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Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback

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Abstract. Efferent motor signals to skeletal muscles concern not only the space/time pattern of motion, but also the setting of muscular performance and through this the control of the current metabolic rate. For an optimal adjustment of metabolic rate during heavy exercise – e.g. in athletic competitions – a feedback control system must exist, including a programmer that takes into consideration a finishing point (teleoanticipation). The presented experiments, using Borg's scale, indicate the existence and functioning of a system for optimal adjustment of performance during heavy exercise and the relevance of teleoanticipatory effects. Thus motor learning includes not only somatosensory control, but also metabolic control. With regard to migratory birds, such metabolic control would have to operate in the individual as well as in the migrating flock as a whole.

Key words. Borg's scale; extracellular metabolic regulation; metabolic control; motor control; motor learning; psychophysiological feedback; RPE-scale; teleoanticipation.

Introduction

This short review is conceived as a proposal for discussion concerning skeletal muscle and the external regulation of its metabolism. The discussion in the literature focusses mostly on the intracellular regulation of metabolism. Extracellular regulation of metabolism can be brought about by hormones as well as by the autonomic nervous system. Quite obviously the somatic nervous system as well as behavioural control are also involved.

Let us imagine a Marathon runner during a competition. He has to perform his run with an optimal speed. That is, he must optimize the biomechanical parameters 'stride length' and 'stride frequency'. Both parameters are the basis of speed and performance and determine, by intracellular coupling mechanisms, the metabolic rate of the skeletal muscle during a run. Concerning the rate of metabolism: if the athlete runs too quickly, he will not be able to finish because of early fatigue, but if he runs too slowly, he will not reach his aim (i.e. optimal racing time). Therefore the athlete has to arrange his energy consumption per unit time with respect to a finishing point, as discussed by Newsholme[1].

The common principles of motor control are based on a feedback system (fig. 1). The efferent signals contain information about the biomechanical pattern of motion: force (F) and displacement(s), both in a time period (t). F, s and t are the parameters of the space/time pattern of motion. They are fed back through afferent somatosensory channels as the basis of our everyday motion, optimized by motor learning. The somatosensory feedback and the motor learning, together with the anticipation of movement permit exercise to be optimized with respect to metabolic economy. From a physical point of view we can write:

$F \times s = W$; $W : t = F \times v = P$ (F = force, s = displacement, t = time, W = work, v = velocity, P = power).

According to this view, the efferent motor pattern (fig. 1) would also contain information about the intensity of physical performance, and finally about muscular metabolic rate, as brought about by the intracellular mechanisms that couple work and the metabolism of muscle tissue. These considerations form the basis of our concept of an extracellular control system for the control of the metabolic rate in muscle during exercise, which includes the somatic nervous system as a part of the central nervous system. The efferent signals (fig. 1) control not only biomechanical parameters, but also muscular metabolism.

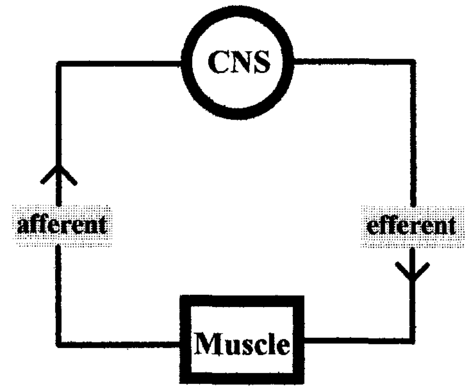

Figure 1. Principle of feedback control in the motor system.

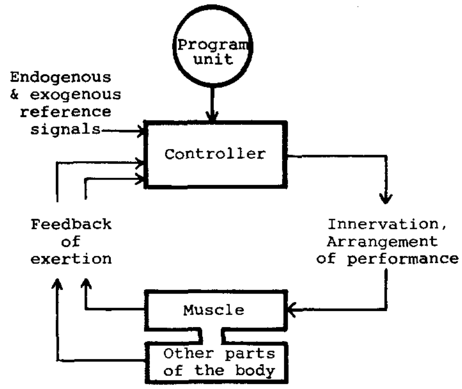

Figure 2. Hypothetical model of a control system for optimal adjustment of performance during heavy exercise, including teleoanticipation by a programmer[2].

