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ERGOGRAPHIC STUDIES IN MUSCULAR FATIGUE AND SORENESS.

THEODORE HOUGH.

(*From the Biological Laboratory of the Massachusetts Institute of Technology.*)

(*Abstract.*)

Ergographic experiments were first made by rhythmically raising a constant weight and recording the height of contractions. Binet, Cattell, Franz, and the writer have used a spring in place of the weight, since the former will always record the strength of the muscle, no matter how great the fatigue, whereas with the latter a point is usually reached sooner or later in which the muscle can no longer lift the given weight, although it is still capable of lifting a smaller weight; the failure to shorten thus evidently gives an incorrect record of the working capacity of the muscle and of its state of fatigue. The graphic record of a series of rhythmic maximal contractions against the resistance of a spring is consequently a more accurate curve of fatigue than is the record of a series of contractions with a constant weight.

It must at the same time be borne in mind that the use of the weight presents certain advantages over that of the spring, since muscles normally contract against constant weight, and it is rather unusual for them to make a series of contractions against maximal resistance. The older method should consequently not be abandoned. With improved technique it must prove very useful in reproducing the more usual conditions of normal fatigue.

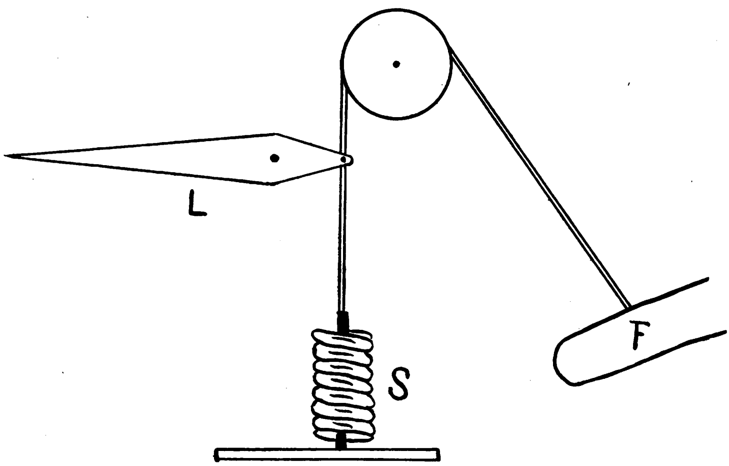

FIG. 1. — Diagrammatic representation of the ergograph used in these experiments.

The construction of the ergograph used in this series of experiments is shown in Fig. I. The movement used was flexion of the middle finger (F). The hand was strapped firmly in the prone position to a rest, straps passing over the dorsal surface of the palm, the first and third fingers, and the first phalanx of the second finger. A v-shaped notch in the rest permitted flexion of the second finger at the joint between the second and third phalanges. Flexion took place against the resistance of the moderately strong spring S, whose extension was directly recorded upon a smoked surface by the magnifying lever L. The spring gave an extension of 2.5 mm. for each kilogramme of pull.

In former ergographic work the entire finger has been flexed. This is, however, not permissible in the study of the fatigue of a simple neuro-muscular mechanism,[1] because,

[1] *i.e.*, a single muscle or group of anatomically similar muscles with the innervating spinal neurones.

while the second and third phalanges are flexed by the *mm. flexores digitorum* in the forearm, the first phalanx is flexed chiefly by the *mm. lumbricales* in the palm of the hand. Maximal extension of the spring must depend in this case on perfect coördination in the working of two very different sets of muscles, thus introducing a third factor over and above those of strength of stimulation and the condition of the muscle as regards fatigue.

A double metal splint was attached to the distal phalanges of the middle finger; flexion was thus possible only at the joint between the first and second phalanges, as already described. The dorsal half of the splint carried an adjustable hook (for the attachment of the finger to the spring) which was made fast at a constant distance (determined by a T square) from the joint, so that the muscle worked with the same leverage in all experiments. The neglect of this mechanical principle is a serious source of error in most ergographic work.

