

SUPRASPINAL CONTROL OF THE MUSCLE SPINDLES AND ITS SIGNIFICANCE

BY E. ELDRED,* R. GRANIT AND P. A. MERTON†

*From the Nobel Institute for Neurophysiology, Karolinska Institutet,
Stockholm 60, Sweden*

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Following upon Leksell's demonstration in this laboratory (Leksell, 1945) of the exclusive role of the small-fibre efferents, his ' γ ' efferents, in determining the outflow of impulses from the muscle spindles, elucidation of their function has proceeded rapidly. Detailed knowledge of the peripheral mechanism, through which γ excitation adjusts the bias on the sensory endings by causing contraction of the intrafusal muscle fibres, derives from the experiments of Matthews (1933) and of Kuffler and his co-workers, summarized by Kuffler & Hunt (1952). The part played by intrafusal muscle contraction in reflex action was first adumbrated in the penetrating hypothesis of Rossi (1927). Recently, several authors (Sommer, 1940; Hoffmann, 1951; Merton, 1950, 1951; Granit & Ström, 1951, 1952) have inferred an action of the γ efferents, but direct evidence was first published independently by Hunt (1951) and Kobayashi, Oshima & Tasaki (1952) who recorded γ impulses in motor nerve twigs and single fibres. Cerebral control of the muscle spindle was established by the work of Granit & Kaada (1952) who found that the 'tonic' background discharge could be selectively augmented in or suppressed from several structures in the central nervous system. In continuing their work we have dealt with a number of unsolved problems centring around the general question of the scope of this control and its significance in the proprioceptive regulation of muscular contraction. A preliminary account has already appeared (Eldred, Granit & Merton, 1953).

Thus it is unknown to what extent supraspinal γ control can display itself after cutting the dorsal roots. It has been claimed by Hunt (1951) that in spinal cats spontaneous discharge in γ efferents ceases after de-afferenting that region of the cord. If this were true and applied also during stimulation of

* Markle Scholar in Medical Science from the Department of Anatomy, University of California, Los Angeles.

† On leave of absence from the Medical Research Council, London.

higher centres, it would mean that de-afferentation had the same effect qualitatively on the γ and the ordinary α motor fibres. Systematic use of de-afferentation in our experiments on decerebrate and anaesthetized animals has, however, disclosed striking differences between α and γ motoneurons such as the servo-mechanism theory of the stretch reflex (Merton, 1953*a*) requires.

In this paper impulses in γ fibres are not themselves recorded, but the general effect of γ activity is observed indirectly by its influence on the sensory discharge in a single spindle afferent isolated in a dorsal root filament. This technique was first used by Granit & Kaada (1952); in their investigation and in two others (Granit, Job & Kaada, 1952; Eldred & Hagbarth, 1953) the results were found to agree with direct recording of γ discharge in the ventral roots or in motor nerve twigs. The advantages of this method are numerous. To isolate a γ fibre and be certain to which muscle it was connected it is necessary to reduce fine motor-nerve twigs until only one small-diameter motor fibre is active; this is more difficult than to obtain a single large afferent in the dorsal roots. In addition, the information obtained from spindle afferents is of greater physiological interest, for what is significant for reflex action is not the discharge in individual γ fibres but the joint influence the several γ fibres innervating a single spindle have on its response under the particular mechanical conditions prevailing.

Mechanical conditions in the muscle and the effects of γ discharge interact in a way that depends primarily on the anatomy of the spindle. A spindle consists of two contractile muscular poles (the intrafusal muscles) jointed by a non-contractile sensory portion. It is believed that the rate of discharge of the end-organ is determined only by the extension of this sensory portion. As the spindle lies among the main muscle fibres parallel to them and shares their attachments its length will change with theirs. In the absence of contraction of the intrafusal muscle bundle, the spindle sensory endings therefore record the length of the main muscle fibres (Sherrington, 1900; Fulton & Pi-Suñer, 1928). It does not record tension; indeed when the tension in the muscle rises during an isometric contraction the spindle slows, because, it is thought, the tendons are elastic and always permit some shortening of the actual muscle fibres. Impulses in γ fibres are motor to the intrafusal muscle and extend the sensory portion by making the poles contract; but this action can be offset by a shortening of the spindle as a whole. Thus the spindle frequency is increased by γ discharge and decreased by muscle shortening and by active contraction. When the γ system is active the spindle signals the difference between muscle shortening and intrafusal fibre shortening.

In this paper we utilize the special information in this signal in two ways. First, during reflexly induced active contraction it decides whether the main muscle or the intrafusal muscle is shortening the faster, i.e. whether γ activity

precedes α activity. If the intrafusal muscle is in advance, the spindle accelerates during the contraction. If the intrafusal muscle is paralysed or lagging, the spindle slows. Such data (which provide a critical test of the servo theory of muscular control) are not to be had by leading from the γ motor fibres themselves. It will be shown that the spindle (in these experiments) always accelerates during active contraction. As spindle impulses are known to excite the main motoneurons through the stretch reflex arc this result implies that the γ system is activating the main muscle through the spindles.

Secondly, by recording the signal from the spindle ending we can derive a quantitative estimate of γ activity by measuring the bias that γ discharge applies to the spindle. When γ impulses cause the muscular poles of the spindle to contract, the sensory ending accelerates. But it will resume its former rate if the muscle be allowed to shorten the necessary distance. We can therefore regard the intrafusal contraction as 'biasing' the sensory ending so that it fires at the old rate at a new muscle length (cf. Kuffler & Hunt, 1952). The amount of shortening necessary, in millimetres, is the measure of the bias. On this principle measurements of bias have been made in resting preparations at different muscle lengths (both with intact reflex connexions and after de-afferentation) and the scope of the maximum obtainable cerebral excitation and inhibition defined. In every case the bias is referred to the paralysed spindle after γ influence has been finally removed by ventral root section.

It is most straightforward to express bias as the frequency difference between biased and de-efferented spindle response at the same length. The present method, however, is superior for several reasons. Bias is a matter of intrafusal muscle contraction and should logically be expressed in mechanical terms. By so doing the answer is made independent of the precise characteristics of the sensory ending, for our method is in principle a null-method, the bias being defined as that shortening required to reduce spindle rate to the *same* frequency as the unbiased spindle at the original length.

A further convenience is that when length/tension diagrams for passive and tetanized isolated spindles become available they can be applied (with certain other more simply measured quantities) to the present data to decide how hard the intrafusal muscles were contracting in our experiments; whether, for example, a spindle was maximally tetanized during cerebral stimulation. With the present data it can be shown that if the spindle is assumed to have the same length/tension diagram as is observed for the whole muscle, then the intrafusal muscle, when the spindle is heavily biased, is apparently exerting about four times the specific tension of ordinary muscle maximally tetanized. It seems therefore that the length/tension diagram of the passive spindle is much flatter than that of ordinary muscle; this may be connected with a greater extensibility of the sensory portion.

The final, but not the least, advantage of expressing bias as an equivalent shortening is the unique functional significance that this quantity possesses on the servo theory of muscular control. For, if it be accepted for the moment

that muscular shortening is initiated through the γ system and the stretch reflex arc in the way outlined above, then the bias we measure is to the first order the actual shortening that would take place if the muscle were allowed to shorten isotonicly.

METHODS

The cats used were either decerebrated or permanently anaesthetized with chloralose and dial. Decerebration was either by the classical trephine method or occasionally by the anaemic technique of Pollock & Davis (1930). In the anaesthetized animals an initial dose of 20 mg/kg of chloralose was given intraperitoneally while the operation was carried out under ether. Afterwards dial was added by intravenous or intramuscular injection as needed, but never more than 20 mg/kg. Laminectomy and craniotomy (when required) were performed, and both hind-limbs immobilized and denervated; this involved section of the femoral and obturator nerves and the ileopsoas muscle on both sides, on one side only section of the whole sciatic nerve, and on the other side section of the hamstring, peroneal and popliteal nerves, leaving only the two branches of the sciatic to gastrocnemius and soleus uncut. In this preparation the second branch to soleus which arises from the popliteal nerve in the lower leg is sacrificed, but this will not adversely affect the results obtained here with that muscle. The magnitude of its stretch reflex must, however, have been reduced. Being chiefly interested in postural or 'tonic' types of activity we generally used soleus, feeling it to be more suitable for our purposes than gastrocnemius, but we also made observations on gastrocnemius when occasion arose. The two muscles and their tendons were carefully dissected apart and the skin sewn over them again. The limb was held rigid by a drill through the condyles of the femur and a clamp at the ankle, while the pelvis was steadied by pins inserted into both trochanters. Tension was recorded by a strain-gauge myograph to which the tendons were connected by stout thread. At maximum sensitivity 1 g represented 2.5 mm on the recording paper or 8.0 mm on the screen of the cathode-ray tube.

