PSYCHOPHYSIOLOGICAL INTERACTIONS LEADING TO INCREASED EFFORT, LEG FATIGUE, AND RESPIRATORY DISTRESS DURING PROLONGED, STRENUOUS BICYCLE RIDING

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INTRODUCTION

One of the important aspects of physical work capacity is the ability to perform prolonged, submaximal work. In spite of the extensive amount of literature on endurance capacity, the limiting factors are not well understood (1,2). Most investigators have concentrated on singular mechanisms located in the peripheral motor system (e.g., muscle glycogen depletion), or in the oxygen transport system (e.g., inadequate cardiac output), or in central nervous system function (e.g., decreased motivation), etc. Few investigators have approached endurance capacity from a multidimensional point of view.

We began our study of endurance capacity by presuming that the subjective symptoms reported at the end of a prolonged cycle ergometer task might reflect these complex factors limiting endurance (3). Clustering of symptoms were found and then labeled the Bicycling Fatigue, Task Aversion, and Motivation categories of a Physical Activity Questionnaire. A further analysis indicated that the Bicycling Fatigue cluster was composed of three sub-groups: General Fatigue, Leg Fatigue, and Cardio-Pulmonary Distress (4). A pyramidal schema has been proposed to integrate the various levels of subjective symptomatology reported during prolonged work (Figure 1). At the most basic level, the assumption was made that discrete symptoms have their genesis in the physiological changes occurring during work, i.e., within the Physiological Substrata. At the lowest level of organization, groups of discrete symptoms form the three subcategories of Bicycling Fatigue. At the next highest level, Bicycling Fatigue is formed along with the Task Aversion and Motivation categories. Symptoms from all of these categories are then funneled into a global report of Undifferentiated Fatigue. Thus, the interaction of physiological changes and

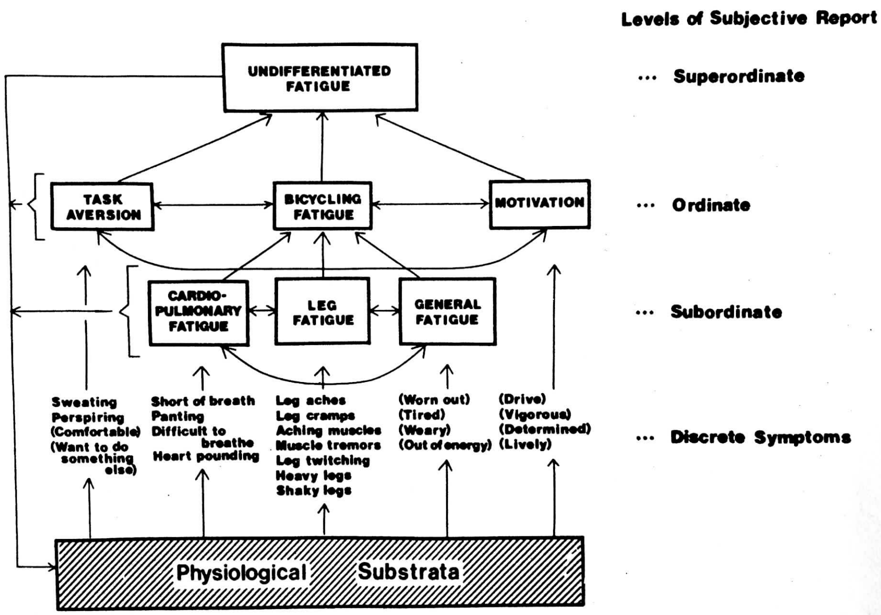

Figure 1. Pyramidal schema for subjective symptomatology during exercise.

sensory processing are proposed to be an important interaction leading to fatigue and consequently to the limits of endurance capacity (5).

The purpose of this report is to show that prolonged physical work is largely determined by the processing of physiological information. Our initial hypothesis was that an alteration in the functioning of the motor and cardio-pulmonary systems would be associated with an increase of symptom severity that would influence the duration a constant work task is performed.