It is very important that more attention be paid to such matters as leverage in ergographic experiments. It has been tacitly assumed that the pull of the flexor on the finger is comparable to the pull of an excised muscle on a weight which it carries. This is, however, by no means the case. In the first place, the attachment of the flexor muscle to the bone introduces a lever system, in virtue of which, as the bone passes from the condition of extreme extension to that of flexion, the pull is applied at increasing mechanical advantage. In the second place, as the finger is flexed, the relative direction of its movement and of the application of the resistance constantly changes, so that, even could the weight be attached directly to the bone at the point of insertion of the muscle, the movement produced in the weight would be a constantly varying component of that produced in the bone. In the third place, the weight is not attached at the point of insertion of the muscle, but by a joint situated between one and two centimeters from this point; consequently, as the finger is flexed, of the total energy applied at this joint the component exerted in the direction of the pull of the weight varies. In Mosso's original ergograph, where the hand was placed in the supine position and the direction of the pull was that of complete extension of the finger, we have the very worst possible form of instrument in this respect, since the directions of application both of power and of resistance with reference to the direction of movement are at first those of the poorest mechanical advantage, improving as the finger is more and more flexed. The arrangement, on the other hand, described in this paper makes these two factors more or less successfully neutralize each other. Reference to Fig. 2 will show at once that, as the muscle pulls at increasing mechanical advantage, the energy of movement of the finger is applied to the resistance at decreasing mechanical advantage.

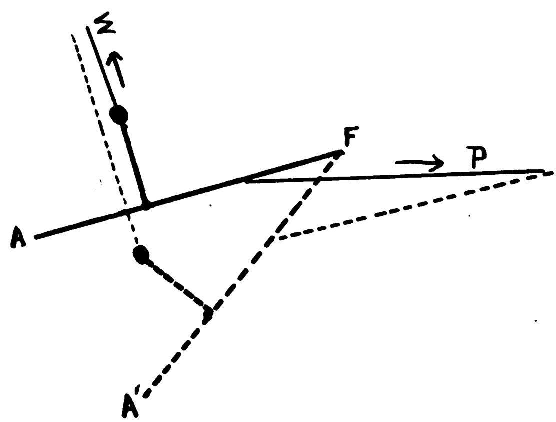

FIG. 2. — Diagram showing changes in direction of application of the power (P) and the resistance of the spring (W) with increasing flexion of the finger. Initial position in solid lines; flexed position in broken lines. F = fulcrum of movement, FA = second and third phalanges of the middle finger.

The most serious source of error in prolonged ergographic tracings is the unpleasant or even painful sensations which result sooner or later from the anemia of the finger to which the splint is attached, and the passive congestion which appears in the rest of the hand. No ergographic curve is worthy of close attention unless it has been taken from a subject who has trained himself to neglect these sensations as far as possible, since the constant streaming into consciousness of any painful sensation must seriously interfere with the exertion of maximal efforts of the will. With practice it becomes possible to make ergographic experiments of from twenty to thirty minutes' duration without serious error from this source. It is, however, an open question whether the afferent impulses thus entering the nervous system may not diminish the amount of volitional innervation even when they do not affect consciousness. The worker with this method of studying fatigue must be constantly on his guard to avoid attributing to fatigue what is really due to other causes.

Fatigue of the Trained Muscle.

We shall see later that when an untrained muscle makes a series of maximal contractions against a strong spring, a soreness of the muscle results which cannot be regarded as a phenomenon of pure fatigue. In the trained muscle, on the other hand, these complications are absent, and the course of events is very regular and typical. It is consequently convenient to begin with the fatigue of the thoroughly trained muscle.

The fatigue curve of a series of maximal rhythmic contractions. — We shall indicate the duration of the periods of work and rest by the convenient formula $\frac{C}{R}=\frac{m\ sec}{n\ sec}$, where C represents the period of contraction and R the period of rest before the succeeding contraction.