The afferent fibres from gastrocnemius and soleus enter the cord mainly in dorsal roots L5-S1 while the motor supply chiefly occupies ventral roots L6-S1. Since de-afferentation and de-efferentation were standard procedures it was an advantage not to have to sever too many roots later in the experiment. For this reason the whole of L4 and the ventral portion of L5 were usually severed intradurally. In some experiments all the contralateral roots from L5-S1 were cut. The spinal cord was sectioned behind S1, a step which also removes the variable influence of the tail, always a sound precaution with such an active organ in the decerebrate animal. The remaining roots were separated at the operating table and equipped with slings of coloured silk to aid identification when the time came to sever them. Single spindle afferents were isolated by splitting small dorsal root filaments; fibres from soleus can usually be found in the posterior and medial part of L7. The loss of one or two such filaments cannot appreciably have interfered with the sensory innervation of the muscle, and we therefore speak of animals in this state as having 'intact' innervation.

Structures in the brain were stimulated through a needle electrode, insulated to the tip, introduced by means of a Horsley-Clarke instrument. Millisecond pulses at a frequency of 300/sec were most often employed. Active spots were marked by an electrolytic lesion and identified histologically; for further details see Granit & Kaada (1952).

On the cathode-ray tube the sweep interval was commonly 1 sec and each sweep lasted 200-250 msec. For most purposes the impulses on four or five sweeps (representing 1 sec) were counted to provide an average value for the spindle frequency. A continuous record was also run on a second tube and used for events of more phasic character, such as frequency counts during stretch.

In every experiment each spindle ending was identified as such by observing the pause in its discharge during a muscle twitch elicited by a shock to the motor nerve (Matthews, 1933; Fulton & Pi-Suñer, 1928). Most spindles in active preparations also showed a pinna reflex (Granit *et al.*

1952) and this when it happens again gives a positive identification. No sensory endings have ever been observed to give a pinna response and not a pause.

No steps have been taken in this work to distinguish between primary (annulo-spiral) and secondary (flower-spray) spindle endings (Matthews, 1933; Merton, 1953*b*), but it is probable that as we always selected the largest available spikes they came from primary endings.

RESULTS

The behaviour of a spindle receptor in a muscle which has its nervous connexions to the spinal cord intact differs strikingly from the familiar rhythmic response to stretch which is seen with isolated muscle (Matthews, 1933). In the intact preparation irregularity is the outstanding characteristic, the spike interval often varying discontinuously from spike to spike (Fig. 1 *A* and *B*, Fig. 6 *A* and *B*). This is immediately obvious by listening to the discharge in a loud-speaker. In addition to these rapid variations the mean rate changes over periods of a second or two, while in lively preparations large alterations in

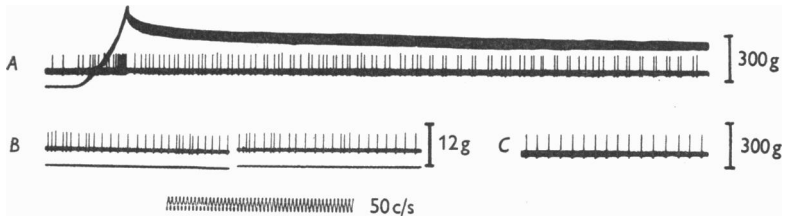


Fig. 1. Effect of activity in γ motor fibres on spindle discharge. *A*, irregular discharge before and during a 10 mm stretch. Note rhythmic bursts. *B*, samples at high myograph sensitivity to show irregularity in the absence of any corresponding muscle contraction. *C*, same spindle after de-efferentation, responding with characteristic regularity. Anaemic decerebration and chloralose (20 mg/kg). Spindle in gastrocnemius. Myograph on second trace. (Spikes retouched.)

rate may take place, often rapid in onset, and lasting perhaps a minute or longer. Hunt (1951) has observed similar changes in γ discharge correlated with waxing and waning of rigidity.

Such spontaneous fluctuations in spindle discharge occur even though the muscle tension observed at the extreme sensitivity of the myograph remains quite constant (Fig. 1 *B*), clear indication that the fluctuations reflect the degree of activation of the spindle by tonic γ efferent discharge and are not due to muscular movement. (When there is an inconstant muscular contraction, as for example in Fig. 10 *A*, no conclusions can be drawn.) In an occasional preparation we seem in fact to hear more directly the effect of γ discharge, when, in contrast to the customary arrhythmicity, the spindle response is accelerated at regular intervals, each burst presumably corresponding to a single intrafusal twitch (Fig. 1 *A*, last part). When, in the usual case, no rhythm is apparent it is possible that the spindle is activated by rhythmic but

asynchronous discharge in several γ fibres; alternatively there is evidence (Granit & Kaada, 1952, fig. 11; Eldred & Hagbarth, 1953, fig. 2) that individual γ fibres may themselves discharge irregularly.

In each experiment the quantitative estimation of γ effect has to await the final de-efferentation which reveals the characteristics of the unbiased end-organ. At the outset, however, the responsiveness of the preparation can be roughly gauged by simple tests. With the muscle disconnected from the myograph and lying quite slack any spindle which maintains a resting discharge of more than five or ten impulses per second will probably prove to be biased by γ activity, particularly if the discharge shows the characteristic irregularities already described. Failing a spontaneous discharge, activated spindles usually have a low threshold and give rapid (often irregular) discharges when lightly pulled upon. It was our habit after isolating a spindle and at frequent intervals throughout the experiment to test the effect of twisting the pinna (Granit *et al.* 1952). Nothing more elegantly demonstrates that a spindle is under the sway of the reflex centres than to hear it (without any change in muscle tension) slow and stop as the experimenter pinches up the ear, and then on release accelerate transiently to a rate much above the initial level. Occasionally a spindle is met with that does not appear to be subject to γ influence. The cause of this is usually obvious; too much anaesthetic, the animal moribund, or the spindle itself sick. A symptom of deterioration is that the spindle discharge decays rapidly to zero when a weight is hung on the tendon; it ought to be nearly indefatigable. The muscle must be kept warm.

Alternative explanations may be offered for spindle endings that are apparently indifferent to γ control. In soleus the efferent supply may have reached the spindle in the distal motor nerve which we cut. Again the secondary sensory endings (flower-spray) are applied to the partially contractile myotube region and are thought, from the experiments of Matthews (1933), not to be excited by γ discharge, so that if impulses were recorded from such an ending they would probably be uninfluenced by γ activity, or even slowed.

γ activity estimated by de-efferentation

In a series of experiments the spindle response was recorded and the rate measured during stretches of varying extent. After de-efferentation these measurements were repeated and in nearly every case a great fall in spindle sensitivity was apparent, the extent of which is an index of the bias that intrafusal contraction had applied to the sensory ending. Typical results for static stretch are shown in Fig. 2, from a spindle in gastrocnemius, and Fig. 3, from one in soleus. Both are from the same animal, a perfect decerebrate preparation, reliable for several hours. The contralateral side had been immobilized by segmental de-afferentation at the operating table. Before the final de-efferentation the effect of cutting the dorsal roots was also studied,

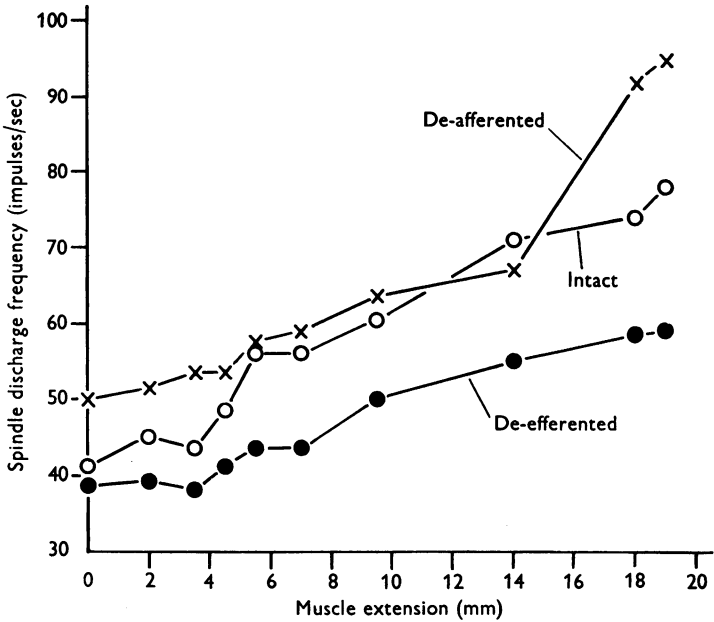


Fig. 2. Discharge frequency of a spindle in gastrocnemius at various extensions. The effect of cutting first the dorsal and then the ventral roots. Decerebrate cat.

