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THE ISOMETRIC RESPONSES OF MAMMALIAN MUSCLES.

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THE researches of Hartree and Hill(1), Liddell and Sherrington(2), and Fulton(3) have produced much evidence bearing on the nature of the response of a muscle to a repetitive stimulus, *i.e.* a tetanus. Differences between the tetanic responses of "slow" and "fast" muscles have been described by Ranvier(4) and others(5) in the rabbit, by Fischer(6) in the rat and cat, and more recently by Denny-Brown(7) in various muscles of the cat, particularly soleus and gastrocnemius. During the further investigation of the building of a tetanus in the soleus, gastrocnemius, extensor digitorum longus, and internal rectus (eye) muscles of the cat, it was found that the records were being distorted by the effect of friction at the myograph bearing(8). When this source of error was removed or largely reduced, the record of the isometric twitch of each of these muscles was found to be a smooth curve showing neither "angle" nor "period of rigidity"(9). Such "frictionless" myographs[1] have been used for the experiments described in this paper, and, in so far as the frictional error allows, the results are confirmed by our more numerous experiments with the older instruments.

METHOD.

After decerebration of the cat the muscle to be used was freed as extensively as possible consistent with an intact nerve and blood supply. The lower limb muscles were stimulated by Sherrington shielded electrodes placed on the peroneal (for extensor digitorum longus) or popliteal (for soleus and gastrocnemius) nerves which were cut centrally; all peripheral branches to other muscles were also cut.

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[1] Owing to technical difficulties in dealing with the very fine torsion wire of the eye-muscle myograph, friction is still sufficiently great to produce an "angle" in most records of the contraction of internal rectus.

An adequate fixation of the origin of the muscle has been secured by drills through the bone, fixed at both ends by clamps and uprights to the cast-iron top of the experimental table. Microscopical observations have shown a negligible give of the bone even with contractions of 15 kg. For soleus and gastrocnemius the freed bony insertion of the muscle was attached to the lever-arm of the mirror myograph (frictionless)(8) by a short steel hook at a moderate initial tension. The tendon of extensor digitorum longus was securely tied to a ring through which the hook passed.

The internal rectus of the eye was stimulated by a bipolar electrode on the oculomotor nerve as it passes through to the orbit. Reflexes evoked by escape of current are avoided if the ophthalmic nerves are sectioned in the region of the Gasserian ganglion. Fixation was secured by two clamps to the sides of the skull.

From all muscles the electric responses were led off by Ag : AgCl electrodes to a Cambridge string galvanometer. A Lucas pendulum has been used to stimulate the motor nerve by break induction shocks at various intervals, and the tetanic stimulus has been produced by a neon-tube device(10). In all cases the stimuli have been rather stronger than maximal.

The temperature of the muscle has been observed throughout the experiments, and care has been taken to keep it constant (usually between 34° and 37° C.).

RESULTS.

Now that the "angle" has been shown to be an artifact, it has been necessary to introduce another basis for the measurement of the duration of the isometric twitch of a muscle. The interval between the onset of the electrical response and the attainment of maximum tension has been chosen; henceforth this will be called the "contraction time." The approximate "contraction times" of the muscles used are: soleus, 100σ; medial head of gastrocnemius, 40σ; extensor digitorum longus, 40σ; and internal rectus of the eye, $7\frac{1}{2}$–10σ. As would be expected, the durations to the "angle" found by Denny-Brown(7) for these muscles were usually somewhat longer than the values for "contraction time" given here.

The first results concern the effect of a twitch of a muscle on a second twitch following at various intervals. Analysis reveals that many of the features of the double response have counterparts in the tetanic response of the muscle; this latter forms the second part of the investigation.

Time is shown by vertical lines 0·02σ apart. The records read from left to right.

