Systems for control of movement
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Inasmuch as physiology is a science that also tries to advance conceptually it finds it difficult to-day to forward its aims by building up experimentation around concepts as diffuse as the pair pyramidal-extrapyramidal. By this remark I do not wish to deny that some definitions of pyramidal and extrapyramidal events could be given which, amplified by clinical experience and pathological anatomy, possess diagnostic value in considering disturbances of locomotion. My intention is merely to emphasize that present-day physiology does not find this particular conceptual framework very useful. Physiology is a frontier science and can apply single-fibre analysis, intracellular recording (cf. Eccles, 1953), statistical mass analysis, root sections, denervations etc. and so will naturally try to avail itself of these possibilities in order to forward its aims which are functional rather than anatomical. The clinician, however, often comes across problems to which neurophysiological anatomy provides the natural answer. The physiologist will have to know a great deal more about how movement is brought about before we can be said to have done our share of the work. However, by keeping mainly to supraspinal events, I shall try to do my best to show how questions of movement control bear upon ideas that have arisen from considering the governors to be either pyramidal or extrapyramidal.

First some critical remarks on electrical stimulation. It used to be held that an electrical stimulus applied to the motor cortex, or any other central structure for that matter, was a relatively simple way of exciting a few cells to produce muscular movement, but the recent precise work of Phillips (1956a, b) with intracellular electrodes in single Betz cells made it possible to measure both size and depth of the area excited by pulses 10 msec in duration. It was found that Betz cells within a hemisphere with a diameter of 8 mm were excited whenever movement was observed, the stimulus then being greatly supramaximal for the cell picked up. Similarly Granit and Phillips (1957) stimulating the cerebellar cortex found that a minimum of 20,000 Purkinje cells were excited whenever a just perceptible inhibition of muscular rigidity occurred in the forelimb of the decerebrate animal. Individual cells were excited by stimuli 1/100 of this strength. The results mean not only that the electrical stimulus is a formidable weapon whenever
current strength is increased to produce muscular movement but also that
the volume of cells excited in such experiments often by far must exceed
the structures one is aiming at so that anatomical accuracy, accordingly, may
be fictitious.

Let us consider but one example: (i) there are in the monkey spread
over a very large area along the central sulcus 18,845 Betz cells, as against
554,000 axons in the pyramids (Lassek, Summary 1954). Very few, if any,
motor effects elicited from the cortex can therefore be dependent upon
this small population, not to mention the fact that Woolsey and Chang (1947)
by stimulating the pyramids antidromically (or backwards) found that the
electrical evoked effect (excluding cortico-bulbar fibres) could be traced to
Brodmann's areas 1, 2, 3, 4 and 5, which is premotor, motor and parietal
cerebral cortex. Some of their effects may have been due to pyramidal
afferents (Brodal and Walberg, 1952; Brodal and Kaada, 1953), but these
seem to be few compared with the pyramidal efferents. No wonder it is
difficult to characterize a pyramidal type of movement by comparison with
an extrapyramidal one. Besides, the gamma motor neurones, which excite
ventral horn cells indirectly, can be stimulated from the motor cortex (Granit,
1955a, b). Are they pyramidal or extrapyramidal? We shall return to them
below.

Considering the necessity of stimulus spread for movement, as dis-
tinguished from excitation, how can we be certain that only one type of
movement is involved, pyramidal or extrapyramidal. Within the utilization
times necessary to produce a movement from the cortex, many circuits
may have been indirectly activated by those cells that were immediately
below the electrode and hence excited within less than one or two milli-
seconds.

The modern work has made it easier to understand and sympathize with
the difficulties encountered by those engaged in cortical stimulation,
ablations, pyramidal sections, etc. The literature in this field is well-known
to be highly controversial as far as type of movement is concerned (see
e.g. Langworthy, 1928; Ranson, 1932; Hines, 1937; Bucy, 1944; Liddell
and Phillips, 1944; Walshe, 1948; Fulton, 1949; Denny-Brown, 1950;
Kaada, 1951; Brookhart, 1952; Lassek, 1954, etc.). A large variety of tonic
and phasic movements have been reported in these and many other papers.
To mention only motor cortex and pyramids, no one can seriously maintain
that only one type of movement is obtained from these regions. Perhaps the
mechanism of control to apply in any particular situation, as set by the
afferent input or otherwise.

cortex neither «thinks» in movement nor in muscles but in terms of what
I shall not at all deal with the problem of cortical localization, merely refer to Fulton’s summary (1949) and to the work of three research centres active in the last decade, Penfield and Rasmussen (1950) in Montreal, Liddell and Phillips (1950, Summary, Liddell, 1953) in Oxford and Woolsey with several collaborators (1952) in Madison, Wisc., which are likely to come up in the discussion, if the problem of localization is touched upon.

In order to understand how movement is controlled and how little we know about it, let us begin by considering the concepts valid still during the forties and then proceed to discuss their shortcomings at the hand of recent evidence. The main idea has been that muscular movement is run by the ventral horn cells which are thrown into activity reflexively or from various central sources, e.g. pyramidal, extrapyramidal, cerebellar. These movements may be of a more tonic or a more phasic character but this depends upon the source from which the ventral horn cells are activated rather than upon themselves. Actually, since 1925, when Stanley Cobb summarized the work of Sherrington and his coworkers and other centres of investigation, the standpoint has been unchanged. Cobb wrote: «From all this evidence it can be seen that static and kinetic movement can be explained on the basis of one neuromuscular mechanism. «Tonic» and «phasic» reflexes, though unlike, are separated by no fundamental difference in physiological mechanism». And, again, in 1932, Frederic Bremer said: «La principale conclusion qui se dégage, de cette revue critique... c'est que le mécanisme et toutes particularités du tonus des muscles squelettiques des Vertébrés s'expliquent parfaitement sans qu'il faille invoquer d'autres propriétés physiologiques que celles de la contraction tétanique ordinaire».