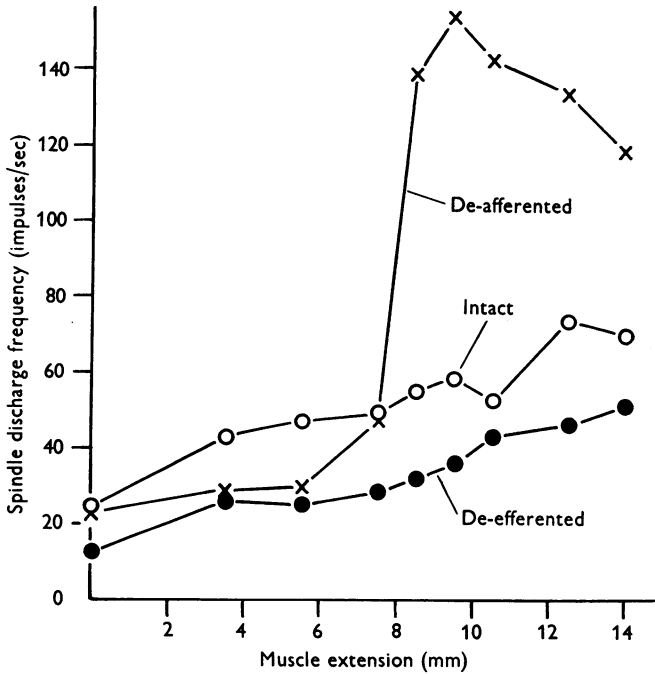


Fig. 3. Discharge frequency of a spindle in soleus at various extensions. The effect of cutting first the dorsal and then the ventral roots. Decerebrate cat, the same as in Fig. 2.

but these results are discussed later. In this experiment the muscle was stretched to predetermined tensions by slowly shifting the strain gauge by means of a screw. The corresponding lengthening was noted on a millimetre scale on the strain gauge slide. All measurements in this and subsequent experiments on static stretch refer to the relatively stationary state after the initial rapid adaptation of the spindle is over and the stretch reflex has settled down to a constant, possibly zero, level. In the present experiment there was no stretch reflex in gastrocnemius at the time records were taken. Soleus probably had some stretch reflex but it could not be measured with certainty. After de-efferentation there could of course be no reflex, but all muscles showed a small viscous yielding after stretch which was allowed to finish before records were taken.

The method of measuring γ bias as an equivalent length has already been described. The bias is that shortening which reduces the rate of the biased spindles to that of the unbiased de-efferented spindle at the original length. To carry out the measurement strictly in accordance with this principle the bias must be held constant while a plot of frequency against extension is made. From this plot the required shortening can subsequently be found when the values for the de-efferented spindle have been obtained. In general, however, the bias is varying in an unknown manner so the plot cannot be made. Fortunately a convenient relationship, apparently not noticed by previous investigators, enables the shortening to be estimated. It is observed that an approximately linear relationship exists between spindle frequency and muscle extension (see Figs. 2 and 3, the curves for de-efferented spindles). Any frequency difference therefore corresponds to a certain extension; thus the extra frequency that γ activity adds at any given extension may be expressed at once as the shortening that would be necessary to reduce the rate to that found after de-efferentation. To derive the bias in this way is equivalent to drawing in the frequency/extension plot for the biased spindle by taking one point on it and an assumed slope. Uncertainty enters here because, as we shall see, there is evidence that the slope itself may increase with the bias. In practice the slope for the de-efferented spindle has generally to be used.

A rough proportionality between spindle frequency and (static) extension might be anticipated from a consideration of the type of information the spindle needs to supply. The function of the gastrocnemius and soleus muscles in posture is to raise the hind-quarters of the animal by extending the ankle joint. If equal increments of elevation are to have the same sensory significance at all starting-points they must produce equal changes in spindle discharge frequency. The geometry is such that this will roughly correspond to the same relationship between increments of muscle extension and frequency, and this is what is observed. An indistinguishable result would be achieved if spindle frequency were actually proportional to the logarithm of muscle length, for the physiological range of extension is only about 25% of the total length and the logarithmic function between 1.00 and 1.25 approximates closely to a straight line.

The observation of Matthews (1933) (see also, van Leeuwen, 1949) that spindle frequency is proportional to the logarithm of applied tension is explained by the fact that muscle departs so

far from Hooke's Law that extension itself is approximately proportional to log. tension (Fig. 4). Frog muscle behaves similarly (Buchthal, 1942; Hill, 1953). Katz (1950) found that spindle frequency (in the frog) was proportional to the depolarization at the terminals (fig. 10). He also plotted depolarization against extension (fig. 9) and drew a logarithmic-shaped curve through the points. This apparent discrepancy with our results can be resolved. His regression of frequency on depolarization cuts the depolarization axis at 0.07 mV, this voltage being the threshold of the spindle. In using the regression equation to transform Katz's fig. 9 to a plot of frequency against extension it is first necessary to subtract 0.07 mV from all the depolarizations. When this is done the points appear most conveniently to lie on a straight line.

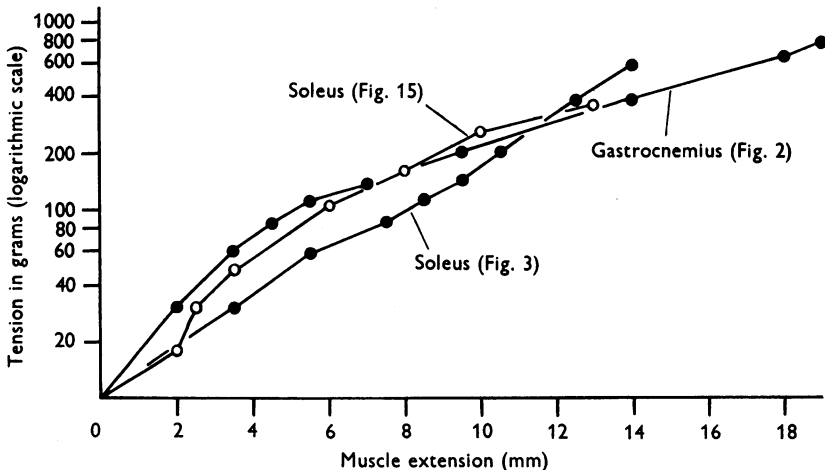


Fig. 4. The relation between extension and log. tension for the muscles of Figs. 2, 3 and 15.

The results plotted in Figs. 2 and 3 show that both spindles were biased by tonic γ activity at all extensions, the curves for the intact (open circles) lying wholly above those after de-efferentation (filled circles). In gastrocnemius (Fig. 2) the slope of the de-efferented curve is 1.2 impulses/mm. The frequency differences for the intact and de-efferented curves run from 3 impulses/sec with the muscle slack to 19 impulses/sec at 19 mm extension, with a mean of 11 impulses/sec. The bias therefore varies from 2.5 to 16 mm, but over the central part of the range it has a value of about 10 mm. In soleus (Fig. 3) the slope is 2.8 impulses/mm. The bias is more constant than in gastrocnemius and has a mean value of 7 mm. In soleus bias falls off at the highest tension, a more common occurrence than the reverse seen in gastrocnemius.

