Physiological Model-Based Decision Making on Distribution of Effort over Time

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Abstract. This paper focuses on a human-like agent model that describes how in high load tasks physiological effort relate to exhaustion and feeling fatigue, and this is used as a form of monitoring the agent's remaining resources. More specifically, it is addressed how based on such an agent model anticipatory model-based decision making can take place in order to obtain an appropriate distribution of effort over time.

Keywords. Physiological model, effort, exhaustion, decision making

Introduction

In human agent behaviour, in addition to the brain, the body often plays an important role. Therefore the design of human-like agents may benefit of incorporating relevant physiological aspects in models developed; e.g., [3, 4, 6, 17]. As an example the focus here is on how an agent manages the effort spent and the related exhaustion (or fatigue) developed in time periods with high load. In humans, to enable intelligent management, the body does not only give a signal when complete exhaustion occurs, but by gradually getting a feeling of becoming fatigued more information is available in the brain before a total breakdown occurs. With this feeling as input, mechanisms in the brain are exploited (1) to monitor levels of fatigue over time, and (2) to decide about distribution of effort over time in such a way that no full exhaustion occurs before the end of the expected period of high load. For example, to avoid premature full exhaustion, a runner will decide to take a lower pace for a *5km* run than for an *800m*.

The approach presented here includes a human-like agent model which describes how based on the physiologically-related aspect of fatigue (which plays a central role in the literature on physical exercise and sport) enables monitoring and intelligent control of resources. It is addressed how such a physiologically-related agent model can be used to formalise anticipatory decision making about an appropriate distribution of effort over time, in order to obtain good performance for given available resources.

The human-like agent model is based on inspiration from literature on physical exercise and sport and how the generated effort is controlled and what is the role of feeling fatigue in this process; e.g., [5], [7-16]. In particular, the interplay of mind and body in this process is addressed. Noakes and his colleagues (e.g., [13-15]) base their theory on the notion of homeostasis: the property of a system (for example, a living organism), to regulate its internal environment in such a way that stable, more or less constant, conditions are maintained. Due to this regulation the body is rarely allowed to reach a 'catastrophic' state where it would run out of essential reserves. In this view the mind receives signals from the body as a form of monitoring, and by regulation keeps the body in appropriate physical conditions.

Such a regulation mechanism is applied in managing time periods with heavy work load and in sports. For example, in long distance running, speed skating or cycling, often it is debated how power should be distributed over time. For example, should the initial phase be used to put extra effort, or the last phase, or should the power be distributed uniformly over the whole time interval? As in sport a difference of less than *0.5%* in time is often decisive for winning or not, making the right decisions on the distribution of power over time is crucial. The model-based decision making approach put forward here provides answers to such questions.

In this paper a computational model for the dynamics of getting exhausted to answer such questions is briefly introduced in Section 1. As a result a model-based decision making approach for distribution of power over time is offered. Next, in Section 2 the special case of a uniform distribution (constant power) is addressed. In Section 3 four patterns of power over time are compared with a uniformn distribution: two intervals with constant power, a linear (increasing or decreasing) pattern of power over time, and an exponential pattern over time. Finally, Section 4 is a discussion.

1. The Agent Model

Within the literature on exercise and sports the notion of *critical power* CP is the maximal level of power that can be generated and sustained over longer periods without becoming exhausted (getting fatigue), assuming no prior exercising. It is an asymptote of the wellknown hyperbolic power-duration curve defined by $(P - CP)\ t = W'$ (also see (9) in Section 2) that models the relationship between a constantly generated power level P (above the critical power CP, both measured in *Watt*) and the time *t* that this level can be sustained; e.g., [7-11], [16]. Here W' is the total amount of work (measure in *Joule*) that can be spent above the critical power (the available stored extra resources based on anaerobic processes). The critical power is the capacity to provide (sustainable) power based on aerobic processes. Although often the critical power CP is assumed constant during one exercising session, in the recent literature there is some discussion on whether this really is the case. Some experiments show that after intensive prior exercising leading to full exhaustion of the basic resources W', for example, power at *90%* of the critical power CP cannot be sustained anymore; e.g., [5].

