Modeling human energy expenditure and recovery

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Biography

I am currently pursuing PhD in mechanical engineering from Clemson university. I graduated with a Master's in mechanical engineering from Clemson in Dec 2015. Prior to grad school, I worked at Toyota Kirloskar Motor, India as a Supplier Quality Engineer (2010-2012) and at John Deere India as Graduate engineer trainee (2009-2010). I graduated with a Bachelor's in Mechanical engineering in July 2009 from Visvesvaraya Technological University (VTU), India. My research interests include modeling human exercise fatigue, expenditure and recovery of anaerobic energy in intermittent cycling and running.

Overview

The objective of this research is twofold 1) develop models of expenditure and recovery of Anaerobic Work Capacity (AWC) as related to the Critical Power (CP) of a human and 2) determine if and how a case for an energy-management system to optimize energy expenditure and recovery can be made in real-time using noninvasive sensors. The human body converts fuel into mechanical power through energy systems (aerobic and anaerobic) while carrying out physical tasks. CP is a value at which a human can expend for infinitely without fatigue [1], while AWC is the amount of anaerobic energy that a human can expend above the critical power in a single exercise session [1]. There is a well-established theory in the literature to predict the depletion of a human's finite AWC based on this CP. The literature however lacks a robust model for understanding the recovery of the AWC.

Motivation

The motivation of this research is to allow for prolonged physical exertion and to understand how energy and power are used within human work expenditure.

Why is modeling the recovery of AWC a worthy problem to solve? (i) We have an uncertain understanding of recovery of AWC. We need to understand the recovery of AWC better, and (ii) without knowing how a cyclist can recover their energy when operating below their Critical Power, their performance in a race cannot be fully optimized. The goal is to ensure that the cyclist's AWC is completely expended and to apply the learnings to other forms of exercise.

State of the Art

Chidnok and colleagues modelled [2] recovery of AWC in intermittent cycling by assuming that recovery is directly proportional to expenditure. Skiba and colleagues [3] assumed the recovery of

AWC in intermittent cycling to be exponential. Skiba's model, though addresses the recovery and expenditure being nonlinear, considers an average recovery power for an entire exercise bout and does not justify the exponential behavior. To address this Bickford [4] attempted to find a recovery factor which is a ratio of extra energy recovered to the recovery area in an intermittent cycling bout (see figure 1a). The recovery factor results in a singularity as recovery power tends towards CP. This singularity needs to be addressed in the next iteration of the model.

Intellectual Merit

The research questions that I want to address are:

1. Can the recovery of AWC be modelled using power and recovery times?
2. Can the AWC model be used to optimize race performance of a cyclist?

This research can provide valuable insight to other research topics pertaining to human powered vehicles, correlating exercise tolerance to cardiovascular diseases, diabetes, applying non-invasive sensor technology to other research areas like understanding human perception of exertion, etc.

Broader Impact

If a mathematical model can be developed, it will result in (i) planning rehabilitation regimes for people recovering from injuries, (ii) parameters like blood lactate levels, gas exchange threshold, and oxygen uptake could be estimated non-invasively without expensive equipment, and (iii) considering exercise as preventive medicine to cardiovascular problems and health problems that are a direct consequence of obesity.

Research Approach

Anaerobic Work Capacity of an individual (W_{Lim}) is given by the hyperbolic relationship [1],