The gastrocnemius spindle had an exceptionally high spontaneous rate after de-efferentation. The mean increase of rate due to bias was about 25%. In soleus, on the other hand, the spontaneous rate was low and bias nearly doubled the rate. The bias, however, was nearly the same in the two spindles. This may be a reflexion of the fact that the present method of measuring bias tends to be independent of the particular characteristics of the sensory endings themselves.

In other experiments of this type, both on decerebrate and anaesthetized cats, it has been the rule to find that the spindles are biased at all degrees of stretch from zero upwards. De-efferentation is thus characterized by a sharp change in the properties of the spindle. The sensitivity drops, i.e. the threshold rises, and the discharge becomes regular, if there is any spontaneous discharge left. This may not be the case at low tension or with the muscle slack. A few spindles retain their original threshold at low tension but do not respond to static stretch with as high frequencies as before.

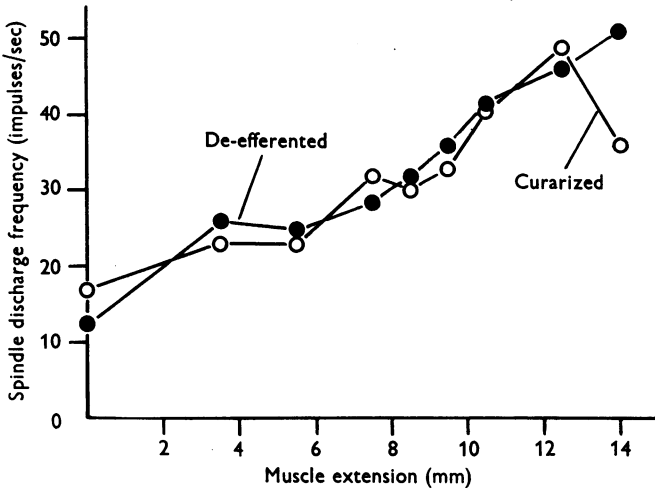


Fig. 5. Check of de-efferentation by curare. The de-efferented curve of Fig. 3 compared with that obtained after a paralytic dose of D-tubocurarine.

It is essential in this type of experiment to be certain that de-efferentation is complete; if a single γ fibre escapes it may invalidate the whole argument. In those preparations which had an active pinna response its abolition was taken to be confirmation that all the ventral roots had been successfully cut. In one experiment a prolonged search for surviving filaments was necessary before this was achieved. When exciting or inhibiting the spindle by electrical stimulation of points in the brain it was of course checked that such effects had completely ceased after de-efferentation. In the cat from which Figs. 2 and 3 were obtained an additional check was made by curare. Curare blocks both α and γ end-plates practically simultaneously (Hunt, 1952*a*; Granit, Skoglund & Thesleff, 1953). D-Tubocurarine was therefore given intravenously until the muscle twitch, observed at high sensitivity of the myograph, disappeared. In Fig. 5 the curve of spike frequency against extension is compared with that obtained after de-efferentation. Only at maximum tension is there some difference between the two curves, the drop at maximum tension with curare

probably being due to the well-known fall in blood pressure after curarization. The spindles are particularly sensitive at high tensions to variations in the circulatory state (Matthews, 1933). Clearly, then, for this spindle, de-efferentation was complete. Furthermore, it can be said that injury discharges in γ fibres from the cut peripheral ends of the ventral roots did not complicate the results. As a precaution against such an eventuality 10 min were allowed after de-efferentation before records were taken.

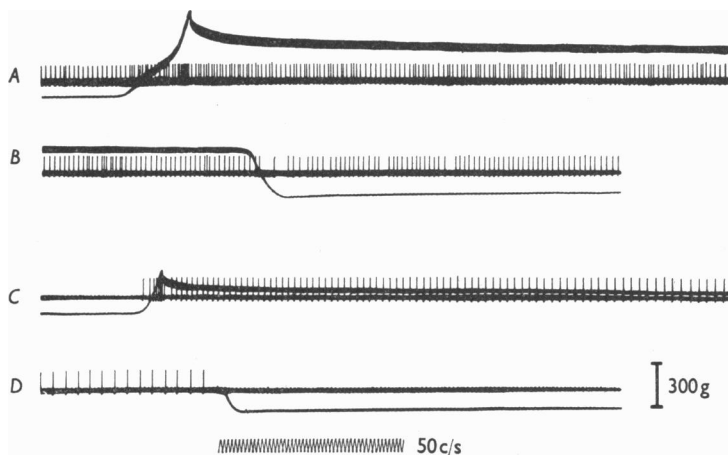


Fig. 6. Effect of γ activity during phasic stretch. Records from a gastrocnemius spindle. *A*, muscle slack and then extended 10 mm. *B*, continuation of *A* after a break of 10 sec. *C*, a similar stretch after cutting the ventral roots, smaller myograph excursion due to absence of stretch reflex. *D*, continuation of *C* after a break of 32 sec. Same spindle as in Fig. 1. (Spikes retouched.)

Phasic stretch. In order to obtain a more complete picture of the effect of γ bias on the spindle's response, a number of experiments were carried out in which the muscle was stretched rapidly. For this purpose the strain gauge was mounted on rollers and could be moved by hand for a given distance between two stops. The movement was uneven so comparisons of behaviour are not possible until extension ends. Records obtained in this way before and after de-efferentation are presented in Fig. 6 (Fig. 1 *A*, was also from the same experiment). In each case the extension was 10 mm. The position of the inner stop was set so that the muscle was just slack and was not altered throughout. With its efferent supply intact (records *A* and *B*) the spindle maintains an irregular resting discharge of about 40 impulses/sec, which is considerably accelerated for the whole duration of stretch. After de-efferentation there was no spontaneous discharge and the rate during stretch was much lower; notice also its regularity (records *C* and *D*). Due to the stretch reflex the rise in tension was approximately twice as large before de-efferentation. The extra tension

from the reflex was approximately 170 g at the beginning and still 150 g at the end of the 13 sec stretch. During stretch the spindle gradually slows down from its initial accelerated rate, a process conveniently referred to as adaptation, although even after de-efferentation it is not clear how much may actually be due to mechanical changes in the muscle associated with the slow fall in tension observed at the same time. In the present records and in those from other cats, there is no evidence that the time constant of adaptation is any different in the intact and de-efferented preparations. This implies that γ bias on the spindle does not fall off during a prolonged stretch reflex, for if it did there would certainly be an apparent increase in the rate of adaptation. Thus the γ machinery not only raises the sensitivity of the spindle but can, as we have also seen in other experiments, maintain indefinitely its enhancing influence under all conditions of stretch and tension. The activated spindle is a very much more flexible and responsive instrument than its paralysed de-efferented counterpart.

Effect of de-afferentation on γ activity

It was established by Sherrington that postural contractions of muscles, particularly those of the hind-limb, are greatly dependent on the proprioceptive inflow. After section of the dorsal roots decerebrate rigidity almost vanishes and the α motoneurons also become less accessible to some other forms of reflex stimulation. The γ motoneurons we have found to behave quite differently. After de-afferentation the spindle may have even greater tonic γ bias than before and is just as easily influenced reflexly, or by electrical stimulation in the brain. Thus it is impossible to tell from the behaviour of the spindle whether the muscle has its afferent connexions intact or not. All the signs of γ activation usually remain, irregular discharge, high spontaneous firing rate (or low threshold if silent) and a brisk reaction to twisting the pinna. Sometimes they may appear accentuated, at others diminished; for example an irregular discharge may become regular.

The pinna reflex illustrates in a simple way the difference between the α and γ motoneurons. In active preparations an energetic elicitation will often cause the γ outburst to be accompanied by discharge of α fibres and movements of the hind-limbs and tail (when they are not denervated). After de-afferentation it is practically impossible to obtain any muscular contraction but the acceleration of spindle discharge through the γ efferents remains. We shall have occasion to mention similar distinctions in several instances.