This section describes an agent model for monitoring of resources, based on concepts from [18]. In the model described here a *basic critical power* CP_0 is distinguished from a *dynamic critical power* CP. The most basic assumptions behind this agent model are:

- The critical power indicates the level of (sustainable) power that can be generated for which the level of fatigue remains the same.
- Lower critical power reflects more fatigue
- Basic critical power is the maximal critical power possible, which means no fatigue and occurs (only) in a state without prior exercising.
- If a level of power is generated above the critical power, then fatigue will increase which makes that for the future efforts less resources are left

The dynamics of critical power is described by a linear dependency of the change in critical power on the effort spent above the critical power, with proportion factor γ:

$$\frac{dCP}{dt} = -\gamma\,(P - CP) \qquad (1)$$

Here P is a function of t indicating the power spent at time t. This power P is the variable for which values over time have to be chosen by the decision making addressed in this paper (for some examples of such power distributions over time, see Figure 1). Note that for $\gamma = 0$, a static critical power is modelled. The extra resources W spent over time (taken from the available resources budget W') are described by

$$\frac{dW}{dt} = P - CP \qquad (2a)$$

If $W_{tot}(t)$ denotes the total work performed up to time point t, then

$$\frac{dW_{tot}}{dt} = P \qquad (2b)$$

Note that the following relations between the derivatives of CP and W immediately follow from (1) and (2):

$$\frac{dCP}{dt} = -\gamma\,\frac{dW}{dt} \qquad\qquad \frac{dW_{tot}}{dt} = \frac{dW}{dt} + CP \qquad (3a)$$

From this it can be derived that for an exercising session during a time interval starting at $t=0$ with initially fully available resources budget W' it holds:

$$CP(t) = CP_0 - \gamma\,W(t) \quad \text{or} \quad W(t) = \frac{1}{\gamma}\,(CP_0 - CP(t)) \qquad (3b)$$

Note that a situation in which that W' has been fully finished (full exhaustion) at t (i.e., $W(t) = W'$) is described by

$$CP(t) = CP_0 - \gamma\,W' \qquad (4)$$

The above relation (3) between $CP(t)$ and $W(t)$ can be used to eliminate CP from the differential equation (2) for W, thus obtaining:

$$\frac{dW}{dt} = P - CP_0 + \gamma\,W \qquad (5)$$

For a given distribution $P(t)$ of power over time this linear differential equation (5) with nonconstant coefficients can be solved analytically as follows:

$$W(t) = \int_0^t e^{\gamma(t-u)}(P(u) - CP_0)\,du \qquad (6a)$$

Moreover, from (2b) it immediately follows:

$$W_{tot}(t) = \int_0^t P(u)\,du \qquad (6b)$$

Using relation (3) between CP and W, (6a) also provides an analytic solution for CP:

$$CP(t) = CP_0 - \gamma\,W(t) = CP_0 - \gamma\int_0^t e^{\gamma(t-u)}(P(u) - CP_0)\,du \qquad (7)$$

As the decision making addressed here concerns the possibility of varying the power P over time, it is also useful to determine the dependence between W and dP/dt (from (6)); this is described by (from (6) by partial integration):

$$W(t) = -\frac{1}{\gamma}(P(t) - CP_0 - (P(0) - CP_0)e^{\gamma t}) + \frac{1}{\gamma}\int_0^t e^{\gamma(t-u)}dP(u)/dt\,du \qquad (8)$$

2. A Hyperbolic-Exponential Power-Duration Curve for Constant P

In this section a uniform distribution of power over time is analysed in more detail (for example, the flat blue line in Figure 1). Traditionally the hyperbolic power-duration curve $(P - CP)\ t = W'$ (9) is used in the literature to describe cases of constant P above the critical power until total exhaustion is reached. For the approach presented here, for constant P the derivative $dP(u)/dt$ is 0, and $P(t) = P(0) = P$. Therefore from (8) it follows:

$$W(t) = -\frac{1}{\gamma}(P - CP_0)\,(1 - e^{\gamma t}) \qquad (10)$$

This provides the following hyperbolic-exponential power-duration relation:

$$W(t) = (P - CP_0)\, t\, \frac{e^{\gamma t} - 1}{\gamma t} \qquad (11)$$

For the time t_{max} becoming fully exhausted for power level P, it holds: $W(t_{max}) = W'$. Therefore

$$W' = (P - CP_0)\, t_{max}\, \frac{e^{\gamma t_{max}} - 1}{\gamma t_{max}} \qquad (12)$$

