Collected Papers on Exercise Physiology from the Human Performance Laboratory University of Salford

PHYSIOLOGY'S CONTRIBUTION TO SPORT* (Some Advances in Physiology and their Application to Sport)

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At the present time the proliferation of scientific and medical journals is enormous. New journals are coming into being almost monthly. A recent British Nobel Laureate and some of his learned colleagues have called for an end to this seemingly endless flood. For one who works in, and attempts to keep abreast of, work in the field of exercise physiology I whole-heartedly support this move.

In the main, most sportsmen and their coaches are interested in being able to perform better, that is to go faster, to go further. They have in recent years looked to the physiologist for help in this sphere. As long ago as 1964 in a joint meeting held in London by the Fitness and Training Section of the Ergonomics Research Society and B.A.S.M., a coach said: "What I really want to know is how to make my athlete go faster and if he is not going faster, why not, and can you do anything to help me to achieve this, for example by altering training methods?"

The term 'training' implies to many the acquisition and development of skill. Therefore, for this paper, I will use the term 'physical conditioning' for it relates to the repeated participation in bouts of exercise to enhance one's physical capabilities including the cardiovascular.

An extensive review of the anatomical and physiological changes associated with conditioning in man and animals can be found in the work of Grande & Taylor, 1965 (1).

Living organisms, including Man, are not machines. In contrast to machines, which wear out and deteriorate faster the more they are used, biological systems generally develop an adaptive increase in functional capacity in response to increased work loads, and undergo a decrease in functional capacity or atrophy when subjected to inactivity. In general, within genetically determined limits, the capacity of an

individual to perform a function depends on the demands placed on him in the preceding period, i.e., the strength of a muscle group decreases with inactivity, and increases as the habitual work load is increased.

The ability of man to perform physical work, his tolerance to it and those factors that limit the amount he can do, have been the subject of much investigation.

Since the work of Benedict & Cathcart, 1913 (2), in a metabolic study with special reference to the 'human', there has been interest in the uptake of oxygen ($\dot{V}O_2$) during physical work.

Classical studies in the early part of this century by Hill and his co-workers highlighted the possibilities of one or more physiological parameters being the limiting factor in the ability of man to perform work.

From these studies he made the following observations:

1. a. that each individual has a maximum level of oxygen intake per minute.
- b. that the level varies from one individual to another.
- c. that the extra work done above the maximum level of oxygen intake is by means of anaerobic metabolism, i.e. the oxygen requirement comprises oxygen intake and an oxygen debt, 1923 (3).
2. that a maximum value of oxygen uptake ($\dot{V}O_{2\text{ max}}$) of about 4 l./min was proposed, it was limited to this range 'not because more oxygen is required, but because the limiting capacity of the circulatory-respiratory system has been obtained', 1924 (4).
3. demonstrated that there is an upper limit to the capacity of the combined respiratory and cardiovascular system to transport oxygen to the

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muscles. There is a linear relationship between oxygen intake and work load until the maximum $\dot{V}O_2$ is reached. Further increases in work load beyond this point merely result in an increase in oxygen debt and a shortening of the time in which work can be performed, 1926 (5).

Hill et al, 1924 (6) and Herbst, 1928 (7), demonstrated that this maximum oxygen uptake attained by gradual increase in running speed could not be increased by any subsequent increase in cadence.

Extension of the knowledge on the relationship of oxygen utilisation and oxygen debt, to include the relationship between these variables was carried out by Dill et al, 1930 (8), 1932 (9), 1933 (10). Dill et al, 1930, op cit, noted individual differences in $\dot{V}O_2$ for a standard work task and Robinson, 1938 (11), noted differences due to age. Åstrand, 1952 (12) showed clearly that there are $\dot{V}O_2$ maximum differences for age and sex in males.