Now the ventral horn cells belong to two main types, large or alpha ventral horn cells, so-called because their conduction velocity fall in the alpha group, 60-100 metres/second in the Erlanger-Gasser (1937) classification, and another group of cells which are small and were called gamma cells by Leksell (1945) who found their fibres to conduct at gamma velocities from 20-44 metres/second. Eccles and Sherrington (1930) had measured fibre spectra and found the gamma cells to be about 30% of the whole output. They held them to innervate smaller motor units but in our laboratory Leksell (1945) removed the alpha fibres selectively by graded pressure on the nerve and then found that the gamma cells were designated for the muscle spindles because no muscle contraction but only an increased afferent discharge appeared when the gamma motor fibres were selectively stimulated. This, in fact, had already been suggested by the work of Matthews (1933). It was soon confirmed by Kuffler, Hunt and Quilliam (1951) with the single fibre technique. In a number of papers the Baltimore group headed by Kuffler showed that gamma motor fibres exclusively stimulated the so-called
intrafusal or contractile fibres of the muscle spindles. By such stimuli the sensory end organs contained in these spindles were stretched and consequently responded with an increase of impulse frequency (see diagram of Fig. 1). Elsewhere I (Granit, 1955a) have given a complete account of the developments in this field and discussed various questions which space does not permit me to take up in detail here. However, it is important to realize that the muscle spindles are separate structures in parallel with the extrafusal or motor fibres so that the sense organs are unloaded and silenced when the alpha motor fibres are made to contract by themselves (Matthews, 1933). This type of behaviour is shown in the inset (an original record) of the diagram of Fig. 1.

![Diagram of muscle spindle and related structures.](image)

**Fig. 1.** Main diagram illustrates the alpha and gamma systems and the methods of recording. Only cerebello-reticular motor control included. Note, intrafusal spindle organ in parallel with main muscle. Activity in the gamma system measured by discharge from single muscle spindle, picked up in dorsal root fibre. There are two possible routes, alpha and gamma, from the brain stem to the muscle (indicated very schematically). Inset shows an original record of gastrocnemius muscle twitch (pure alpha contraction) during which the large spike from a muscle spindle pauses owing to the spindle being in parallel with the main muscle and hence deloaded. The small spike is from a Golgi tendon organ. (Diagram from Granit, Holmgren and Merton, *J. Physiol.*, 130, 213, 1955, supplemented by inset.)

The afferents from the muscle spindles run to the ventral horn cells and, as should be well-known, are responsible for the stretch reflex. Thus the alpha ventral horn cells giving rise to ordinary motor fibres can be driven indirectly through the gamma loop to the spindles as well as directly by
other pathways converging upon the alphas. The indirect driving again implies that the gamma motoneurones make the spindle’s intrafusal fibres contract. This stretches the sense organ which accordingly, discharges impulses destined for the motoneurones. The questions therefore arose as to what this indirect activation of the ventral horn cells might signify and if it would be important enough to play a decisive role in motor control.

The first important point to mention is that the gamma activity is truly tonic and persistent, never resting, except when actively inhibited (Kuffler, Hunt and Quilliam, 1951; Hunt, 1951; Granit, Job and Kaada, 1952; Granit and Kaada, 1952; Kobayashi, Oshima and Tasaki, 1952). This means that the muscle spindles similarly are kept discharging in a tonic fashion and so maintain the ventral horn cells facilitated, as long ago suggested by Rossi (1927). In fact, when the spindles are contracted or «biassed» by their gamma supply, they resist adaptation better and maintain high, constantly varying discharge rates, varying because of variations in gamma control dependent upon sources to be discussed below (Hunt, 1951; Granit and Kaada, 1952; Eldred, Granit and Merton, 1953; Eldred and Hagbarth, 1954). Fig. 2 shows the difference in spindle activity during stretch with

![Diagram](image)

**Fig. 2.** Effect of gamma activity in decerebrate cat during stretch of gastrocnemius muscle. Records refer to isolated spindle fibre and myogram (below). A and B (in direct continuation of A) have been recorded while gamma loop still is intact. Note the intense firing of the spindle, also in the resting state, before the muscle is stretched (and after). Irregularities of rhythm characteristic of high spindle bias from gammas. There is also a good stretch reflex, as seen by comparison with C and D, recorded in the same way after de-efferentation, when the stretch reflex is absent and the myograph records the internal muscular tensile forces alone. Note the great diminution of the spindle response in the absence of gamma support and that it adapts quickly and is silent before and after stretch. (From Eldred, Granit and Merton, *J. Physiol.*, 122. 498, 1953.)
intact gamma loop and without it. A large number of reflexes activate the spindle loop through the gammas, in fact, it is doubtful whether any motor adjustments except the fastest ones take place without simultaneous gamma adjustments. The workers in this field are in perfect agreement upon the important observation that in most acts of movement the alphas do not start discharging before the gammas through the spindle loop have initiated their activity. Sherrington used to emphasize that postural or tonic adjustments precede movement and so we face the question of whether or not the gammas are likely to be a starting mechanism for movement.

