# Designing ergometer tests for the calibration of physiological endurance models

Thorsten Dahmen,
*University of Konstanz, Konstanz, Germany;*

Physiological endurance models are widely used to characterize the capabilities, limitations, and dynamics of human performance (Morton, 2006). Their calibration is a classical curve fitting task, where the parameters are chosen to minimize the deviation of model estimations from measurements of performance indicators such as power, heart rate, oxygen consumption, and lactate level for a particular ergometer test. The design of an appropriate ergometer test setup is often based on heuristics and experience of sports scientists. However, the sensitivity of the model parameters with respect to variations of the measurements depends on that design. Here, we focus on the 3-parameter critical power model and present an alternative ergometer test setup, which improves the parameter calibration for the modeling of short intense workload and choose interval lengths to maximize the sensitivity of the parameters.

The 3-parameter critical power model (Morton, 2006) assumes, that there is an (aerobic) critical power $P_c$, which is the maximum power a human can perform for a long (infinite) time. In addition, an anaerobic resource $E_a$, which is initially filled with and limited by an anaerobic capacity $E_0$, is at the athlete's disposal. Upon exercise with power $P$, the anaerobic resource is tapped: $\dot{E}_a = P_c - P$. The maximum available power $P_m$ decreases linearly with the relative consumed anaerobic resource from the fixed total maximum power $P_{max}$ to the critical power: $P_m = (P_{max} - P_c)\, E_a/E_0 + P_c$.

The estimation of the model parameters $\boldsymbol{k} = (P_c, P_{max}, E_0)^T$ is typically done with ergometers based on series of tests using constant power, ramp or interval setups, (Morton, 1997, 2004), where the time until exhaustion indicates the anaerobic capacity. In contrast, we exploit that $P_m$ depends on $E_0$ and design a test protocol of *fixed* duration $T$ that consists of $N$ maximum power intervals $P = P_m$ interrupted by $N - 1$ recovery intervals $P = r\tilde{P}_c$, where $r < 1$ is a recovery factor and $(\tilde{\cdot})$ stands for an a-priori guess. Modern ergometers provide an isokinetic modus for the $P_m$-intervals so that the athlete can perform the maximum power at his preferred cadence. During the recovery intervals, the ergometer ensures constant power $r\tilde{P}_c$. For the cost function $J$ the least squares method is used to fit $\boldsymbol{k}$ to measurement data. Due to the $P_m$-intervals, $J$ is sensitive to variations of each parameter in $\boldsymbol{k}$. The quality of the minimum depends on its curvature $\mathbf{d}^2 J/\mathbf{d}\boldsymbol{k}^2|_{\tilde{\boldsymbol{k}}}$. The curvature, however, is a function of the switching times $t_1, \cdots, t_{2N-2}$ between the intervals. Therefore, varying the switching times to ensure a sufficient curve in *any* direction on the surface $\boldsymbol{dk}/\widetilde{\boldsymbol{k}} = \text{const}$ is used to maximize the sensitivity.

The approach is extensible to optimize the test protocols for any curve fitting based calibration of constrained dynamical systems.

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