MUSCULAR WORK AND FATIGUE—*A REVIEW*

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The question of work performance is closely linked with fatigue. It is often stated that work capacity in the temperate climate is greater, but this may not be entirely true. The socioeconomic, scientific and technological development certainly depends on work performance. Fatigue assumes a special importance in Himalayan Border Warfare. In the mountainous regions, anoxia due to high altitude and freezing temperature grossly limit the work performance. The space astronaut and space flight in general are also faced with the problem of rapidly developing fatigue and grossly reduced work performance. Academically the Physiology of fatigue has not yet been well understood. And unless the Physiologic correlates of fatigue are precisely defined, its control would continue to pose a problem. This is why I have selected this topic for present discussion. The account given below clearly shows the fragmentary nature of knowledge about various aspects of fatigue and work performance. The aim of this article is to collect available data in a condensed form and to stimulate scientific thinking on this rather intricate problem.

The term Fatigue is used very commonly to imply different meanings. Fatigue can be broadly classified as psychological, mental and physical. We so often talk of feeling fatigued or tired. Sometimes we speak of feeling fatigued even when no work is being done or has been done recently. Also, at times one simply does not feel like working and wants to relax completely. Sometimes our mind is so tired that we do not want to think seriously about anything but wish to seek some source of recreation. Disinclination towards study is very common in students just after the examination. Disinclination to work also develops if the work is not interesting. A feeling of boredom and aversion to work frequently result from repetition of uninteresting or unrewarding work or forced work. Perhaps all such feelings are purely psychological when neither decrease in strength nor a decrease in the capacity of working can be demonstrated.

No suitable explanation has yet been furnished in terms of any definite physicochemical change in the body which may form the basis of such psychological reactions. However, occurrence of real mental fatigue perhaps can not be denied. Impairment or blunting of higher mental faculties could occur after continuous mental work. We feel fresh for mental work after rest and recreation. Another aspect of fatigue is purely physical. For the assessment and analysis of physical fatigue, objective methods are available. Although psychological, mental or physical fatigue could occur independently, generally conventional fatigue presents a combination of features of more than one variety.

In physiological terms fatigue implies a decrement in response coming as a result of activity. Various organs of the body can be fatigued by artificially induced, prolonged and intense

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activity. The energy expenditure of most of the tissues under normal conditions is such that there is a considerable reserve for increasing the activity, within limits, without induction of fatigue. However, this is not quite true for skeletal muscles which may be called upon to perform very strenuous exertions within a short time. The energy requirement under such conditions could be so exacting that the reserve is rapidly crossed and with all the available circulatory and respiratory resources, the muscles can not continue to work to their full capacity. The work performance fails till no work is possible at all. This is pure physical fatigue. Physical work involves a combined neuromuscular action. Either the neural elements or the muscular elements or both could be the site of fatigue. Transmission of nerve impulse across synapses involves special processes. The synapses in the central nervous system or at the periphery could also be the site of fatigue. Frequently a feeling of discomfort develops during and after exertion partly because of dyspnoea and partly due to the action of sensory impulses arising in the active muscles. Actual muscular pain and cramps may also develop. The feeling of discomfort and disinclination to repeat the work soon after exertion, have both psychological and physical basis. The development of the psychological feeling to avoid work, also implies a link between physical and psychological fatigue. However, the physicochemical changes in the muscle seem to form the main basis of physical fatigue.

The physicochemical changes in the body during fatigue have been investigated scientifically in three main ways :

1. Fatigue in nerve muscle preparations using artificial stimulation.
2. Fatigue in innervated muscles with intact circulation using artificial stimulation with surface electrodes placed over motor points.
3. Fatigue produced by exercising animals or human subjects and recording various physicochemical changes.

The information furnished by these different methods is by no means uniform. It should be realized at the very outset that activity involves many metabolic changes associated with electrical and mechanical responses. For these changes to continue normally during prolonged activity it is essential that energy continues to be utilized and restored in a cyclic manner e.g. for repeated development of action potentials the membrane must be repolarized following each depolarisation and similarly high energy phosphates must be resynthesized following their breakdown. Further the active metabolites, transmitters and enzymes may have to be removed and/or replenished at required rates. Obviously the isolated tissues can not be expected to behave in the same manner as tissues in the intact body where enough resources are available through the medium of circulating blood. The parameters of stimulation may also be related to rate of exhaustion and it is not easy to match the artificial stimulation with natural course of events in the body inspite of the fact that qualitative as well as quantitative responses may apparently seem to be similar. The literature on fatigue has got to be analysed and understood in this perspective.

