Calculating Power Output and Training Stress in Swimmers: The Development of the SwimScore™ Algorithm

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Legal Notes:

Introduction:

There exists a dose-response relationship between training stimulus and adaptation of the athlete (Bannister et al 1975, Busso 2003). Training load can be expressed simply as:

Training load = Intensity · Duration (Eq. 1)

It is clear that different types of stimuli will effect different physiologic responses. It is less clear how to compare/quantify differing stimuli and their ability to affect the same response. A number of systems have been proposed, the most widely used of which is TRIMPS, which was devised by Dr. Eric Banister in the 1970's. Simply put, Banister sought to relate an easily measured parameter (heart rate) to lactate production through the use of a population study. This made a great deal of sense, perhaps even more so today as it is now widely accepted that the work rate at lactate threshold (defined as a rise of serum lactate of 1 mmol/L over exercise baseline) is the primary determinant of endurance exercise performance (Coyle 1988, 1999)

TRIMPS = Duration · Average HR during exercise · A HR-dependant, intensity based weighting factor (Eq. 2)

The benefit of Banister's system is that it takes into consideration the observation that higher workloads are more metabolically taxing (exponentially so, via the weighting factor) than lower workloads of equivalent duration (Bannister 1996). However, it is still dependent upon the measurement of heart rate, which is variable based on factors such as hydration, rest, illness, or cardiac drift. Furthermore, though HR is dependent upon workload, it may take minutes to stabilize when that workload changes. Because of these complicating factors, it would be preferable to measure work rate directly.

In 2003, Dr. Andrew Coggan refined Banister's concept by developing a system that also incorporated lactate response to workload. This system related the *change* in lactate concentration with the *change* in an *objective* measure of exercise intensity: power output, which can be directly measured by on-bike power meters.

Coggan devised a mathematical algorithm similar to that of Bannister, called the Training Stress Score (TSS).

TSS = Exercise duration · Average power · Power-dependent, intensity weighting factor (Eq. 3)

The power dependent intensity weighting factor was derived directly from a plot of blood lactate concentration as a percentage of concentration at threshold against % of threshold power. His work indicated a near 4^{th} power relationship between the two.

The elegance of Coggan's system is that while it successfully relates lactate concentration to power output, it is not dependent upon invasive tests. In 1988, Coyle et al. illustrated

that the highest power output or pace an athlete can maintain over the course of an hour long exercise task is highly correlated with LT. Thus, to determine threshold intensity, the athlete need only perform such a test and use the resulting average power in the calculations. The concept carries over to the running literature as well, where 8k-10k to 1 hour runs at the maximal pace sustainable for the duration of the run have been shown to be strongly correlated to both LT and maximal lactate steady state (MLSS); that is, the highest exercise intensity that does not result in a continual increase in serum lactate (Jones and Doust 1998, Daniels 2002). The swimming literature also concurs, where a 3000M TT has been correlated to MLSS, as well as OBLA and IAT (Sharp 1993, Olbrecht 1986).

While Coggan's system is in wide use amongst recreational and professional athletes, and was recently validated in a small populations of athletes (N=6, Skiba 2007), transferring this conceptual framework to other sports is problematic, as there is often no practical way of measuring mechanical power output. Dr. Philip Friere Skiba developed the first solution suitable for walking, running and cross-country skiing utilizing GPS and a novel mathematical approach which is now in wide use amongst runners and triathletes (GOVSS^{TM}, see Skiba 2006).

Many sports professionals and enthusiasts have sought to apply this methodology to swimming. However, these pursuits were fraught with problems because GPS does not work indoors, and currently available GPS meters are not compatible with immersion. However, swimming is rather unique in that lap splits are easily and regularly recorded. Thus, given the anthropometric data of a particular athlete and recorded velocity data, it is possible to calculate power output and training stress scores using first principles and the published literature on the subject.

