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Sherrington Memorial Lecture

The Functional Role of the Muscle Spindle's Primary End Organs

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Wondering by what kind of lecture I could best show my gratitude to the Royal Society of Medicine for the great honour bestowed upon me, I finally decided that the subject at least had to be of some clinical interest and not be too exclusively theoretical. It would also have to have some connexion with the work of Sir Charles Sherrington. He could not – to be sure – in his old age begin studying the behaviour of individual muscle spindles but his extensive early work on postural tone and that with Liddell on the stretch reflex (Liddell & Sherrington 1924, 1925) had set the snowball in motion. Growth and expansion in this field has since been largely concerned with the functional role of the muscle spindles, which has not been easy to understand and even today cannot be regarded as fully understood. Partly this is because any interpretation of function going beyond the barest outline of description always involves speculation in advance of available evidence; partly, *mirabile dictu*, also to some extent because of Sherrington's authority.

The latter statement may seem odd but the truth is that synthetic experimenters of Sherrington's order of magnitude influence the next generation to such an extent that it finds it difficult to cast adrift from them and start navigating its own vessels. Yet this is what one must do and Sherrington would have been the first to admit it. His many contributions to muscle sense and the stretch reflex, based on myography and the use of extensors in the decerebrate preparation, were in fact so well synthesized that there did not seem to be any room left for the efferent control of the muscle spindles which was the missing link that did not seem to be missing. Let us summarize his standpoint: The decerebrate preparation gave a good stretch reflex from (at the time unknown) muscle receptors. This was described as exaggerated standing. Its basis was a 'release' of the extensor motoneurones, the alpha motoneurones as we tend to call them today. The stretch reflex disappeared when the afferent nerves were cut and so the basis of postural tone was an autogenetic facilitation of the stretch reflex from muscular afferents. The impulses arose from a muscle and influenced its own motoneurones; hence 'autogenetic'.

Problem Reformulated

The clinician was actually better equipped than the physiologist for the understanding of the difficulties involved because he knew very well that it is hard to demonstrate a stretch reflex in a normal human being at rest: why is the afferent barrage ineffective? The work of the late Paul Hoffmann (1922), beautifully developed in precision by David Lloyd (1943), had shown that the stretch reflex has a potent monosynaptic component and therefore the appropriate impulses are bound to reach the motoneurone. Let us enumerate some possible explanations and then consider them in detail:

(1) Excitatory impulses do arrive under all circumstances from end organs sensitive to stretch but the latter have their own intrafusal muscles which may have to be contracted by efferent nerve impulses in order to make the end organs sufficiently responsive.
(2) The basis of motoneurone activity being depolarization, some depolarizing activity from sources other than stretch afferents may be required.
(3) If this is so, why cannot a healthy and intelligent human being consciously activate the motor nerves for the so-called intrafusal muscle fibres?
(4) There may be inhibitory end organs sensitive to stretch and these may prevent the motoneurones from reaching the required degree of depolarization.

