THE EFFECT OF FATIGUE ON THE RELATION BETWEEN WORK AND SPEED, IN THE CONTRACTION OF HUMAN ARM MUSCLES. By A. V. HILL, C. N. H. LONG AND H. LUPTON.

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In recent papers A. V. Hill(1) and Lupton(2) have shown that in a maximal contraction of the flexor muscles of the elbow the work done is related to the time occupied in doing it by an equation of the type $W = W_0 (1 - k/t)$. The dependence of work done upon speed of contraction is being further investigated by Prof. Gasser here, who finds the same phenomenon to occur in the case of isolated frog's muscle subjected to a maximal tetanus: one is obviously dealing with a fundamental characteristic of muscular tissue and not merely with a property of its innervation. Some doubt has been thrown by Hansen and Lindhard(3) upon the use of the equation to describe the phenomena: their objections, however, have been shown by Hill(2) to reduce to the fact that the constant W_0 determined from the observations relating W to t is some 10 p.c. to 20 p.c. less than the theoretical maximum work calculated from an "indicator" diagram relating force exerted to amount of shortening.

The cause of this divergence is not explained. It is small and has no influence on the essential fact that the work increases with duration of shortening: it makes the real "theoretical maximum work" slightly greater than W_0.

In a paper appearing in the present number of this *Journal*, and very courteously communicated to us before publication, Hansen and Lindhard show that fatigue appreciably diminishes the value of W observed, when the duration of shortening is prolonged. In order to obtain sufficiently long times on the wheel at their disposal they employed subjects of "inferior strength." This method undoubtedly shows qualitatively the incidence of fatigue in prolonged pulls by such subjects, but we felt it advisable to make a direct quantitative estimate of the effect of fatigue upon the work done by the vigorous male subjects with whom most of our experiments have been made. The following method was employed.

A given pulley of the wheel being chosen the subject made a series of maximal contractions (usually about 25 in number) employing the quick release mechanism previously described. On the signal "go" he made, and maintained, a maximal effort, and after an interval accurately measured on a stop-watch the wheel was released. The interval was varied arbitrarily between 0 and 3 secs., the subject having no idea beforehand what it would be in any given contraction. In this way the same identical movement was carried out in all about 25 times, preceded by an interval of maximal isometric contraction varying up to 3 secs. Plotting the work against the duration of the isometric interval we can obtain an estimate of the effect of fatigue. The experiment was made on a number of healthy male subjects, on various pulleys (*i.e.* against various equivalent masses), and starting either with the arm completely extended, or bent at an angle of 40°. No consistent differences (for any given subject) were found, either for different pulleys, or for different positions of the arm in the initial isometric contraction. The results obtained from each group of about 25 observations on a given subject were expressed in terms of the percentage diminution in the work done, resulting from each 1 sec. of preliminary maximal contraction. Altogether about 1000 observations were made, so enabling a fairly accurate estimate to be obtained of the effect of fatigue.

TABLE. Per cent. reduction in the work done, resulting from each 1 second of preliminary maximal contraction.

[Each number given is the mean value obtained from a series of about 25 observations.]

Downing	6·8	7·2	6·0	4·0	12·0	10·4	Mean 7·8
Parkinson	6·4	6·0	—	—	—	—	" 6·2
Lupton	3·6	3·0	7·0	7·8	—	—	" 5·4
Long	7·0	8·0	4·0	9·6	6·0	9·6	" 7·4
Liljestrand	7·4	5·0	—	—	—	—	" 6·2
Azuma	7·6	5·6	6·0	6·4	4·2	—	" 6·0
Gasser	0	3·6	2·0	0	3·2	—	" 1·8
Weakley	4·0	7·0	—	—	—	—	" 5·5
Scheinfein	6·6	5·2	5·4	9·8	—	—	" 6·8

The individual subjects varied somewhat from one another, but a 6 p.c. reduction is a good mean estimate for the effect on the work of each 1 sec. of previous exercise. Thus if 10 kg. m. of work be done in an undelayed contraction, about 9·4 kg. m. will be done if shortening be delayed for 1 sec. after the signal "go." Clearly A. V. Hill (2, p. 352) was in error in stating that no appreciable diminution in the work results from a second or two delay in the release, though this appears to be the case with himself and Gasser. We must consider the effect of this diminution on the form of the relation between W and t.