Power Output Calculation:

A number of studies have described the power requirements of movement in terms of a power balance model. In swimming, such a model must include a rather obvious term: the power required to overcome drag (P_d), and a somewhat less intuitive term, the power required to change the kinetic energy of the water (P_k) (Toussaint 1988).

$$P_o = P_d + P_k \text{ (Eq 4)}$$

where:

$$P_d = F_d \cdot V$$
$$P_k = 0.5m(\triangle u)^2 \cdot f$$

and:

F_d = Force required to overcome drag
V = swimming velocity
m = mass of the displaced water
$\triangle u$ = velocity change of the displaced water
f = stroke frequency

Drag has been demonstrated to be related to the square of velocity. Thus, the P_d is related to the cube of velocity ($V * V^2$), and a constant drag factor. Thus:

$$P_d = KV^3 \text{ (Eq 5)}$$

where K is a drag factor that is essentially constant within any given individual. According to Toussaint (1988, 1990, 1998) this factor may be estimated by:

$$K = 0.35 * \text{Mass} + 2 \text{ (Eq 6)}$$

Calculating P_k is more troublesome, because it is not clear how it is related to velocity. However, in 1988, Toussaint et al introduced the concept of propelling efficiency (e_p), that is the ratio of P_d to P_o, which is independent of swimming velocity and is essentially constant within an individual.

$$e_p = P_d / (P_d + P_k) = P_d / P_o \text{ (Eq 7)}$$

This construct assumes constant velocity, which which is reasonable given the typical swim workouts of competitive athletes (e.g. intervals of various lengths / velocities, each of which is typically completed as a constant velocity). Introducing Toussaint's concept of propelling efficiency:

$$P_o = P_d / e_p = KV^3 / e_p = K / e_p \cdot V^3 \text{ (Eq 5)}$$

Addressing Variability:

It is somewhat easier to address the variability of power output in swimming exercise than in other sports. The great majority of swimming workouts involve covering set distances at a constant pace. (The greatest source of variability in most athletes involves direction / velocity changes and acceleration / deceleration on the turns, which are ignored for the purposes of this analysis). However, there can be substantial variability in rest intervals, which may have a significant effect on the physiologic impact of the workout. Thus, an exponentially-weighted moving average algorithm is applied to the raw power data to account for the fact that the body has many process / responds to many stimuli with a half-life of approximately 25-30 seconds (Figure 1).