Static stretch. The effect of de-afferentation on the response of a gastrocnemius and a soleus spindle at varying tensions is shown in Figs. 2 and 3 (crosses). We must add to the previous description of this experiment that after taking the records for the 'intact' curve the cat was given ether for 5 min and the remaining ipsilateral dorsal roots then severed. There was no spinal bleeding afterwards. (L4 was cut previously and the spinal cord severed behind S1;

contralateral dorsal roots L4-S1 had also been cut.) Half an hour was allowed for recovery before recording was resumed.

It is seen that in gastrocnemius (Fig. 2), de-afferentation, so far from abolishing the bias on the spindle, actually has somewhat augmented it; notice particularly the increase at the two greatest extensions. Such an increased rate of firing after de-afferentation with the largest extensions has been a frequent feature in our experience and probably reflects the removal of inhibition of γ discharge which would have been present during stretch with afferents intact, as described by Hunt (1951). In some animals there was a drop in spindle rate after de-afferentation, but not down to the de-efferented level (Fig. 9). In soleus (Fig. 3) the acceleration at the right-hand end of the graph is so sudden and pronounced that we hesitate to attribute it entirely to release from inhibition and it seems probable that these five successive records coincided with one of those spontaneous outbursts of γ activity already described. From the present point of view, however, the essential fact is that, whatever the source of the rise in this particular case, it very clearly shows that de-afferented spindles can respond excellently to tonic activation. Hence the γ fibres cannot have been silenced by de-afferentation.

The mean bias during these five records rises to the improbable value of 42 mm if calculated with the frequency/extension slope of the de-efferented spindle. An experiment to be described later gives reason to suppose that with this large frequency difference a greater slope would be more appropriate, giving a true bias of about a third of the above figure. Even this rough value (14 mm) corresponds to a shortening of the muscle 5 mm below its resting length.

Autogenetic inhibition of γ motoneurons by stretch. The inhibition of γ activity by stretch was more forcibly brought out in another experiment in which the discharge patterns of single spindles were followed continuously during slow stretch. As autogenetic inhibitory afferents for a single muscle enter the cord widely over several segments it is an advantage in this type of experiment not to denervate the limb. After decerebration a single dorsal root filament was taken for dissection, no other roots being touched. The Achilles tendon was not detached from the calcaneus but the ankle extensors (gastrocnemius and soleus) were stretched by manual flexion of the ankle to its limit. Fig. 7 shows records from the split dorsal root filament containing one active spindle afferent and one fibre from a Golgi tendon organ. Record *A* identifies the two end-organs by their responses during a muscle twitch (no myograph record, but the twitch would occupy the left-hand half of the trace); the Golgi (large spike) accelerates during the twitch, whereas the spindle (small spike) pauses. At the right of the figure a series of five records (*K-O*) confirms the nature of the small spike by its acceleration from the resting rate (*K*) during twisting of the pinna. Records *B* and *C-J* show the resting

rate of the spindle and the behaviour during progressive slow flexion of the ankle. Flexion could be felt to elicit a powerful stretch reflex. The greatest tension is reached in record *H* when the tendon organ achieves its peak, but by this time the spindle has passed its maximum rate (300 per sec in record *G*) and in the final record (*J*), despite the further stretch that has taken place, the spindle has slowed almost to the resting rate it had at the beginning of stretch. At the same time the muscle tension has dropped sharply (lengthening reaction) as evidenced by some slowing of the Golgi ending. Similar results are shown in Fig. 8 from another spindle in the same muscle. Here the actual

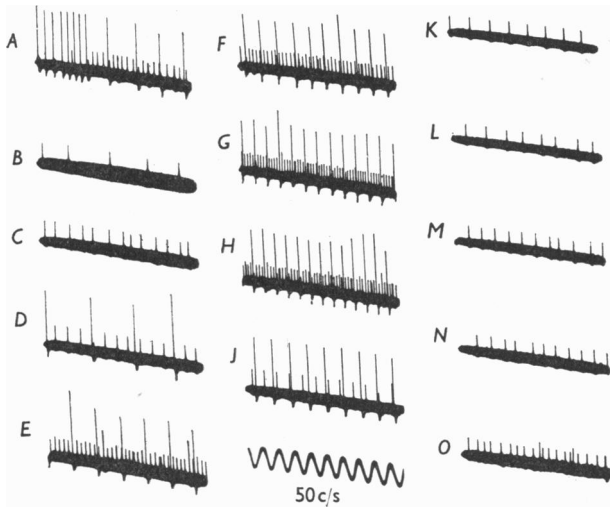


Fig. 7. Inhibition of γ discharge by stretch. Records from a spindle (small spike) and a Golgi tendon organ (large spike) in the ankle extensors. *A*, responses during twitch (no myograph). *B*, base-line discharge with ankle fully extended *C-J*, responses during slow continued flexion of the ankle. *K*, second base-line. *L-O*, response during twist of pinna. Decerebrate cat. (Spikes retouched.)

spindle frequency is plotted throughout a similar slow flexion of the ankle lasting 35 sec. This picture is of interest because it shows a period of rivalry with excitation and inhibition pitted against each other before inhibition finally overwhelms. The sequence of events in these two figures can only be interpreted by supposing that γ activity sensitizes the spindle for the greater part of flexion but is removed, or greatly diminished, towards the end (Fig. 7*J*). In a de-afferented muscle a spindle merely accelerates slowly and continuously during ankle flexion. It is to be noted that the concomitant stretch reflex will tend to mask rather than to accentuate the effect of γ bias, for it is known from Matthews's (1933) work that active contraction tends to slow the spindle, an effect attributed to elasticity in the tendons. A stretch reflex will, therefore, diminish the rate in records *C-H* as compared with *J*

where the stretch reflex has been inhibited. This is the reverse of what is observed. Hence the presence of a stretch reflex cannot account for the results.

Two further points in Fig. 7 merit attention. First, the very high rate of 300 per sec during *slow* stretch which the spindle can attain under the influence of γ bias. Such a frequency could only be seen as a transient burst from jerking the muscle if it were de-efferented (cf. Matthews, 1933, p. 17). Secondly, the interesting conjunction of the lengthening reaction with the fall in spindle

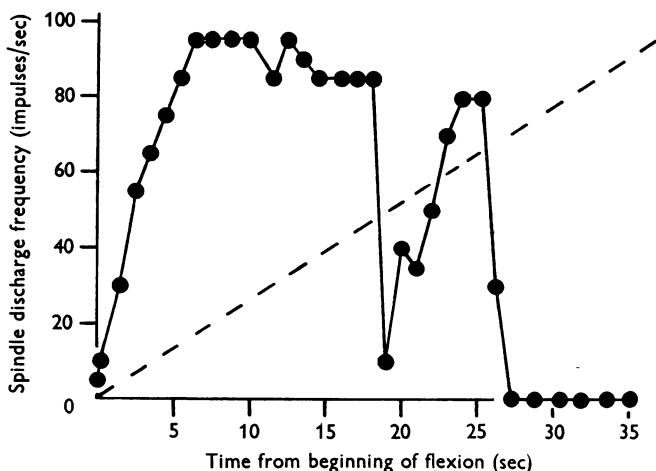


Fig. 8. Inhibition of γ discharge by stretch. Plot of the frequency of discharge of a spindle in the ankle extensors during slow ankle flexion up to the maximum. Flexion indicated by diagonal dotted line. Same cat as Fig. 7 but another spindle.

response, suggesting that one factor, at least, in the lengthening reaction is the decrease in spindle discharge which occurs when inhibition of γ discharge overbalances the favourable effect of continued stretch. The lengthening reaction would then be a slowing of the α motoneurons due to decrease of excitatory spindle discharge to them, together with parallel inhibition by Golgi tendon afferents, in unknown proportions.

Cerebral stimulation after de-afferentation. We have already observed that the reflex effects of the pinna on the γ motoneurons remain when the dorsal roots are cut. The same persistence is found when excitation or inhibition of the γ system is procured by electrical excitation of points in the brain in the manner of Granit & Kaada (1952). Fig. 9 presents the results of an experiment with a gastrocnemius spindle in a chloralosed cat. Measurements of spike frequency were made during static stretch as in the experiment illustrated in Figs. 2 and 3. As in that experiment, curves are shown for the intact preparation and for the modifications produced by de-afferentation (in this case with 15 min for recovery) and by the final de-efferentation. In addition, the uppermost curve shows the great increase in spindle activity

produced, after the de-afferentation, by repetitive stimulation of the mid-brain reticular formation at 300 shocks per sec. This finding illustrates the independence of afferent support possessed by the supraspinal pathways converging on the γ motoneurons.