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

Figure 3. Modified Borg's scale in English (referring to ref. 3, arrangement 6).

What do we have to consider with respect to the afferent channels in figure 1? They obviously must include essential biomechanical feedback for optimizing the 'somatosensoric' control. But do they also include metabolic feedback parameters for optimizing the 'metabolic' control? For an optimal adjustment of energy consumption the runner needs such feedback, assuming that he possesses an extracellular feedback control system for optimal adjustment of metabolic rate. Such a control system could use behavioural psychophysiological mechanisms (fig. 2).
To verify whether such a system exists, four aspects should be analyzed: (1) efferent channels, (2) afferent channels, (3) the center as an input/output black box, and (4) muscular output as a consequence of modifications of the central programmer. An established psychophysiological instrument for testing perceived exertion is Borg's RPE-scale (Ratings of Perceived Exertion, fig. 3, cf. ref. 3, reviews in refs 4, 5). The shortest time required for adequate rating of exertion is about 1 min (fig. 4).

Procedure and methods

Two series of psychophysiological experiments were done. We analyzed the possibilities of aspects 2 and 4 (above) in exercise experiments with athletes and non-athletes, using Borg's RPE-scale (fig. 3). In the first series we analyzed the afferent channels by assessing RPE-values during exercise of different intensity-levels and in the second series we analyzed the muscular output during exercise after setting the programmer at different RPE-values. The detailed methods are described in the references given in the figure legends.

Results

In experiments with 10 athletes we tested the linearity of the system (figs 5 and 6) in individual cases as well as for the means. Different levels of work had to be performed and the RPE-values were obtained after 1 min of exercise. The mean intraindividual reproducibility expressed as the coefficient of variation ranged between 9% (200 W) and 13% (100 W).
In the next series of experiments we prescribed RPE-values to the subjects, and requested them to adjust their performance during different types of exercise in laboratory and field experiments to meet these RPE-values. The figures 7, 8 and 9 show the time courses of performance for durations of about 1–2 min and 5 or more min, respectively.
In all cases the levels of performance were graduated systematically according to the RPE-values. The time courses were very different, depending on the duration of work. In the short time activities, the performance declined without a plateau or a final spurt. In the longer activities the subjects chose a longer plateau phase and a final spurt. In the ergometric experiments (fig. 9) the time course depended on the level of exertion: At the low RPE-values the power increased until a plateau was

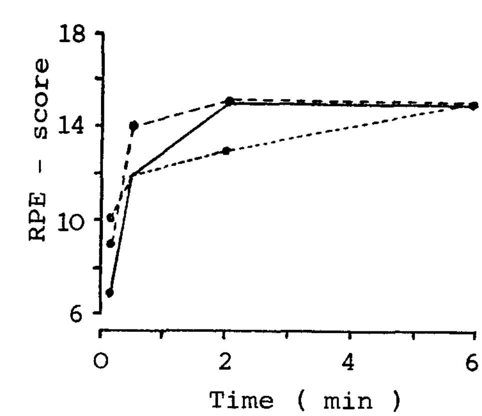

Figure 4. Time behaviour of perceived exertion of three subjects, performing exercise at 165 Watt. Drawn after values from Edwards et al.[7]

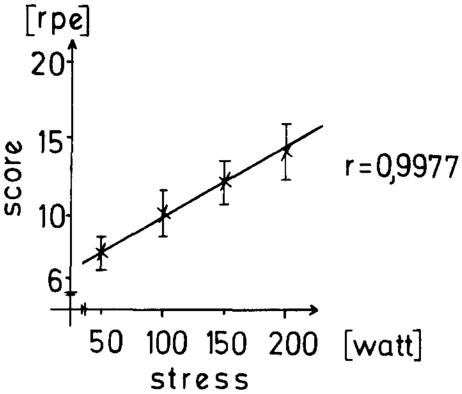

Figure 5. Relation between perceived exertion and stress (load). Interindividual means with sd; r is calculated from the 4 means[6].