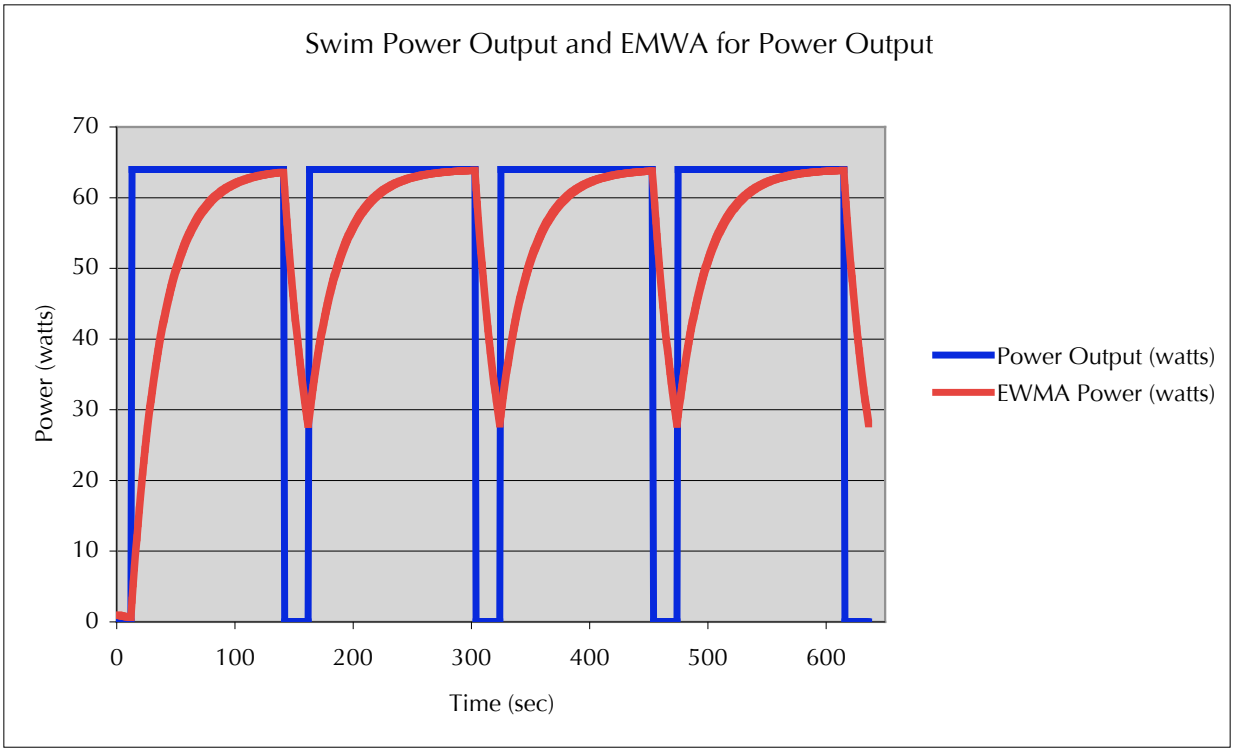

Figure 1: Instantaneous power output (blue) and exponentially weighted moving average for power output (red), which is indicative of the time course of the physiologic response to the effort.

Addressing Intensity:

Because of the well described relationship between the intensity of exercise and the physiologic strain induced in the athlete, it is advantageous to differentially weight the exercise task as described in the introduction. To this end, lactate data collected from 9 trained collegiate swimmers during an incremental exercise protocol previously reported in the literature was analyzed (Wakayoshi 1992). Lactate concentration as a percentage of concentration at lactate threshold was was plotted against power output expressed as a percentage of power output at lactate threshold, and a regression was calculated (Figure 2).

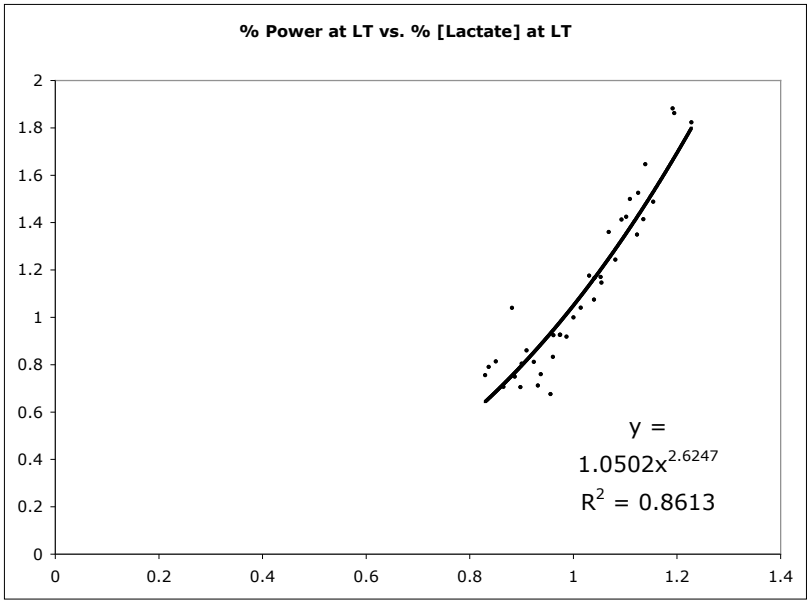

Figure 2: Percent power at LT vs. percent concentration of lactate at LT. For the purposes of intensity weighting, the exponent is rounded up to 3.

SwimScore Calculation:

Using the above information and a protocol modified from that first described by Coggan (2003, 2006), it is now possible to calculate a training stress metric for swimming.

1. Find the athlete's threshold velocity via a 3000M TT
2. Convert this velocity to a power value using Equation 4. This is the Threshold Power.
3. Analyze the data from a particular workout, computing an exponentially weighted moving average for power for each interval from the distance and time, including rest intervals.
4. Cube the values in step 3.
5. Average for the values from step 4.

6. Take the cube root of step 5. This is the xPower.
7. Divide xPower by Threshold Power from step 2 to get the Relative Intensity.
8. Multiply the xPower by the duration of the workout in seconds to obtain the normalized work performed in joules.
9. Multiply value obtained in step 8 by the Relative Intensity to get a raw SwimScore.
10. Divide the values from step 9 by the amount of work performed during the threshold test.
11. Multiply the number from step 10 by 100 to obtain the final SwimScore.

This calculation appears laborious at first glance, however, inexpensive software has been developed which automates the process (http://www.physfarm.com?page_id=12).

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