Further, altering the work task changes the maximum value for $\dot{V}O_2$, i.e. high values have been recorded by Christensen, 1969 (13) using a very hard treadmill task and short term (5 seconds) expired air collection with two subjects, mean values for $\dot{V}_e$ (BTPS) of 151.2 l./min and $\dot{V}O_2$ (STPD) of 5.31 l./min. The highest values reported are those by Saltin & Åstrand, 1967 (14), using 95 male athletes of the Swedish National Team, the best 15 subjects, $\bar{x}$ $\dot{V}O_2$ max (STPD) was 5.75 l./min, upper limit 6.17 l./min and $\bar{x}$ $\dot{V}_e$ max (BTPS), 158.7 l./min, upper limit 203.3 l./min.

It is generally now agreed that the ability to perform hard physical work is related to the maximum capacity of the cardio-vascular system to take up, transport and deliver oxygen to the active tissues.

Wilmore, 1968 (15) stated that maximal oxygen uptake has become widely accepted as the primary physiological variable which best defines the efficiency or capacity of the cardio-vascular systems. This variable is now regarded as synonymous with the term cardio-respiratory fitness and has been designated by some investigators as the most significant criterion of physical fitness, Balke, 1961 (16).

Theoretically, oxygen uptake ability is associated with work capacity. Hanson, 1965 (17) found the high occupational work output in lumberjacks correlated with large maximum oxygen uptakes. Archer, et al, 1965 (18), used $\dot{V}O_2$ max l./min to differentiate powerful from cyclists

Harris, 1958 (19) and Åstrand, 1956 (20), both feel that maximum oxygen uptake should be a good index of maximum physical power performance as it is held to be representative of the capacity of the energy delivering

processes. Åstrand, 1964 (21) stated that "A high transport capacity also implies that a given energy output can be accomplished with relatively less physiological strain." However, Davies, 1969 (22) states:

"At the present time the measurement of maximum aerobic power is widely accepted and favoured as a test of endurance fitness but, in my view, it only provides limited information on an individual's ability to perform work. In particular, it does not give a good guide to the capacity for exercise; the maximum aerobic capacity would be more informative in this respect, but as yet no reliable methods have been developed for its measurement. However, $\dot{V}O_2$ max does remain a decisive measure of the potential ability to perform at high intensity with large muscle groups."

Shephard, 1969 (23) stated that

"The maximal oxygen consumption is theoretically a good measure of cardio-respiratory performance, since it integrates the effective 'maxima' of the several processes concerned in the steady state transfer of oxygen from the environment to the active tissues."

Di Prampero and Cerretelli, 1969 (24) state:

"Maximal oxygen uptake ($\dot{V}O_2$ max), maximal aerobic power is one of the most significant functional characteristics of the individual and an index of his capacity for performing work."

However, one must remember that a 'maximal' test is difficult to perform except on experienced laboratory subjects, Durnin, et al, 1960 (25).

Kelman, 1970 (26), stated that there is much to be said for the point of view that the physiological load on the body is related more to its rate of CO_2 excretion than to its rate of oxygen uptake. Muscular exercise of more than a few seconds duration requires an increased supply of oxygen to the exercising muscles. This can be achieved only by an increase of pulmonary ventilation and an increase of cardiac output. If the cardiac output is insufficient, the muscles are forced to obtain energy by anaerobic metabolism. This produces lactic acid which reacts with plasma bicarbonate ions and increases the effective rate of CO_2 production of the body. The elimination of this excess CO_2 by the lungs requires a further increase of pulmonary ventilation which may be more than the subject can tolerate because, when the actual pulmonary ventilation becomes more than a certain proportion of the maximum possible ventilation, the sensation of dyspnoea becomes extremely unpleasant.

Under conditions of severe exercise, CO_2 production exceeds oxygen consumption. It is useful to consider the physiological load on the body as its need to eliminate

CO₂ rather than its need to take up oxygen.

Shephard, 1969 *op cit*, reviewed the work on these physiological parameters and additional ones to establish the physiological determinants of endurance fitness. These included effective alveolar ventilation, oxygen cost of breathing, pulmonary diffusing capacity and cardiac output and its relative determinants. He concluded that the main limiting factor is the haemoglobin level of the blood and maximum cardiac output. This becomes more obvious if account is taken of the shape of the oxygen carriage curve, since cardiac output max further limits the increase in oxygen transport that can be achieved by an increase of alveolar ventilation or pulmonary diffusing capacity.