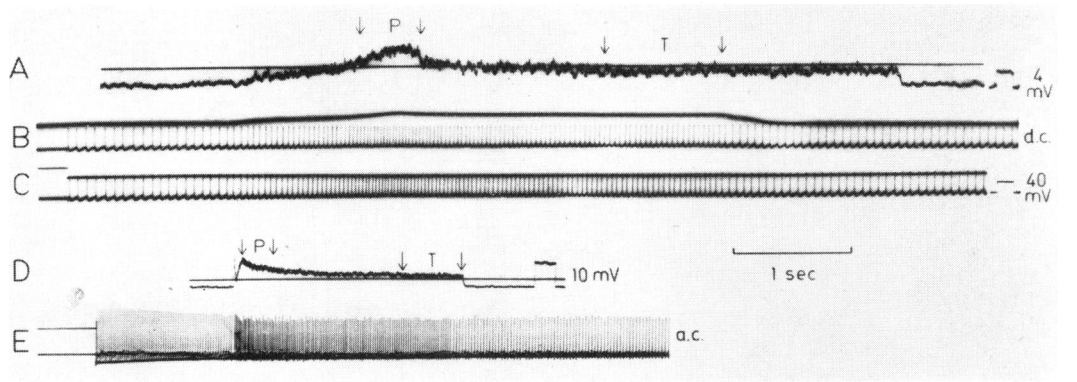

Fig 1 *Records of post-synaptic potentials and of repetitive discharges set up in two different motoneurones by injected currents (2 M potassium citrate electrode) in two anæmically narcotized cats.* A-C *from a gastrocnemius-soleus motoneurone of spike height 78 mV. In* A, *excitatory post-synaptic potential produced by a 10 mm stretch of the gastrocnemius-soleus muscle.* B *and* C *recorded simultaneously. Repetitive discharge initiated by depolarizing transmembrane current of 14 nA (indicated by the downward deflexion of the upper trace in* C). *Stretch of the gastrocnemius-soleus muscle indicated by myograph record in upper trace of* B *beginning about 1·5 sec after onset of transmembrane stimulation.* A *illustrates the measured phasic and tonic component potentials of the synaptic test stimulus (labelled* P *and* T *respectively). Hence, two facilitated values were obtained, one referring to the phasic rise of impulse frequency, another to the semistationary state of firing, as measured between arrows.* D *and* E *are from a hamstring motoneurone of spike height 84 mV. In this case, the synaptic effect elicited by high-frequency stimulation of cut hamstring nerve.* D, *excitatory post-synaptic potential produced by nerve stimulation alone. In* E, *the cell is fired repetitively by transmembrane current of 43 nA (downward deflexion of upper trace) and, after about 1 sec, the synaptic test stimulus is added. Here again, two facilitated values of spike frequency were obtained; one phasic, the other tonic (*P *and* T *between arrows). (Reproduced from Granit, Kernell & Lamarre 1966a, by kind permission)*

These four suggestions contain questions which are intertwined in many ways but cannot be understood unless some elementary facts have been mastered. Thus it is essential for us to realize that the muscle spindles *are* the organs concerned (cf. Granit 1955) and that they are inserted in parallel with the main or extrafusal muscle fibres so that they are unloaded and silenced when the latter contract by themselves (Matthews 1933). For the conceptualization of Liddell and Sherrington it sufficed to know of the existence of a stretch receptor. The act of standing, in their interpretation, was elicited by gravity acting on the extensors to produce an autogenetic stretch reflex in them. This reflex counteracted the pull of gravity, thereby diminishing the autogenetic facilitation of firing so that the muscle slackened and again was pulled upon by gravity and in this manner the cycle repeated itself in an oscillatory fashion. What they visualized was after all a servo mechanism of negative feed-back for the maintenance of constant length, if we express their result in more fashionable language (Merton 1951). Matthews' demonstration of the pause in the spindle discharge during a pure extrafusal contraction improved the theory but was no *conditio sine qua non*. The pause is initiated at the moment when the extrafusal fibres in contraction become shorter than the intrafusal ones. This, expressed very generally, is what is meant by the unloading of the spindles. There is often a corresponding silent period in the output from the motoneurones (Hoffmann 1922).

Power of Gamma Loop

Our first proposition (1, above) was that spindles need to be activated by their own efferent gamma fibres in order to be able to operate a stretch reflex (Granit 1955, Matthews 1964, for reviews). This means that the intrafusal fibres are contracted by gamma motor impulses thereby exerting stretch on the sense organs located in their midst. These respond by delivering the excitatory impulses that otherwise external stretch would have had to produce. As a consequence the motoneurones become depolarized across the gamma loop round the spindles. The motor cells are therefore brought nearer to the threshold at which depolarization of them leads to the firing of impulses down their axons. Adding external stretch by pulling on the muscle now makes depolarization supraliminal and produces the stretch reflex. Clearly the motoneurones could have been depolarized from some other source to achieve the same effect, but let us consider spindles first.

It is now necessary to discuss experimental work for a while and turn to intracellular recording (Granit, Kernell & Lamarre 1966*a*) in order to visualize the autogenetic depolarization at the cell membrane caused by stretch of a muscle – the ankle extensor gastrocnemius-soleus – in one of its own motoneurones. The ventral roots are cut

and so this muscle is deprived of its efferent, so-called fusimotor gamma innervation. We now want to demonstrate the effect of pure 'external' stretch. The depolarization produced across the membrane of the motor cell in the spinal cord is shown by record A of Fig 1, pull itself being indicated by the upper line of Fig 1B. The intracellular record shows a subliminal depolarization with a phasic (P) and a maintained or tonic (T) component, corresponding to equivalent variations in the firing rate of the spindles that project upon this motoneurone. In this case any attempt to record from the muscle itself would have been futile. We then proceed to depolarize the motoneurone artificially by running some current through the tip of the intracellular electrode. This current is separately recorded by the upper line in Fig 1C. The current is made strong enough to fire the motoneurone, as recorded in both B and C simultaneously. Stretch added to this amount of basic firing increases the rate of discharge a great deal, i.e. there is now a definite stretch reflex that would have been measurable myographically, had the motoneurone been in functional connexion with its muscle.