Ergographic work has usually been done with the rhythm $\frac{C}{R}=\frac{1\ sec}{1\ sec}$. In most of my experiments I have used, instead, the rhythm $\frac{C}{R}=\frac{\frac{1}{2}\ sec}{\frac{3}{2}\ sec}$, the metronome beating half seconds. The latter rhythm is not so monotonous as the former and a trained muscle can reach its maximal contraction in a half second as well as in a second.

The curve in Figure 3 is accurately plotted from one of these tracings. The abscissæ represent time in minutes, while the ordinates represent height of contraction. As a contraction occurs every two seconds, the experiment consisted of 600 maximal contractions. It will be seen that the height of contraction falls gradually as an asymptotic curve to what is practically a constant level. My experience has been that

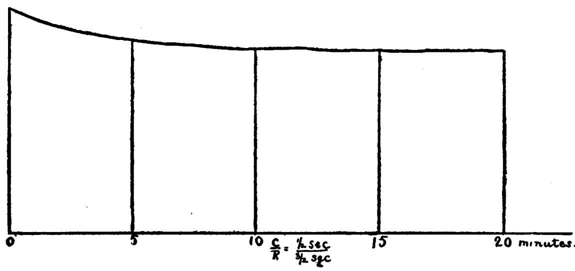

FIG. 3. — Curve of fatigue, plotted from the tracing of Feb. 15, 1899. The initial contraction represents a pull of 8.25 kilo. The fatigue level represents a pull of 6.4 kilo.

with the thoroughly trained muscle, whenever soreness and undue congestion of the hand are excluded, the curve always approaches closely to this form and in a fair percentage of cases establishes a perfect fatigue level; when we remember that the more common errors of experiment tend to diminish the height of contraction by diminishing the amount of volitional innervation, it seems fair to conclude that the curve of pure fatigue is essentially of the character described. The height of the fatigue level as well as the height of the initial contraction varies in different persons and in the same person at different times. Training accounts for some but not for all of the differences thus observed. In one of my own experiments the fatigue level established itself at about the two-hundredth contraction and was maintained throughout a series of 1,300 succeeding contractions (total duration of the experiment, fifty minutes).

In previous ergographic work too much attention has been paid to the first portion of the curve and too little to the ultimate level established. The total number of contractions has seldom exceeded one hundred, and generally falls far below this. For this reason the establishment of a constant level of fatigue has almost if not entirely escaped attention.

Figure 4 gives a curve plotted from an experiment which shows very clearly the effect of changes in rhythm on the curve of fatigue. Upon changing from the ordinary to the slower rhythm, the curve gradually ascends to a higher fatigue level, from which it gradually falls to the former level on changing to the former rhythm. When the rhythm is $\frac{C}{R} = \frac{1 \text{ sec}}{9 \text{ sec}}$ or $= \frac{\frac{1}{2} \text{ sec}}{4\frac{1}{2} \text{ sec}}$, or slower, there is no diminution in the height of contraction in the trained muscle; and the height of the initial contraction can almost always be reached after fatigue by adopting the slower rhythm. One cannot fail to be im-

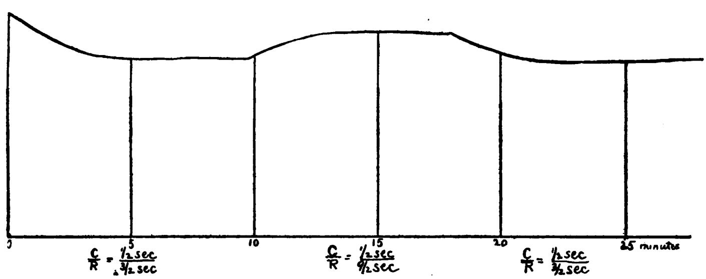

FIG. 4. — Curve of fatigue, plotted from the tracing of May 4, 1900, showing the effect of changes in rhythm upon the curve of fatigue. Figures 3 and 4 are drawn to the same scale.

pressed with the mathematical accuracy of very many of these fatigue curves, and with the fatigue level as the most accurate indication of the working capacity of a muscle.