Davies *op cit* states:

"It has often been claimed that one can infer the fitness of a subject from measurement of his maximum aerobic power. Clearly, this is not so; indeed, the VO₂ max may tell you very little about the actual state of the individual's training or physiological status."

This point emerged clearly from Cotes et al, 1967 (27), and Davies, 1968 (28) on males and females, with an age range of 20-50 years. In young subjects the function and dimensional components of the oxygen transporting system were closely matched to VO₂ max and at least to some extent intercorrelated. The lower VO₂ max of the females and the higher oxygen uptakes in athletes, compared to healthy male adults, were mainly a result of quantitative differences in organ size, which contributed to the capacity for exercise. Thus, though an individual, through natural (genetic) endowment, may be blessed with optimum physical dimensions of the relevant organ system, which contribute to a high VO₂ max, his actual state of fitness will depend on whether a close integration exists between the size of the organs and their functional capabilities.

A person who is fit in the physiological sense will possess a complete integration between his functional and dimensional oxygen transporting components – his aerobic power and capacity will be high. On the other hand a person who is unfit, may have a relatively high VO₂ max but be without the capacity to utilise it. This close association between genetic and environmental factors in the assessment of fitness is important and should be noted.

The transportation of the metabolic substrates to, and the products of metabolism from, the active tissue is carried out by the cardiovascular system. This transportation is dependent on the cardiovascular response to exercise to meet increased demands.

The cardiac response to exercise is complex and involves the interaction of changes in heart rate, ventricular end diastolic volume, ventricular end systolic volume, and the heart's neurohumoral background. The relative roles of each of these variables in the adaptation of the heart to the stress of exercise have been debated for many years.

The regulation of the circulation in exercise is probably guided primarily by factors sensitive to an adequate cardiac output. Heart rate and stroke volume are the variables, and stroke volume is more likely to be directly influenced by such factors as venous return or peripheral vascular resistance.

Green, 1970 (29) states:

"In man an alteration in heart rate may or may not alter the cardiac output. It is unwise to assume that it does unless it is known that the stroke volume is unaffected. But in exercise, up to quite high levels of work, the increase in heart rate may account for practically all the increase in cardiac output with stroke volume remaining constant".

Then, using the data of Asmussen & Neilson, 1955 (30), stated that:

"In severe supine exercise with cardiac outputs of 40 l./min an increase in stroke volume must occur, since such outputs require a stroke volume of 200 ml, with a heart rate of 200 beats/min."

Åstrand, 1960 (31) concluded, from a measure of the oxygen transport per heart beat, that (except for those in the 4-8 years age range): "There are no findings indicating a decrease in stroke volume with increasing heart rate, not even at the highest rates.

Åstrand *op cit*, 1964, and Saltin, 1964 (32) using cardiac catheterisation, stated that at heart-rates above 110 beats/min almost maximal stroke volume was reached.

Glick et al, 1965 (33), suggest that, although a simple increase in heart-rate in a resting individual improves the contractile state of the myocardium, the shift of the myocardial force-velocity curves that occur during exercise can be attributed only in part to this change in rate. During maximal exercise, the acceleration of the heart rate alone is not sufficient to allow the achievement of a cardiac output large enough to satisfy the requirements of the peripheral tissues, unless stroke volume also rises substantially. Although the increase in cardiac output that occurs during moderate exercise is accomplished almost exclusively through an increase in heart rate, if the latter is held constant, the heart is still capable of elevating its output to an appropriate level by raising the stroke volume.

Braunwald et al, 1968 (34) concluded that:

"The normal cardiac response to exercise involves the integrated effects on the myocardium of simple tachycardia, sympathetic stimulation and the operation of the Frank-Starling mechanism. During sub-maximal levels of exertion, cardiac output can rise even when one or two of these influences are blocked. However, during maximal levels of muscular exercise, the ventricular myocardium requires all three influences to sustain a level of activity sufficient to satisfy the greatly augmented oxygen requirements of the exercising skeletal muscle.