METHODS

Subjects

The subjects were eleven male students whose anthropomorphic characteristics are listed in Table I. The students were obtained from the physical education classes. For their participation in the study the students received no monetary reward but were told that they would receive information regarding their present physical fitness that they would find informative. Prior to beginning, each subject was seen by a physician to determine if they had any physical condition which would preclude them from safely participating in strenuous work. At the beginning of the study, the entire test procedure and possible health hazards were explained to them, and they signed a subject consent statement indicating that they were made aware of the entire test procedure and the possible health hazards.

Apparatus

The work was performed on an electrically braked cycle ergometer (Quinton). Expired air was collected using open circuit spirometry with subjects wearing a face mask (Monahan) which led to a dry gas meter (Parkinson-Cowan) and finally into meteorological bags. The dry gas meter was interfaced with a chart recorder (Physiograph, Narcobio). The gas collected in the bags was analyzed for O_2 and CO_2 using Godart Rapox and Capnograph analyzers, respectively. The dry gas meter was checked three times during the course of the study, and the error was determined to be <2L per 100 L. The gas analyzers were calibrated before and after each session with gases analyzed by the Scholander technique. The electrocardiogram was monitored via a telemetry circuit and recorded on the chart recorder. The electromyographic signal was obtained from surface electrodes interfaced to the chart recorder.

The Physical Activity Questionnaire was administered by a slide format from a slide projector (Kodak) to a screen placed

TABLE I. Anthropomorphic characteristics of the subjects (n=11)

	Age (years)	Weight (kg)	$\dot{V}_{O_2}$ max (ml/kg/min)
Mean	20.7	70.0	55.4
SEM	±0.5	±2.6	±2.8
Range	(18-24)	(56.7-85.7)	(42.2-71.7)

directly in front of the subject. The PAQ reports were obtained by asking the subject to hold up one to five fingers to indicate the number corresponding to the five point Likert-type adjective scale for each item that best described how he was feeling at that moment. The approximate time required to complete the PAQ was one minute 30 seconds to one minute 45 seconds.

Procedure

Session I for the subject entailed the signing of the consent form and practicing of the taking of the questionnaire. Determination of $\dot{V}_{O_2}$ max was made according to the graded cycle ergometer procedure of McArdle et al (6). A workrate of about 65% $\dot{V}_{O_2}$ max was selected from a graphic representation of Table A-1 of Åstrand and Rodahl (7).

The sequence of events during each test session follows. First, the subject was told that he was to begin pedaling at 60 rpm and that he was to keep the bicycle at 60 rpm's until he could not maintain that rate any longer. The scheduled recording of the physiological and PAQ data occured at 3, 6, 9, 12, 20, 30, 40 minutes, etc., until he indicated that he was going to stop. Recording of the physiological data occurred during the one-minute interval prior to the above indicated sample times, while the symptomatology reports were obtained in the period immediately afterwards. This was done to reduce the likelihood of the PAQ procedure to affect physiological measures, e.g., respiratory rate. The subject was told that when he wanted to stop, he was to hold up two fingers, indicating that he would

TABLE II. Work performance characteristics

Group		$\dot{V}_{O_2}$ max (ml/kg/min)	Workrate (%$\dot{V}_{O_2}$ max)	Duration (min)
I- Least Fit	(n=3)	47±4	67±5	13±3
II- More Fit	(n=4)	58±11	70±4	25±5
III-Most Fit	(n=4)	59±6	62±7	59±6

ride for two additional minutes. The PAQ was then begun, and one minute later the physiological measures were taken for a one-minute period.

To test for between-group and time course differences, appropriate analysis of variance were performed. To test for inter-relationships, Pearson product-moment correlations were done.

RESULTS

Table II shows the overall work characteristics. The range in ride duration was large from 9.87 min to 68.95 min. The group of subjects riding for 55.30 min or more clearly are distinct from the other subjects who rode 32.00 min or less. The latter group was arbitrarily divided roughly in half. This produced three endurance capacity groups for comparison: I- best fit; II- more fit: III- most fit. $\dot{V}_{O_2}$ max was statistically not different for any group. Also the workrate (mean ± SEM), 66.2 ± 1.8 % $\dot{V}_{O_2}$ max, was not different for any group.