This question was attacked by Eldred, Granit and Merton (1953) who studied the so-called Magnus-reflexes to turning of the head of the decerebrate animal. These, like other postural reflexes, were found to start by gamma activation of the spindles which in turn bombarded the ventral horn cells by impulses in advance of or simultaneous with the direct activation by the alpha route (see legend of Fig. 3). We then severed the dorsal roots so that the spindle input no more could reach the ventral horn cells. When the Magnus-reflexes after this operation were tried again, the gamma component was almost as active as before but now, when the spindle impulses were prohibited from reaching and activating the ventral horn cells, no reflex activity ensued. This is shown in Fig. 3. Yet the alpha path was intact and, if decisive by itself, should have been able to set up movement when the head was turned. Similarly when movement was elicited by electrical stimulation of the brain stem, this movement failed to come off when the gamma loop was severed. In this case, too, the gamma impulses and the consequent spindle discharge showed up despite de-afferentation. The failure was entirely a failure of the alpha or ordinary motor units to go off unless started by the gammas. Incidentally this shows that the route over which the gammas are driven is independent and different from the route for the alphas a fact that would seem to be of considerable clinical interest.

The interpretation of this work is that the body possesses a separate indirect tonic motor system run from the gamma fibres through the spindle loop and designated to initiate the postural adjustments by which movement is begun. When the gamma system is allowed free play it cooperates with the alphas throughout the motor acts. Only tendon jerks and other fast types of movements run through to the alpha system without direct gamma control. Yet, also in these cases, the tonic gamma effects contribute to setting the level of excitability of spinal cord over the spindle sense organ (Granit and Henatsch, 1956).

This being the case, we must give brief consideration to the sources of gamma control, particularly the supraspinal ones, if our main theme is to be pyramidal and extrapyramidal movement. In general it has been found
Fig. 3. Magnus reflexes on alpha and gamma system (recorded as in previous figures). Gastrocnemius muscle and decerebrate cat. A, spontaneous activity in muscle spindle, caused by gamma system, and small movements in muscle, caused by alpha system. Two tendon taps to illustrate pause of the spindle discharge during alpha reflex contraction. B, same without tendon taps, is baseline with head level. C, head flexed backwards inhibits gamma and alpha motoneurones. D, st interruption of the traces, head is suddenly swung downwards and held there. Note, intense spindle activity despite large muscular contraction bringing myograph out from recording range of oscillograph.

After de-afferentation the same sequence (E-G) produces spindle response through the gammas, but no motor response. Thus the gamma ventral horn cells strongly activated but, with the loop severed, incapable of reaching the alpha ventral horn cells which do not discharge without this support.

that every site in the brain from which movement can be initiated or inhibited also is capable of initiating or inhibiting gamma activity (Granit and Kaada, 1952), and, generally, the gamma system also has the lower threshold, provided that iterative stimulation is employed. It seems, however, as if the brain stem so-called reticular system of Moruzzi and Magoun (1949), which definitely is extrapyramidal, had particularly strong effects on the gammas so that this region of the brain stem may well serve as an important collecting net for influences destined to mobilize the gamma system. This is, perhaps not entirely unexpected in view of its role as activating centre and receiving station for a vast inflow of afferents from various sources (e.g. Starzl, Taylor and Magoun, 1951a, b; Dell, 1952; French, van Amerongen and Magoun, 1952; Magoun, 1952). The gamma system, like its alpha counterpart, can be both inhibited and excited from the cerebellum (Granit and Kaada, 1952), iterative stimulation of the motor cortex excites it (Granit, 1955a, b), the excitatory and inhibitory centres in
the upper portion of the medulla (Magoun and Rhines, 1946; Niemer and Magoun, 1947) have like effects upon the gammas which suggests that these regions should be re-analyzed before and after de-afferentation. All these effects from the brain stem and medulla are slowly recruiting and long maintained and thus well suited for tonic action. There is nevertheless both a precise, fast, crossed path in the lateral column as well as a diffusely spread supply of fibres from brain stem to ventral horn gamma cells (Granit and Holmgren, 1955). The fast path makes it possible for the supraspinal gamma influence to be as fast as the experiments mentioned have proved it to be. It can easily be interrupted in the lateral column. The diffuse path survives practically any amount of criss-cross cutting in the spinal cord. This differentiation would seem to be of clinical interest.

In the state of decerebrate rigidity of the Sherrington type which is obtained by intercollicular section of the brain stem and leads to a spastic animal with exaggerated stretch reflexes, there is very high tonic gamma activity (Granit and Kaada, 1952). The experiments described were carried out with such animals and thus support the notion that this type of spasticity is due to hyperactivity in the gamma system maintaining excessive excitation of the ventral horn cells by the spindle loop. There is a very convenient way of stopping the gamma system in addition to the radical way already described (of severing the loop). The animal can be given chlorpromazine, as was done by Henatsch and Ingvar (1956) in our laboratory, and when, in such experiments, the gamma discharge vanishes, so does the spasticity, just as if the loop had been cut across (references to antispastic effect of chlorpromazine in their paper). There is thus a great deal to support the idea that gamma release accounts for certain forms of spasticity. Alternatively the gamma fibres can be selectively removed by cocainization of the peripheral nerve (Leksell, 1945; P. Matthews and Rushworth, 1957a) because cocaine attacks small fibres in advance of large ones (Gasser and Erlanger, 1929). When this is done the stretch reflexes of the decerebrate cat disappear, as shown by P. Matthews and Rushworth (1957b).