Heart rate response to increasing work in laboratory tests have shown this relationship to be linear at sub-maximal work levels, Åstrand, 1970 (35). There is a widening of the arterio-venous oxygen difference as more oxygen is transferred from haemoglobin to myoglobin and the mitochondria in the working muscles to accommodate increased metabolism. (39), and Davies, 1965 (40), showed a non-linear response of heart rate to increasing work load in male time-trial racing cyclists. This curvilinearity of response was noted between 60-80% into the task. Thomason, 1972 (41) noted that those subjects who worked longest curved earliest and at a lower heart rate.

Shephard, 1969 (42) suggests that endurance fitness can best be achieved by the pulse response at 1969 (42) suggests that endurance fitness can best be described by the pulse response at measurements during exercise are better than ventilatory measurements in showing dependence with total work capacity. Brooke, Hamley & Thomason, 1969 (44), found no correlation between maximum heart rate and total work capacity. Numerous other workers have reported a similar lack of correlation.

Work by Thomason, 1972 op cit demonstrated high correlation between sub-maximal heart rates (lower) and total work capacity in skilled cyclists. (lower) and total work capacity in skilled cyclists.

Wasserman et al, 1967 (45) noted that the interdependence of work, heart rate and ventilation suggests that control mechanisms during exercise are closely related to cellular metabolism and to changes in the internal chemical environment, and it is on this interdependence and on the characteristics of the cellular metabolism that a complete test of exhausting physical work capacity needs to be based. However, measurement of these parameters needs both accuracy and precision. Recently, Taylor, 1970 (46), stated that the measuring procedure and the precision of the measurements of cardiac output in resting supine patients, by catheterisation, is poor and that these measures in exercising humans leave much to be desired.

Figs. 1-4 summarise these findings of the response of

the cardio-respiratory system to exercise.

Increase in blood flow under maximal exercise conditions

Working skeletal muscle	+ 18x	Brain	No change
Heart	+ 4x	Liver	- 4x
Skin	+ 2x	Kidney	- 4x
		Other tissues combined	- 6x

Contributions made by various components of the oxygen transport system to working muscle incremental increase during transition from rest to maximal exercise

Oxygen uptake	+ 12x	S.V.	+ 1.4x
Cardiac output	+ 4x	A.V.	
Heart rate	+ 2.7x	(oxygen diff.)	+ 3x

Changes in haemodynamic values – transition from rest to maximal exercise

Systolic blood pressure	+ 1.6x	Systemic resistance	- 2.7x
Diastolic blood pressure	+ 1.1x	Pulmonary resistance	- 2x
Mean blood pressure	+ 1.4x		

from Buskirk 1973 (52)

That differences do exist between sedentary men and athletes in their responses to exercise is well documented. However, coaches are interested in athletes alone. Is it possible to distinguish within this group using physiological parameters?

In a recent study, Costill and Thomason, 1973 (49), using competitive endurance runners, n = 16, measures were made for oxygen consumption, heart rate and blood lactate accumulation during sub-maximal and maximal treadmill running. Several days after the laboratory test all of the runners competed in a ten mile road race. The correlation between max $\dot{V}O_2$ (ml/kg x min) and performance in the ten mile race (min) was -0.91. At a selected speed (268 m/min) the percentage max $\dot{V}O_2$ and percentage maximum heart rate were found to be highly related to distance running performance ($r = -0.94$ and 0.89 respectively). At all running speeds above 70% max $\dot{V}O_2$ the faster runners were found to accumulate less blood lactate than the slower runners at similar speeds and relative percentage of their aerobic capacities. The findings suggest that successful distance running is dependent on the

Average cardiovascular values for sedentary and well-conditioned men

	Heart wt. g Body wt. kg.	Heart volume ¹ ML	Blood volume liters	Total haemoglobin G
Sedentary men	5.8	769	5.3	805
Well-conditioned men	6.5	986	7.5	1130
Δ	+0.7	+217	+2.2	+325

¹ Resting, presystolic

[as summarised by Grande & Taylor]

Slide 1

Relationship of stroke volume, cardiac output and arteriovenous oxygen difference to oxygen intake in subjects who were sedentary, well conditioned or endurance athletes in training (53).