Physiological Features of Fatigue

The structure and function of muscles have been investigated both from physiological and

biochemical points of view (11). Some work has been devoted to demonstrating the sites or seats of fatigue. Since the metabolic level of nerve activity is rather low, the nerves take a long time to get fatigued. It is a common knowledge that when nerve stimulation fails to elicit muscle response in a nerve muscle preparation, direct stimulation of the muscle still gives a response. Simultaneous recording of the action potential indicates that the impulse is being conducted normally over the nerves. These observations suggest that the seat of fatigue is neither in the muscle nor in the nerve but it is probably the neuromuscular junction (motor end-plate) that gets fatigued. Brown and Burns (9) had originally suggested that the neuromuscular synaptic junction is the site of fatigue, although Hoffman (32) had earlier observed that there was no conduction block at the neuromuscular junction in fatigue. In the nerve muscle preparation fatigue is associated with increase in the latent period, slow and smaller rise of tension and slow and incomplete relaxation before the muscle response finally ceases altogether. Del Castillo and Katz (21) think that neuromuscular fatigue could be due to a slow but steady decline in the amount of acetylcholine released by each nerve impulse, so that the amount of released acetylcholine falls below the threshold level needed for transmission or below the firing level of the muscle fibres. They have shown that there is a reduction in the number of acetylcholine quanta released per impulse although the amount of acetylcholine per quanta remains unaltered. At the same time the rate of spontaneous release of acetylcholine, indicated by miniature end-plate potentials, is increased.

Denny Brown (22) observed that a superimposed twitch with an electric shock can not be produced during maximal voluntary contraction when the muscle is already in a state of tetanus. Using a record of contraction of adductor pollicis muscle, Merton (47, 48) found that the size of the superimposed twitch fell off linearly with increasing voluntary tension. Also, he observed that not only the voluntary effort but the size of the superimposed twitch due to an electric shock to the nerve from the surface, fell off with the onset of fatigue and this he interpreted to imply a peripheral site of fatigue in the muscle itself. Merton recorded muscle action potentials and noted that during extreme fatigue the potential did not diminish in amplitude. He, therefore, concluded that the fatigue is not due to neuromuscular conduction block. Merton (47, 48) also observed that the curve of fatigue due to maximum voluntary contraction flattened off to a plateau if the circulation was intact but touched zero line if circulation was blocked by a sphygmomanometer cuff tied round the arm. Recovery only occurred when circulation was restored. Thus recovery was an aerobic process. Wilkie (61) showed that there is a ceiling to the maximum voluntary contraction of flexor muscles of arm. This 'ceiling' is reproducible from time to time in the same individual. He, however, thought that tetanic contraction would be greater than this maximal ceiling tension. Cooper and Eccles (18) found that in cat muscle the curve showing the relation of tension to frequency of tetanic stimulation was S-shaped and suggested a peripheral site of fatigue.

The phenomenon of fatigue has also been investigated in the intact whole body both in animal and in human subjects (11, 38, 49). In muscular work involving the whole body, e.g. running, the supply of oxygen is the main limiting factor. Fatigue of exercise is, however, not well understood. It has been attributed to slight cerebral anoxia, increased H^+ ion concentration and local changes in the muscle. Stiffness of muscle after fatiguing exercise is due to

swelling from accumulation of fluid. Afferent impulses from muscle carry the sensation of weakness, discomfort and pain. The sensation of muscular fatigue is carried through the spinothalamic tract. Thus in the intact body fatigue has peripheral, central as well as psychological components, all working simultaneously.

In the case of fatigue of small movement e.g. working of finger ergograph, central fatigue and neuromuscular block both have been held responsible (43), although the evidence for this has been criticized (40). Merton (47, 48) conceded that most skilful small movements may have a central component of fatigue as they are repetitive in character.