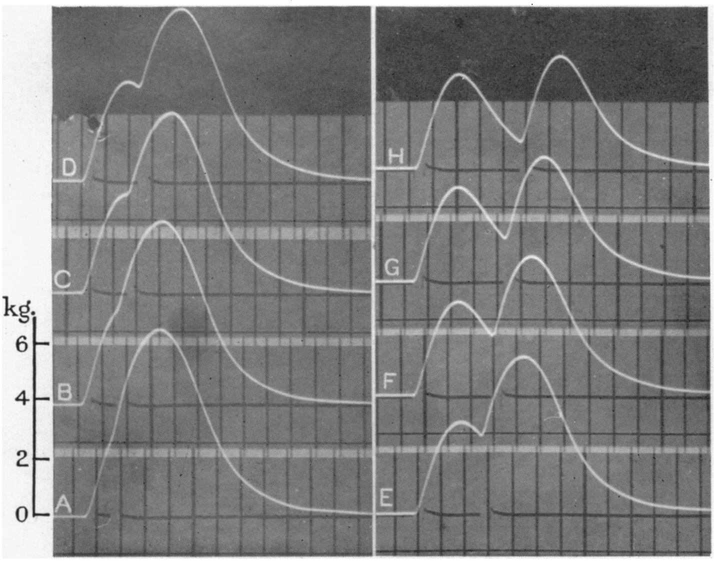

Fig. 5. Mechanical and electrical responses of median head of gastrocnemius to double shocks to peroneal nerve. Temp. 34·5° C. The stimuli were maximal break shocks. Interval between stimuli: *A*, 24σ; *B*, 32σ; *C*, 40σ; *D*, 48σ; *E*, 57σ; *F*, 69σ; *G*, 77σ; *H*, 88σ.

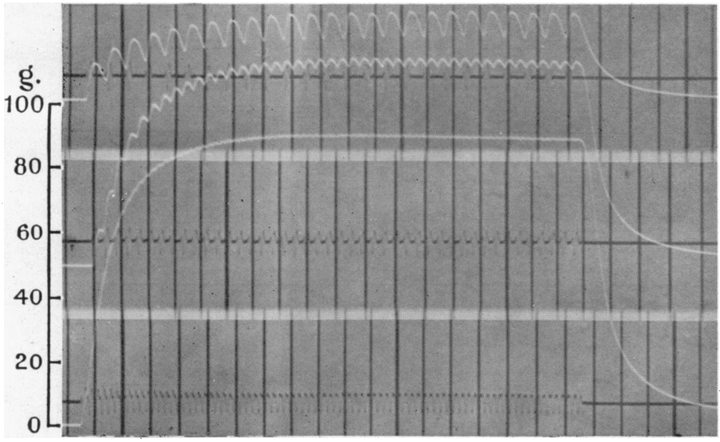

Fig. 6. Mechanical and electrical responses of internal rectus (eye) to tetanic stimulation of n. III. Temp. 36° C. Maximal stimuli from neon-tube device. Rate of stimulation: upper records, 70 shocks a second; middle records, 125 shocks a second; lower records 210 shocks a second. See Fig. 3 *b* for tension-rate curve.

Response of muscle to two stimuli.

Maximum stimuli to the motor nerve have been used to evoke muscular twitches at time intervals, varying from a period just longer than the relative refractory period to one where the second twitch was almost unaffected by the first. Pl. I, fig. 5, shows a series of photographs of double twitches of median head of gastrocnemius. The maximum tension and the "contraction time" of the second response (from the second action-current to the point of maximum tension) give an indication of the alteration of the muscular response as the interval between the two stimuli is increased. Curves with the stimulus interval as abscissæ and both *A* the maximum tension and *B* the "contraction time" of the second response as ordinates are shown in Figs. 1 and 2 for soleus and extensor digitorum longus respectively. Curve *C* shows the single twitch drawn to the same tension time scale; subtraction[1] of it from curve *A* gives curve *D* which represents, for each interval, the corresponding total tension addition from the beginning of the second mechanical response. This tension addition is produced by the second contraction plus any active contractile stress remaining from the first response.

Despite a considerable difference in the time scale, a fairly close resemblance is apparent between Figs. 1 and 2. In both the tension of the double response reaches a maximum with the shortest stimulus interval; however, the ratio to the single twitch tension is 2·2 for extensor digitorum longus and only 1·9 for soleus. Curve *D* reaches a minimum (considerably less than a single twitch tension) at an interval just greater than the "contraction time"; with increasing intervals it slowly returns to the single twitch tension. The early maximum of curve *D* is due to the enhancement of the second response by a considerable amount of active contractile stress of the first response. The gradual increase at intervals beyond the minimum can be explained as the passing off of some influence due to the first response. Certainly for soleus this influence is not entirely the tension remainder of the first response, which for long intervals is less than the tension deficiency of the second response (Fig. 1).