Motor System Response

The time course of vastus lateralis EMG amplitude for the three groups is shown in Figure 2. The EMG record was not interpretable for one subject from Group I. A highly significant decrease in EMG amplitude occurred at 6 min in the other two subjects in Group I. The decrease in EMG amplitude became significant at 20 min for Group II and at 30 min for Group III. A similar time course pattern of each group was found for the Leg Fatigue Score (Fig. 3). The 3 min score was not different for any group, but the rate of score increase was highest for

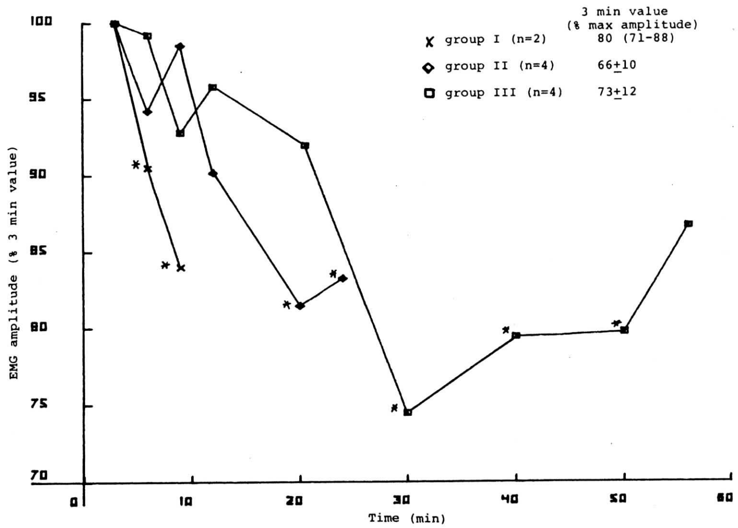

Figure 2. Decrease in EMG amplitude.

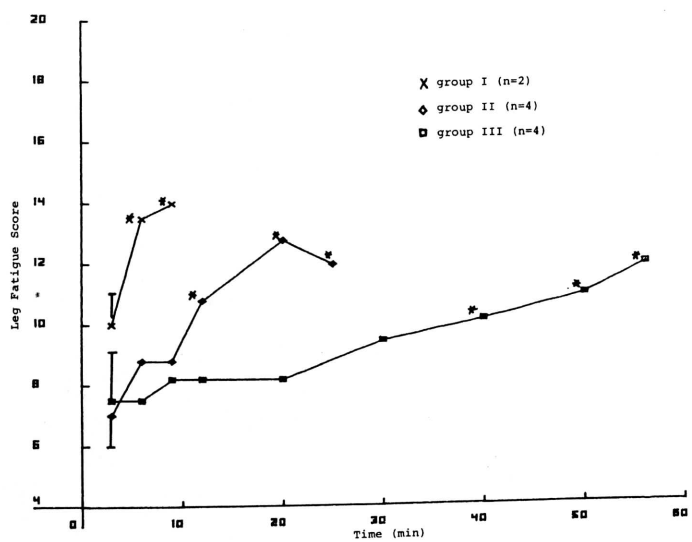

Figure 3. Increase in Leg Fatigue Score.

Group I, intermediate for Group II, and least for Group III. In each group, the increase in Leg Fatigue Score was highly related to the decrease in EMG amplitude (Fig. 4).