The intercollicular rigidity is of a plastic type, particularly when the operation is done by section, and plasticity could hardly exist without an active gamma system capable of adjusting the ordinary or extrafusal motor fibres to the length of the intrafusal fibres of the muscle spindles so as to maintain the same amount of tonic firing independent of length (Granit, Holmgren and Merton, 1955). The spindles may be thought of as instruments measuring the difference in length between extrafusal and intrafusal fibres—the misalignment detectors of servo-theory—and are, as we have seen, capable of setting the length of the extrafusal fibres through the so-called stretch reflex arc. (For a good brief account of
these problems see Hammond, Merton and Sutton, 1956). A more complete account is the one referred to (Granit, 1955a).

I have already emphasized the important fact that the gamma and alpha systems appear to be linked in most motor acts with the possible exception of the fastest and most powerful ones, the gammas generally preceding the alphas. This is true also of supraspinal effects and so one may well ask if not cerebellum as a co-ordinating and regulating structure might be of importance in this process. Tonic regulation must depend on information from the muscles whose functions are to be regulated. Assume, for instance, that the gammas are paralyzed so that the muscle spindles are slack and insensitive to stretch. Every active motor contraction would immediately unload them more effectively, relative to the contracting extrafusal muscle fibres with which they lie in parallel, and so they would be silenced and information cease to flow in. Therefore, if cerebellum is supposed to regulate or co-ordinate tonic muscular movement, it cannot act without information from spindles and hence must also contain nervous arrangements capable of forcing gamma fibres to go off together with the alpha motoneurones. Cerebellum must be able both to set the misalignment detector which provides information and to make use of the servo-properties of the spindle loop.

Out of such considerations arose some experiments in which we tried to cool or remove the anterior lobe of the cerebellum in order to find out how the muscle spindles behaved (Granit, Holmgren and Merton, 1954). It turned out that the well-known extreme extensor rigidity obtained by such measures (e.g. Bremer, 1922; Stella, 1944a, b; Moruzzi, 1950, 1953; Terzuolo and Terzian, 1953) totally differs from the Sherrington type of rigidity in that the gamma-spindle loop behaved as if it were passive. We can, for instance, compare Fig. 3 with Fig. 4. By destroying the activity in the anterior lobe of the cerebellum the behaviour of the spindles has changed from active to passive. Instead of co-contraction, as in Fig. 3, there is now in Fig. 4, relaxation and reduction in frequency of the spindle discharge. The cerebellar rigidity therefore is an alpha type of rigidity. The hyperactivity in the ordinary or alpha motoneurones is so strong that the spindles are silenced during reflexes elicited in animals of this type instead of being active and co-contracting, as in the intercollicular cat. Long ago it was found by Pollock and Davis (1931) that the cerebellar type of rigidity does not disappear after section of the dorsal roots and this result has often been confirmed.

It is not surprising that dysmetria should be such a striking feature of cerebellar disease. Normal muscular co-ordination presupposes that the two motor systems, alpha and gamma, are linked. Movement with passive muscle
spindles is movement without control of this curious organ for integrating motor and sensory activity, the gamma-rulled spindle. In agreement with these concepts it was found by Henatsch and Ingvar (1956) that chlorpromazine does not destroy the alpha-type of cerebellar rigidity. Similarly P. Matthews and Rushworth (1957b) find that selective removal of the gamma fibres by cocainization in the periphery does not demolish the stretch reflexes of an alpha cat.

Fig. 4. Magnus reflexes in soleus to flexion and extension of the neck (cf. Fig. 3), showing their indifference to de-afferentation in cerebellar of alpha type of rigidity as caused by anaemic decerebration. Recorded as in Fig. 3 but in addition electromyogram on lowermost line. A and B before de-afferentation. A, head level initially and then bent upwards. After an initial slight contraction (to be disregarded) the muscle relaxes as expected, but spindle behaves passively and accelerates. B, head level initially, and then bent downwards. Muscle contracts and spindle again passive and slow. In Fig. 3 muscle (alpha) and spindle (gamma) were both active and linked to give similar responses. C and D, after de-afferentation. This does not alter type of response (cf. Fig. 3). (From Granit, Holmgren and Merton, J. Physiol., 130, 213, 1955.)

It is not to be concluded that the two extremes, pure gamma and pure alpha rigidity, merely occur as mutually exclusive alternatives. Probably many forms of rigidity and spasticity are mixtures and, indeed, in some of our cerebellar experiments there was some gamma control left. Conceptual clarity is, however, aided by these distinctions which also serve to emphasize that there are two fundamentally independent, though in postural reflexes mostly interlinked, motor systems. In all analyses of movement both systems
have to be studied. Particularly when tonic types of movement are discussed, the gamma system should be given serious consideration. Disturbances of gamma control may well account for many so-called extrapyramidal symptoms in addition to cerebellar symptoms. This system is very lively and active. Recently C. von Euler and Söderberg (1956, 1957) have shown that one need but stimulate the heating centre in the hypothalamus by local diathermy to suppress the gamma system and the discharge from the end organ in the intrafusal fibre. Simultaneously the EEG alters to the type seen in sleep or barbiturate anaesthesia, slow waves and spindles. Cooling the animal activates the gamma system while the cortex displays the so-called arousal response of the EEG. In the cat one has only to pinch its ear to find a heavy gamma response, sometimes preceded by gamma inhibition (Granit, Job and Kaada, 1952). The gamma-spindle system is probably the most sensitive indicator we possess of what is present-day brain physiology is called «activation» and is assumed to arise in the brain stem (Magon’s reticular activating system). It has the advantage over the EEG that one knows what one measures and knows when the effect is excitation and when inhibition.