Turning for the moment to considerations of the theory of fatigue, I think it is evident that the establishment of a level is what we should expect. The one indisputable cause of ordinary fatigue thus far established is the presence of waste products of activity; it would seem reasonable to suppose that these limit the expenditure of energy (and so the work done) in proportion to their amount. At the same time, under the conditions of our experiments, the blood is removing them; and it would seem that when the rhythm is $\frac{C}{R} = \frac{1 \text{ sec}}{9 \text{ sec}}$ the removal is complete, no fatigue appearing in the tracing. As the rhythm becomes more rapid, these wastes are not completely removed between contractions; they gradually accumulate, limit more and more the work done, until ultimately an equilibrium is established in which just as much waste is produced with each contraction as is removed before the next contraction. Under these circumstances a fatigue level of work is established, the height of which varies inversely with the rapidity of the rhythm. If the diminution in explosive fuel substance is also a cause of ordinary fatigue, plainly this factor would act in the same manner, the level being established as soon as the muscle manufactures from its reserve material or from the blood just as much fuel as it consumes with each contraction.

The fatigue of volitional tetanus is essentially the same as that of rhythmic contractions, except that it is more rapid, and establishes a much lower level. It is, moreover, very difficult to maintain a constant fatigue level in tetanus, because of the painful sensations which usually accompany sustained maximal contractions.

In no case after the establishment of the fatigue level have I seen any rise, so long as the rhythm remained constant (metronomes can run down!), the position of the splint on the finger remained unchanged (if not securely fixed the pull of the spring may bring the hook nearer the axis of movement and thus shorten the weight arm of the lever), and maximal efforts were made with each contraction. In other words, there is no such thing as "second wind" in ergographic experiments with simple neuro-muscular mechanisms.

In three experiments, after the establishment of the fatigue level (ten minutes), the subject lit and smoked a cigar or pipe, and continued to smoke it during the remainder of the tracing (ten minutes). A rest of fifteen minutes was then taken, during which the hand was released from the ergograph and the splint removed, in order to allow congestion in the fingers to pass away. At the expiration of this rest a second tracing of twenty minutes was taken, the subject smoking both during the rest and the second tracing; this was followed by a second rest of fifteen minutes and a third tracing of twenty minutes, the smoking continuing to the end of the experiment. The fatigue levels of these three tracings are in no respect different from those of controls on other days without smoking. Indeed, in one of them exactly the same level was established in all three tracings, and this was the same before and after lighting the cigar, although the prolonged smoking had exerted a marked physiological effect before the conclusion of the experiment.

Observations upon Muscular Soreness.

In the latter part of November, 1899, the writer began a series of experiments upon the ergograph after a rest of a little over six months. The tracing taken on the first day was without discomfort. On the following day, however, the flexor muscle was quite sore. Tracings were taken on this and the four succeeding days, the muscle remaining very sore during the entire period; a rest of three days was then allowed and another tracing taken. This procedure was repeated during the succeeding three weeks, and the condition of the muscle during the recovery from soreness tested by tracings. When compared with the fatigue curves of the same muscle in training six months before, these curves show the following features:

1. The untrained muscle failed to come to a constant fatigue level, the height of its contractions continuing to diminish to the end of the experiment (20–25 minutes). This was not accompanied by any painful sensation (soreness) either during the tracing or for some hours afterward.

2. Eight or ten hours afterward the muscle began to feel sore, especially when made to contract against resistance. This soreness increased and was at its height about twelve or more hours after taking the tracing.

3. The tracings given by the muscle in this condition were at first very painful; the pain, however, gradually wore away in the course of five or ten minutes, or was noticed only at the height of contraction.

4. Such tracings showed a marked diminution in the height of contraction (against a spring), even when all feel-

ing of soreness had passed away. The initial contraction was generally of the same height as those which followed.

5. Little or no power of recovery was noticed upon changing to a slower rhythm. The height of contraction seemed to be independent of the rhythm.

6. No improvement was noticed in the working capacity of the muscle so long as daily experiments were made. Improvement, however, took place as soon as periods of four or more days of rest were allowed.