It is of interest that before cutting the dorsal roots mid-brain stimulation first accelerated the spindle and then caused a contraction of the muscle. After de-afferentation there was no contraction but the spindle response persisted.

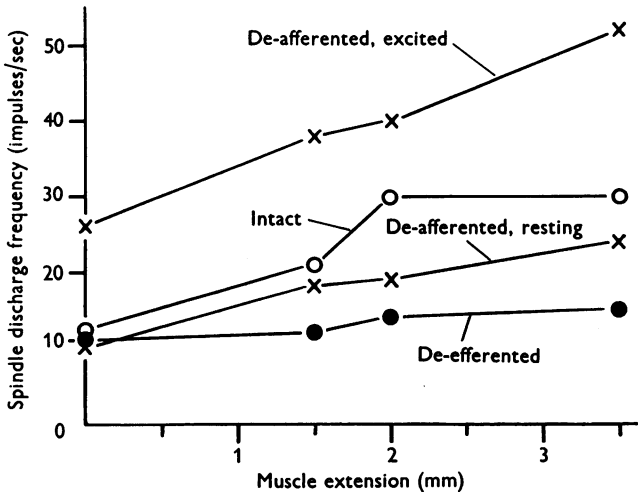


Fig. 9. Effect of brain-stem excitation after cutting the dorsal roots. Discharge frequency of a gastrocnemius spindle at different tensions. Cat under chloralose. Stimulating needle in mid-brain reticular formation.

We may emphasize here that in our experience of cerebral stimulation (cf. Granit & Kaada, 1952) acceleration of γ activity seems to precede α discharge if this occurs. The same is true of reflex stimulation as Hunt (1951), Kobayashi *et al.* (1952) and Eldred & Hagbarth (1953) also observed.

Neck reflexes. Hunt (1951) described briefly the effect of movements of the head on γ discharge to the gastrocnemius. We have found such reflexes suitable for demonstrating in a different way what appears to be our most striking finding; that de-afferentation treats the α and γ motor cells differently.

In the experiment illustrated in Fig. 10 the decerebrate cat had an active ankle jerk and spontaneous α activity producing incessant movement of the myograph trace. We tried first the effect of movements of the head in the vertical plane. The experimenter grasped the animal's head firmly and waiting till the disturbances consequent on touching the ears had settled down (record B), slowly extended the head backwards to elicit Magnus's reflex of minimal hind-limb tonus. The spindle discharge was inhibited and the

myograph record flattened out (first part of record *C*). At the instant marked by the interruption of both traces the head was suddenly flexed downwards. There followed a violent spindle response and a no less violent muscular contraction which swung the myograph trace off the tube face (records *C*

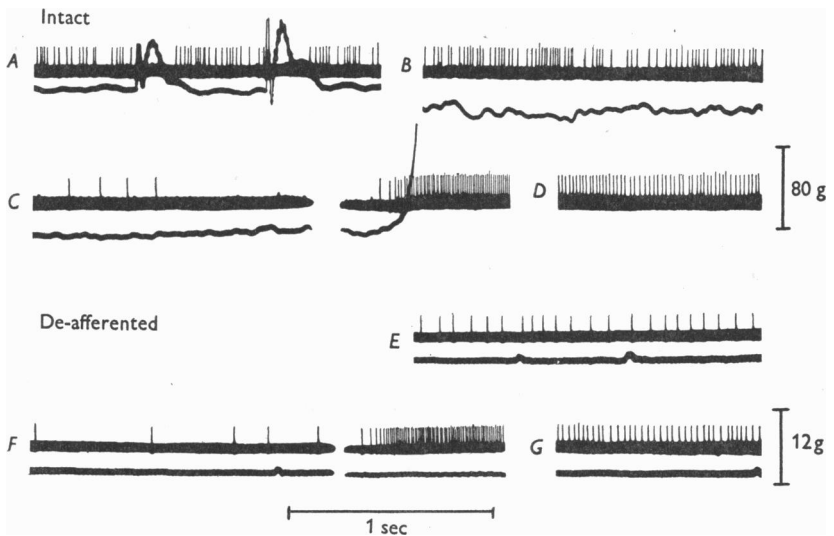


Fig. 10. Reflex activation of α and γ systems by head movement in the vertical plane. Rigid decerebrate cat with brisk ankle jerk and spontaneous α activity (record *A*). Myograph shows tendon tap succeeded by jerk. Records from soleus spindle with head level (record *B*), flexed backwards (*C*) and suddenly (at the interruption of the traces) flexed downwards and held there (*D*). After de-afferentation the same sequence (*E-G*) produces γ response but no α discharge. Initial tension approximately 85 g. (Spikes retouched.)

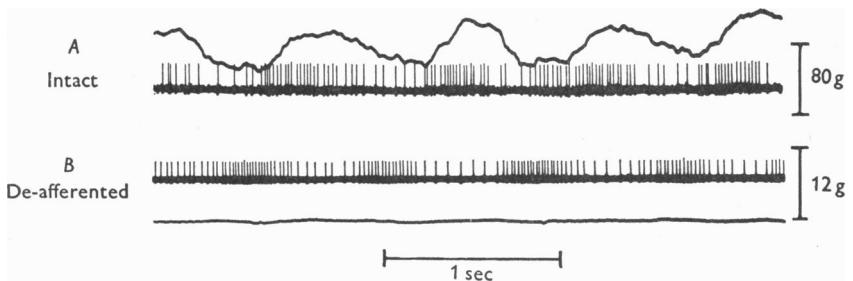


Fig. 11. Reflex activation of α and γ systems by rhythmic turning of the head in the horizontal plane. Records from soleus spindle. With intact reflex connexions both α and γ systems respond synchronously. After de-afferentation α response vanishes. Same experiment and spindle as Fig. 10. (Spikes retouched.)

and *D*). After de-afferentation the spindle repeated its previous performance almost as if nothing had happened (records *E-G*) but the myograph, despite the increase in its sensitivity, shows no hint of the previous α outburst.

Fig. 11 shows, in the same animal, the effect of turning the head rhythmically

from side to side in the horizontal plane. Before de-afferentation there are variations in both α activity and in spindle bias synchronous with the head movements. After de-afferentation the muscle contractions disappear but the behaviour of the spindle is quite unaltered.

In both these experiments muscle contractions and spindle acceleration always take place together, behaviour exactly the reverse of what would be expected if the spindle were de-efferented (Matthews, 1933). Clearly, then, movement cannot explain the spindle's acceleration; in fact if any causal relationship exists between the two it must be the reverse one, namely that the spindle acceleration excites the α discharge. To this point we return in the discussion. Meantime, it can be concluded that the spindle's behaviour in Fig. 10*B-D* and Fig. 11*A* is due to γ activation, as indeed its persistence when α activity is absent suggests.

It remains to be added that this cat had an active pinna reflex which originally involved both muscular contraction and spindle activation. After de-afferentation only the effect on the spindle could be seen. Thus in every detail these tests have borne out the previous conclusions; the spindle mechanism can run against segmental de-afferentation, whereas the main motor cells are greatly depressed.

The scope of cerebral control. The capacity of the γ motor cells to withstand de-afferentation at least in our preparations, which have the brain stem or the whole brain left, suggests that these cells are subservient to powerful supraspinal mechanisms. For this reason among others it is of interest to determine the limits to which cerebral excitation and inhibition can be pushed, under optimal conditions. The last proviso is something of a challenge because not only has the whole experiment to be done on a single spindle, preferably in the parallel-fibred soleus, but it is, necessary, in addition, to be able to locate two cerebral spots, one of which produces intense excitation, the other one complete inhibition of this spindle. These foci must be capable of doing so without eliciting contractions in the muscle for fear of complicating the issue by changing the load on the spindle owing to extrafusar variations in tension. Both central effects have to be constant for hours, and the spindle must still be in good condition when ultimately tested in the de-efferented state for its unbiased firing frequency. The experiment now to be reported was favoured in all these respects.