At the shortest stimulus interval the "contraction time" of the second response (curve *B*, Figs. 1 and 2) is considerably longer than

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[1] By means of this subtraction it is not intended to make any correction for the effect of the first response on the summated contraction. Any allowance for the influence of one response on another is misleading, as the factors involved are but vaguely understood and certainly not quantitatively estimated

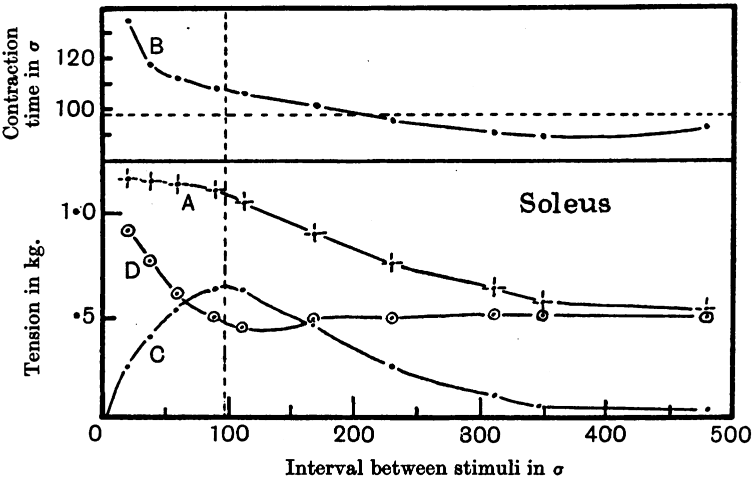


Fig. 1. Curves taken from responses of soleus to double shocks to popliteal nerve. *A*. Maximum tension of double responses. *B*. "Contraction time" of second responses. *C*. Tension of the first response at the beginning of the second response. *D*. The total tension addition from the beginning of the second mechanical response; obtained by subtracting the tensions of curve *C* from those of *A*. The dotted lines show the "contraction time" of a twitch.

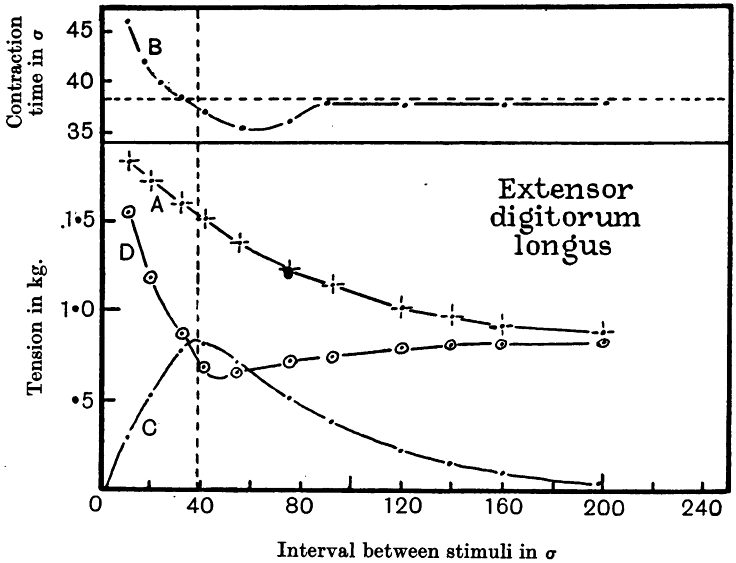


Fig. 2. Curves taken from responses of extensor digitorum longus to double shocks to peroneal nerve. Lettering as for soleus.

that of a twitch. With increasing intervals it gradually diminishes to a value less than a normal twitch "contraction time," and then slowly increases. The return is much slower for soleus, even when calculated on the basis of its longer "contraction time." Gasser and Hill ((11), p. 429) have pointed out that, in the isometric twitch, the maximum tension is reached when the external tension development (as recorded by a myograph) has increased to equal the declining internal contractile stress of the muscle. Now, at the moment of maximum tension in the double twitch and still more so in the tetanus, the internal contractile stress is greater than it is for a single response, for, at this instant, it equals the maximum tension which is greater for the repetitive responses. Therefore, in these, the moment of maximum tension indicates an earlier phase of the declining internal contractile stress, and so their "contraction times" are not comparable to the "contraction time" of a twitch, and the marked shortening with certain response intervals must at least be partly explicable in this way.

Gastrocnemius closely resembles extensor digitorum longus, but the ratio of the tension of the maximum double response to that of a single twitch is only 1·9, and the absolute tension values are much greater (see Table I).