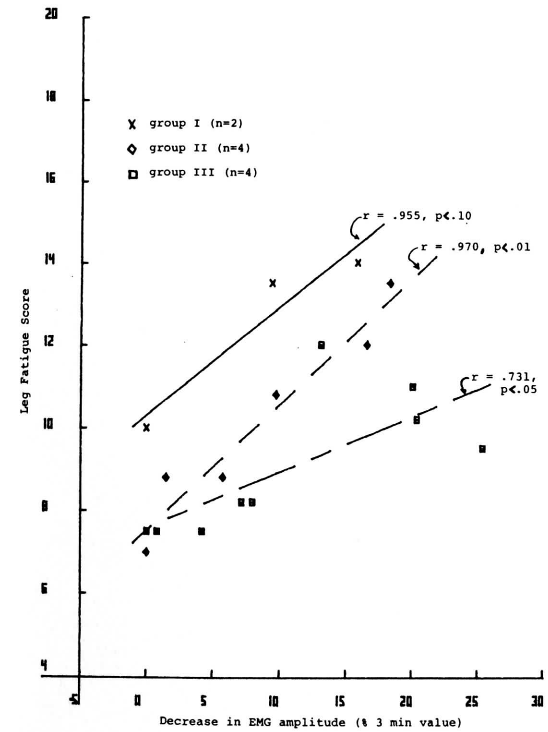

Figure 4. Relation of Leg Fatigue Score to the decrease in EMG amplitude.

During prolonged work, the duration of EMG activity also decreased. The correlations of Leg Fatigue Score to decreased EMG duration were significant but the correlation coefficients for Group I, II, and III were .765 (p=n.s.), .766 ($p<.05$), and .792 ($p<.01$), respectively.

Thus, during prolonged work, vastus lateralis EMG amplitude and duration decreased. This decrease was significantly associated with an increase in leg fatigue symptom severity. Greater leg fatigue was reported for a given decrease in EMG amplitude for

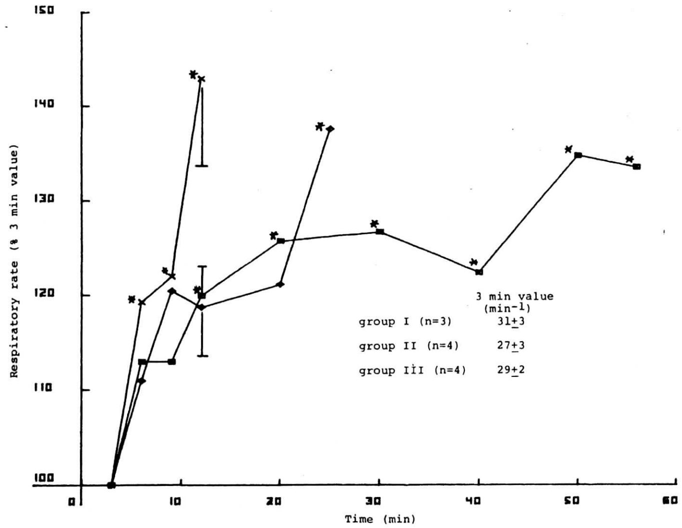

Figure 5. Increase in respiratory rate.

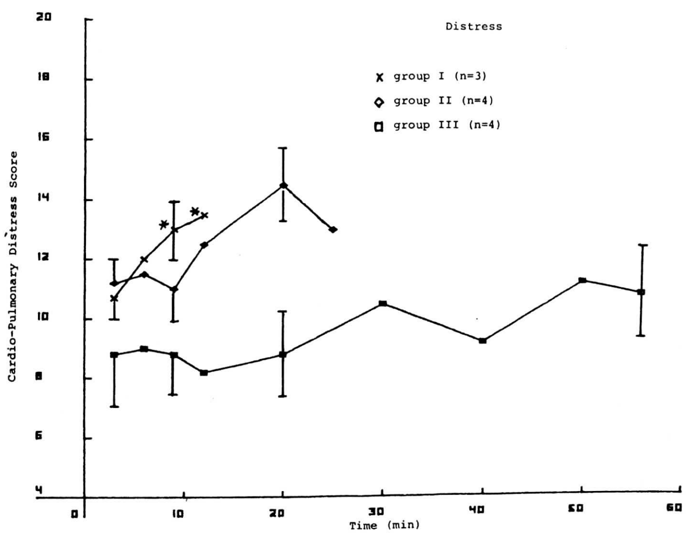

Figure 6. Increase in Cardio-Pulmonary Distress Score.

the least fit and the more fit groups of subjects than for the most fit group. The more the group rode before stopping, the less rapid were the changes in EMG activity and leg fatigue symptoms.