Fatigue of responses elicited reflexly through the central nervous system exhibits longer latent period and smaller and gradual decrease of tension. When the flexor reflex can no longer be elicited, the peripheral contractile mechanism remains fully active. Anoxia, ischemia and anaesthesia induce fatigue earlier. The characteristics of central and neuromuscular fatigue in terms of muscle response are quite similar. Reflex fatigue is produced both by excitatory and by inhibitory afferent impulses. The motor neurones are not fatigued, for a reflex can be brought about by stimulating another afferent nerve. Hence it is the active synapses of the motor neurones or intermediate neurones that show fatigue. In case of steady reflexes like the flexor reflex, the onset of fatigue may be indicated by the development of rhythmicity. Reid (53) thought that inhibitory impulses were set up in the muscle to restrict voluntary contraction to protect the muscles from the supposedly dangerous effects of complete fatigue.

Fatigue is probably less common in autonomic viscera. On stimulating some autonomic nerves there is little indication of fatigue in the response of innervated organs. Tonic vagal action on the heart does not show fatigue. Similarly reflex vasomotor control by barocepters does not show fatigue. This may be due to the fact that tonic activity involves generation of impulses at quite low frequencies which may permit adequate recovery.

The onset of fatigue is antagonised by sympathetic stimulation (Orbeli effect). Noradrenaline produces similar effects and also increases the excitability and contractility of muscles above normal limits. Adrenaline enhances contractile response of muscle during tetanic stimulation (29, 50). The action of epinephrine is direct on the muscle (8).

Electrophysiological studies by Hutter and Loewenstein (35) have shown that sympathetic agents restore the amplitude of end-plate potential reduced by nerve stimulation. These agents increase the sensitivity of postjunctional receptors to Ach or they may have a direct facilitatory effect upon contractile mechanism. Although a definite relationship between the intensity of electrical activity and mechanical response has not been observed, it has been suspected that the size of the contraction is related to the size of the negative after-potential of the spike (30). Stretch of partially curarized muscle (36) also produces neuromuscular facilitation. The mechanical deformation affects the release mechanism in such a way that larger number of acetylcholine quanta are released per impulse. Post tetanic facilitation or potentiation also occurs in partially curarized muscle (34). This post tetanic decurarization is a prejunctional phenomenon and is also a quantal process (34, 42).

Muscle function and work performance are significantly influenced by hormones (56).

Probably through its effect on phosphorylase (19) work capacity is reduced in adrenalectomised animals (37). Muscular weakness is present in castrated and eunuchoid man. Increased strength and endurance have been induced in castrated and hypogonadal man by androgen administration (57). Generalised muscular hypertrophy has been produced in guineapigs by androgen administration (51). Acromegaly is associated with lethargy. Muscular weakness is also a sign of Cushing's syndrome. Patients with panhypopituitarism usually have apathy, lethargy and lassitude. Both hypothyroidism and hyperthyroidism are associated with altered muscle metabolism and reduced work performance and muscular weakness. Neuromuscular excitability is profoundly effected in parathyroid disorders. Neuromuscular dysfunction has also been reported in other endocrinopathies. Neuropathies and myopathies are also common after steroid therapy. Further electrolyte disturbances in the body like changes in serum potassium level, influence muscular contractility and work performance. Reduced work performance and easy fatiguability are also associated with myasthenia gravis and cerebrellar diseases. Adrenaline injection prolongs muscular exercise in fatigued dogs (12).

Work Capacity and Fatigue

Physical fitness depends on ability of organism to maintain various internal equilibria close to the resting state during exertion and to bring about prompt restoration of disturbed equilibria after exercise (6, 20). It has been suggested on the analogy of machines that a margin of 50% reserve capacity should be allowed to man and animals to avoid untimely death and that increasing the metabolism over 50% of capacity will give rise to marked feeling of discomfort and strain. Thus physical fitness, work capacity and fatigue are closely related (3, 5).

Skeletal muscles can raise their oxygen consumption from a resting level of 2 *ml/kg/min* to 200 *ml/kg/min* during maximum work with a 50 times increase in circulation (1). Still greater energy output is possible through anaerobic processes. The physical fitness tests usually determine the circulatory capacity (5).

The rise in the lactic acid during severe exertion is related to the physical fitness (25). Blood lactic acid rise is an indication of oxygen debt (46). Blood lactic acid may rise from 10 *mg* to 200 *mg* per 100 *ml* after a 400 meter race. A sensation of strain and fatigue is closely related to blood lactic acid concentration. Increased lactic acid concentration in muscle and blood will bring changes in the *p*H with a possibility of reduction in the alkali reserve of the blood. Metabolites generated during anaerobic period as well as disturbances in the *p*H are likely to cause alterations in the internal equilibria. Trained adult individuals have a better tolerance to increased lactic acid concentration (54). High carbohydrate diet is conducive to work performance and delays onset of fatigue in man (14, 16, 17, 58). Production of mechanical energy is also more efficient from carbohydrates (39). It is quite likely that the main cause of fatigue in work experiments with small carbohydrate reserve is low glucose level in the central nervous system and not lack of fuel in the muscle (16, 17), although there are indications that depleted glycogen reserve in working muscles may reduce capacity for anaerobic work (31).

