

ON THE VOLUNTARY CONTROL OF THE FORCE OF MOVEMENT.

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The muscle sense, if the term be used in a comprehensive way to include all sensations arising in the interior of a muscular member of the body, furnishes sensations that form the basis of a variety of perceptions. Judgments of weight and resistance, of extent of movement, of speed and force of movement, and of position, are all based in large measure on this class of sensations. There have been more or less definite attempts to reduce some of these types of perception to others, as for instance to explain the perception of the extent of movement as a derivative from the perception of the time of movement.

In another place,¹ I have brought together a variety of evidence all going to show that the extent of a movement is not inferred from judgments of the force and duration of the movement or from a comparison of the initial and terminal positions of the movement. These other judgments may indeed assist in certain cases. But there exists a judgment of extent, independent and in its own right.

The present paper is an attempt to examine the force of movement in a similar way. The main question is whether the force of a movement is perceived directly or inferred from a perception of extent.

Any form of apparatus in which force is applied gradually to a spring—as in a dynamometer or ergometer—serves admirably to raise this question, but not to answer it. In such an apparatus, increase in the force of movement is only to be attained by increasing the extent; and it does not appear whether the force is perceived directly or in terms of the extent.

¹ *PSYCHOLOGICAL REVIEW*, Monograph Supplement, 13; pp. 76-86.

I have, accordingly, had recourse to another form of movement, namely, a *blow*. Its advantage for our present purpose lies in the fact that, when the blow is struck on a firm object, the actual exertion of the force occurs practically in an instant of time and in a point of space. The factors of extent and duration are thus eliminated from the actual exertion of the force. On the other hand, the distance and time during which the force of the blow is *developed*, vary widely; but they can also be measured separately from the force of the blow. And when we have obtained separate but corresponding records of the force of the blow, and of the extent (and duration, if need be) of the preliminary movement or 'start,' we shall be in a position to discover any relation between the two.

The apparatus used consists, then, of two parts, one for recording the back movement that precedes the blow, and the other for recording the blow.

The preliminary movement is recorded on a rotating smoked drum by the short arm of a lever, the long arm of which is attached to the hand. The attachment consists of a light silk thread, running over pulleys above. As the hand rises to get a start for its blow, the lever falls of its own weight and so records the extent of the start; as the hand descends to strike the blow, the lever is of course raised. The lever that has been used is of wood, 56 cm. long, pivoted at the end, with the writing point one quarter of the distance out from the pivot. The movements of the hand are thus reduced to a quarter of their true extent. The weight of the lever is sufficient to make it fall promptly when the hand rises, but not enough to impede free movement.

For recording the force of the blow two devices have been used. At first an instrument was constructed in the form of a piston, with the plunger projecting upward and capped with a flat metal disc 3 cm. in diameter. The blows were struck on this disc against the resistance of a stiff spring placed in the cylinder beneath the plunger. To record the blow, a little additional cylinder was attached to the wall of the main cylinder, and in it moved a little plunger attached to the main plunger. The little cylinder and its piston were air-tight, and were con-

nected by rubber tubing with a Marey tambour writing on the same drum as the lever that recorded the movements of the hand. The drum turned at a slow rate, and simultaneous records were taken of the preliminary movement and of the force of the blow.¹

This instrument, while possessing great advantages in recording a rapid series of blows, on account of the quickness of its return to the zero point, had also a disadvantage in that it was necessary to strike it very squarely in order to have the full force of the blow recorded. A simpler device that obviates this difficulty, and works well when the interval between the blows is one second or longer, consists in simply making use of the momentum of the lever above described. If, as the lever is being carried upward by the downward motion of the hand, the hand is suddenly stopped by striking a table, the lever will continue to rise by its own momentum. The height to which it will rise is proportional to the square of its velocity, or, what is the same thing, the velocity of the hand on striking the table. As the *vis viva* of the hand is also proportional to the square of its velocity, it follows that the height to which the lever rises by its momentum is directly proportional to the energy of the blow. This proportion will be modified somewhat by the friction of the writing point on the drum, but is still accurate enough for the present purpose. By this second device can be obtained records like Figs. 1 and 2, that give at a glance a record of the blow and of the start.²

The procedure was usually as follows: the person tested sat before a table of ordinary height—or before a low table on which the spring instrument was clamped—and the thread of the lever was attached to his thumb. He was directed to make with his fist a series of downward blows on the table, of no great force but as uniform as possible. Each blow was to be made the standard for the next. The interval between them was prescribed by a metronome, and was usually one-and-a-half

¹ This instrument was constructed for me by E. Horstmann, instrument maker to the department of psychology, Columbia University.