TABLE I.

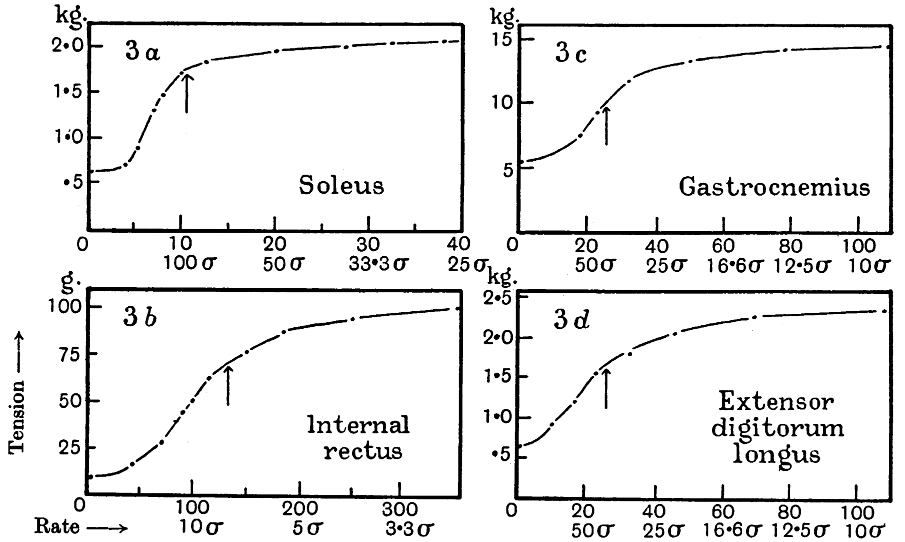
Muscle	Twitch tension (kg.)	(Tension double response) ÷ (Tension single response)	Tetanus tension (kg.)	(Tetanus tension) ÷ (Twitch tension)	"Contraction time" of twitch	Rate of stimulus having intervals = "contraction time" = R (per sec.)	Tension of tetanus at rate of stimulus = R (kg.)	(Tension at rate = R) ÷ (Max. tetanus tension)	Rate of stimulus necessary for complete mechanical fusion (per sec.)
Soleus	·65	1·9	2·44	3·8	100σ	10	1·85	0·76	—
	·65	1·9	2·10	3·26	94σ	10·6	1·73	0·82	33
	·875	—	2·77	3·26	120σ	8·3	2·16	0·78	31
Gastrocnemius	4·64	1·94	14·58	3·3	39σ	25·6	10·1	0·685	100
Extensor digitorum longus	·63	3·3*	3·12	4·95*	23·4σ	42·7	2·40	0·77	115
	·65	2·2	2·35	3·76	38·2σ	26·2	1·65	0·74	108
Internal rectus	·0093	>3	0·100	10·7	7·5σ	133	0·070	0·70	350

* These values are high owing to the rather low initial tension used throughout this experiment.

The responses from the internal rectus of the eye correspond to those from the other muscles if the very short "contraction time" be allowed for; however, the ratio of the tension of the maximum double response to that of a single twitch is greater than 3. When the "contraction time" was 9·1σ, the second twitch was unaffected by the first at an interval of 24σ. The brief "contraction time" is thus associated with a corresponding speed in all the phases of the response.

Response of muscle to repetitive stimuli.

Pls. I and II, figs. 6, 7, and 8, show the responses of soleus, gastrocnemius, and internal rectus to repetitive stimuli of varying rates. In Fig. 3



Rate, stimuli per sec.; and interval between shocks, σ

Fig. 3. Curves showing the effect of rate of stimulation on tetanus tension for the four muscles studied. The values in sigmata under the rates give the interval between stimuli at those rates. The arrow in each case is placed at the interval which equals the "contraction time" of a single response.

measurements from records of this type are plotted with the maximum tension development as ordinates and, as abscissæ, the rate of stimulus rhythm (as shown by the electrical responses). The curves are similar in shape, but, except for gastrocnemius and extensor digitorum longus, corresponding points differ widely in their respective rates of stimulus. If, however, the twitch "contraction time" is used as the standard for time measurement, a very good agreement is found. Thus in Fig. 3 the arrow shows the frequency of the rhythm where each successive stimulus is separated by the "contraction time" characteristic of that particular muscle. At slow rates of stimulus successive twitches have no influence on one another and so the maximum tension of a series is equal to the twitch tension. With quicker rhythms the tension progressively mounts until an undulatory plateau is reached (Pls. I and II, figs. 6, 7, and 8). This is the region of the steep part of the S-shaped curves shown in Fig. 3.

