Some Physiological Aspects of Fitness for Sport and Work

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Fitness for sport and work has both an absolute and a relative meaning. In absolute terms, the man that can run the fastest, jump the highest, lift and handle the heaviest burdens, and attain the highest output during a working day, must be the most fit for that particular activity. The word fitness takes another meaning when it is applied in, for instance, a health programme. Here the word becomes a relative term: a person of small size may not be able to compete in weight-lifting with a bigger man, and his maximum work output in, say, shovelling coal, may be much less – but still he may be physiologically the most fit. Fitness for sport and work is thus an ambiguous expression, and whereas its use in the absolute meaning may be quite clear, its definition as a relative term is, at least, as difficult as the definition of health.

With respect to its definition a comparison with the definition of health may be worth while. The best authority on this is, presumably, the World Health Organization. In the *Technical Report Series* (1957) one finds: 'Health . . . may be expressed as a degree of conformity to accepted standards of given criteria in terms of basic conditions of age, sex, community and region, within normal limits of variation.' Substitute 'physical fitness' for 'health' and we get: *Physical fitness is a degree of conformity to accepted standards of given criteria* . . . . The keywords in the definition are: (1) criteria, (2) standards and (3) degree of conformity.

The criteria that must be considered from a physiological point of view are several. The most important probably are: mobility, muscle strength, anaerobic power, aerobic power and endurance, and neuromuscular co-ordination. For each of these accepted or acceptable standards must be given, and in individual cases it must be possible to determine the degree of conformity to these standards within normal limits of variation. It is a formidable task, and even though physiologists have been working on it for several years it must be admitted that very little has been achieved. As far as time allows I shall treat some of the problems, more or less thoroughly.

Beginning with mobility, standardization of this criterion of fitness has to a high degree been left in the hands of anatomists. It is usually in textbooks of anatomy that one finds standards of mobility generally expressed as angles of movements for the various joints. But a person's mobility is not simply the sum of the possible movements of his joints – there are forces that limit these movements, and these are quite often located in the connective tissues in ligaments, tendons and muscles. These undergo changes with use and disuse, and with age. Mobility consequently varies considerably with age and 'accepted standards' can rarely be found.

Muscle strength is the basis for all kinds of work and sport. Its measurement is apparently quite simple: one maximal voluntary isometric contraction against a dynamometer gives the isometric strength. But doubt has been raised as to whether it is possible voluntarily to engage a muscle maximally. This may mean that one has a reserve of strength that normally cannot be mobilized but which may be called up in emergencies.

It is interesting in this connexion to recall the ideas formulated by Henneman *et al.* (1965) of Harvard concerning the composition and function of the motor pool furnishing a muscle: it is built up of smaller and larger motor-neurones, the smaller ones supplying small motor units of predominantly slow, red muscle fibres, the larger supplying large motor units of predominantly fast, white muscle fibres. The small motor-neurones have a low threshold to stimulation, the large a high threshold. According to Henneman it follows that in ordinary conditions only the low-threshold motor-neurones are used, and the larger, with their larger, faster motor-units are only called up when very strong or maximal contractions are needed. If this never occurs it seems natural to assume that a certain atrophy takes place – and this means a decrease in fitness.

Muscular fitness is not completely described by a certain degree of conformity to accepted standards of isometric muscle strength. Muscle strength is only occasionally called upon in the form of single isometric contractions. Quite as often the demand is for dynamic contractions, for instance in lifting of loads; and there may be demands for endurance, either in repeated isometric or dynamic contractions, or in the continuous maintenance of a certain percentage of the maximal isometric tension. These aspects of muscle strength – although generally closely correlated with one another – need not always be so. Two series of measurements will illustrate this: Table 1, based on results of Ikai from 1966, shows how two groups of athletes and a group of normal students differ with respect to en-

Table 1

Maximal number of knee extensions with 67% of maximum load in 3 groups of young men (Ikai 1966)