Cardio-Pulmonary System Response

The time course of respiratory rate for the three groups is shown in Figure 5. Group I showed a continuously rapid increase in respiratory rate; Group II plateaued and then increased at the end of the ride; Group III showed a slightly increasing plateau. Figure 6 shows the time course for the Cardio-Pulmonary Distress Score. The 3 min value was not significantly different for any group. Group I reported a significant increase in symptoms at 9 min, whereas Groups II and III did not increase significantly. In each group, the increase in Cardio-Pulmonary Distress Score was significantly associated with the increase in respiratory rate (Fig. 7) with all groups having similar slopes but Group III having a lower intercept.

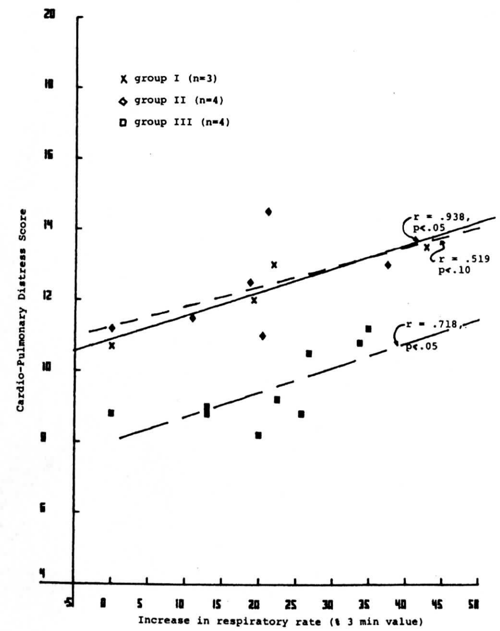

Figure 7. Relation of Cardio-Pulmonary Distress Score to the increase in respiratory rate.

With prolonged work, the tidal volume decreased slightly and the heart rate increased slightly for all groups. The correlation coefficients between Cardio-Pulmonary Distress Score and decreased tidal volume or increased heart rate were of a similar magnitude as that observed for respiratory rate.

Thus, during prolonged work, heart rate, respiratory rate increased and tidal volume decreased. These changes were significantly associated with an increase in cardio-pulmonary symptom severity. Greater cardio-pulmonary distress was reported for a given change in heart rate, respiratory rate, and tidal volume for the least fit and more fit groups of subjects than for the most fit group. The more the group rode before stopping, the less rapid the changes in cardio-pulmonary functioning and cardio-pulmonary symptoms.

DISCUSSION

The dissimilarities in the ability of each fitness group to maintain physiological steady-states found in this study were striking. For dynamic work the observed decrements in EMG activity apparently has not been reported. These decrements suggest that major alterations in motor unit recruitment and rate coding must have taken place. The subjects in the least fit group were weight lifters and bowlers; those in the most fit group were distance runners and cross-country skiers. Vastus lateralis muscle fiber type is predominantly fast twitch and glycolytic in weight lifters and slow twitch and oxidative in distance athletes (8). If fast twitch muscle function becomes rapidly impaired during prolonged work, it is not surprising that subjects who have predominantly fast twitch fibers comprise group I and those who have mostly slow twitch non-fatiguible fibers comprise group III.

The changes in cardio-pulmonary function are well-known (9, 10). However, no report apparently has examined individual differences in the rate of impaired function. The work rate above which ventilation no longer remains at a steady-state level has been

defined as the anaerobic threshold (11). Recently, individual differences in the anaerobic threshold have been correlated with a predictor of muscle fiber type predominance: the lower the anaerobic threshold, the predominant are fast twitch fibers (12). It should be noted that Asmussen et al. (13) used curare to reduce muscle function and also observed a neurogenically stimulated hyperventilation. Thus, one would expect weight lifters and others having fast twitch fibers to hyperventilate and comprise Group I and those with slow twitch fibers to comprise Group III.