PLATE II

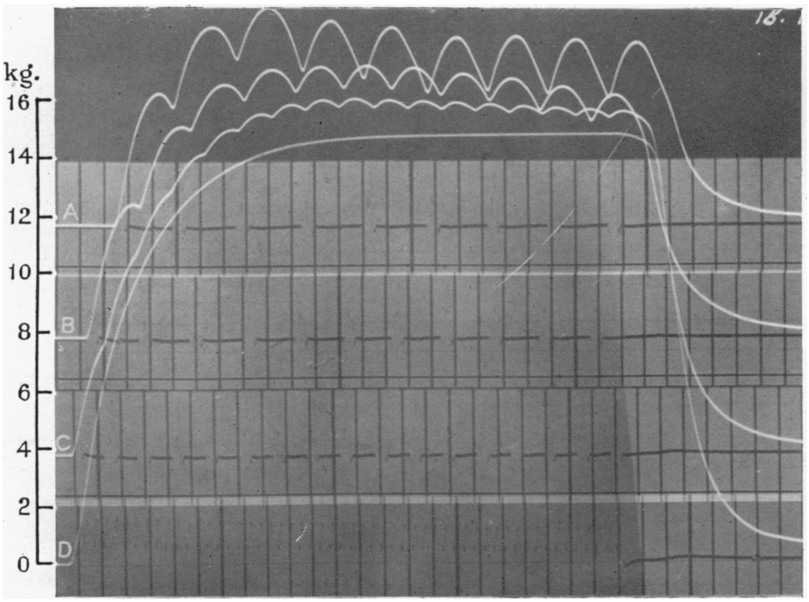


Fig. 7. Mechanical and electrical responses of median head of gastrocnemius to tetanic stimulation of popliteal nerve. Temp. 33° C. Rate of stimulation: record *A*, 19 shocks a second; record *B*, 23·5 shocks a second; record *C*, 35 shocks a second; record *D*, 115 shocks a second. See Fig. 3 *c* for tension-rate curve.

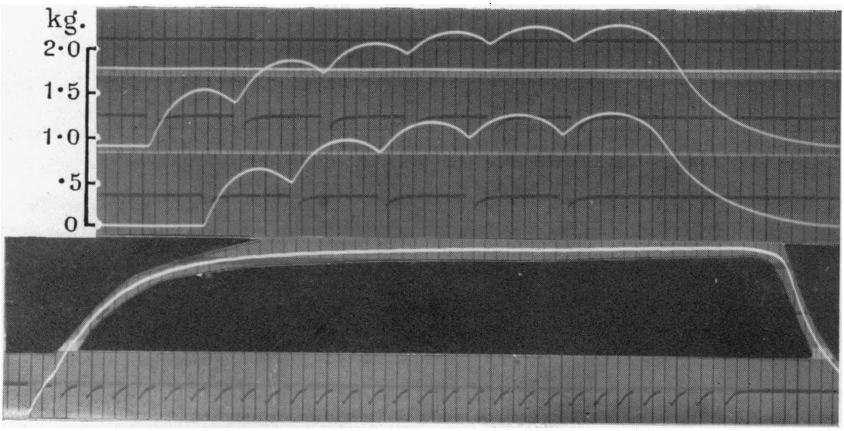


Fig. 8. Mechanical and electrical responses of soleus to tetanic stimulation of popliteal nerve. Temp. 33° C. Rate of stimulation: upper record, 5·3 shocks a second; middle record, 7 shocks a second; lower record, 23 shocks a second. See Fig. 3*a* for tension-rate curve.

Further increases in the stimulus rate produce a more complete fusion, until finally all myographic evidence of the repetitive nature of the response ceases. Practically no extra tension is developed by stimulus rates higher than this. The ratio of the tension produced by such a tetanus to the twitch tension varies for the different muscles (see Table I). The stimulus rate necessary for complete fusion is much higher for internal rectus (about 350 per sec.) than for gastrocnemius and extensor digitorum longus (about 100 per sec.), and this in turn is much higher than that for soleus (about 30 per sec.), *i.e.* the stimulus interval of the rhythm necessary for complete fusion is proportional to the respective "contraction times."