	Knee extensions 67% of max. 1 per sec
'Normal' young men n=35	60·6±9.6 times
Olympic jumpers, sprinters, throwers	60 – 80 times
Olympic middle-distance, marathon	300 – 500 times

durance for dynamic, submaximal contractions. Table 2, a composite table based on experiments by Petersen *et al.* (1961) and Hansen (1961, 1963 *a*, *b*, 1967), both of Copenhagen, shows correspondingly that different training forms result in different degrees of growth in strength and endurance. One may speculate as to the reason for this variance and there are several likely explanations, based on assumptions of circulatory or neuromuscular adaptations to training. It is, however, possible that the changes take place within the muscle fibres themselves, namely in their contents of chemically bound energy and in the enzymatic systems that transfer energy to the contracting mechanism. According to the afore-mentioned supposition of Henneman, the red, slow muscle fibres are subserved by small, low-threshold motor-neurones, and will consequently be active at all intensities of training, whereas the white, fast fibres, innervated by larger motor-neurones with higher thresholds, will be active mainly at the highest intensities.

The red fibres have many mitochondria and a high content of respiratory enzymes, whereas the white fibres are especially rich in glycolytic enzymes. The different aspects of muscular function, strength and endurance in isometric and dynamic contractions may thus be partly independent parameters, susceptible to different training programmes. Fitness, as far as muscle functions are concerned, therefore involves several factors; thus 'conformity to accepted standards' will be rather hard to establish.

Anaerobic power is a measure of the ability to liberate energy anaerobically. The energy that is liberated may come from breakdown of high-energy phosphate bonds in ATP and creatin-phosphate (phosphagens), or it may stem from glycolytic processes resulting in lactic acid formation. As mentioned above, these two sources may be located in different parts of the muscle, respectively in red muscle fibres, which are poor in glycogen, and in white muscle fibres, which are relatively rich in both glycogen and phosphagens.

It is, therefore, quite possible that these two sets of muscle fibres may be called upon under quite different conditions of work and may be selectively trained and selectively kept fit. The lactic acid produced by the glycolytic processes inhibits further activity if not removed from the muscle cells. The removal is a comparatively slow process that depends on the diffusion rate of lactate into the blood, and on the blood flow through the muscles. Anaerobic power, and especially anaerobic capacity, may therefore also be a question of local blood flow. High lactate concentrations in the muscles cause a sensation of fatigue, which is tolerated differently by trained and untrained persons. The psychological aspects of being fit are thus not negligible factors.

The most widely studied and most popular criterion of physical fitness is the maximum aerobic power. The reason for this is obvious: it can be measured quantitatively with considerable accuracy; it can be expressed in terms that more or less eliminate differences in dimensions; an abundance of 'normal standards' is available – and, as aerobic power undeniably depends on the

Table 2

The effect of different types of strength-training on various muscular functions

	Isometric strength (increase %)	*Dynamic strength (increase %)*	*Static endurance (increase %)*	*Dynamic endurance (increase %)*	*Source*
Dynamic training					
Max. load, 10/day, 5 weeks	19	41	27	45	Hansen (1963*a*)
0·6 max. load, 150/day, 5 weeks	0	29	—	5,040	Petersen *et al.* (1961)
0·6 max. load, 100/day, 4 weeks	—	13	−2	630	Hansen (1967)
Static training					
0·6 max. load, 5 sec duration, 150/day, 5 weeks	4	6	122	41	Hansen (1961)
0·6 max. load, max. duration, 10/day, 5 weeks	11	15	84	92	Hansen (1963*b*)

Table 3

Maximum rate of oxygen uptake ($\dot{V}O_2$ max) in its relationships to ventilation ($\dot{V}E$), lung diffusion constant (DLO_2), cardiac output ($\dot{Q}$) and tissue diffusion constant (DTO_2)

$$\dot{V}_{O_2}\text{max} = \dot{V}_E \times (F_{IO_2} - F_{EO_2}) = V_T \times f \times (F_{IO_2} - F_{EO_2})$$

$$\dot{V}_{O_2}\text{max} = D_{LO_2} \times P_{(A-\bar{c})O_2}$$

$$\dot{V}_{O_2}\text{max} = \dot{Q} \times (a-\bar{v})O_2\text{-diff.} = SV \times HR \times (a-\bar{v})O_2\text{-diff.}$$