On the other hand electroencephalography can be applied to man. How about the possibilities for the gamma system? It does not seem utterly hopeless to find gamma spikes by electromyography. The small muscles of the hand, for instance are abundantly provided with muscle spindles, often many in series (Cooper and Daniel, 1956). These tandem spindles should be tried. Indeed, if the fingers are to perform controlled movements ranging from violin playing to weight lifting, their muscle spindles require to be well controlled or they would not be able to «monitor the performance of the muscles themselves» (Hammond, Merton and Sutton, 1956). The joints contribute excellent and important information (see e.g. S. Skoglund, 1956) but spindle control is necessary for setting the muscular instrument correctly over its own servo-loop. Some interesting fresh attempts have been made by Hammond, Merton and Sutton (1956) and by Paillard (1955, especially p. 204 onwards) to apply the new knowledge to man. In view of the demonstration by P. Matthews and Rushworth (1957b) that cocaine removes the stretch reflex by selectively attacking the gamma fibres (peripheral application), old work on stretch reflexes, as influenced by alcohol and cocaine (Liljestrand and Magnus, 1919; Walshe, 1924; Liddell and Olmsted, 1929; Bremer and Titeca, 1930) injected into the muscle or allowed to diffuse into the nerve, again becomes of interest. Thus, as pointed out by Matthews and Rushworth, removal of rigidity in paralysis agitans in man by such means suggests that it is a gamma disturbance.
Finally it should be emphasized once more that the gamma system is permanently active, truly tonic, and hence that no discussion of tonus and spasticity can neglect it. Yet the permanent discharge need not necessarily set up movement through the alphas. It suffices to keep the alpha cells themselves in a higher or lower state of preparation, depending largely upon the general state of activation of the animal but also upon demands from special sources. Most acts leading to movement involve collaboration of several systems. Not only the gammas but also the pyramidal system discharges constantly, the latter at a rhythm reflecting the 10/sec. rhythm of the brain waves, yet the animal may be quiet (Adrian and Moruzzi, 1940; Whitlock, Arduini and Moruzzi, 1953). It is a long way from tonic discharge to movement which may be described as the consummation of events stemming from various sources, any one of which probably may make the neurone spill over. Motor control rather than movement is therefore the first problem the physiologist faces. It is very difficult if not impossible to deduce answers to this problem from gross movement alone, be it elicited from the pyramidal or extrapyramidal system and very difficult, too, unless by de-efferentation or otherwise (e.g. cocaine on the peripheral nerve) the gamma system can be selectively removed. Does any particular movement involve more of the gamma system than another? And how about the alphas? Are there also systemic differences between them or do they for any one muscle form a unidimensional system, quantitatively graded?

The first question that comes to one’s mind is obviously whether some alpha ventral horn cells are specialized for tonic behaviour, others less capable of delivering long-lasting discharges as easily and smoothly, as tonic cells must do. Though the idea of special tonic alpha ventral horn cells is by no means new and turns up at irregular intervals, I agree with Stanley Cobb and Bremer, quoted above, that (until recently) there has been no evidence for it. Such evidence can only be obtained at the single-fibre level; and, above all, the animals must be de-efferented to avoid confusion with secondary reflex action and pure gamma effects. These must be excluded. It is also necessary to be able to force the motoneurones to maximum performance in reflex action in order to be able to form an estimate of what is happening and to be able to distinguish fundamental differences between neurones from mere quantitative gradations. It will be realized that if there were separate tonic alpha ventral horn cells the whole question of pyramidal and extrapyramidal types of movement must be reopened also from this point of view in addition to the many new aspects suggested by the necessity of differentiating alpha from gamma types of control.

The evidence we now have obtained for the existence of a special tonic system of alpha ventral horn cells (Granit, 1956; Granit, Henatsch and
Steg, 1956; Granit, Phillips, Skoglund and Steg, 1957) is based on work with isolated ventral root fibres responding to extensor stretch in de-efferented, decerebrate animals. Thus the gamma loop has been severed. The experiments originally arose from a desire to explain how muscle spindles forced to intense activity by the gamma system could create states of spasticity. This, to a physiologist, seemed likely to be on account of the process called post-tetanic potentiation which is a state of long-lasting presynaptic facilitation following in the wake of a tetanus to a nerve forming synapses. The state of post-tetanic potentiation is a change at these synapses. Such potentiation has been known for more than half a century in motor end plates, was proved by Bronk and his collaborators (see e.g. Larrabee and Bronk, 1947) to exist in sympathetic ganglions and by Lloyd (1949), Eccles (1953) and others in the monosynaptic path of muscular afferents upon the ventral horn cells. Lloyd had carried out his work with monosynaptic testing but new aspects of the process appeared when we began testing by stretch (Granit, 1956). There are shown in the experiment illustrated in Fig. 5.

![Diagram](image)

**Fig. 5.** Records from single ventral root filament during stretch of soleus muscle in decerebrate and de-efferented cat. C, control stretch elicits no reflex spikes in the filament. T, tetanization of the gastrocnemius-soleus muscular afferents for 2.1 sec, at a rate of 500 shocks per sec, causes direct contraction of the muscle and some reflex impulses and leaves a state of post-tetanic potentiation in the spinal cord so that when in P1, the early potentiation period, stretch is repeated, the alpha ventral horn cell now fires reflexively through its root fibre. P2, same a little later, but with myograph exchanged for a muscle spindle record (below). Thus this single fibre stretch reflex was greatly facilitated for a long time by high-frequency afferent stimulation such as the gammas also would have caused if they had been activated by natural means. This is a basic component in the mechanism of spasticity (= exaggerated stretch reflex). (From Granit, *J. Physiol.*, 131, 32, 1956.)