The best data available are those given by Lupton(2, p. 72), from which we obtain:

Corrected work	10·51	9·76	9·15	7·72	6·67	5·76	4·66
Calculated work	10·24	9·69	9·11	7·75	6·71	5·71	4·55

The "corrected work" is calculated as follows. It is assumed that in any given contraction every element in the work done by the shortening muscle is reduced 6 p.c. by each previous 1 sec. of maximal contraction, and proportionately for other durations. If the shortening occupy t secs. and be uniformly accelerated (as Hill(1) previously showed to be approximately the case) the total reduction can then be shown to be 6 p.c. $\times\ 2/3t$, *i.e.* $4t$ p.c. If we employ the formula $W = 11{\cdot}78\ (1 - {\cdot}283/t)$ we obtain the numbers given in the last row for "calculated work," which clearly agree closely with those given for "corrected work." The allowance for fatigue, therefore, does not alter the general character of the curve, or the accuracy with which the observations may be expressed by the equation. Lupton gave 10·96 and 0·264 as the values of W_0 and k determined from the observations uncorrected for fatigue: the values 11·78 and 0·283 imply that the true "viscosity" coefficient $k = 0{\cdot}283$ and the true theoretical maximum work $W_0 = 11{\cdot}78$ are both some 8 p.c. greater than the values calculated from the uncorrected data.

We may conclude therefore that the effect of fatigue is comparatively unimportant. In vigorous male subjects it reduces the apparent theoretical maximum work (calculated from the observations) by some 8 p.c., and alters the apparent "viscosity" coefficient k to about the same degree. The character of the curve is unchanged by fatigue, there is the same increase of work with duration of contraction, the same equation applies with equal precision to the observations. The 10 p.c. to 20 p.c. difference found by Hansen and Lindhard(3) between W_0 and the area of the "stress-strain" diagram is clearly due, as they claim, in part to fatigue: unless, however, their subjects were more liable to fatigue than ours (which seems unlikely), it would appear that other factors must be invoked to explain the remainder of the difference.

The relation between work and speed of shortening can be shown diagrammatically much better by plotting W against $1/t$ than (as we have done hitherto) against t. If we call $1/t$ the "speed" of shortening, the relation between work and speed should be a linear one, as Fig. 1 indeed shows it to be. The lower line of Fig. 1 is drawn through the observations given by Lupton: the upper line is drawn through the observations after correction for fatigue, as described above. The linear relation shown in Fig. 1 is the simplest possible expression of the facts demonstrated by the inertia wheel: the work done decreases in a linear manner as

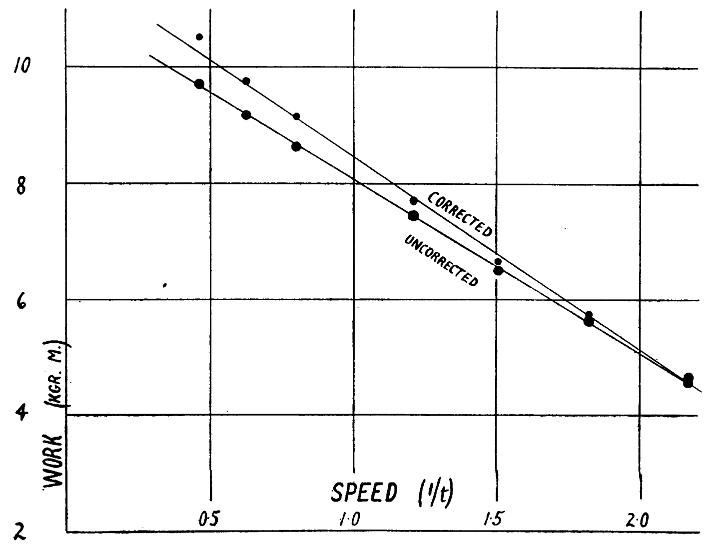

Fig. 1.

the speed of movement increases: and the small correction necessary to allow for fatigue obviously has no influence upon the accuracy with which this relation is obeyed.

SUMMARY.

The effect of fatigue in diminishing the work done in a prolonged maximal contraction of the flexor muscles of the elbow has been determined. Every previous 1 sec. of maximal contraction diminishes the work by about 6 p.c. The relation between work and speed of shortening is not seriously influenced by fatigue. The work decreases in a linear manner as the speed of shortening is increased.

The expenses of this research have been borne in part by a grant from the Royal Society to A. V. Hill.

REFERENCES.

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(2) Lupton. Ibid. 57. p. 68. 1922. Appendix by A. V. Hill.
(3) Hansen and Lindhard. Ibid. 57. p. 287. 1923.