Reduction of O_2 tension in inspired air reduces capacity for prolonged sustained work

(14, 45). The limit for maximal aerobic performance is reduced at high altitude (7, 52, 60) both in unacclimatised and in fully acclimatised subjects. During acute exposure to a simulated altitude of 12000 feet lung ventilation reaches 200 *litres/min* in unacclimatised individuals at maximal work load (4). Increase in the heart rate only partially compensates for diminished O_2 content of arterial blood (15). The blood lactic acid values for a given work load are also higher at high altitude than at sea level (24, 44.) Work load which hardly produces any rise in the blood lactic acid may cause maximal rise in blood lactic at high altitude in unacclimatised individuals (2). Gradual acclimatisation gives a smaller rise in heart rate at high altitude than at sea level at maximal work (13). Acclimatisation also lowers the degree of rise in the blood lactic acid concentration for a given grade of work (27). The level of lung ventilation at maximal work at high altitude is not influenced by acclimatisation. In acclimatised mountaineers O_2 breathing improves work capacity but does not restore it to normal sea level values (4).

Hot and humid climate (26, 28) may reduce the maximal work capacity due to progressive rise in the rectal and skin temperatures. Shunting of blood to skin may produce extracirculatory load, resulting in reduced stroke volume at high pulse rate (23). In man increase of 10°F in air temperature above skin temperature increases circulatory strain equivalent to 29 *cal/sq. meter/hour* (10). Pooling of blood in the extremities and skin vessels during standing may seriously reduce the blood pressure leading to syncope (55). Thus sensation of fatigue and discomfort may also result from adverse postural and atmospheric conditions.

The length of intervals of work and rest have very significant influence upon work capacity and fatigue. A trained subject working on bicycle ergometer with a work load of 2160 *kpm/min* was completely exhausted after 9 min; the blood lactic acid rose to 150 *mg*/100 *ml*, lung ventilation increased to 124 *litres/min*. With 1/2 *min* interval of work and rest, the work could be continued for 1 hour without fatigue and the alterations in the internal equilibria were minimum. Same benefits are, however, not seen if the interval of work and rest is increased to 2-3 min (14, 41).

Training improves work performance (33) and inactivity for a few weeks may drastically reduce it (59). The improvement in the capacity for sustained muscular work and reduction in fatiguability as a result of active physical recreation or training appear to be due to improvements of O_2 transport system, increased muscular strength, improved efficiency of muscular co-ordination and adaptation in hormonal system.

The muscular effort seems to be limited by the maximal contractile activity of muscles, the rate of supply of oxygen and nutrients to the muscle and the removal of products of muscular contraction. Cardio-respiratory insufficiency may occur simultaneously in severe sustained exercise. Psychological influences, both in work performance and in onset of fatigue, also play definite role. The autonomic nervous system plays a more significant part in work performance and fatigue than is commonly realised. Dissipation of extra heat generated during muscular work is quite important. The sympathoadrenal system has some influence in enhancing work capacity, in preventing onset of fatigue and in facilitating psychological adaptations.

From the above discussion it is clear that theoretically fatigue could occur anywhere in the central or peripheral synapses and in the effector organs. More than one site could be in-

volved in various types of fatigue or in physical fatigue under various conditions. Fatigue is just an indication and result of overaction. Whichever structure is subjected to greater overaction beyond its reserve capacity will perhaps get fatigued first. The capacity for continuance of work at a given load and work endurance appear to depend on availability of accelerated and augmented resources. The metabolic changes at various sites are not absolutely identical. The biochemical expression of fatigue could, therefore, be different at different sites. For example, accumulation of lactic acid may depress muscular metabolism and altered cholinergic mechanism may be associated with fatigue at the neuromuscular junction. Obviously, therefore, we are dealing with a multifaceted problem and it may be more fruitful to analyse the relative contribution of important factors in the causation of physical fatigue with the aim of controlling it therapeutically.

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