In this type of experiment it is possible to fire the motoneurone at varying frequencies by simply altering current strength (= amount of depolarization). To the varying frequencies of discharge we can add constant amounts of stretch, subliminal if we choose, as in the experiment just presented. The outcome of such experiments is that, within a very large range of firing rates even exceeding those observed in tonic reflexes, a constant amount of stretch always adds a constant

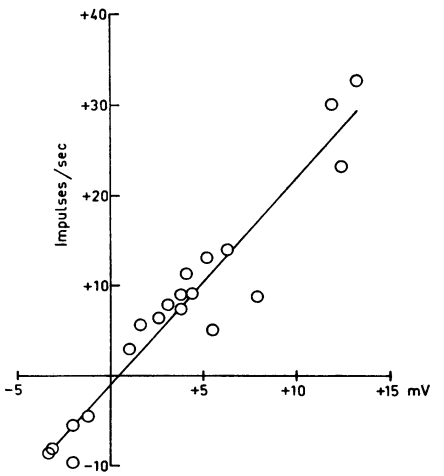

Fig 2 *Plot of constant increase or decrease in impulse frequency (ordinate), caused by synaptic stimulation using intracellular recording in the manner of Fig 1, against the amount of synaptic potential in mV (abscissa) required to elicit it. Each point a separate experiment. The slope constant is 2·28 impulses/sec/mV. Five readings refer to synaptic inhibition. (Reproduced from Granit, Kernell & Lamarre 1966a, by kind permission)*

number of impulses (Granit, Kernell & Lamarre 1966*a*, *b*). This very general rule we could establish with considerable accuracy. It is not necessary to use stretch as a stimulus. Any other excitatory or inhibitory stimulus which in itself is constant always adds or subtracts a fixed number of impulses, adding them if the net effect is depolarizing, subtracting them if it is hyperpolarizing (inhibitory, Eccles 1957) in nature. The motoneurone is thus a perfect adding machine responding to the net effect of all the synaptic and artificial currents involved.

This being the case one can proceed to multiply the number of such experiments in order to obtain the frequency of impulses produced per mV depolarization, a figure that we shall need for the evaluation of the power of the gamma loop. Experimental data are plotted in Fig 2, millivolts on the abscissa, impulses per second on the ordinate. Both excitations and inhibitions from various afferent sources have been used, many of them polysynaptic. The slope of the line is 2·28 impulses per second per millivolt and refers to large motoneurones because long-lasting good penetrations are required for exacting work of this kind.

In order to introduce the gamma loop (Granit, Kellerth & Szumski 1966*b*) into this analysis we proceed to stimulate the peripheral stump of the cut ventral root of gastrocnemius-soleus at the fast rate and high strength known to be necessary for the thin gamma fibres. Again the intracellular electrode is found inside one of the motoneurones of this muscle. Stimulation in this fashion across the gamma loop produces shortening of the intrafusal fibres and stretches the end organs 'internally'. Clearly the question to be answered by this experiment is: How well can the motoneurone be depolarized across the fusimotor gamma loop? A difficult task is here assigned to the indirect gamma-spindle route, because the concomitant extrafusal contraction tries to unload the spindle and thus to silence it. Another complication is that the spindles in those muscles have a secondary type of end organ, to stretch which produces autogenetic inhibition (e.g. Laporte & Bessou 1959). As a final complication, the extrafusal contraction activates tension-sensitive receptors, the Golgi tendon organs, and these, too, inhibit the motoneurones autogenetically (*see* e.g. Granit 1950). The remarkable outcome of the experiment, as shown in Fig 3, is that the gamma loop to the spindle primaries is powerful enough to overcome all these adverse effects and fire the motoneurone, the better, the greater, within limits, the stimulus strength. At low strength (1·0 in Fig 3) loop activation merely elicited a subliminal depolarization of 11 millivolt; for maximal effect four times threshold strength was needed (Fig 3 at 4·0).

