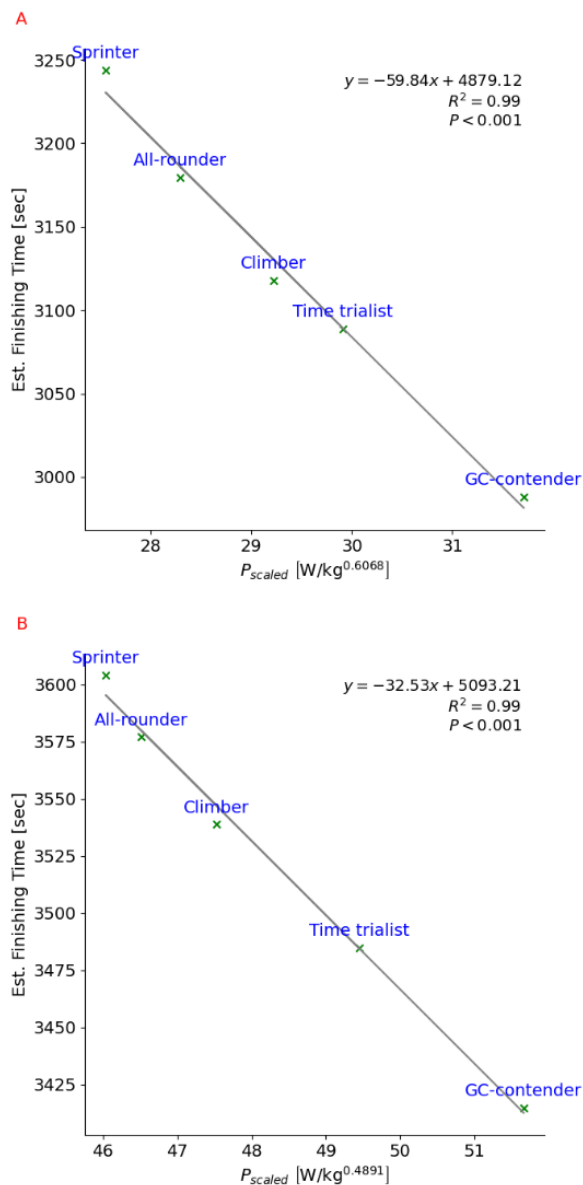


Figure 1. Estimated optimally scaled power output (P_{scaled}) and estimated total finishing times of typical cyclists for Stage 21 of Tour de France 2024 (panel A) and Stage 7 of Giro d'Italia 2024 (panel B), demonstrating the performance prediction accuracy of the presented method.

The calculated duration-weighted optimal mass exponents for the 2024 Giro d'Italia and Tour de France individual time trial (ITT) courses were 0.4891 and 0.6068, respectively. These values would represent cycling at constant inclines of 0.44° and 1.16° , considering the mean estimated speed of typical cyclists over these specific courses and no wind. Linear regression analyses demonstrated that the derived duration-weighted optimal mass

exponents effectively explained the variation in estimated total finishing times, indicating strong predictive capability for performance (Figure 1).

4 Practical Applications

The optimal mass scaling of power output enables the accurate prediction of estimated cycling performance along complex time-trial courses. This enhances the interpretability of power profiles and supports the development of targeted training interventions, as well as improving performance optimization, rider assignment, and strategic decision-making.

5 Conclusions

This study presents a numerical method for determining how external forces influence the optimal power output-to-body mass ratio. The findings indicate that optimal mass exponents are course-specific, with their variation largely explained by changes in headwind velocity relative to the cyclist and the gradient of the course.

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References

- Atkinson, G., Davison, R., Jeukendrup, A., & Passfield, L. (2003). Science and cycling: current knowledge and future directions for research. *Journal of sports sciences*, 21(9), 767-787.
- Heil, D. P. (2005). Body size as a determinant of the 1-h cycling record at sea level and altitude. *European Journal of Applied Physiology*, 93, 547-554.
- Jobson, S. A., Woodside, J., Passfield, L., & Nevill, A. M. (2008). Allometric scaling of uphill cycling performance. *International journal of sports medicine*, 29(09), 753-757.

- Leo, P., Spragg, J., Wakefield, J., & Swart, J. (2023). Predictors of cycling performance success: traditional approaches and a novel method to assess performance capacity in U23 road cyclists. *Journal of Science and Medicine in Sport*, 26(1), 52-57.
- Martin, J. C., Milliken, D. L., Cobb, J. E., McFadden, K. L., & Coggan, A. R. (1998). Validation of a mathematical model for road cycling power. *Journal of applied biomechanics*, 14(3), 276-291.
- Nevill, A. M., Jobson, S. A., Davison, R. C. R., & Jeukendrup, A. E. (2006). Optimal power-to-mass ratios when predicting flat and hill-climbing time-trial cycling. *European journal of applied physiology*, 97, 424-431.
- Papakonstantinou, J. M., & Tapia, R. A. (2013). Origin and evolution of the secant method in one dimension. *The American Mathematical Monthly*, 120(6), 500-517.
- Pinot, J., & Grappe, F. (2011). The record power profile to assess performance in elite cyclists. *International journal of sports medicine*, 32(11), 839-844.
- Swain, D. P. (1994). The influence of body mass in endurance bicycling. *Medicine and science in sports and exercise*, 26(1), 58-63.
- Valenzuela, P. L., Muriel, X., van Erp, T., Mateo-March, M., Gandia-Soriano, A., Zabala, M., ... & Pallarés, J. G. (2022). The record power profile of male professional cyclists: normative values obtained from a large database. *International journal of sports physiology and performance*, 17(5), 701-710.