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THE RELATION BETWEEN INTEGRATED ACTION POTENTIALS IN A HUMAN MUSCLE AND ITS ISOMETRIC TENSION

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During a study of load-carrying it became necessary to determine the presence of activity in certain superficial muscles. For this purpose an electromyograph and surface electrodes were used. Some of the experiments, conducted on muscles supporting loads isometrically, appeared to show a quantitative relationship between the applied weight and the amplitude of the electromyograph tracing. Although such a relationship could be expected to exist only under certain, limited conditions, it seemed worthwhile to investigate it more fully.

In the past, most work has tended to show the absence of a quantitative relationship between action potentials in a muscle and its tension (cf. Schaefer, 1940). Rosenblueth, Wills & Hoagland (1941) showed that there is no relation between the mechanical tension record of a maximal twitch in the frog's sartorius and the accompanying action potential spike. They concluded that end-plate potentials and slow positive components of the electromyogram mask any relationship that might exist between tension and fibre potentials.

On the other hand, Watts (1924) described a parallelism between mechanical response and action potential when the sartorius muscle of a frog was indirectly stimulated with submaximal induction shocks. Loofbourrow (1948) investigated the problem using the tibialis anterior muscle of the anaesthetized cat and found no correlation between the amplitude of the electromyogram and isometric tension in the muscle, excited directly or via the motor nerve. If the muscle was submaximally excited via the motor cortex, however, the isometric tension recorded was always paralleled by the amplitude of the electromyogram.

In the experiments reported here, conscious human subjects made voluntary contractions of varying known strengths, while simultaneous electromyograms were recorded and integrated mechanically.

METHODS

The gastrocnemius-soleus muscle group of the right leg, producing plantar-flexion of the foot, was used in this study. The various contraction strengths of the muscle were measured with a dynamometer, while simultaneous electromyograms from it were recorded by means of an amplifier and cathode-ray oscillograph.

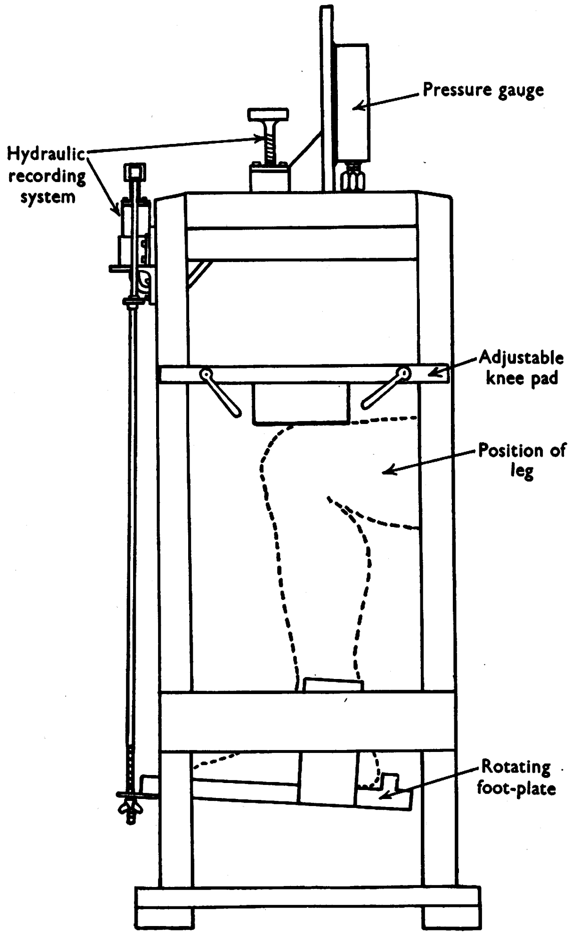

Fig. 1. The dynamometer.