In this figure a weak stretch is applied which is subthreshold in the sense that it does not elicit any reflex spikes in the ventral root isolated. Then follows tetanization of the muscular afferents at a high frequency for a couple of seconds. One can see the muscle contract and reflex spikes being produced in the ventral root fibre. After this brief tetanus, which imitates a spindle afferent discharge, as put up by sudden activation of the
gamma fibres from the brain stem, stretch of the muscle suddenly elicits a tonic discharge. Stretch is twice repeated and the second time the record of muscle stretch has been supplanted by one from a muscle spindle afferent. Here then we have by tetanization produced spasticity (= an exaggerated stretch reflex) which may linger on for minutes and is presynaptic in character so that it labels the particular set of motoneurones supplied by the very muscular afferents tetanized. This is interesting in itself from the point of view of a theory of spasticity, explaining how a release of an active system can hypersensitize a set of synapses. This neurone would have been silent unless tested by stretch. Post-tetanic potentiation does not in itself create a discharge, it facilitates it. From the present point of view, however, our interest in this experiment derives from the fact that tetanization has been proved to be a method of pushing motoneurones to maximum performance. Hence the question arises if all motoneurones can behave like the one illustrated in Fig. 5 and become tonic after tetanization.

This did not prove to be the case. It is quite common in splitting ventral root filaments to obtain more than one fibre and by selecting a pair of

![Graph of gastrocnemius stretch reflex in filament of ventral root with original records inserted. Decerebrate, de-efferented cat. Left, controls, before post-tetanic potentiation by a 10 sec. tetanus of the gastrocnemius afferents, show three stretch reflexes at intervals of 10 sec. Then follows 1 sec. of the 10 sec. tetanization period. Finally, plotted against time, the potentiated stretch reflexes (experimental spasticity) which only appear in the small spike. The large spike has remained phasic. (From Granit, Henatsch and Steg, *Acta Physiol. Scand.*, 37, 114, 1956.)](image-url)
cells discharging through the same filament one very often finds that only one of them can be made to respond iteratively. We have now carried out a considerable number of such experiments and our uniform experience is that the tonically responding cells as a rule must be smaller than the phasic ones because the tonic spikes rather uniformly have turned out to be smaller than the phasic ones, as shown by the records of Fig. 6. It seems reasonable to assume that small spikes which come from thin fibres must emanate from small cells. These are above the gamma size and belong to the small alphas. The gammas, besides, are inhibited by stretch (Hunt, 1951, confirmed by Eldred, Granit and Merton, 1953) while these are excited by stretch. They are thus easily differentiated. It is clear that spikes may be small because one happens to record far from the living portion of a fibre but, since our rule holds so well, and, since there is no reason to assume tonic fibres to be more brittle than phasic ones, it is impossible to explain our result as artefacts. Our first results (Granit, Henatsch and Steg, 1956) were published on the basis of 100 fibres but we have since, in regular experimentation, found the rule well obeyed.

The next step in the analysis of such tonic cells, so far defined only with respect to extensor stretch reflexes, was to find out if they also behaved tonically when activated from some other sources. For this work we generally selected filaments with one tonic and one larger phasic spike. The sources chosen were the crossed sural nerve for a crossed extensor response and the pinna reflex to twisting the tip of the animal’s ear. Now, if the attributes «tonic» and «phasic» were merely quantitative gradations depending, say, upon the number of end feet or synapses, there is no reason why three reflexes, stretch, pinna and crossed extensor, selected at random, should not also be randomized with respect to the number of end feet on any particular ventral horn cell. They ought not to treat the tonic and phasic cells similarly. Yet this, within limits, is what they were found to do.

There exists in the pool of motoneurones a set of fairly small alpha cells which are easily stirred to long-lasting tonic discharges to stretch, crossed extensor, and pinna reflex.

Strong stimuli, of course, produce short-lasting tonic discharges also in cells which to testing by stretch in the potentiated state (after a tetanus) behave as if they only could produce phasic responses. But the truly tonic cells differ from them in maintaining long-lasting concealed states of facilitation and by being so easily activated by three as widely different stimuli as the ones mentioned. Thus, for instance, if by testing with a potentiated stretch reflex one has defined some extensor cells as truly tonic in their response, a twist to the pinna or a tetanus to the crossed sural nerve will elevate them to a level of concealed facilitation so that they now respond
to the slightest provocation by stretch several minutes after cessation of
the original stimulus. In other words, these types of stimuli potenti ate one
another. Potentiation being a presynaptic state, there must be a common
tonic interneurone to give the three input sources a common focus of post-
tetanic potentiation. In this sense, therefore, these small, tonic, alpha cells
appear to be unique.

It is pertinent to recall that Bremer, Bonnet and Moldaver (1942a, b) in
frogs found special tonic and phasic reflexes differing also in a number of
central characteristics. Thus, for instance, more afterdischarge was seen in
tonic reflexes and this also is the case in cats.

This line of work is still so new that it would be premature to venture too
far into the realm of theory. It does, however, already in this present phase
suggest that it will become necessary to survey the problems of motor control
from at least three new points of view: (i) to what extent is a normal or
pathological movement gamma-controlled, (ii) does it specialize on the sys-
tem of tonic cells or (iii) on phasic cells or cells which at the moment have
no special designation. Excluding the problem of localization by central
stimulation of special muscle groups, all other problems of movements in-
volve distinctions between tonic and phasic types. How do pyramidal and
extrapyramidal centres of control handle this machinery of which we now
have been studying the outlines? This is an arduous road to follow but I
see no escape from it.

