

Advances in the Leiden Power-Heart Rate model

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Received: 22 May 2026

Accepted: 27 May 2026

Published: 28 October 2026

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Abstract

Purpose: To better model riders' physiological response to prolonged exertion beyond the non-linear relationship between power and heart rate, with the aim of assessing fitness in the field. **Methods:** The Leiden PHR model captures the non-trivial relationship between power (external load) and heart rate (internal load), shown to provide insights into a rider's fitness level ^{1,2}. Because heart rate is influenced by factors beyond recent power history, we modeled the remaining unexplained variance using the machine learning model XGBoost. Additional explanatory variables included cumulative effort (in five alternative ways), atmospheric conditions, geographic location, and current altitude and slope. Feature importance methods were used to assess the relative contribution of variables. **Results:** As in the earlier models, convolved pedal power was the strongest predictor, followed by a mixture of local parcours properties and cumulative effort indicators. Although atmospheric conditions and geographic location offered some minimal contribution, the same information can be obtained from other variables. The most accurate model used a mixture of variables ($R^2 = 0.81$, compared to $R^2 = 0.70$ for the existing model, with the average error being $\sigma = 5.8$ bpm). Besides convolved pedal power, several cumulative effort indicators played an important role, with cumulative heart rate (the number of heart beats since the start of the session) being the most prominent. The accuracy of the model allowed the discovery of several artefacts in the data where the actual heart rate deviated from the predicted heart rate substantially, pointing to either physiological or sensing anomalies. **Conclusion:** Variables capturing cumulative effort provide substantial additional explanatory power beyond recent power history in the PHR model, particularly in relation to cardiovascular drift. The enhanced model predicts heart rate with considerable accuracy, thus enabling day-to-day monitoring of riders and supporting the detection of anomalous physiological responses not yet explained by predictable factors such as exertion and cardiovascular drift.

Keywords

power-heart rate modeling; durability; endurance training; cycling

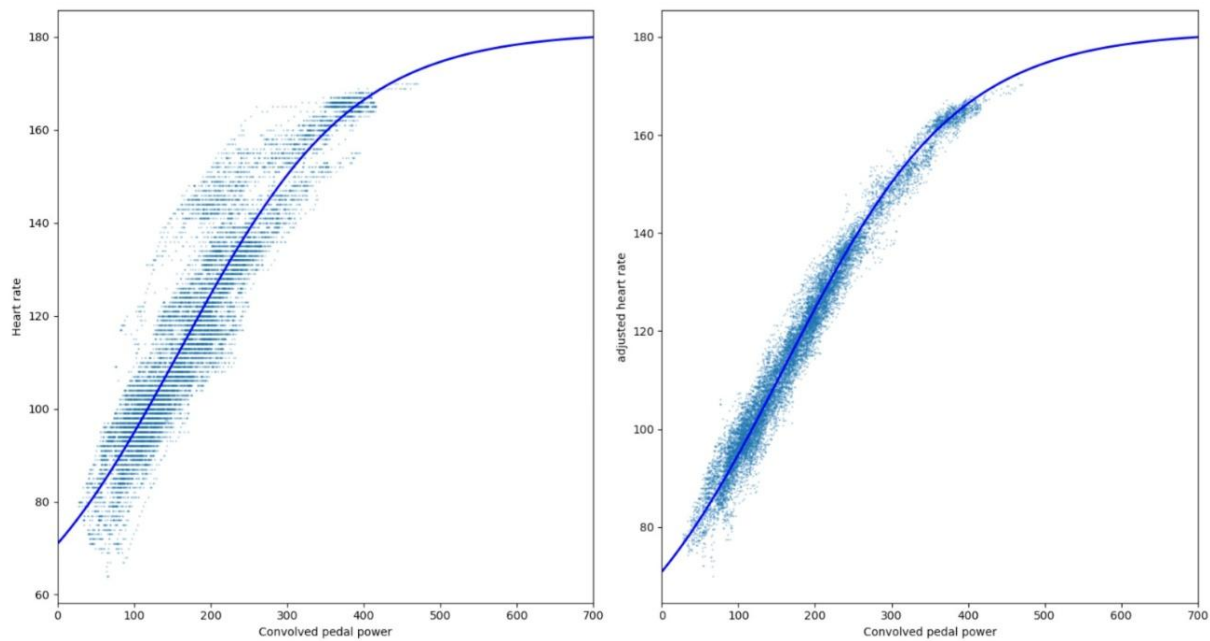


Figure 1. Example of PHR data for a single day. On the left, the existing PHR model, where heart rate is modelled as a sigmoid curve over the convolved pedal power (3-minute exertion history). The existing model ignores influences of cardiovascular drift, parcours, and atmospheric conditions. The plot on the right shows the data distribution of the enhanced PHR model, showing much less unexplained variance.

References

1. AW de Leeuw, JG Voet, T van Erp, RP Lamberts, JJ de Koning, A Knobbe Coupling heart rate and power data in professional road cycling: shorter heart rate response indicate better 10-min time trial power output, *Journal of Sports Sciences* 43 (10), pp. 978-985
2. A Knobbe, J Voet, T van Erp, AW de Leeuw, Heart rate response times measured in the field as indicators for endurance performance in cycling, *Journal of Science and Cycling* 13 (2), 111-112
3. de Leeuw, A.-W., et al., Exploiting sensor data in professional road cycling: personalized data-driven approach for frequent fitness monitoring. *Data Mining and Knowledge Discovery*, 2023. 37(3): pp. 1125-1153.
4. van der Zwaard, S., et al., Capturing the Complex Relationship Between Internal and External Training Load: A Data-Driven Approach. *International Journal of Sports Physiology and Performance*, 2023. 18(6): pp. 634-642.