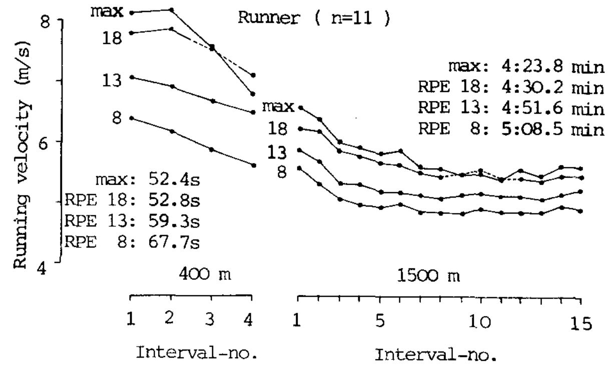

Figure 7. Arrangement of running velocity over the 400 m (left) and 1500 m (right) distances at different given RPE-levels, means of 11 athletes. max = running with maximal, racelike effort (cf. ref. 2, values from ref. 8).

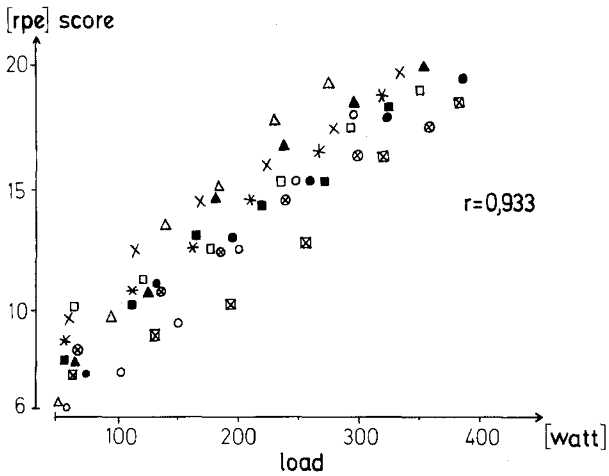

Figure 6. Correlation diagram for the relation between perceived exertion and load (stress). Intraindividual means of 10 athletes, based on the experiments with 6 fixed strain values (% of W_{170}[6]).

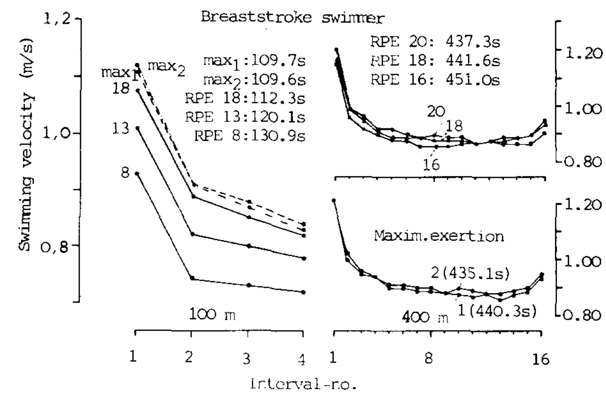

Figure 8. Arrangement of swimming velocity for the 100 m and 400 m distances (breaststroke) at different given RPE-levels[2]. Left: Means of 15 female sport students[9]. Right: Means of 5 female and 5 male sports students[10,11].

reached. In the case of the high RPE-values a distinct power overshoot was observed. In figure 10 performance, and heart rate as an indicator of physiological strain, are related. The discrepancy between power (W) and heart rate during the first minutes is evident.

Discussion

Borg's RPE-scale is an internationally well established instrument to measure perceived exertion[4,5]. Perception of exertion is obviously a capability, acquired by using Borg's-scale not only in experiments, but also during everyday activities as well as athletic activities. The wide applicability of the test results from this everyday practice. There are no difficulties in using Borg's-scale, nor is specific practice necessary for adults. A working person can rate his or her value instantly, and if he or she is asked to work at an RPE set point, (s)he can adjust his or her performance – and through this his or her metabolic rate – systematically and adequately. This supports the hypothesis that perceived exertion is part of a feedback system for optimal adjustment of exertion; and this adjustment includes performance and metabolism as well.