Slide 3

Relationship of changes in maximal oxygen intake with physical condition and age

Slide 2

Buskirk 1973 (52)

The influence of intensity of exercise (expressed as oxygen consumption, ml/kg min STPD), initial fitness (expressed as aerobic power, ml/kg min STPD) and frequency of exercise upon the gain in aerobic power during training (from Shephard, 1969) (23).

Slide 4

economical utilisation of a highly developed aerobic capacity and the ability to employ a large fraction of that capacity with minimal accumulation of lactic acid. This demonstrates that distance running performance can be accurately estimated from sub-maximal and maximal treadmill data.

From this study we suggest that future studies of the physiological prerequisite for successful distance running should be directed toward the fibre distribution and metabolic qualities of the running musculature. For more recent work on this topic see Saltin, 1973 (50).

The problem of altitude and effects of training at altitude on performance at sea-level have been covered extensively in the recent BASM/BOA (51) meeting and I do not propose to discuss it further.

What does this knowledge tell us, as physiologists, that can be of use to the athlete and his coach?

Brooke, 1973 (52), stated that "data from the science of sports performance are fundamental starting points in defining the structure of knowledge about adaptation for sport. They do little to provide answers to some of the key problems, e.g. what type of progressive overload training, that is specific by speed or by distance or without reference to specificity? How often should a performer train/day/week/month? How long is it necessary to train? Is a particular performer over-trained? What are the principles of peaking? These are the questions that are asked and it is proposed that the scientific literature does not supply the answers. The science of sports adaptation (not folk account or dogma but a scientifically assembled structure from or of data) is fragmented even from the most optimistic viewpoint."

Åstrand & Rodahl 1970 *op cit* have reviewed the effects of physical conditioning and have attempted to put down some guide lines using the data that is available. They commented on the lack of longitudinal studies of sufficient length but noted that most work had been done on two groups – (1) comparing results from athletes against sedentary men, (2) looking at subjects before and after bed rest of varying lengths.

They have summarised this and from a practical standpoint it may be logical to list four components of a rational conditioning programme aimed at developing the different types of power:

1. Bursts of intense activity lasting only a few seconds may develop muscle strength and stronger tendons and ligaments.
2. Intense activity lasting for about one minute repeated after about four minutes of rest or mild exercise, may develop the anaerobic power.

3. Activity with large muscles involved, less than maximal intensity, for about three to five minutes, repeated after rest or mild exercise of similar duration may develop aerobic power.

4. Activity at sub-maximal intensity lasting as long as 30 minutes or more may develop endurance, i.e. the ability to tax a larger percentage of the individual's maximal aerobic power.

Conclusions

The work of the physiologist in sport has led to some advances in knowledge with regard to how the athlete performs and some of the limiting factors in his performance.

Much, however, needs to be done. One must always take into account the full facts of any findings before one can relate them to sport, i.e. many changes in physiological variables are not greater than the changes due to error in actually measuring these parameters. One must be sure that no other factors can contribute in any way to increasing performance, i.e. motivation may be a greater spur than a new wonder product.

Before one can say what conditioning will help sportsmen one must be very specific in what the sportsman is trying to achieve (e.g. heart rate decrease during leg only exercise conditioning will not give a similar heart rate decrease when arm only exercise conditioning begins).

A full list of data of various physiological and anatomical parameters taken from an athlete performing a work task may be of little or no use to the coach. What is needed are longitudinal studies taking all parameters into account, looking for meaningful physiological changes that can be scientifically associated with conditioning changes.

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MEETINGS OF OTHER ORGANISATIONS

INSTITUTE OF BIOLOGY – NORTH WESTERN BRANCH

ADVANCE NOTICE

A meeting is to be held at 2.30 p.m. on Saturday, December 7th, at the University of Salford, Chapman Building on
HUMAN PERFORMANCE.

Provisional programme: "Assessment of human physiological load in field performances" – J. D. Brooke.

"Control of biological systems with special reference to the heart" – Prof. H. M. Power and H. Thomason.

B.A.S.M. members will be welcome. Further details can be obtained from, and applications should be made to:—

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