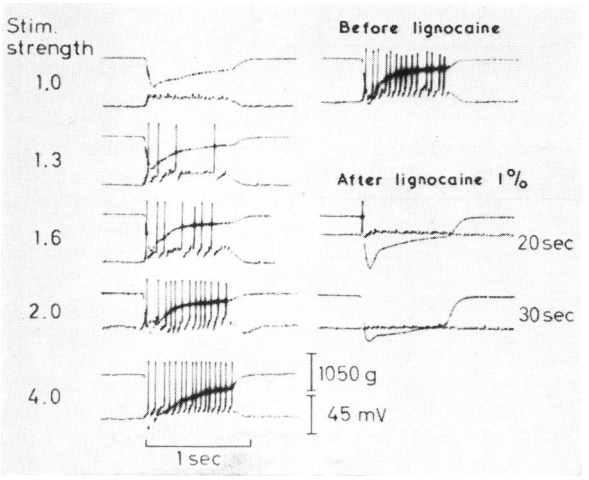

Fig 3 *Pentobarbitone cat. Stimulation of peripheral stump of cut lumbosacral ventral roots innervating isolated gastrocnemius-soleus muscle. Recording, intracellular from gastrocnemius-soleus motoneurone in lumbosacral region of the cord. Relative stimulus strength varied in left vertical row from 1·0 to 4·0. Stimulus frequency constant, at 500/sec. Myograph records isometric muscle contraction downwards. Note, synaptic potential around 11 mV at threshold (1·0) and firing of motoneurone by stimulation in this manner across gamma loop at greater stimulus strengths. On the right, constant stimulus strength (about 3·0 on relative scale) to demonstrate the selective effect of lignocaine on to the nerve removing most of the discharge (after 20 sec) while myogram (and thus alpha conduction) still unimpaired. (Reproduced from Granit, Kellerth & Szumski 1966b, by kind permission)*

The isometric muscular contractions are recorded downwards in Fig 3. Cocaine, applied in a pad of cotton wool on to the muscle nerve, paralyses the small gamma fibres before the large ones are attacked (Gasser & Erlanger 1929, Matthews & Rushworth 1957, 1958). To the latter category belong the thick afferent fibres from the spindle primaries and the motor ones for the extrafusal muscles. Such an experiment – making use of lignocaine – is shown on the right in Fig 3. After 20 sec, while the extrafusal contraction was still intact, only a single spike remained of the brisk discharge from the motoneurone. Clearly, before cocaine, the shortening of the intrafusal muscles under the full gamma barrage of impulses must have exceeded that of the co-activated extrafusals, or the spindles would have been unloaded and silenced. As we remember, even the inhibitions from tendon organs and spindle secondaries were easily overcome by the excitatory effect from the large spindle primaries.

Matthews (1964, 1966) has recently questioned whether the gamma loop is powerful enough or – more technically – has enough gain for being a really important governor of muscular contraction. Information on this point is decisive for the development of our theme. It was really in order to be able to provide an estimate of the power of the loop that I have taken up this much intracellular detail. But we are ultimately ready to fill in the figures of a very simple equation: activation across the gamma loop elicited 11 millivolts at the threshold. Each millivolt corresponds to 2·28 impulses per second. Accordingly loop activation, even at the threshold and opposed by the inhibitions mentioned, which hyperpolarize the same cell membrane, produced a *minimum* of $11 \times 2{\cdot}28$ or about 25 impulses per second. This is as much as a cat soleus makes use of in going about its business of delivering postural reflexes (Denny-Brown 1929). It is therefore concluded that the gamma loop is a very powerful instrument of motor control. The spindles themselves are known to be able to respond to loop activation by impulse frequencies as high as 300–400 per second (Eldred *et al.* 1953, Whitteridge 1959, Crowe & Matthews 1964*a*). In the decerebrate cat, soleus sometimes goes clonic. I have then seen spindle primaries normally active at rates around 400 per second (Granit 1959).

Spindle sensitivity may be obtained by plotting impulse frequency against mm extension in stretch. The slope constant of such curves, which tend to be linear, measures it in impulses per second per mm. As we shall see below, loop activation often increases the sensitivity (the slope constant), sometimes it merely shifts the whole curve bodily upwards (*see* e.g. Eldred *et al.* 1953, Whitteridge 1959, Harvey & Matthews 1961, Crowe & Matthews 1964*a*). It is not known in what manner gamma stimulation produces this real increase of spindle sensitivity but the fact is important when considering the power of the circuit.

