A New Pathway to Approximate Energy Expenditure and Recovery of an Athlete

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ABSTRACT

This work proposes to use evolutionary computation as a pathway to allow a new perspective on the modeling of energy expenditure and recovery of an individual athlete during exercise.

We revisit a theoretical concept called the "three component hydraulic model" which is designed to simulate metabolic systems during exercise and which is able to address recently highlighted shortcomings of currently applied performance models. This hydraulic model has not been entirely validated on individual athletes because it depends on physiological measures that cannot be acquired in the required precision or quantity.

This paper introduces a generalized interpretation and formalization of the three component hydraulic model that removes its ties to concrete metabolic measures and allows to use evolutionary computation to fit its parameters to an athlete.

CCS CONCEPTS

• **Computing methodologies** → *Modeling methodologies*; *Model verification and validation*; *Simulation by animation.*

KEYWORDS

performance modeling, metabolic response modeling, optimization

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1 INTRODUCTION

The research area of performance modeling can be considered as the generalization of physiological processes into mathematical models with the purpose of approximating a body's response to exercise. Created models represent an objective understanding of body responses and provide opportunities to serve as reasoning tools to be applied in performance prediction, training simulation or exercise prescription [3]. Jones and Vanhatalo [4] as well as Sreedhara et al. [7] agree, that current approaches require refinement but highlight their potential for future research opportunities.

With their in 2019 published findings, Caen et al. [2] propose that recovery kinetics depend on previous work rate in addition to time and exercise intensity during recovery. Established performance modeling approaches separate energy expenditure and recovery into two separate models [3, 4, 7] and are too restricted to address these findings.

This work proposes that evolutionary computation allows to revisit an alternative concept: The so-called "three component hydraulic model" is investigated by Morton [5, 6] and represents human energy systems as three interconnected tanks. Energy is represented by liquids, the flow out of a tap corresponds to energy expenditure, and the refilling of tanks can be understood as recovery. Its conceptualization allows to combine expenditure and recovery in one model and recent findings by Caen et al. [2] can be addressed. However, Morton still highlights that the model is not absolute realistic in its assumptions and that more—and more precise—physiological measurements are needed to see how many predictions of this model conform to reality [6].

We introduce a generalized form of the three component hydraulic model that removes ties to such concrete metabolic measures and opens up the opportunity to use evolutionary computation as a new pathway to apply it to individual athletes.

2 A PATHWAY TO APPLY THE HYDRAULIC PERFORMANCE MODEL

To enable the application of evolutionary computation, the three component hydraulic system is further generalized. In short, concrete relations to lactate, carbohydrate or phosphocreatine are removed. The three interacting components of the model are instead understood as more abstract entities and referred to as the anaerobic fast component (*AnF*), the anaerobic slow component (*AnS*), and the aerobic contribution (*Ae*). Model equations are developed in accordance to approaches by Morton [5]. Detailed equations and more information about the generalization are provided in Appendix A.

A configuration of our generalized three component hydraulic model consists of eight parameters, which affect how the model's three components (*AnF*, *AnS*, *Ae*) interact. To fit such a configuration of eight parameters to an athlete, two objectives are defined: One for energy expenditure and one for energy recovery.

For the energy expenditure objective, the so-called "critical power concept" is employed as the ground truth. It is the established model to estimate times to exhaustion and used in most of the currently applied performance models [3, 4, 7]. A total of 12 performance tests at a constant exercise intensity until exhaustion are simulated by the generalized three component hydraulic model. The normalized root mean squared error of all differences between simulated and

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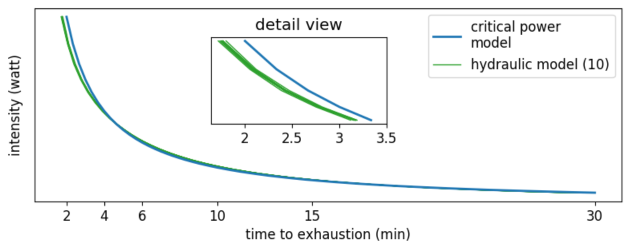

Figure 1: Exercise to time to exhaustion relationship of fitted hydraulic models in comparison to the critical power model.