$$W_{Lim} = (P - CP) * t_{Lim} \tag{1}$$

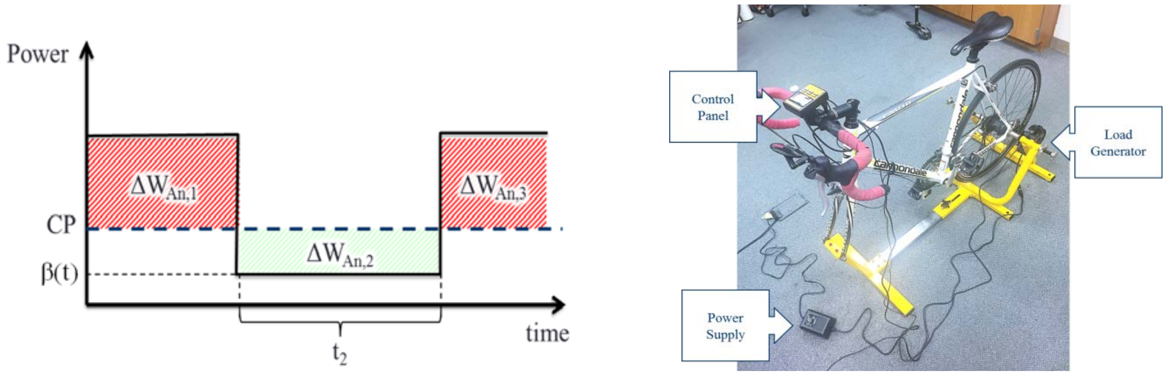
where P is Power is Watts, t_{Lim} is the time to exhaustion in seconds. To determine the CP of an individual, the subject is required to exercise at a constant power (P) until they were completely exhausted on 3-7 different visits to the lab [5]. Vanhatalo and colleagues [6] validated a single 3-minute all-out test protocol to determine CP and AWC, which would avoid a subject visiting the lab several times.

The hypothesized model presented for combined expenditure and recovery of AWC is based loosely on the model presented by Skiba's model in [3]. During an intermittent exercise bout, a segment of AWC is expended or recovered as (See Figure 1a),

$$\Delta W_{An} = CP\left(\beta(t) - 1\right) \tag{2}$$

where $\beta(t) = P(t)/CP$ is the ratio of the operating power P(t) at time t and CP. The energy recovered during the entire exercise bout at exhaustion is given by,

$$E_{rec} = AWC - \left(\Delta W_{An1} + \Delta W_{An3}\right) \qquad (3)$$



(a) (b)

Figure 1: (a) CP4 interval test representation, (b) Set-Up of the CompuTrainer System

The energy recovered is hypothesized to be a function of both recovery power and duration of the recovery interval, which needs to be modeled.

Testing setup and protocols

A system that includes a CompuTrainer cycling trainer system with Racermate software (see Figure 1b), BSX Insight NIRS sensor (muscle oxygenation sensor), and Garmin Heart Rate monitor is used to conduct experiments and gather data. A preliminary cycling study [4] was conducted by my colleague to model the recovery of AWC with nine subjects (8 male, 1 female aged 23-44). First, the CP and AWC of the subjects were determined by a 3-minute all-out intensity cycling test [6]. The subjects then performed several interval protocols to exhaustion with recovery intervals to quantify the amount of AWC recovered.

Current findings

It was determined that (i) sub-Critical Power recovery is not proportional to above-Critical Power expenditure, (ii) the amount of AWC recovered is influenced more by the power level held during recovery than the amount of time spent in recovery (iii) during recovery, muscle oxygenation increases and heart rate either decreases or stops increasing.

Conclusions

The results from the preliminary study indicate the potential to mathematically model expenditure and recovery of Anaerobic Work Capacity. Following this, human performance for a given task can be optimized using data from non-invasive sensors in a human-in-the-loop feedback control system (See Fig 2) using Burke's power requirement equation in [7].

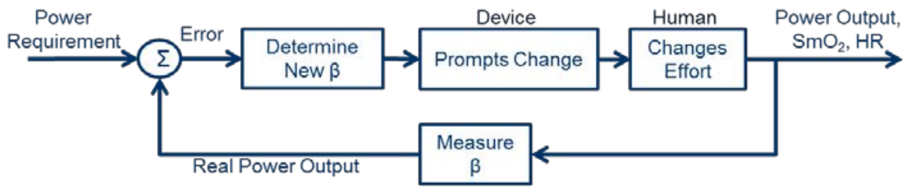


Figure 2: Hypothesized Human-In-The-Loop Feedback Control System

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