The tension of the repetitive response of soleus does not reach a steady plateau, but, as shown in Pl. II, fig. 8, continually increases. Since fatigue would be produced by the long continuation of the stimulus (several seconds) necessary to develop maximum tension, the somewhat lower tension produced by a stimulus duration of just over a second has been used throughout. On the other hand the responses of gastrocnemius to comparatively slow rates of stimulus have declined in tension after

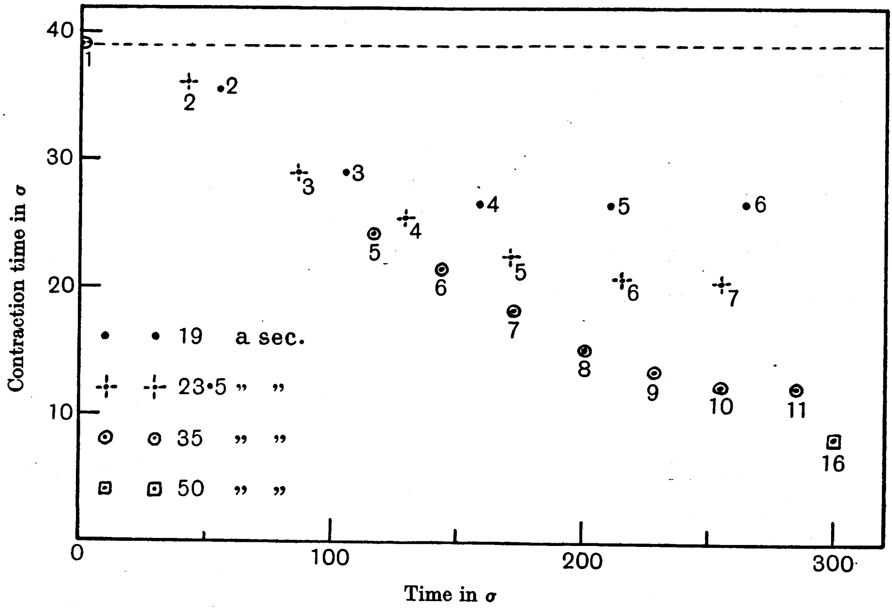


Fig. 4. Median head of gastrocnemius tetanized at various rates through the popliteal nerve. The points in a series show the "contraction times" of successive responses at the rate indicated, and they are plotted at the actual times after the first response. The dotted line shows "contraction time" of a twitch.

an initial increase (Pl. II, fig. 7). This is due to a progressive shortening of the "contraction time" of the successive responses (Fig. 4), which clearly cannot be completely explained by the increased tension. This difference between soleus and gastrocnemius can be correlated with the observed increase in the duration of the second response in soleus at relatively greater intervals than in gastrocnemius (*vide supra*, p. 381). Extensor digitorum longus also shows the decline in tension with comparatively slow rates of stimulus.

DISCUSSION.

Table I summarizes the principal features of the results which have already been discussed. In several respects muscles differing greatly in power and in "contraction time" are closely similar when their responses are measured relative to these respective quantities, *e.g.* the values of the second last column. However it will be noticed that the ratio of the tension development of a repetitive response to that of a single response is greater the shorter the "contraction time."

The **S**-shaped curves showing the relationship between stimulus rhythm and tension development resemble curves obtained by Adrian and Bronk(12) despite the fact that their contracting muscle was allowed to shorten by 5 mm. or more. Denny-Brown(7) and Adrian and Umrath(13) agree that the rhythm of reflex stimulation of soleus (maximum 30–40 per sec.) is usually slower than that of gastrocnemius (maximum 50–60 per sec.), and suggest that the rhythm of stimulation probably depends on the type of muscle fibre. If this is so, it would be interesting to know the rate at which the internal rectus of the eye normally receives impulses.

SUMMARY.

By means of a frictionless myograph the mechanical isometric responses of mammalian muscles with diverse "contraction times" have been investigated.

It has been found that the responses of the muscles, both to two stimuli at various intervals and to repetitive stimuli at various rates, show similarities if the time intervals are measured relative to the respective "contraction times"; but the ratio of the maximum tetanus tension to the twitch tension is usually greater for muscles having a short "contraction time."

The relation between rate of stimulation and tetanus tension follows an **S**-shaped curve for all the muscles studied.

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