In addition the influence of the time delay (fig. 4) on reaching the set value (figs 7, 8, 9 and 10) supports our hypothesis of a feedback regulating system. If the appropriate feedback comes too late an adequate plateau cannot be attained. If there is enough time, such a plateau can be reached, including energy reserves for a final spurt. In cases where sufficient time is available it is possible to graduate plateaus of performance and heart rate systematically in correspondence to RPE-values (fig. 10). In the first minutes there is obviously a time delay for RPE, and a time delay with another response time for the heart rate (figs 4 and 10). These different time delays underline the difficulty of achieving an adequate feedback in the first minutes of heavy exercise.

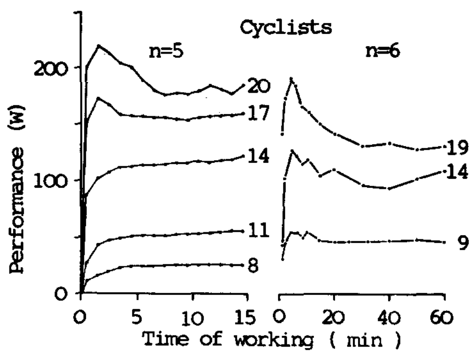

Figure 9. Arrangement of performance during cycling on an ergometer at different given RPE-levels[2]. Left. 5 athletes of different sports, cycling 15 min[12]. Right: 6 cyclists, performing 60 min[13].

Our experiments demonstrate:

1. Efferent motor signals to muscle include information not only for the biomechanical aspects of motion, but also for the intensity of metabolic rate.
2. There exists a capacity to feed back the intensity of metabolic rate to the motor control system, which is analogous to the somatosensory feedback.
3. This suggests the existence of an extracellular closed-loop-regulation of muscular metabolic rate during heavy exercise.
4. Motor learning is usually restricted to the somatosensory system ('biomechanical aspect'), but it also includes the optimal adjustment of exertion and performace during heavy work ('metabolic aspect').
5. Anticipation concerns not only the basis of harmonic, biomechanically optimized motion, but also a teleoanticipation for the optimal arrangement of exertion, which avoids early exhaustion before reaching a finish point[14].
6. The 'regulation center' of the behavioural feedback system has to perform complex calculations: The efferent signals of the motor system have to take into consideration metabolic reserves, actual metabolic rate and the time required to finish the exercise.

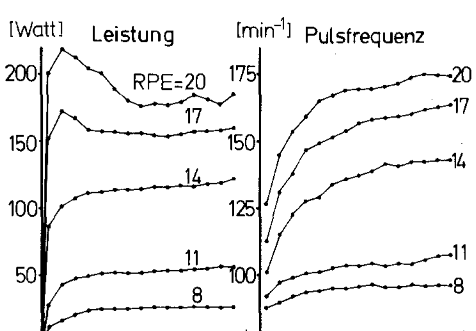

Figure 10. Set power ('Leistung') and resulting heart rate ('Pulsfrequenz') during 15 min of ergometric exercise with different RPE-levels[12].

These considerations underline the complexity of the motor system, not only concerning the regulation of biomechanics, but also for the extracellular regulation of muscular metabolic rate during heavy exercise[15,16].

Our experiments indicate the existence of such a system for the regulation of muscular metabolic rate by psychophysiological feedback and show its limits of accuracy. By this control system humans are able to adjust their level of performance (and through this the metabolic rate) during heavy exercise in an optimal way.

Finally, one might ask whether such a closed-loop feedback system exists in other animals, for example in racehorses or in migratory birds? Migratory birds need fat as fuel[1]. They have to use their energy stores by an optimal adjustment of the intensity of energy consumption over time. Furthermore, this is necessary not only for individuals, but also for the flock of birds. The fact that this type of adjustment can regularly be observed reflects a fantastic achievement of nature.

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