Viewed from the perspective of decision making about the power to be chosen for a given time duration t, relation (12) can be used to determine which constant P is maximally possible so that full exhaustion is just occurring at time t:

$$P_{max} - CP_0 = W' / t\, \frac{e^{\gamma t} - 1}{\gamma t}$$

$$P_{max} = CP_0 + \gamma W'/(e^{\gamma t} - 1) \qquad (13)$$

For this constant maximal power given by (13) the total work W_{tot} performed is

$$W_{tot}(t) = \int_0^t P(u)\, du = (CP_0 + \gamma W'/(e^{\gamma t} - 1))\, t$$

$$= CP_0\, t + W' / \frac{e^{\gamma t} - 1}{\gamma t} \qquad (14)$$

For γ approaching 0 this approximates $CP_0\ t + W'$, since then the exponential factor will approximate 1. When γ is higher, the work performed will be lower. Based on (11) and (3b) the critical power for constant P can be expressed in t:

$$CP(t) = CP_0 - (P - CP_0)(e^{\gamma t} - 1) \qquad (15)$$

or $\quad CP_0 - CP(t) = (P - CP_0)(e^{\gamma t} - 1)$

In Figures 1 and 2 both the hyperbolic-exponential and the hyperbolic curve are shown for $\gamma = 0.002$, resp. $\gamma = 0.0005$. In the upper graph (a) time t is on the horizontal axis, and in the lower graph (b) one divided by time: $1/t$. On the vertical axis the maximal power P sustainable for a duration t is depicted. Figures 1 and 2 show how hyperbolic-exponential power-duration curve described by (11) is approximated by the traditional hyperbolic power-duration curve when γt is small. This can be analysed from a different perspective by verifying that the factor

$$\frac{e^{\gamma t} - 1}{\gamma t}$$

approximates 1 when γt approaches 0.

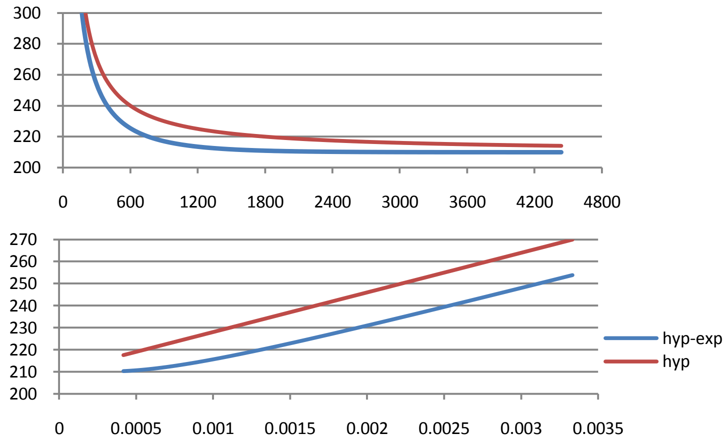

Figure 1. Hyperbolic and hyperbolic-exponential power-duration curve*:* maximal sustainable power (*Watt*) (a) against duration *t* (in seconds) (b) against *1/t* (in *1*/seconds) ($\gamma = 0.002$, $CP_0 = 210W$, $W' = 18000J$)

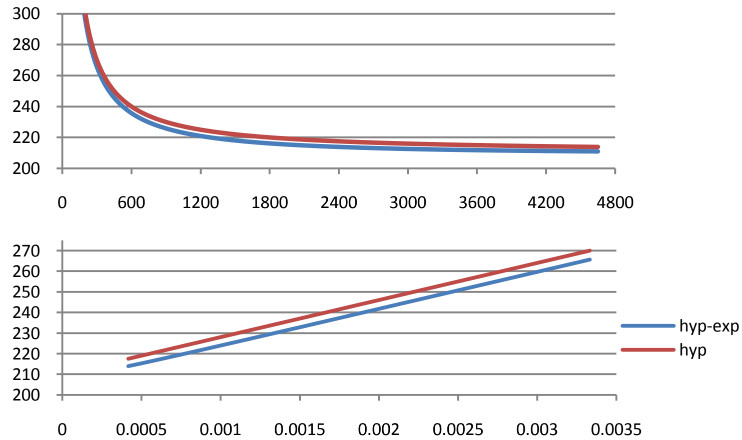

Figure 2. Hyperbolic and hyperbolic-exponential power-duration curve: maximal sustainable power (*Watt*) (a) against duration *t* (in seconds) (b) against *1/t* (in *1*/seconds) ($\gamma = 0.0005$, $CP_0 = 210W$, $W' = 18000J$)