² The graduation of either of these blow-recorders must be made empirically, and is attended with some difficulty. I have no occasion to use the absolute values in this study.

seconds. The movement with which the blow was made consisted chiefly in extension of the elbow.

The question to be tested in the records was: Is there a direct correlation between the force of a blow and the extent of the preliminary movement? If every increase or decrease in the force is accompanied by a corresponding increase or decrease in the extent, the reasonable conclusion would be that the force is regulated by the extent.

Two facts are obvious from the outset. Large differences in the force will surely correspond with differences in the extent, since on the one hand it is physiologically impossible to strike a strong blow from a short start, and on the other hand it is inconvenient to strike a weak blow from a long start. What we have to consider is therefore the fine discrimination of the force, to see whether that is dependent on discrimination of the extent. The other obvious fact is that it is perfectly possible, within narrower limits, to strike a blow of given force from starts of different extent. It is possible to strike alternately strong and weak blows from the same start. This fact shows at once a certain amount of control over the force independent of the extent.

On examining the records, we find both of these facts exemplified. In Fig. 2, for instance, large changes in the force are accompanied by changes in the extent; yet the same blow is sometimes struck from different extents of start, and different blows from the same extent. On examining a large number of blows I find that there is no one extent that can be regarded as the normal start for a blow of a given force. In a series where the blows average stronger than in another, the starts may average shorter.

What we wish specially to examine is, however, the fine gradations in force, in order to see whether or not they are correlated with gradations of extent.

Fig. 1 gives a fair idea of the degree of correlation observed. The blows here recorded were intended to be equal, each to the preceding. We notice in the majority of instances that an increase in the force is associated with an increase in the extent of the start, and a decrease with a decrease. But we

notice also a number of exceptions. If there were no correlation between the two, the force and the extent would be equally likely to change in the same direction or in opposite directions: 50 per cent. of the cases should show like changes in the two,

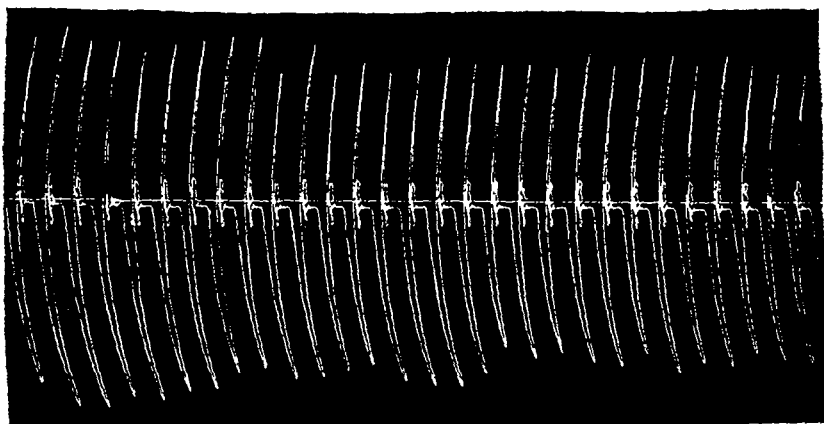


Fig. 1. Simultaneous record of the force of a series of blows, and of the extent of the movement preliminary to each. The portion of the tracing below the horizontal line records the extent of the preliminary movement. The further down the tracing extends, the higher the hand was raised. Above the line is recorded the force of the blow, the height of the tracing being proportional to the force of the blow. In this series each blow was intended to be equal to its predecessor.

and 50 per cent. unlike.¹ If, on the contrary, the force were completely dependent on the extent, then 100 per cent. of the cases would show like changes. The truth is found to lie between these extremes, and much nearer to the 'no correlation' mark. The like changes were found to make up the following proportion of the total number of cases:

With subject	<i>M</i> ,	62.8	% of	670	cases examined.
"	"	<i>R</i> ,	54.6	"	928 " "
"	"	<i>S</i> ,	52.6	"	207 " "
"	"	<i>W</i> ,	61.7	"	2115 " "

The correlation between the fine gradations in the force of a blow and in the extent of the preliminary movement, is therefore direct, but rather slight in degree. The force is not closely dependent on the extent. The extent of the start is apparently one of several causes that influence the force of the blow.