The dynamometer (Fig. 1). This consisted of a rigid wooden framework, fixed to a firm base, into which the subject's leg was clamped from the knee to the heel. The foot rested on a plate hinged in such a manner that its axis of rotation passed through the ankle joint, thus ensuring that only the forces tending to rotate the foot about the ankle joint were measured. Vertical forces due to the weight of the limb, pressure of the upper knee pad and transference of the body weight of the subject to the foot (by fixation of the knee joint) were all eliminated.

Measurement of the pressure exerted by the sole of the foot, when the calf muscles contracted, was made by a hydraulic system and Bourdon gauge. The full-scale deflexion, equivalent to a force of 125 kg on the sole of the foot, necessitated rotation of the plate by approximately 5°. Calibration has shown this instrument to be linear over the whole experimental range.

Electrodes and amplifier. The electrodes were three small brass suction cups $\frac{1}{4}$ in. in diameter and $\frac{1}{4}$ in. deep connected by thin pressure tubing to a vacuum pump. Photographs taken before each experiment from the same point facilitated standardization of electrode position. Most experiments were performed with the electrodes equally spaced along the gastrocnemius belly in the mid-line (see Fig. 2). The amplifier was of conventional design with a push-pull input stage, having inphase degeneration, followed by a Tönnies compressor feeding two further stages in cascade. The effective input impedance was 4 MΩ and the overall time constant was 2·7 sec. The gain was measured before and after each experiment.

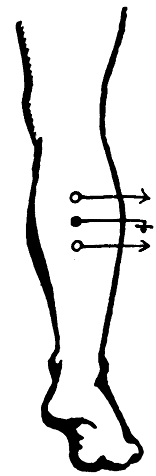

Fig. 2. Position of recording electrodes on right leg.

Recording system. One beam of the oscilloscope recorded the muscle action potentials while the other recorded a trace at 49 c/s produced by a phase shift oscillator driving a tuned vibrating reed. The camera recorded these traces on 70 mm perforated bromide paper travelling at 100 cm/sec.

Integration. Three lengths of action potential recording, chosen at random, were integrated for each tension reading on the dynamometer. Two lines at right angles to the centre line of the tracing (which is zero potential; recorded automatically during the experiment by means of a stationary spot on the oscillograph screen) exactly $\frac{1}{8}$ sec apart were drawn on the record. The area enclosed by the zero line and the electromyogram trace, in the positive sense, between these two lines and the similar area in the negative sense, were then measured with a planimeter (Fig. 3). A mean area of the three randomly selected stretches of recording provided the measure of electrical activity of the muscle integrated over a period of $\frac{1}{2}$ sec.

RESULTS

Action potentials were recorded from thirty different subjects during contractions of the calf muscles at ten different strengths of contraction from 4·5 to 45 kg on the gauge. In order to eliminate any effects due to muscular fatigue certain experiments were performed in random order. Subjects found it quite easy to increase pressure smoothly to the required level and maintain it there for the 5 sec during which a recording was made. There was a large variation between the maximum tension that could be exerted by different subjects, ranging from about 30 to over 100 kg. Deep pain, possibly due to overstretching fibres in the muscle, appeared to be the commonest limiting factor in performance. In some subjects this pain persisted for several days; a few others had persistent stiffness. The maximum pressure of 45 kg in all experiments was well within the capabilities of all thirty subjects included in these results.

Fig. 3B is a typical stretch of recording with the area integrated shown black. A certain periodicity in the trace was present in most subjects at about $\frac{1}{3}$ to $\frac{1}{4}$ sec intervals, apparently coinciding with muscular tremor. In one subject this periodicity was very marked. A prolonged series of contractions generally resulted in an accentuation of this periodicity as also did the maintenance of a maximal contraction for more than a few seconds. Fig. 4 shows the integrated action potentials plotted against the tension exerted by the muscle, the points shown referring to two experiments on the same subject. Table 1 shows the values obtained in the second of these experiments.