3. Decision Making by Comparison of Different Distributions of Power over Time

In this section it is discussed how the computational model can be used for decision making: for any effort distribution scenario considered the model can be used to make predictions on the overall work that can be obtained by following such a scenario. When different scenarios are evaluated in this way (by a form of what-if analysis), they can be compared. In this section four types of such scenarios for distributions of power over time are considered (see Figure 3):

- constant power *P* (Section 2)
- two intervals with constant *P*
- linear (de- or) increasing distribution over time
- exponential distribution over time

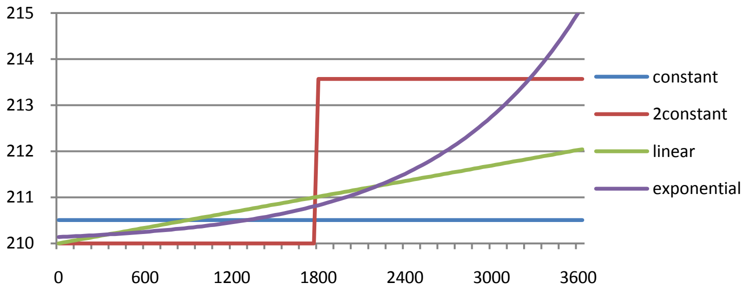

Figure 3. Four patterns for distribution of power P over time (for $\gamma = 0.001$, $CP_0 = 210W$, $W' = 18000J$)

The four patterns for distribution of power over time are depicted in Figure 3 for an exercising session of *60* minutes ($t=3600$) for $\gamma = 0.001$, $CP_0 = 210W$, $W' = 18000J$. An overview of the specifications of the scenarios for distribution of effort over time and their outcomes can be found, respectively, in the second and third column of Table 1 (for a session of length t). As from some first analysis it was found that distributions with higher levels later in time perform better, the three non-constant patterns were taken as starting at the basic level CP_0 and increasing over time. The pattern for fully *constant power* was used from (13). For the pattern with *two constant levels*, the interval was divided in [0, t/2[where the constant level CP_0 was used, and [t/2, t]. In the latter interval (13) was applied again, but with interval length t/2 instead of t. For the *linear distribution* a function

$$P(u) = CP_0 + au$$

was used, with $a>0$. Using (8) it was found that

$$a = \gamma W'/t\,(\frac{e^{\gamma t}-1}{\gamma t} - 1)$$

when it is assumed that W' is fully used during the interval [0, t]. For the *exponential distribution* a function

$$P(u) = CP_0 + \alpha\, e^{-\gamma(t-u)}$$

was used. From (6) it follows that $\alpha = W'/t$ when W' is fully used during the interval [0, t]. This explains the formulae in the second column of Table 1. The formulae in the third column were obtained by using (6b) and symbolically determining the integral.

Table 1. Overview of the four different patterns for power over time

pattern	**power distribution over time**	**work performed**
constant	$P(u) = CP_0 + \gamma W'/(e^{\gamma t} - 1)$	$W_{tot}(t) = CP_0\, t + W'/\frac{e^{\gamma t}-1}{\gamma t}$
two constant intervals	$P(u) = CP_0$ when $0 \leq u < t/2$ $P(u) = CP_0 + \gamma W'/(e^{\gamma t/2} - 1)$ when $t/2 \leq u \leq t$	$W_{tot}(t) = CP_0\, t + W'/\frac{e^{\gamma t/2}-1}{\gamma t/2}$
linear	$P(u) = CP_0 + u\,\gamma W'/t\,(\frac{e^{\gamma t}-1}{\gamma t} - 1)$	$W_{tot}(t) = CP_0\, t + \frac{1}{2}\gamma t\, W'/(\frac{e^{\gamma t}-1}{\gamma t} - 1)$
exponential	$P(u) = CP_0 + W' e^{-\gamma(t-u)}/t$	$W_{tot}(t) = CP_0\, t + W' e^{-\gamma t}\, \frac{e^{\gamma t}-1}{\gamma t}$

In Figure 4 it is shown how the four different strategies compare for different lengths t of the session and $\gamma = 0.0005$, by depicting the average total power $W_{tot}(t)/t$ (calculated by the four formulae in the third column of Table 1) for different time periods. The constant power distribution is the lowest, and the pattern with two constant intervals the highest. The exponential and linear pattern are in between, with the linear pattern a bit higher.