The cat in question was anaesthetized with chloralose and dial; there was at the times of taking records no stretch reflex in the muscle (soleus) in which the spindle lay. The inhibitory and excitatory foci are marked by arrows in the sections in Fig. 12, the inhibitory spot in the contralateral internal capsule, the excitatory spot in the contralateral inferior colliculus (cf. Granit & Kaada, 1952). Fig. 13 shows that repetitive stimulation of these two points (at the stimulus rates and strengths used throughout the experiment) gave selective

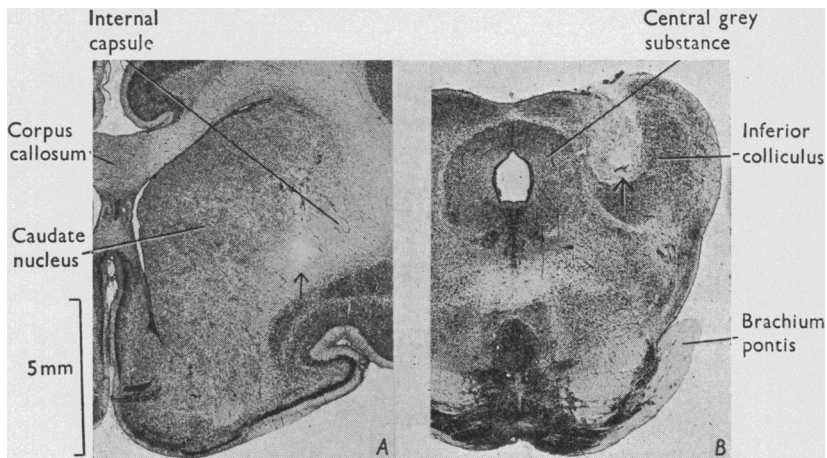


Fig. 12. Sections to show the position of the stimulating needles in the experiment illustrated in Figs. 13–15. *A*, the inhibitory point in the contralateral internal capsule. *B*, the excitatory point in the contralateral inferior colliculus. The scale applies to both sections.

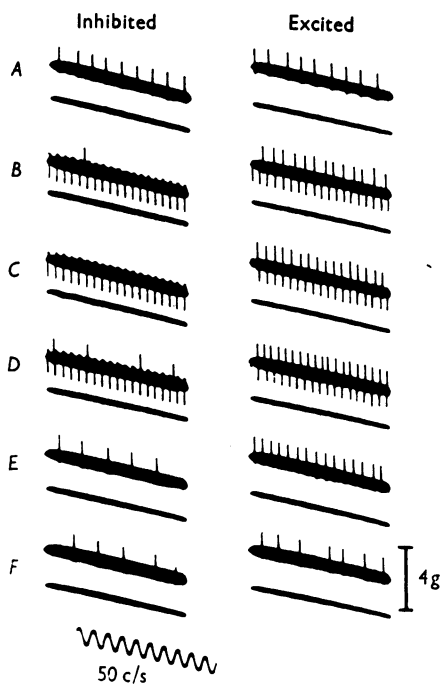


Fig. 13. Spindle in soleus. Effect of stimulation of the inhibitory and excitatory loci shown in Fig. 12. *A*, base-line. *B*, first record during stimulation (note shock artifacts). *C*, during stimulation. *D*, last record before cessation of stimulation. *E*, *F*, immediately afterwards. Myograph record on lower trace; initial tension 55 g. Cat under chloralose and dial. (Spikes retouched.)

inhibition and excitation of the spindle without significant change of tension even at maximum myograph sensitivity. There is, to be sure, a fall of 0.1–0.2 g during inhibition which may or may not have been accidental. Assuming it to be concomitant α inhibition, the spindle would have been pulled upon and hence accelerated. Actually it was inhibited down to zero, so the fall in tension is inconsequential. Inhibition took some seconds to build up when the stimulus began, and it lasted some time after it was switched off. The maximal effect at the greater extensions lasted over two sweeps but declined little before the end of the standard stimulation period of five sweeps (5 sec). If the stimulus was continued longer the depth of inhibition diminished considerably as shown in Fig. 13. A possible explanation of this effect is offered below.

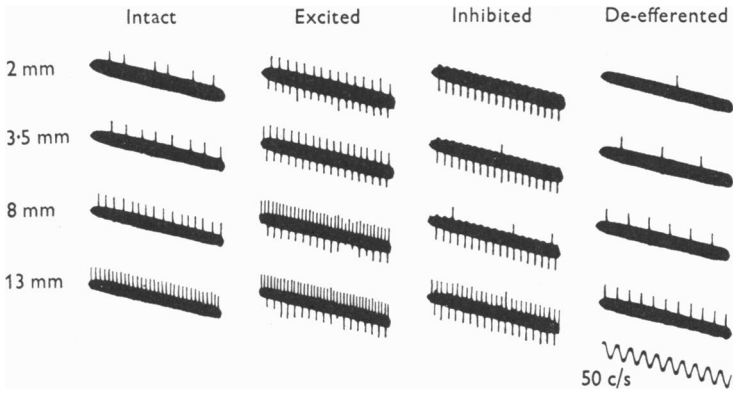


Fig. 14. Same spindle as Fig. 13. Records at various extensions of the resting, maximally excited, maximally inhibited, and de-efferented spindle. Stimulating loci as in Fig. 12. (Spikes retouched.) Shock artifacts downwards.

Fig. 14 illustrates sample records at different tensions of the four states examined: (1) the intact unstimulated preparation with normal 'tonic' bias, (2) during stimulation of the excitatory focus, (3) during stimulation of the inhibitory focus and (4) after de-efferentation. The complete results are plotted in Fig. 15. There was a considerable amount of bias, 5–25 mm (mean 10 mm), in the intact unstimulated spindle. Inhibition completely abolishes this normal 'tonic' bias except at the greatest extensions; in fact it actually pushed the rate below that of the de-efferented spindle. In this experiment the usual tests with the pinna reflex and with central stimulation were made to check that de-efferentation was complete. It therefore seems necessary to seek a purely peripheral explanation of why inhibition slows the spindle more than de-efferentation. Unloading of a spindle by allowing the whole muscle suddenly to shorten a millimetre is known to cause a pause in spindle discharge lasting several seconds, before it builds up to a new rate somewhat slower than

the original (Matthews, 1933). An apparently similar phenomenon occurs here when the intrafusal muscles relax suddenly. Clearly the same mechanism can explain both effects if it has its seat in the sensory ending itself, and this is likely enough (Katz, 1950). This mechanism may also account for the renewal of discharge, described above, towards the end of a prolonged inhibitory stimulus. It may merely represent the slow recovery of the spindle from sudden unloading, rather than any diminution of the supraspinal inhibition of γ discharge.

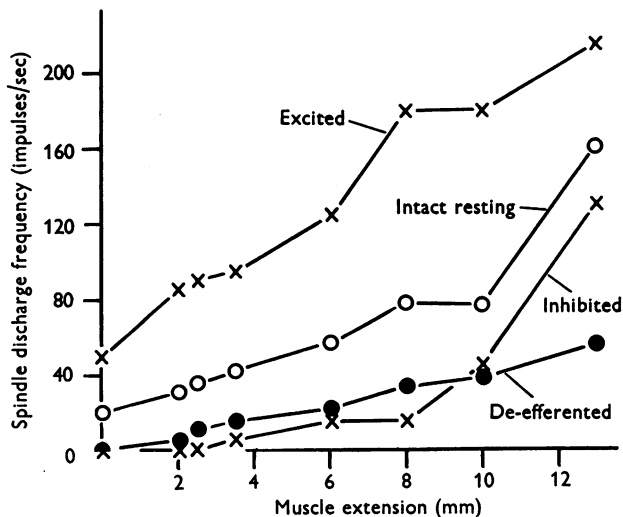


Fig. 15. Discharge frequency of a spindle in soleus at various extensions. The effect of stimulating an excitatory and an inhibitory locus in the brain (shown in Fig. 12). The muscle afterwards de-efferented. Same spindle as in Figs. 13 and 14. Spindle frequencies during stimulation averaged over 0.2 sec instead of the usual 1.0 sec.