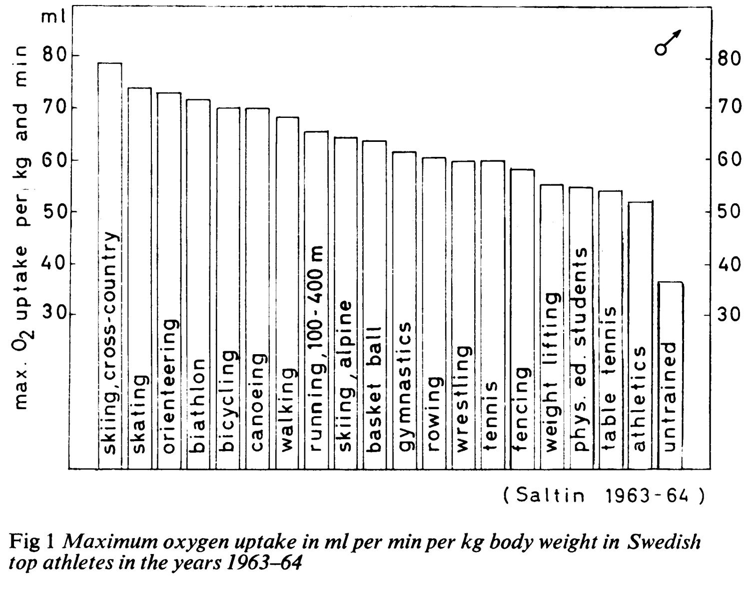
$$\dot{V}_{O_2}\text{max} = D_{TO_2} \times \left[\frac{P(a-\bar{v})O_2}{2} - \bar{P}_{TO_2}\right]$$

fitness of the heart, it has attracted great interest because of its use as an indicator of health in relation to coronary heart diseases. Maximum aerobic power depends on a whole chain of functions, from the ventilation of the lungs, through the transport of oxygen by the blood to the uptake of oxygen in the mitochondria of the muscle cells (Table 3). Limiting factors may be found in all the links of the chain, and they may vary from subject to subject.

When speaking of fitness for sport and work a large maximum aerobic power may not always be synonymous with fitness. Here, the size of the body plays an important role. It is, consequently, quite common to express fitness by the aerobic power per kg body weight. Its value varies within very wide limits. In a survey made by Saltin (1968) among Swedish athletes and physical education students it was found to vary between nearly 80 and 40 ml O_2 per kg per min (Fig 1). It goes without saying that all these athletes are fit for their sport, and even though an orienteerer may have an aerobic power that is 50% higher than that of a high jumper or a javelin thrower it would be nonsense to postulate that he is 50% more fit for sport.

The general population naturally has smaller values of aerobic power per kg body weight. Some of this may be due to overweight, but one cannot, therefore, conclude that they are less fit from a cardiorespiratory point of view than a very lean person with a somewhat higher value. An overweight man may be less fit for external work, but may otherwise be completely fit: he is using his aerobic power for carrying his extra body weight. Total body weight, therefore, is probably not the best parameter to use, when aerobic power is used as an index of general fitness or health. Some function of body height, lean body mass or fatfree body mass, may be better, but which one is hard to decide.