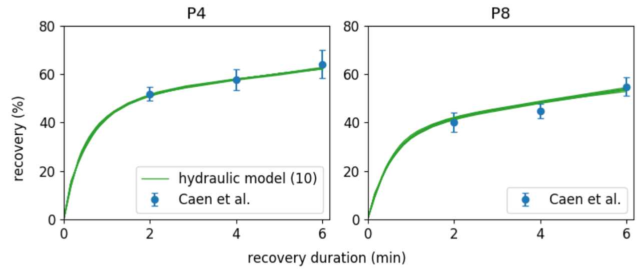

Figure 2: Recovery dynamics of fitted hydraulic models in comparison to published observations by Caen et al. [2].

expected times to exhaustion is to be minimized as the expenditure objective.

The energy recovery objective uses the exercise protocol that Caen et al. [2] employed to obtain their published recovery ratios. The generalized hydraulic model simulates all trials that were conducted by Caen et al., which results in 12 differences between simulated and expected recovery ratios. Also here the normalized root mean squared error of all differences is used to determine the energy recovery fitness measure to be minimized. More information on the exercise protocols and corresponding simulations is provided in Appendix B.

To find a configuration for the hydraulic model that optimizes both objectives, the established Multi-Objective Evolutionary Algorithm with Decomposition (MOEA/D) approach coupled with the asynchronous islands functionality of Pygmo [1] is used. Since both objective functions result in a normalized root mean squared error of 12 measurements, they are directly comparable. Knowledge of the evolved Pareto front allows to derive the best trade-off between both dynamics as the configuration that has the smallest Euclidean distance to the minimal error, i.e., point $(0, 0)$. If more details on this rationale are needed, please see Appendix C.

We want to emphasize that the introduced approach serves as a proof of concept and much more room for parameter optimization and exploration of problem-specific algorithms is left for future work. Nearly all parameters are at the default that Pygmo provides and only four parameters were investigated by grid search. More details are given in Appendix C.

3 RESULTS AND DISCUSSION

Ten independently estimated evolutionary fittings with the described hydraulic model and algorithm parameters are investigated and compared regarding consistency and quality.

All ten results behave similar to each other. As observable in Figure 1, the—by the critical power concept suggested—hyperbolic relationship of exhaustive exercise intensity and time to exhaustion is closely recreated with only slight deviations in the high intensities. Also simulated recovery ratios after various conditions are similar to the ones observed by Caen et al. [2]. The values P4 and P8 represent preceding exhaustive work bout intensities, i.e., P4 is the intensity that is predicted to lead to exhaustion after 4 min. Published means and standard deviations for P4 (2 min : 51.8% ± 2.8%, 4 min: 57.7%±4.3%, 6 min: 64%±5.8%) and P8 (40.1%±3.9%, 44.8%±3%, 54.8% ± 3.8%) are denoted in Figure 2.

Overall, evolved configurations make the hydraulic model successfully resemble the hyperbolic intensity to time to exhaustion relationship (Figure 1) as well as recovery ratios that are affected by previous energy expenditure characteristics (Figure 2). The outlined evolutionary computation approach successfully allows to apply three component hydraulic model as a performance model that addresses findings by Caen et al. [2] and combines expenditure and recovery in one concept.

4 CONCLUSION

The proposed evolutionary computation pathway and generalized understanding of the three component hydraulic model add a beneficial new perspective to research in performance modeling. Results clearly motivate further investigations as a validation strategy for the hydraulic concept and to bring the model closer to the application on individual athletes.

The implemented hydraulic model and evolutionary approach are available at https://github.com/faweigend/three_comp_hyd.

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