An experiment made later with volitional tetanus and upon a trained muscle brought out a new phase of the matter. The frequently painful character of these tracings has already been mentioned, and this was no exception to the rule. It was also noticed that the soreness which began during the tracing persisted for three or four hours afterwards, gradually passing away. On the following day an ordinary rhythmic tracing $(\frac{C}{R} = \frac{\frac{1}{2}\text{ sec}}{\frac{3}{2}\text{ sec}})$ was taken to test the working condition of the muscle, which was thus shown to be in condition to give a perfectly normal curve, without the least trace of soreness or discomfort.

These facts suggested that there are at least two kinds of muscular soreness, one of which, characteristic of untrained muscles, is not noticed at the time of the work, but develops in twelve or more hours thereafter; the other, characteristic of sustained tetanus, even in trained muscles, may persist for some time after the work, but then passes away without leaving a trace in the working condition of the muscle. I therefore decided to study the course of soreness in a large number of untrained muscles and with different types of contraction. Four members of the senior class of the Boston Normal School of Gymnastics kindly undertook to make these observations under my direction, first upon themselves and then upon other students of the same school. In each case the muscle had not been previously used in ergographic work, and hence may be looked upon as untrained. The results may be tabulated as follows:

Kind of contraction.	Number of subjects.	Soreness.		
		During work.	3-4 hours after.	12-24 hours after.
$\frac{C}{R} = \frac{\frac{1}{2}\text{ sec.}}{\frac{3}{2}\text{ sec.}}$	6	0	0	5
$\frac{C}{R} = \frac{1\text{ sec.}}{1\text{ sec.}}$	9	1	0	3
$\frac{C}{R} = \frac{1\text{ sec.}}{9\text{ sec.}}$	10	2	2	7
Tetanus	14	10	2	4 (2?)

These results bear out in general what I had suspected from my own experience. While soreness may be caused by any kind of muscular work, either during or after the work, it would seem that rhythmic contractions, and especially those in which the slowness of the rhythm excludes fatigue, are apt to be followed by a soreness twelve or twenty-four hours later, although at the time of work no pain whatever is felt. Tetanic contractions are not so apt to result in soreness on the following day, although the muscle usually feels sore at the time of work.

The most striking feature of the above table is the clear distinction which it draws between fatigue and soreness. As measured by the ergograph, fatigue is most marked in the tetanic contractions, although but rarely are these contractions succeeded by that marked soreness which comes on the following day. In the rhythm $\frac{C}{R} = \frac{1\text{ sec}}{9\text{ sec}}$, on the other hand, fatigue is practically absent at the time of the tracing, and yet the sorest arms noticed were those which had done this kind of work for fifteen or twenty minutes.

Fatigue, strictly speaking, is a phenomenon which accompanies work and is the change in the working capacity of the living cell. It is quite obvious, on the other hand, that other things may interfere with the doing of external work by a muscle fibre; for example, the rupture of the connective tissue which joins the fibre to the tendon, or injury to the nerve fibres upon which it depends for stimulation. For this reason we must always be cautious about attributing diminished working capacity to fatigue.

I believe that the soreness which the experiments given in this paper differentiate so clearly from fatigue is one of the most important secondary factors against which we must guard in drawing conclusions from ergographic work. Its very gradual onset; the marked diminution in the height of contraction, even when pain is absent; the apparent inability of the muscle to do more than a greatly lessened amount of work, suggesting diminished cross-section from throwing certain fibres out of play; the painful sensations produced by movement, suggesting the tearing apart of adhesions which may have formed in the processes of repair, and the fact that rest seems absolutely essential to recovery, — all suggest that muscular soreness is not a fatigue phenomenon, but is due to lesions in the organ, either ruptures of the muscle fibres or of the connective tissue or of the nerves. It may even involve inflammation of the interstitial connective tissue. Whatever the explanation, it would seem clear that no muscle is suitable for experiments in fatigue which has not been trained to do its work without resulting soreness.