Maximum aerobic power is only one aspect of working capacity – endurance is another. The ability to maintain a high submaximal aerobic energy liberation over prolonged periods of time depends on physiological functions other than the cardiorespiratory system: it depends on the energy stores of the body and on the ability to



(Saltin 1963-64)

Fig 1 *Maximum oxygen uptake in ml per min per kg body weight in Swedish top athletes in the years 1963–64*

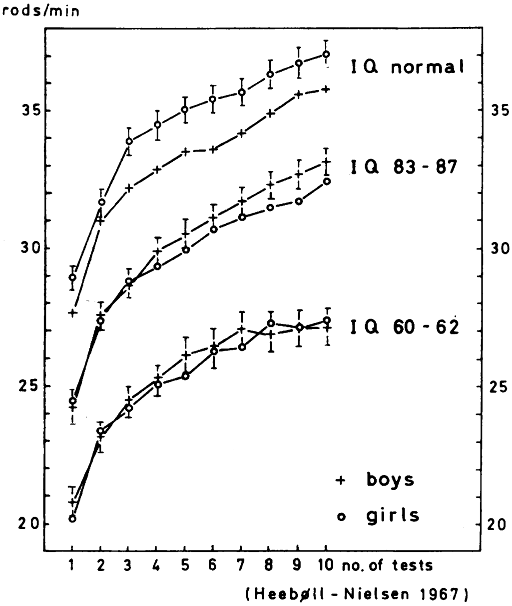


Fig 2 *Number of rods passed through a hole in psychotechnical tests on children at different intelligence levels. (Reproduced from Heebøll-Nielsen, 1967, by kind permission)*

utilize them. Carbohydrates and fat are the sources of energy in exercise. The carbohydrate stores – i.e. the glycogen in muscles and liver – are restricted, whereas the fat stores are relatively unlimited. In moderate exercise a mixture of carbohydrate and fat is used as fuel, but when exercise becomes heavier, relatively more and more carbohydrate is burned. The endurance-trained athlete can utilize fat up to a higher work intensity than can the untrained athlete, and his stores of muscle glycogen may be twice as large as the untrained person's.

As the last of the criteria for physical fitness that I listed at the beginning of my lecture, neuromuscular co-ordination must be mentioned. I shall do this very briefly, because so much of the work done on this aspect of fitness has been done by psychologists and so belongs to their field of work. Tests for neuromuscular co-ordination are plenty, and accepted standards are also available. Age, sex and occupation apparently are factors that influence neuromuscular co-ordination in definite tasks – and general intelligence apparently also is an important parameter. This can be seen from Fig 2 (Heebøll-Nielsen 1967) which shows that in a simple task of putting metal rods through a hole, pupils from a normal school are far better than pupils from schools for retarded children.

Mobility, strength, anaerobic and aerobic power and endurance are of little avail if neuromuscular co-ordination fails. Physical fitness obviously must depend on an efficient nervous control system.

In conclusion, may I sum up what I have been trying to communicate: Physical fitness from a physiological point of view is not a well-defined, simple entity, that can be expressed by a single or a few figures. 'Conformity to accepted standards' if used as a definition is so vague that it opens possibilities for all kinds of interpretations. Even when the term 'fitness for sport and work' is used its content varies so much, that a common denominator is difficult to find.

But physical fitness in all its aspects is correlated with physical activity. I believe that properly conducted physical activity at all levels of intensity, and for all age groups, made possible and attractive by extended public facilities for varied kinds of sports and games may stop the decline in general physical fitness that is being observed in most industrialized societies.

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DISCUSSION

The Chairman said that he was interested from the neurological point of view in the distinction between fast and slow fibres, large and small motor neurones. He wondered whether Professor Asmussen could give a little more information about his biopsy technique, because he felt that it was something that one could scarcely dare to do in England. He asked what the diameter of the biopsy from the vastus lateralis was and whether it had been possible to do any histological studies in addition to the biochemical studies of glycogen content. He presumed that the effect of training could be gauged and the hypothesis that two kinds of training were needed for these two different neurological systems could be tested.

Professor Asmussen admitted that the biopsies had not been done in Denmark but in Sweden and were mostly biochemical studies of the content of glycogen, creatin-phosphate and ATP in human muscles during and after exercise. But histological studies had also been done. He had seen beautiful electron-microscopical pictures of human muscle fibres showing glycogen content before and after exercise. Regarding the distinction between white and red muscle fibres, Professor Asmussen admitted that he had extrapolated from animals to humans, but he said that studies were going on in Copenhagen, in Professor Buchthal's laboratory, on the behaviour of white and red muscle fibres in human muscles and a report should shortly be available from that source.