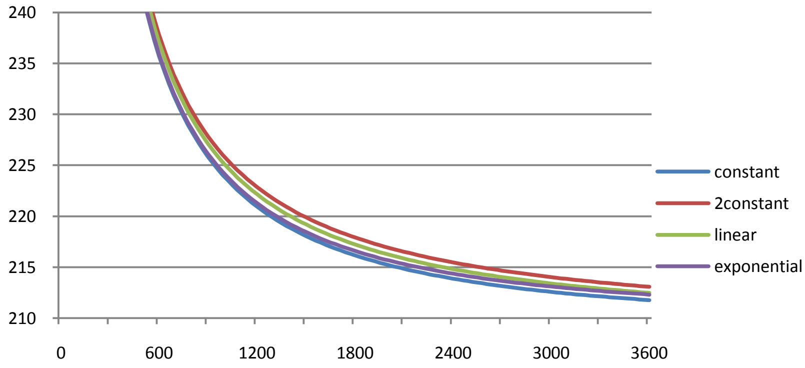

Figure 4. Average total power W_{tot}/t for the four cases against duration of the session ($\gamma = 0.0005$, $W' = 18000J$, $CP_0 = 210W$)

In Figure 5 a more detailed picture is given for the same γ. Here the differences with the constant pattern are shown. Notice that these differences are in the order of magnitude of *0.5* to *1*%. For example, for a sport session of about *10* minutes, this may make a difference of *3* to *6* seconds in time, which may be significant enough to be decisive for winning a race or not.

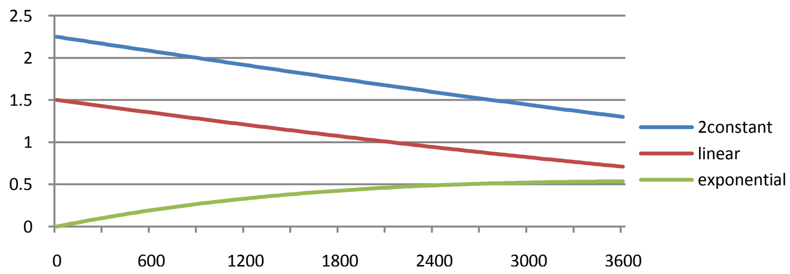

Figure 5. Difference between the average power W_{tot}/t for the three nonconstant distributions compared to the constant case against duration of the session ($\gamma = 0.0005$ $W' = 18000J$, $CP_0 = 210W$)

4. Discussion

This paper addressed how a computational approach for anticipatory model-based decision making can be used to decide for an appropriate distribution of effort over time in high load tasks. The model referred to in 'model-based' is a human-like agent model that describes how physiological effort relates to feeling exhaustion or fatigue, which is used as a form of monitoring the agent's remaining resources. The agent model makes use of the concept of dynamical critical power that indicates the level of (sustainable) power that can be generated for which the level of fatigue remains the same. In the model this critical power is dynamic. More fatigue means lower critical power. If a level of power is generated above the critical power, then fatigue will increase which makes that for future efforts less resources are left. Maximal critical power means no fatigue, occurring (only) in a state without prior exercising. The presented approach includes this human-like agent model formalising monitoring of levels of fatigue over time, and model-based techniques formalising decision making on the distribution of effort over time.

To illustrate the decision making approach, three possible nonuniform patterns for distribution of effort over time were considered and compared to the uniform pattern of constant power over time. For all of these three nonuniform patterns it turned out that a distribution with higher power levels later on in the time interval provide the best performance. For example, for a linear distribution an increasing linear function performs best, and for a distribution based on two subintervals each with constant power, the best performance is obtained when the power level in the second interval is higher than in the first interval. Also a pattern based on exponential increase performs better than the uniform distribution. These outcomes suggest a general heuristic: to initially keep the effort a bit modest and increase the effort later on in the time interval, in such a way that full exhaustion is reached just at the final time point.

As a point of departure for the human-like agent model, basic concepts were adopted from the model in [18]; the latter model was also applied as part of the more complex model presented in [1]. The more extensive mathematical analysis and the model-based anticipatory decision making addressed in the current paper were not addressed in [1] or [18]. In order to apply the agent model to persons an adequate estimation of the parameters is important, which was described in [2] for the more complex model from [1].

An application area for this approach is formed by ambient intelligence used in physical exercise and sport: devices that monitor human functioning are able to analyse this functioning, and give appropriate advices. When an approach is used as presented here, more advanced ambient intelligent agent applications can be developed.

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