Other experiments, not included in the series, were recorded from electrodes in various non-standard positions. Provided that the two recording electrodes were sited over the muscle belly or its tendons, the relationship was always a linear one, of the nature shown in Fig. 4, although when the electrodes were close together the output was lower and the scatter of the values about the plotted line was greater. Prolonged cleaning of the skin beneath the electrodes and the use of an electrode paste consisting of saturated salt solution made up in a water soluble base, increased the voltage of the recording slightly, resulting in an upward displacement of the plotted line.

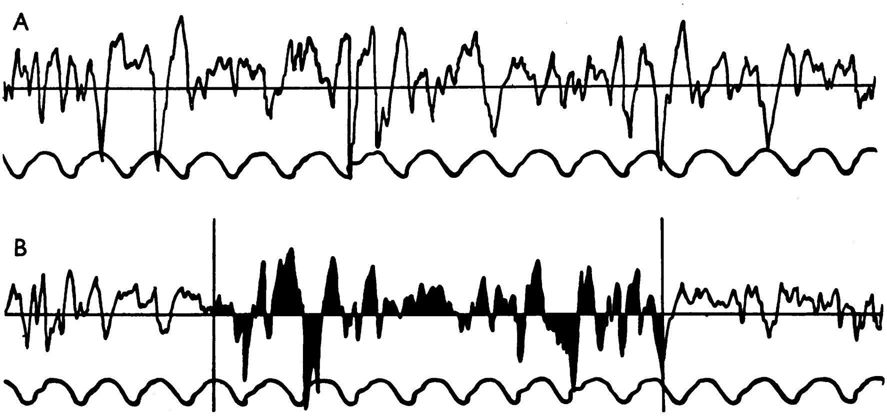

Fig. 3. A, normal electromyogram of calf muscles contracting isometrically. Pressure on dynamometer 35 kg. Surface electrodes. Time at 49 c/s. B, electromyogram (same record) showing area integrated in black.

Some experiments were performed at contraction strengths increasing to the maximum that could be exerted by the subject. These showed the linear relationship to hold throughout the contraction range of the muscle, although scatter of the values became greater at near-maximal contractions because of the accentuated periodicity in the trace, and the difficulty experienced by the subject in maintaining a constant reading on the dial.

The lines in Fig. 5 are regressions of integrated activity on the exerted pressure, one for each of ten experiments (i.e. they are the lines 'statistically best fitting the plotted points'). The coefficient of correlation varies between $+0{\cdot}93$ and $+0{\cdot}99$. These regression lines vary between different subjects in residual variances and in their regression coefficients as shown in Table 2.

The residual variance is a measure of the scatter of values of integrated activity about the regression line. It is probably dependent upon several factors, such as an inaccurate measure of tension, owing to lack of muscular skill on the part of the subject, the presence of tremor and hence periodicity in the trace and errors in the integrating process. It becomes less as the period