Mr Vaughan Thomas (*St Mary's College, Twickenham*) asked Professor Asmussen how he defined exhaustion in his subjects and how he managed to motivate them to reach advanced stages of exhaustion in his laboratory.

Professor Asmussen said that if a subject was working on a bicycle he had to follow a metronome. When he was no longer able to do that his condition was then called 'exhausted'. As for motivation, many of the studies had been carried out on members of the staff and they were well motivated. Even with voluntary subjects it was quite easy to get them so interested in the problem that they really exhausted themselves.

Mr Michael Down (*Department of Ergonomics, Loughborough University*) said that in the work by Petersen and Hansen which had been quoted, it had been mentioned that subjects had lifted 0·6 of their maximum load: one group, that in the study by Petersen, 150 repetitions per day for five weeks, and Hansen's group 100 per day for four weeks. The percentage improvements were very striking, but Mr Down thought there was also a discrepancy, and he asked for further comment on this. Petersen's study showed a 5,040% improvement but Hansen's study only 630%. He asked whether there was any critical threshold value in the number of repetitions that the load was lifted each day, because mathematically there was nothing like that amount of difference in the training done.

Professor Asmussen replied that the only comment he had to make was that the number of daily contractions was different: 150 in one case and 100 in the other. The period of training had been five weeks in the first group and only four in the other. He admitted the discrepancy but pointed out that there was not a proper analogy between the number of days spent on training and the percentage increase, but he had no better explanation for it. The subject's initial state of fitness might offer an acceptable explanation.

The Champion Athlete – Limiting Factors in Record-breaking

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The following equation (Lloyd 1967):
$Rt+S(1-e^{-gt})=At+\alpha mv^2+C\int_0^t v^3dt+By$
sets out the energy balance of a maximal speed straight-line run, in which the runner accelerates maximally from the starting gun ($t=0$), reaches a peak velocity v (=dy/dt; e.g. 11·2 m sec^{-1}) at about 8 seconds, and then steadily slows down as his oxygen debt increases to a limit to reach a terminal velocity (e.g. 6·3 m sec^{-1}).

The terms on the left represent energy supply, R being the maximal aerobic power for the whole body, and S the oxygen debt energy, made available at an exponentially decreasing rate governed by the first order rate constant g. This is about 0·05 sec^{-1}, so that after two minutes only about 0·25% of the original oxygen debt store remains unspent.

The terms on the right represent energy used. At = 'standing' metabolism, which no doubt increases as body temperature rises, αmv^2 represents kinetic energy stored in the running body, and $C\int_0^t v^3dt$ represents external work done against air resistance; the final term, By, is much the biggest, and represents the energy needed to run the body horizontally over the ground. This energy varies directly with distance y, whether the runner runs fast or slow (Lloyd 1966), and the parameter B, which for a 72 kg man is *c.* 64·8 cal m^{-1}, has the dimensions of a (horizontal) force.

To get the distance-time relation the equation may be rearranged to give:
$y=(R-A)t/B+S(1-e^{-gt})/B-\alpha mv^2/B-C\int_0^t v^3dt/B$
and solved on an analog or digital computer. In 1966 Dr D F Mayers of the Oxford University Computing Laboratory was kind enough to solve this equation at 2 second intervals between $t=0$ and 260 seconds, using $(R-A)/B=6{\cdot}847$ m sec^{-1}, $S/B=212$ m, $g=0{\cdot}05$ sec^{-1}, $\alpha m/B=0{\cdot}266$ sec^{2}m^{-1} and $C/B=0{\cdot}002025$ sec^2 m^{-2}.

The effect of altitude may be examined by placing a factor $p(<1)$ in front of $(R-A)$ to represent the reduction of $\dot{V}o_{2\ max}$ at altitude, and a factor q (<1) in front of C to represent the reduction in air density. With $p=0{\cdot}975$ and $q=0{\cdot}75$ (the barometer at Mexico City is about