The relative precision of the recent intracellular data tempted me to unfold my views on the power of the gamma loop backwards, starting with the latest results. The moment has now arrived for beginning from the beginning of the experimental attempts to understand this challenging piece of bio-engineering, as visualized through the spectacles of our laboratory.

Alpha-gamma Linkage

Leksell (1945), among the early workers, produced the most clear-cut evidence for the control of the intrafusal musculature by special motor fibres, his gamma fibres, but refused to abandon neurosurgery to extend his stay in spindle physiology. Seven years later, when Kuffler *et al.* (1951) already had started elucidating the same problem at the single-fibre level, Kaada and I (Granit &

Kaada 1952) decided to study a large number of structures in the brain (including the cerebellum) stereotactically for their possible contribution to gamma control. We found that, in general, the sites known to have excitatory or inhibitory effects on the muscles had corresponding effects on their spindle primaries. Already at the time this was best interpreted to mean that the gamma loop was sensibly employed by the brain together with the alpha motoneurones in the motor acts.

Taking stock of the knowledge available in 1954 (Granit 1955) it seemed to me that so many instances of co-excitation and co-inhibition of the alpha and gamma systems were known that it was legitimate to launch a concept such as that of 'alpha-gamma linkage' at the neuronal level as a basis for one major functional role of the spindle primaries. Everything that has happened since has confirmed me in this opinion. A number of linked alpha and gamma reflexes were seen by Hunt (1951) and Kobayashi *et al.* (1952) using electrical stimulation. Granit & Kaada (1952), with stimulation of sites in the cerebrum and cerebellum, saw the correlations mentioned above. Eldred *et al.* (1953) found the Magnus-de Kleijn reflexes from head movements to operate by alpha-gamma linkage. Eldred & Hagbarth (1954) used the characteristic patterns of excitation and inhibition that the latter (Hagbarth 1952) had obtained by pinching different skin areas to demonstrate that excitation and inhibition also in this case ran parallel for alpha and gamma reflexes. All these and a large number of later publications have as a rule reported lower thresholds for the gamma than for the alpha fibres and very often the impulses from the muscle spindles have been found to precede alpha motor action. It is thus by no means a tardy system but, on the contrary, most co-operative and ready to spring into action when the alphas are mobilized by the living organism. Special emphasis must be laid on those of the experiments mentioned above in which natural stimuli were used because electrical excitation may or may not combine the different afferent fibres in their correct proportions.

For this and other reasons the more recent experiments by Curt von Euler and his co-workers on the role of the spindles and the gamma-loop in respiration are singularly instructive. Euler & Fritts (1963) began this work by demonstrating that the afferents in the dorsal roots carrying impulses from the chest facilitated respiration. Nathan & Sears (1960) have given a brief review of their own and earlier results sup-

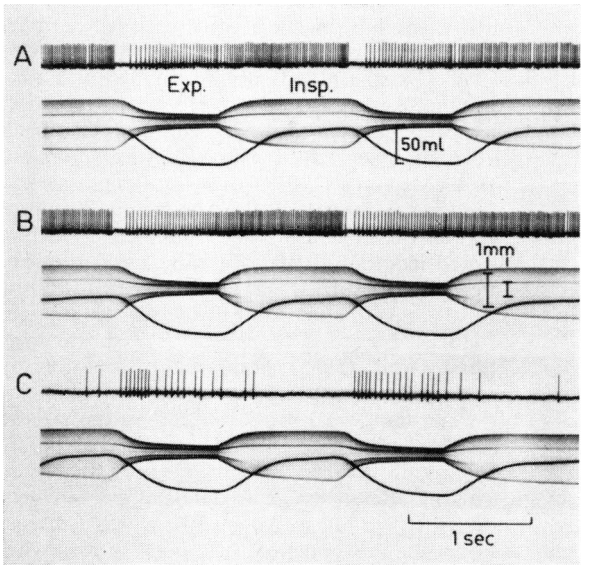

Fig 4 *Pentobarbitone cat. Neurogram of afferent discharge from an 'inspiratory' muscle spindle recorded together with intercostal width and tidal volume.* A, *control;* B, *2·5 min after application of lignocaine 0·25% to intercostal nerve.* C, *3·5 min after the lignocaine application. Note that the spindle fires in* A *when the intercostal contracts, while, after completion of the lignocaine action on the small gamma fibres in* C, *the spindle fires passively to stretch of its own muscle. This change takes place without influence on alpha conduction to the intercostal muscle. (Reproduced from Critchlow & Euler 1963, by kind permission)*