¹ The equalities can be eliminated by minute measurement.

The error in reproducing a blow of given force is not to be regarded as in the main an error in the extent of the preliminary movement.

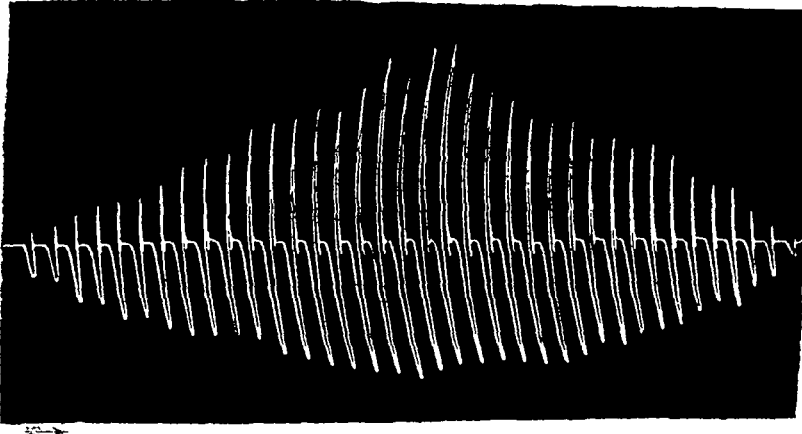


Fig. 2. In this tracing, each blow was intended to be just stronger than the preceding blow, up to the maximum, after that just weaker than the preceding. No heed was paid to the preliminary movement.

If instead of calling for equal blows, we call for blows progressively stronger or weaker, we obtain such tracings as Fig. 2. The increase in force is usually accompanied by increase in the start. The correlation between the two is sometimes, but not always, stronger here than in the former style of experiment. The most significant question is whether the mistakes made in graduating the force can be explained as the result of unsuitable changes in the extent. It is found that mistakes are relatively more frequent when the change of extent is contrary to the desired change of force, but that, even so, the force is rightly graduated in the majority of such cases: and, finally, that less than half of the mistakes made are associated with like changes in the extent. While, therefore, the proper modulation of the force is favored by a corresponding modulation of the extent, the latter is not necessary: the force will usually be made right without the help of the extent.

This conclusion is helped out by the results of experiments in which there was a deliberate attempt to vary the force as in the last experiment, but keep the extent constant; or, to vary

the extent, while keeping the force constant. This experiment was difficult and 'unnatural' at first, but after a little practice it could be carried out with a fair degree of accuracy.

We may approach our general question in still another way. If the force of a blow were regulated mainly by the extent of the preliminary movement, the proper means of *improving* the accuracy of the blow would be to increase the uniformity of the extent. This can be tested in several ways :

1. If a bar is placed over the hand so as to limit its upward movement, the start will always have the same extent, and the accuracy of the blow should be increased. This was tried on three subjects, and succeeded to a certain degree with one, but failed with the other two. The average errors of the force were as follows :¹

Subject <i>S</i> , without bar,	2.50 ± .10,	with bar,	1.80 ± .10.
" <i>M</i> , " "	3.72 ± .23,	" "	5.62 ± .35
" <i>W</i> , " "	1.41 ± .04,	" "	1.82 ± .05

For the latter two subjects, the uniformity of extent was not so important as a free, unimpeded movement of the arm.

2. To avoid the impeding of free movement by the bar, another means was adopted for making the start uniform. The drum was so placed that the subject could see the record of his preliminary movements as he made them, and was told to make them as equal as possible. On the whole, this did not increase the accuracy of the blows.

This may be seen by reference to the following table, which gives, besides the errors in force, the average change in the extent of the preliminary movement. The first subject, it will be noted, did not succeed in making the extent more uniform by attending to it.