At the greatest extension used, which corresponded to the relatively modest tension of 450 g, it was found that when the inhibitory stimulus was prolonged beyond the customary five sweeps (5 sec), the impulses began to drop out in blocks of a half to one-third of a sweep (sweep duration 200 msec) to return in between at their previous inhibited rate. Higher tensions were therefore considered to be unphysiological for this particular muscle.

During excitation at the greatest extension used (see Fig. 15) the spindle frequency reached a peak value of 215 impulses/sec (averaged over 0.2 sec), which is an extremely rapid rate for a discharge during static stretch. After de-efferentation transient bursts of 500 impulses/sec could be obtained, but only by vigorous jerking of the tendon. The spindle bias, if calculated with the de-efferented frequency/extension slope, would be 38 mm at maximum extension. In this experiment, however, there being little scatter among the

points during excitation, it seems safe to use this actual frequency/extension curve, or its extrapolation to the left, to derive the bias. The slope for the heavily biased spindle is much greater than that after de-efferentation, a tendency we have also noticed in other experiments. As a result the true bias measured in this way is 13 mm at the greatest extension, falling to 5 mm with the muscle slack.

We have presented two instances in which γ bias corresponds to a shortening of the muscle 5 mm below its length at zero tension. This is probably as short a length as it ever reaches in life. Thus by cerebral stimulation we have succeeded, on the one hand, in abolishing normal γ bias altogether and, at the opposite end of the scale, we have excited the intrafusal fibres to apply so intense a bias that it becomes doubtful how much more could be of use to the spindle in life.

DISCUSSION

The γ efferents emerge from these experiments as a highly active and potent system. The clarity of this impression depends largely on the peculiar advantages of the technique of listening in to single spindle afferents (rather than single γ fibres) which among other things has permitted a quantitative estimation of γ spindle bias on a scale of direct functional significance. In this way we have measured the bias in resting intact muscle and reached the basic conclusion that the motor centres in the brain can augment and diminish it over probably the whole physiologically useful range. During static or very slow stretch a heavily biased spindle can attain rates of 200–300 per sec which are enormously in excess of the unbiased rates and approach the maximum attainable early in fast phasic stretch in de-efferented spindles. These powerful mechanisms were indisputably shown by several different methods to be largely independent of proprioceptive support, in fact the predominant proprioceptive influence on the γ motoneurones is inhibition at high tensions.

Our interpretation of these findings contrasts with that developed from their own experiments by Kuffler and Hunt (Kuffler & Hunt, 1952; Hunt, 1951, 1952*b*; Hunt & Kuffler, 1951*a, b*), for whereas these authors conceive the γ system as a mechanism for keeping the spindle correctly biased to the sensitive part of its range, whatever the muscle length, we, on the other hand, see it at the behest of the higher centres regardlessly switching the spindle up and down even to the extremes of its range. It may be observed that, since the relation between spindle frequency and muscle length is a straight line, as we have shown, there will be no part of the range which is more sensitive than another. Hunt's and Kuffler's theory also implies that γ discharge should be determined mainly by the length of the muscle; but we have given evidence for precisely the opposite relationship, namely that γ activity reflexly controls contraction of the main muscle. Hunt's (1951) experiments on spinal cats seemed to confirm the view that the firing rate of γ motoneurones depended

on proprioceptive reflexes, although it is noteworthy that he observed in reflex activation of muscle that increased γ activity preceded α discharge.

By systematic use of de-afferentation we have shown that the pattern of γ activity is not primarily set by proprioceptive reflexes (although these are not without influence), nor does it depend directly on concomitant α discharge. On the contrary, in many modes of muscle activation de-afferentation leaves unaffected the γ response but silences α discharge altogether. Therefore, in our construction of these facts, excitation of the main motoneurons is dependent on the inflow in spindle afferents, the level of which is set in its turn by the γ system. In the intact preparation γ activity, by biasing the spindles, sets up an afferent discharge which contributes decisively to the excitation of the α cells. After de-afferentation the causal chain is broken and acceleration of the spindles occurs alone.

Thus an essential pathway for excitation of muscle (in the type of contraction we have investigated) lies through the γ system to the intrafusal muscle bundles, thence back through the large spindle afferents, which are known to be facilitatory for their own and synergistic α motoneurons (Lloyd, 1943; Granit, 1950; Hunt, 1952*b*) and finally over the monosynaptic stretch reflex arc to the main muscle. On this scheme the speed and simplicity of the stretch reflex arc, already inferred from human experiments by Paul Hoffmann (Hoffmann, 1922; Hoffmann & Keller, 1928) before Lloyd's demonstration of its monosynaptic nature (Lloyd, 1943), becomes intelligible. If the γ system is the force which (partly at any rate) initiates and drives muscular contraction, its relative independence of mechanical events in the muscle (as seen in the de-afferentation experiments) is entailed. γ and spindle activity must also be antecedent in time to the α discharge if they cause it. Everyone who has recorded γ impulses has been struck with this sequence (see p. 513) and we have here confirmed it. Particularly interesting instances were observed with the neck reflexes (Fig. 11) where acceleration and slowing of the spindle was clearly leading both contraction and relaxation, and with the lengthening reaction (Fig. 7) where autogenetic inhibition of spindle bias preceded muscular relaxation.

Kuffler & Hunt (1952) consider that during isotonic shortening of the muscle, excitation of γ fibres could not prevent the spindle discharge from pausing. This would imply that isotonic shortening could never be driven from the γ system. In our experience this is not true, spindle acceleration during contraction has several times been seen when the muscle was detached from the strain gauge and allowed to shorten without load. The γ system is therefore sufficiently powerful to drive the muscle under all conditions, for contraction under zero load is presumably the least favourable.

As further discussed by one of us elsewhere (Merton, 1953*a*) the principal advantage of driving the muscle through the γ system is that the valuable

self-regulating or servo properties of the stretch reflex are retained at all lengths and during shortening or relaxation. Nevertheless, movements initiated in this way, indirectly via the spindles, suffer delay from conduction time to and from the muscle, so that for rapidly starting movement descending pathways converging directly on to the main α motoneurons are also to be expected, and indeed are known to exist from many classical experiments on de-afferented limbs. Instances of such activation have recently been studied in animals by one of us (Granit, in preparation), while Merton (1951) investigating the servo-loop in the human subject observed that sudden movements could always break through, presumably by this path. In the mainly postural type of contractions we have studied in this paper the γ pathway is seen, through the de-afferentation experiments, to be the decisive influence. The same would appear to be true for steady voluntary efforts (Merton, 1951). The exact conditions under which the other pathways become dominant remain to be determined.

In recent years many details have been learnt of the contrasting functions of the α and γ groups of motor fibres in the muscle itself, but the results presented here provide for the first time clear evidence that the influences converging on their respective motoneurons are also quite distinct.

SUMMARY

1. Action potentials of single spindle afferents from soleus and gastrocnemius were recorded in dorsal root filaments with the remaining innervation of the muscle, motor and sensory, intact. In this way activity in the γ motor system was studied through its effects on the spindle.

2. In both decerebrate and chloralose-dial cats γ bias of the spindles was in evidence at all tensions from zero upwards. De-afferentation commonly did not significantly diminish this activity but de-efferentation led to a sudden drop and regularization of spindle frequency, and often a rise of threshold.

3. The γ system was excited by cerebral stimulation or through various reflex channels. In such cases de-afferentation reveals a fundamental difference between α and γ motoneurons, for the γ responses were little affected after section of the dorsal roots but concomitant α discharge was abolished.

4. The supraspinal control of the spindles is thus not dependent on afferent support as, to a large extent, is the main muscle. Proprioceptive influence on the γ motoneurons is chiefly inhibition during stretch, confirming Hunt (1951).

5. The 'bias' that γ activity applies to the spindle can be expressed numerically as the muscle shortening necessary to reduce the spindle to its unbiased, de-efferented, rate. On the servo theory of muscular control this length is also the distance the muscle would tend to shorten under the stretch reflex.

6. Rough measurements of bias on this principle during cerebral stimulation indicate that the range of bias at the command of the supraspinal centres is adequate to cover the whole physiological range of movement.

7. In the types of contraction studied the fact that activity in the γ system keeps in advance of muscular contraction, and that de-afferentation abolishes the latter selectively, indicates that a decisive fraction of its excitation reaches the α motoneurons via the γ system and the monosynaptic spindle afferents.

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