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Discussion on paper of Ragnar Granit
«systems for control of movement»

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As a clinical neurologist, I consider it a tremendous honor to be invited to discuss this fascinating electrophysiological approach to the extrapyramidal system that Professor Granit has just given.

The astute clinical descriptive observations of the great Parkinson in 1817 began an era of trying to understand the diseases of this system. A little more than 100 years later (1925) Kinnier Wilson, almost a pure clinical neurologist, gave in the four Croonian lectures the best of all that was known to that date. His own brilliant observations and studies of movement deficits resulting from disease in the striate area were fully covered here. He forcefully and clearly pointed out many fallacies in the theoretical notions of many of how the two pyramidal and extrapyramidal systems worked. He also, since he was a blunt and honest man, admitted that 108 years had led us really nowhere as to how and where in the central-nervous system voluntary motor patterns were controlled and how lesions in the globus or nigral regions could cause such profound disturbances in motor patterns. Another 30 years since Wilson has not added much. Penfield, when working over area IV in a conscious human, recorded the electrocorticogram or electrogram as he calls it before during and after a voluntary closing of the fist. He showed how the pattern was reduced and changes preceded movement. He felt that the motor cortex was only a way station of the movement pattern that came from more central deep areas. This new physiological approach, tying the gamma fiber system to this problem, to me seems like the dawn of a more promising knowledge.

In the simplest voluntary motor act of opening and closing of the human hand—an exquisitely smooth balance between a series of different flexor and extensor groups while another set holds the wrist, elbow and shoulder in whatever posture we wish, we must consider 12 different states of the muscle, 4 electrical and 3 spatial. These are, for the electrical:

a) No activity, completely relaxed and passive in relation to the others, so it may be lengthening or shortening or remaining fixed in length.
b) Increasing amplitude of the electrical discharge for the 3 spatial positions.
c) Even amplitude of electrical discharge for the three.
Fig. 1. — Electromyograms (inkwriting oscillograph, surface electrodes) of left finger extensors and flexors.

Top, normal person. Middle, patient with cerebellar ataxia.

Bottom, patient with Parkinson’s disease. Left to right, relaxed and resting.

Note no electrical activity at all in the normal or in the cerebellar ataxia. In the Parkinson’s, there is the characteristic to-and-fro resting tremor, 5.5 per second, that shows the flexor discharges occur between those of the extensors.

When reaching for bulb, the Normal starts with electrical activity in extensors and has a number of different patterns in this motion.

The Cerebellar case shows a marked tremor at 5 per second (intention tremor), while the Parkinsonian loses his tremor during this voluntary muscle act.

In squeezing bulb, the differences are minor except for more extensor activity in the Parkinson’s.

The last part shows all three at rest again, showing patterns similar to the first group.

d) Decreasing amplitude of electrical discharge for all three.

Obviously such elaborate variability must be monitored exactly by a reliable feed-back message system.

The gamma system of Professor Granit is beautifully set up to take care of most of this, since each spindle next to contracting or working fibers can keep by its own discharges data as to which of the 10 are going on and by reflex feed-back learned patterns let this smooth machinery do its job without more than a tiny piece of the center of consciousness.

This shows how the cerebellar deficit, Parkinson deficit and normal look in rest—pre-set—and contraction.

For example, the so-called associated swing of arms in walking depends on a subtle feed-back so the muscle power merely lets the arm swing as a pendulum acting like an escapement in a clock so only a small energy increment is needed. The gamma system is ideal to manage this.
The natural gait with an arm pendulum length (double compound one) of 30 cm length has a period of 0.7 sec. which is the average smooth step of most people without effort. The poor Parkinson, however, must with his "petit pas" use either a pendulum arm length of 4 cm if he keeps to pace or 4 meters if he keeps his own time—both impossible values to achieve on this earth. On the Moon with gravity one-fifth of ours, the Parkinson could walk comfortably at 2 to 3 seconds per step and have the pendulum work for him too.

It may be of some help, or it may just be my clinical "naïveté" that leads me to emphasize the following motor deficits that we are faced with (for example) in Parkinson's disease.

1. The greatest, and indeed the earliest, deficit is in the fine movements of the fingers.

2. The second deficit is in the fine variations in speech, including facial expressions and gesticulatory supplements.

3. A third deficit is the partial loss of the semi-automatic, or as Wilson calls them, cooperative postural settings and holding of a limb before the specific motor action (as, for example, prior to grasping an object that requires some effort, the extensors of the wrist pull the wrist up to 45 degrees of extension). Many of these may be learned patterns to increase efficiency, skill and power.

4. A fourth deficit lies in the inability to continue a repetitive complicated motor action with a fraction of willed attention while the mind or seat of consciousness starts off on another different motor task.

5. A fifth deficit is progressive loss of motor performance at ordinary levels of motivation. This loss can be temporarily reversed by increasing motivation.