	Attention to force		Attention to extent	
	Extent	Force	Extent	Force
<i>M</i> ,	2.61 ± .18	3.55 ± .25	3.16 ± .25	5.16 ± .40
<i>R</i> , right hand,	2.83 ± .13	4.59 ± .21	1.85 ± .11	5.23 ± .31
left hand,	3.45 ± .21	5.87 ± .37	1.49 ± .10	4.58 ± .30
<i>W</i> , right hand,	1.40 ± .04	1.53 ± .04	1.08 ± .03	2.03 ± .05
left hand,	1.80 ± .04	2.13 ± .05	1.46 ± .03	2.82 ± .06

¹ The unit is purely arbitrary, being simply a millimeter applied to the record. The numbers following the averages furnish a measure of their reliability. The chances are 68:32 that the true value of the average does not differ from the observed value by more than this amount.

On the whole, if the object is to keep the force uniform, it is of no advantage to attend to the extent. It is better to attend directly to the force.

3. Even if no attention is paid to the preliminary movement it will be sometimes much more uniform than at other times. If controlled by the extent, the force should be most accurate when the extent is most uniform. But this is by no means always the case. There are series in which a high degree of accuracy is accompanied by great variability in the extent, and others with the contrary combination. What is the general rule? To answer this question we may take the separate sets of 20 trials each, into which the experiment was originally divided, and discover what correlation exists between the accuracy of the blow and the uniformity of the extent. We correlate the average error of the 20 blows with the average change in extent of the 20 starts. We must avoid the interference of practice, which makes both the blow and the start more uniform—but probably in independence of each other—and so introduces an artificial appearance of correlation into the statistics. I have therefore taken the last 60 sets of 20 blows each belonging to one series, and grouped them to bring out the correlation.

First, they are grouped according to uniformity of extent, and the average error in force computed for each group. The numbers represent the total error or change of a set of 20 blows. In the line labeled 'Range' are given the limits which served as the basis of division; below this is the average change in extent per set; and below that the average error in force for the same sets.

Range,	—25 mm.	25-30	30-35	35-40	40 +
Average,	20.5	26.9	31.7	37.2	44.9
Average error in force,	32.7	34.0	40.0	40.6	37.0

As the extent becomes less uniform, the blow becomes somewhat, and on the whole, less accurate in force. But the accuracy of force does not follow the uniformity of extent with great closeness.

Again, the same series is grouped on the basis of accuracy in force, and the average change in extent is computed for each group.

Range,	—30 mm.	30-35	35-40	40-45	45 +
Average,	25.9	32.6	37.3	42.0	51.2
Average change in extent,	29.5	30.3	30.7	34.4	34.0

The correlation here is even slighter than on the other basis of division. Where the error in force is great, the extent is somewhat less uniform, but not much less. The different accuracy of different sets can only in small measure be explained in terms of extent.

The different ways in which we have approached the problem have led to the same conclusion. There is a certain amount of correlation between the extent of the preliminary movement and the force of a blow, but the correlation is not strong. The force can perfectly well be varied while the extent is kept constant, or kept constant while the extent is varied. The error of the blow cannot be explained as a result of variation in the extent, nor can the accuracy of the blow be attributed to uniformity of extent. There is a certain amount of cause and effect between the two, but there is also a large amount of loose play.

The conclusion to which these experiments lead is that the regulation of the force of movement, at least in the case of a blow, is not simply a derivative function, dependent on regulation of the extent. Nor is it dependent on the duration of the movement, since that varies—though not in exact proportion—with the extent, and whatever has been said of extent would apply with slight change to duration. And if the regulation of force is an independent function, so is also the perception of the force of movement, since the control of the force of any one blow is based on the perception of the preceding blow. The muscle sense informs us of the force of a movement directly.¹

What the muscle sense primarily gives us is not definite sensations of force, extent, duration, or position. The rudimentary quality of each of these abstractions is present in the muscular sensations, but they come to have definite meaning and use only by association, and especially by association with

¹ We may substitute 'speed' for 'force' in most of our discussions, since the force of a blow made with a hand and arm of constant weight varies only with the speed.

the production and results of movement. Any other sensations, such as those of sight or hearing, may join with the muscle sensations in forming the basis of a given judgment. And, as the present studies show, the groups of sensations on which two different kinds of judgment are based are in great measure separable from each other.