In this study, symptom severity was highly associated with physiological changes. Stevens and Cain (14) and Bujas et al. (15) have found that changes in EMG activity parallels changes in effort or fatigue resulting from prolonged static work. We propose that the psychophysiological model shown in Figure 8

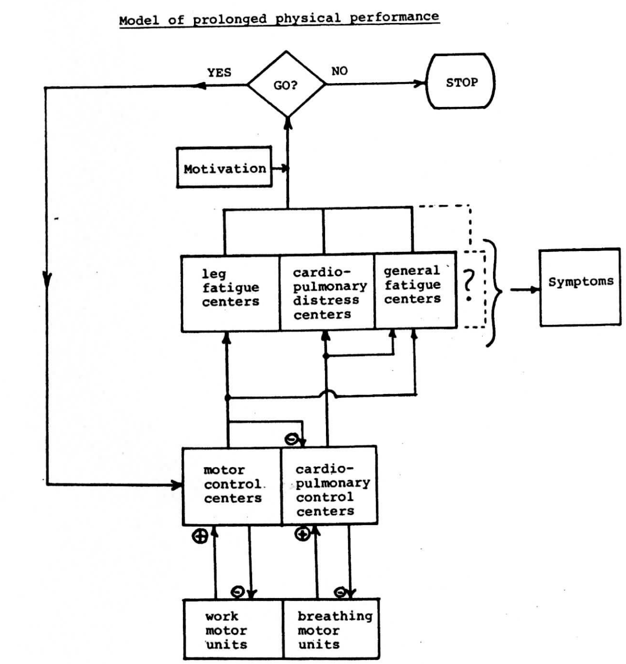

Figure 8. Model of prolonged physical performance

might be a major influence in determining endurance capacity. Its implications are threefold. First, those who are less able to achieve and maintain a steady-state in muscle function will be those who voluntarily terminate work more quickly. Second, those who are less able to achieve and maintain a cardio-pulmonary steady-state will voluntarily terminate work more quickly. A non-steady-state response might be related to impaired muscle function. Last, general fatigue and motivation whose physiological correlates are vague, also influence the decision to continue.

If this model of prolonged performance has validity, then changes in symptoms reported should predict endurance capacity. Table 3 shows the prediction of ride duration from a multiple regression of the symptom scores reported at 6 minutes. After all clusters are included, the multiple regression accounted for 76% of the variability in ride duration. Leg Fatigue Score and Motivation Score contributed most. The other symptom scores contributed less since they were highly correlated to Leg Fatigue. Thus the processing of changes in physiological functioning appears to be an important factor in the decision to continue work.

CONCLUSIONS

1. During prolonged physical work, physiological changes of the motor and cardio-pulmonary systems are highly associated with the severity of symptoms reported.
2. The decision to continue work is suggested to be the result of an individual's processing of the changes in motor system functioning.

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Table 3. Multiple regression of ride duration from symptoms reported at 6 minutes

Variable	Multiple r	r square	Overall F	Significance
1. Leg Fatigue	.718	.515	11.70	.006
2. Motivation	.812	.661	9.71	.005
3. Perceived Effort	.830	.688	6.63	.012
4. General Fatigue	.848	.719	5.11	.024
5. Cardio-Pulmonary Distress	.872	.760	4.44	.038

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DISCUSSION

Knuttgen was concerned about the decrease in some physiological variables when an increase was expected. Since the work load had been set to correspond to 70 per cent of maximal oxygen uptake, Knuttgen was astonished that Weiser's subjects stopped working after such a short time and that they described their sensations as though they had just participated in a marathon. According to studies by Saltin and others, one would expect them to continue working for about four hours instead of about half an hour. Knuttgen concluded that to build a psychological system upon such unusual physiological responses might be fettered with methodological problems.

Weiser answered that the high altitude, 1,600 m above sea level, of his laboratory might be an important factor in explaining why his subjects were such short riders. Also, he was not looking for exceptionally high efforts and therefore did not push subjects particularly hard. Weiser noted that different groups of athletes differ as to maximal oxygen uptake, muscle fiber composition, endurance performance and capacity. For example, people who become short of breath at a moderate work load are typically sprinters, jumpers and weight-lifters and have a lot of fast twitch fibers. In order to work at 70 per cent of maximal oxygen uptake, a weight-lifter has to recruit many fast twitch fibers that are causing sensations of fatigue. Persons whose muscular structure is composed of fast twitch fibers may also be culturally conditioned to behave and perceive in another way than long-distance runners.