6. A sixth is difficulty in releasing motor contractions, «freezing».

7. The lack of specific relationship of any or all of these to the amount of tremor or rigidity present. Table I, Figs. 1 and 2. Here, Wilson felt that in most patients with Parkinson's there was intact continuity of motor effector pathways so any part of any deficit could be overcome if motivation were high enough. Example: We do not find in most Parkinson's diseases breaks in the long tracts such as cause the spasticity of pyramidal tract disease. These do not change under emergency motivation levels. I therefore do not believe there is loss in continuity in the gamma system. For example, a famous baseball pitcher invalided for years with severe Parkinson’s disease so that he could not feed or dress himself, and sat immobile most of the day, was able to catch a thrown baseball and get up easily and throw it vigorously and accurately back without obvious deficits in this complicated
A. Normal voluntary bulb ergogram of left hand. Note even amplitude; bulb is squeezed once per second.

B. Same left-hand ergogram while right hand draws triangle and bisects each side, drawing line to vertex. Note the ability to keep ergogram amplitude and timing as before. Time: 7 seconds.

C. Left-hand ergogram in Parkinson’s with no tremor and moderate (+++) rigidity only on left. Note gradual fall in amplitude and rise in baseline, indicating difficulty in release at this time.

D. Same day, left-hand ergogram while right does triangle. Note less of amplitude, gaps, and disintegration of pattern. Time: 17 seconds.

E. Same patient, another day, left hand: 35% of normal. At end, patient urged to make supreme effort in a big squeeze which reaches normal level.

F. One-half hour later, same hand, but with constant urging by nurse, wife, and me plus reward of silver box for his pills in sight. Still falls off in amplitude but last squeeze nearly doubles to normal line.

G. One day later, same patient, but now the right hand which has—rigidity (minimum value) and no tremor. Note irregular pattern and diminished amplitude (40%).

H. Same patient, one-half hour later, with prize and strong urging by wife, nurse and doctor to increase motivation. Curve very like left hand. Final special squeeze omitted in G. and H.

The electromyograms of the muscles of the fingers while doing the ergogram show in the normal flexor (below) regular pattern of envelope quiet in between, holding tone in extensors with increase set at the squeeze. The bell signal is easily followed (rate: 1 per second).

In the Parkinson’s case, there is irregular envelope which is twice as long as normal, nearly continuous pattern in between, no true extensor set, and inability to keep up with the bell.
pattern involving 4 limbs. A bedridden patient with the house burning down
could run downstairs briskly without falling, to the fireman come to rescue
her.

Therefore, it seems most reasonable to look for a series of critical feed-
back circuits running at both spinal and mid-brain levels that are intact
and available to even the Parkinsonian, but the control of which may be
related to cell losses in the substantia nigra or mid-brain reticular substance.
These anterior horn gamma cell-motor spindle loops tying into more critical
direct and indirect pathway circuits to the mid-brain give an organism the
machinery for modulating muscle outflow continuously and smoothly accord-
ing to its needs, just as a pianist brings out music by starting, reducing,
or stopping different vibrating strings. There would be no music if we had
literally and synchronously to participate in each frequency we wish to use.
We all agree now that there are multiple pathways from higher centers to
spinal centers.

The physiological pathology in this disease is rather in the loss of the
easiest pathways from the highest centers of awareness to the effector areas
tied to these loops. But there are left some devious trails that are passable
under emergency motivation. Interruption of the fibers passing through the
globus will significantly reduce and in some cases eliminate tremor or the
involuntary movement of dystonia. In most situations such surgery takes
away rigidity, but it will not restore this loss of close control over these
necessary and complicated feedback systems of the gamma type or others.
Patients whose stiff and tremulous hands are now quiet and relaxed still
can’t set their wrists in 45° extension or keep a squeeze going evenly as
they use the other hand. They don’t know why, and as Wilson put it, it
seems they don’t care enough to.

We know that adrenalin which activates midbrain reticular cells towards
the alerting stage greatly increases Parkinsonian tremor. Anticholinergic
drugs like atropine reduce both tremor and rigidity as they affect these
same cells towards inhibition of the alerted state. Apomorphine does this
too. Chloropromazine increases rigidity in Parkinson’s as it affects these
reticular cells towards the relaxed or sleep state. Analeptics like amphetamine
and Metrazol do not affect either rigidity or tremor as they activate the
alerting influence over the cortex. Granit has shown that the reticular area
can increase or decrease activity in the gamma fiber system. This is a strong
hint that the secrets of voluntary motor control and its pathological deficits
in Parkinson’s disease lie in this region rather than in the basal ganglia
themselves.

Remember, too, that there are 10 discharges per second in each active
fiber in the pyramidal tract—related perhaps to the 10 per second alpha of
the EEG. The gamma system, disturbed by pathology in the reticular formation over sensitizes alternate groups of alpha cells—flexors first, then extensors. With the awake tonal discharges in the pyramidal tract, we would have a 5 per second tremor. In the normal behaviour this sensitization of alternate groups would be low enough so only voluntary impulses would use it. The usual to-and-fro rates (jugglers, patting, etc.) are 5 per second too.

I wonder if Professor Granit feels that these spinal loops are much the same in man and dog? Do we with our fingers emancipated, as Wood-Jones put it, from supporting us, develop in the reticular substances or in the nigral area a way to utilize these loops in a different way from four-footed creatures? Is this because of a better and bigger pyramidal tract even if Area IV supplies only one-fifth of it, or have we connectors that reverberate between cortex and thalamus and basal ganglia that are lacking in lower vertebrates?

Does he believe that with the newer electrophysiological tools he uses so well in the optic pathway and spinal systems of animals we can in the surgery with man learn how we begin and control that marvelous motor pattern of buttoning our collar?

This is a most exciting beginning, and the future is linked to the team of physiologist, neurologist and neurosurgeon—and we add neuropathologist for the failures.