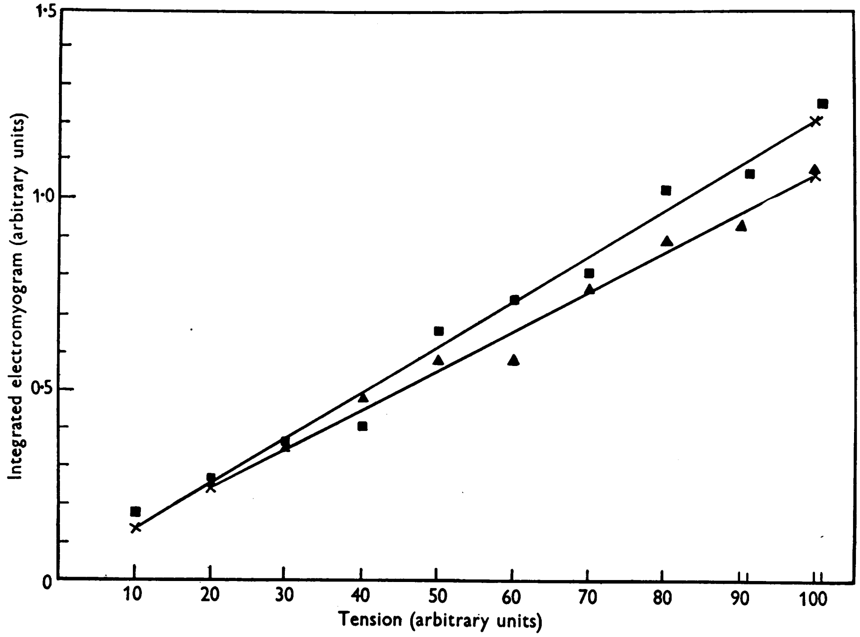

Fig. 4. The relation between electromyogram and tension during a voluntary contraction. (Subject E.E.E.T.) ■, on 30 November 1950. ▲, on 26 April 1951.

Table 1. Results obtained in one experiment; records shown in Fig. 3 and plotted in Fig. 4

Tension in muscle (arbitrary units)	Integrated action potentials						
	Period 1 (1/8 sec)		Period 2 (1/8 sec)		Period 3 (1/8 sec)		
	+ve	−ve	+ve	−ve	+ve	−ve	Mean
10	—	—	—	—	—	—	—
20	0·16	0·20	0·27	0·24	0·25	0·27	0·23
30	0·31	0·30	0·42	0·38	0·33	0·35	0·35
40	0·37	0·39	0·45	0·49	0·57	0·58	0·48
50	0·61	0·60	0·62	0·63	0·49	0·51	0·58
60	0·58	0·60	0·64	0·62	0·50	0·51	0·58
70	0·85	0·82	0·67	0·65	0·84	0·80	0·77
80	0·85	0·87	0·80	0·81	0·98	1·00	0·89
90	0·75	0·80	1·12	1·16	0·85	0·87	0·93
100	1·00	1·01	1·20	1·18	1·05	1·02	1·08

integrated is lengthened and is least when periods of ½ to 1 sec are measured. Residual variance tends to increase again when longer periods of integration are employed. Some subjects habitually showed a large residual variance which could be reduced to within the normal range by administration of quinal barbitone prior to the experiment.

The regression coefficient expresses the output of electrical activity required to produce unit increase in tension. It varied considerably between different