Knuttgen objected, saying that it was a bit dangerous to make assumptions about composition and fatiguing of fast twitch fibers when no measurements had actually been made. Knuttgen did not agree that the high altitudes were an important factor since not absolute exercise intensity but relative exercise intensity was being measured.

Teghtsoonian agreed that the different sensory events underlying the perception of exertion should be isolated. He was troubled by the changes over time which all of the measures underwent, thereby becoming correlated with each other.

Weiser replied that he had performed partial correlations in which the time factor was excluded, but he obtained about the same relationships.

Linderholm found it interesting to see in Weiser's final multiple regression that muscle sensations and local factors determine the point at which the subject terminates his work. He pointed out that it was also important to distinguish between different types of work as to the amount of muscles and muscle mass involved. When working with small muscle groups, the local factors become much more important than when working with large muscle groups, in which cases central circulatory and respiratory factors are stressed very much. Linderholm alluded to some comparisons which he has made, with this purpose in mind, between leg and arm work and also between different kinds of arm work. He obtained higher ratings of perceived exertion for arm work in a high position than in a lower position.

Euler commented on the possible effects of elevated body temperature in response to the prolonged, strenuous work load. In contrast to hypercapnia, hypoxia, exercise per se and moderate doses of anesthetic drugs, which do not change the relationship between ventilation and tidal volume (or between ventilation and rate), elevation of body temperature (or hypothalamic temperature) does have a stimulating and fairly selective influence on the respiratory rate with but small concomitant changes in tidal volume (Hey et al., 1966; see also Euler et al., 1970; Euler & Trippenbach, 1976), thus changing the relative proportion between the two.

With regard to Weiser's last, schematic figure Euler emphasized that in addition to the automatic, metabolic control of ventilation governed mainly by central and peripheral chemoreceptors, breathing also subserves important behavioral functions. He noted that these two control systems have separate pathways all the way down to the spinal motoneuron pools for the respiratory muscles.

The behavioral system, located mainly in sensorimotor cortex and limbic forebrain structures, seems to be of importance not only for adapting the breathing system to speech and other behavioral activities, but also for preparing the body for the metabolic demands coupled with high activity and exercise (Plum, 1970).

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GENERAL DISCUSSION

Borg: We have been discussing many different kinds of problems: definitions, methods, physiological and psychological facts or observations and intercorrelations between them. I am sure we do not agree upon many of the definitions given during this conference - e. g. how is "fatigue" to be defined? - nor upon when to use psychological concepts rather than physiological or physical concepts. The discussion of "stress and strain" elucidates one of these problems. Depending upon our different scientific backgrounds we have been focusing our interest on different aspects of the stimulus - response relation and using terms drawn from somewhat different scientific vocabularies. We are working on more or less complex and more or less objective and subjective levels of description or explanation. There is a definite need to integrate facts obtained through these different approaches to psychophysiological problems of work and effort to which we all devote our efforts and find so fascinating.

Among the methodological problems we have been discussing are the different techniques of measurement and scaling, one of which concerns the question of when we should use a ratio scaling method and when it is sufficient or perhaps better to use a simple category method. Though this problem has attracted greater interest from the psychologists, it is also very important to the physiologists. And when we want to look at psychophysiological interrelations we must be careful that the measuring system can accommodate the different kinds of values used for the comparisons. When determining, for example, how a perceptual or a physiological variable changes with a variation in physical intensity, we should use ratio scales, but when only ascertaining which of several work tasks is the hardest or when making differential or clinical observations, category scales of an interval type such as the RPE-scale are very useful.

Since this is an interdisciplinary symposium, the psychophysiological intercorrelations are, of course, very fascinating and we must seriously consider how they are to be interpreted and understood. We have spoken of perceived exertion as a gestalt. The behavior, the complex performance