System Identification of Physiological Models for Endurance Sports

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During the last decades, the use of sensors for tracking sport activities got more and more common for professionals and amateurs. This goes side by side with technological advances in miniaturization and computational power which make devices smaller, less distracting and cheaper. Thus, more and more data with increasing precision is gathered and motivates the use of modeling techniques for analysis and prediction. This results in computer driven improvements for training plans and competitive strategies.

Optimization of competitive strategies in endurance sports requires knowledge of the physics involved and the capabilities of the athlete. Our research focuses on road cycling because of the well know and validated physical model by Martin et al.[1]. For a given power input and a know course profile, the model provides speed and therefore distance covered.

In opposite to the well researched mechanical model, existing models describing the possible power output of an athlete during endurance exercises are less precise and very abstract due to the high complexity of the human body.

Physiological Models

An often used model for optimization of pacing strategies and also for analysis of endurance capabilities of an athlete is the critical power model by Monod and Scherrer[2] (Figure 1, left). With a base of two components, unlimited aerobic and limited anaerobic capacity, it is a very simple model describing something as complex as the human body. A more complex model is the three component Morton-Margaria model[3] (Figure 1, right). This model is only rarely used for modeling or optimal pacing strategies because, although still being very abstract, estimation or measuring of all included parameters is already challenging.

Both models describe recovery with the flow from the unlimited vessel. Therefore, following this models, exercises taking less out of the system than regained by the maximum incoming flow can be continued forever. The models don't take into account time dependent changes in recovery or time depend raise in fatigue.

This lead to the idea of developing a model somewhere in between of the critical power model and the Morton-Margaria model which covers fatigue and recovery well and allows complete calibration. In the Morton-Margaria model the oxygen flow is crucial for exercise capabilities.

Thus, we chose to examine respiratory gas dynamics which are a valuable source of information since they allow for a non-invasive, continuous and precise measurements of the gross oxygen uptake and carbon dioxide output of the hole body. Particularly in endurance sports, the metabolic rates of the fuel and the degradation product of exercising muscles are reflected in that rate.

Examination of respiratory gas and heart rate measurements during lab testing showed a similar behavior in heart rate, oxygen demand and carbon dioxide output. Thus, the same models can be employed for estimation and prediction of all three physiological quantities. As heart rate can easily be measured directly, the ability of predicting heart rate is rarely needed with exception of some medical applications. However, we can benefit from the similarity between heart rate and respiratory gas by taking heart rate as additional input besides power for our models.

There are two kinds of approaches to get such a model. The first model type is directly based on concepts of physiology, such as exponential saturation functions with appropriate time-constants. Another approach are black box models from the field of system identification without relation to physiology such as Hammerstein-Wiener models.

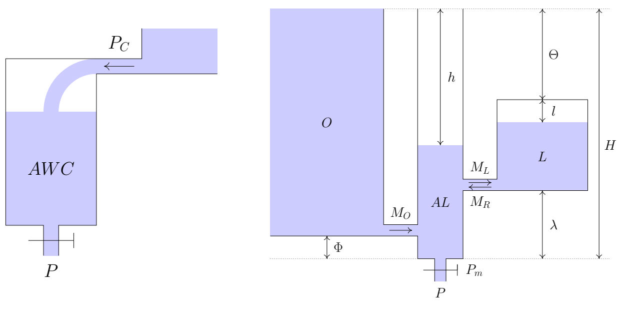

Figure 1: *Left: Two component Critical Power model.*
Right: Three component Morton-Margaria model.

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Dynamic Models

We generalized successfully the established constant work rate models towards a dynamic model for variable work rate[1]. The result is a model that consists of two differential equations based on a steady-state function. Different steady-state functions have been evaluated. This model outperformed other approaches from literature which we adopted for cycling: a model by Stirling et al.[4] for $\dot{V}O_2$ during constant speed running and a model by Cheng et al.[5] for heart rate during treadmill exercises[2]. Results of at least two more models will be added in future[6][7].

In addition to the application for modeling and prediction, the estimated model parameters of most of these dynamic models can be used as indicators for performance capabilities of athletes or enhance the comprehension of physiological processes.

Black Box Models

Black box models do not offer the same understanding as physiological models have, but they bring other advantages. Detached from physiological evidence they are more flexible and can adjust better to data and therefore, may deliver better fitting results. Though not derived by principles of physiology, it is still important to select the right model type and model settings to obtain good results.

Different linear (ARX, ARMAX, State-Space) and nonlinear (ARX, Hammerstein-Wiener) models from MATLAB®s System Identification Toolbox™ have been tested on selected data sets. Best results have been achieved with State-Space and Hammerstein-Wiener models. In a direct comparison Hammerstein-Wiener models have shown the best modeling results[3].

These models also perform slightly better than the developed dynamic model, but the results of both models are in the range of the the natural variability of the modeled quantities[4], and therefore suitable for modeling and fitting.

Future Work

Physiological Endurance Model

Using the respiratory modeling results we will build our new physiological model. We established co-operations with a professional coach and the German cycling association (Bund Deutscher Radfahrer) for access to large databases of training and competition data and the exchange of ideas. With that data, we will train and validate several models and compare their usefulness for optimization of pacing strategies.

Simulation

Testing and data collection is done on our own cycling simulation software, which offers scientific precision and an accurate simulation of real-world courses. The simulation is used for validation of optimal pacing strategies computed with our physiological models. We are constantly working on improvements of the simulation and data collection tool. Current research addresses inertia simulation[5], mountain bike simulation (algorithms for braking in sharp curves and steep downhill sections, surface types) and feedback techniques.

Adaptive Strategies

It cannot be expected that a rider is able to follow an optimal strategy on field rides. Surface, wind and erroneous course data can interfere. Thus, we need a feedback device where we can adapt the strategy. A first solution will be an android application for a smartphone that can be mounted at the handlebar. The right format of the feedback is also of importance: bars or arrows in different color, numbers or something different. Another option could be glasses which eliminate the need of the rider to watch frequently at the smartphone.

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