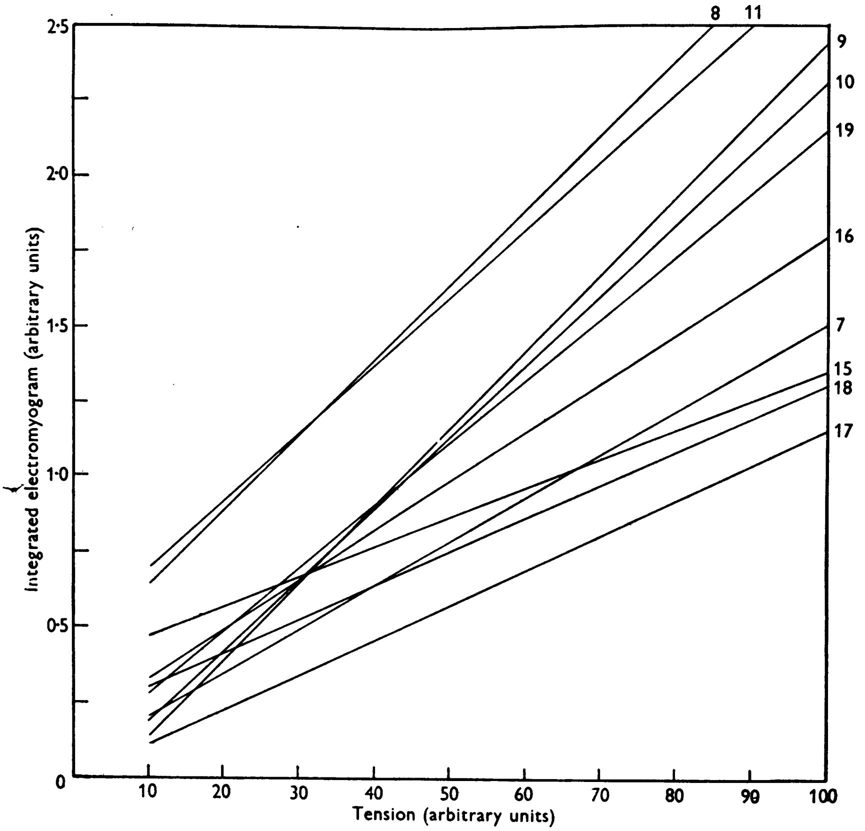

Fig. 5. Regressions of integrated activity on tension. Ten experiments. (See Table 2.)

Table 2. Analysis of results of ten experiments

Expt. no.	Product moment correlation	Regression coefficient	Ratio of variances residual/total	Ratio of standard deviations
7	+0·991	0·0118	0·018	0·134
8	+0·964	0·0197	0·070	0·265
9	+0·935	0·0202	0·126	0·355
10	+0·971	0·0189	0·057	0·238
11	+0·942	0·0187	0·114	0·338
15	+0·994	0·0099	0·012	0·110
16	+0·995	0·0131	0·010	0·100
17	+0·977	0·0103	0·045	0·212
18	+0·992	0·0102	0·016	0·127
19	+0·970	0·0166	0·059	0·243

experiments, because differences in limb posture change the mechanical advantage at which the system operates, thus altering the ratio between activity and tension. Preliminary work has shown that providing precautions were taken to reproduce the electrode and limb position in the dynamometer accurately, the regression coefficient tended to be characteristic of the subject on different occasions.

DISCUSSION

The results show that under the limited conditions of the experiment there is a linear relation between the integrated electromyogram and the tension produced by a voluntary isometric contraction in a human muscle.

Although there is no proportionality between the mechanical and the electrical responses of a single motor unit, when the summated effect of a large number of units is recorded by surface electrodes from the whole muscle, the variation is statistically cancelled out. It has been shown (Adrian & Bronk, 1929; Eccles & Sherrington, 1930; Gilson & Mills, 1941) that changes in the strength of contraction of a muscle are brought about in two ways: as the strength of contraction increases the number of motor units active becomes greater and there is a rise in the frequency at which these units repetitively contract.

Both these factors must increase the integrated electrical output of the muscle, so that the existence of this linear relationship indicates that the recruitment of motor units, bringing about increased strength of contraction, is spatially random. Similarly, there are either random increments of discharge frequencies of the active units, or once a particular unit has become active its rate of contraction smoothly increases.

The lack of correlation between electrical and mechanical activity, found previously in animal experiments, may be due to a differential stimulation of the fibres of the motor nerve resulting in localized regions of activity within the muscle. Such localized activity would be unequally picked up at the surface, that from distant regions—although still exerting tension on the tendon—being attenuated to a greater degree than those potentials arising close to the electrodes.

Under the artificial conditions of supramaximal stimulation of the motor nerve to a muscle the linear relationship cannot be expected to hold, because all the motor units are active and thus furnish a constant electrical output, while the strength of contraction can vary with other factors such as the frequency of stimulation (Adrian & Bronk, 1928, 1929; Brown & Burns, 1949) and initial tension on the muscle (Adrian & Bronk, 1929). Loofbourrow, performing such an experiment upon the tibialis anterior of the cat, showed varying degrees of contraction without concomitant changes in the *amplitude* of the electromyogram, by varying the repetition rate of supramaximal stimuli. The amplitude of the electromyogram seems from his observations to be a function of the number of active units, rather than the frequency of their discharge. The integrated output, on the other hand, would appear from our results to be dependent upon both these factors.

SUMMARY

1. The relation between the isometric tension of a voluntarily-contracting human muscle and its integrated electromyogram has been investigated.

2. In thirty experiments on different subjects the relationship is always directly linear.

3. The coefficient of correlation in these experiments varies between +0·93 and +0·99.

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