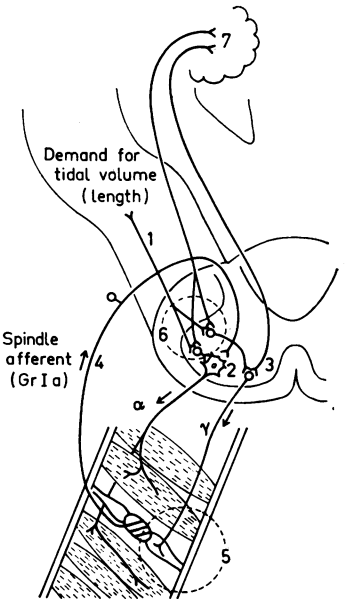

Fig 5 *Diagram to illustrate alpha-gamma linkage at the spinal cord level by interneurones in a pool* (6) *to which arrive commands from the respiratory centre* (1) *and the cerebellum* (7). *Alpha motoneurone* (2), *gamma motoneurone* (3) *and spindle afferent* (4). *(Reproduced from Euler 1966, by kind permission)*

porting the same inference. The next step by Euler was to show with Critchlow (Critchlow & Euler 1963) that in normal respiration the spindles of the external intercostal muscles fired during the active phase of the contraction of those muscles instead of being silenced by unloading (which took place after cocainization of the fusimotor gamma fibres in the manner mentioned above). This result is pictured in Fig 4 and again means that normally the shortening of the intrafusal muscles in respiration exceeds that of the external ones for a while. The inspiratory phase ends when they get even.

Supplementary work with individual alpha and gamma motoneurones (Eklund *et al.* 1963, Sears 1964) has confirmed their linked behaviour, basically controlled by the respiratory centre responding to the composition of the blood gases. In addition Euler and his co-workers found a tonic gamma discharge which was uninfluenced by the respiratory rhythm. Instead of jumping to the conclusion that a certain number of gamma fibres are unlinked with alphas, Euler with Corda and Lennerstrand (Corda *et al.* 1966) proceeded to investigate how these fibres were activated and soon found them controlled by cerebellar stimuli and postural reflexes from the chest. The more likely explanation of the existence of a tonic gamma outflow of impulses is therefore that it is linked in action with the postural alpha reflexes to which the respiratory volume changes of the chest have to adjust themselves continuously. Fig 5 is a schematic presentation of the way Euler (1966) has synthesized their observations on linkage. The link is held to be in the spinal cord.

Servo Theory

It is now easily understood why, in accepting co-activation of alphas and gammas in motor acts, we must also assign a new role to the stretch reflex, meaning by the old role the one that Liddell and Sherrington had elucidated so clearly. Adding a linked contribution of gamma activity to the design of the motor machinery means that the spindles, so far from being silenced, actually become all puissant in contraction, responding automatically with a burst of impulses to the slightest increase of load, as directly observed by Corda *et al.* (1965) in the inspiratory muscles when they made the preparation breathe against tracheal occlusions. They call it a 'load compensating reflex'. Slack spindles would take little if any notice of changes of load in contracted muscles.

We spent some time in the beginning of this Lecture to demonstrate how strongly a *firing* motoneurone responds to a barrage of spindle impulses caused by stretch. Contracting muscles evidently presuppose firing motoneurones, so that here we are in the end with the stretch reflex normally serving active instead of passive muscles. The linkage is automatic and so the gammas cannot be started volitionally in a resting muscle. Biologically it does not make sense to activate the gammas selectively in a resting muscle and, without them, there is no stretch reflex.

Unwittingly, as it were, Sherrington studied the stretch reflex in the correct manner because in the decerebrate animal he made use of a muscle contracted in rigidity which means that he studied firing or depolarized motoneurones. Elsewhere I have collected the evidence for the conclusion that in decerebrate rigidity these motoneurones actually are maintained in activity across the loop by central gamma release (Granit 1955, 1964) so I need not return to such problems here. This time it has been my endeavour to insert the missing link that did not seem to be missing in Liddell and Sherrington's account of the stretch reflex and to show that the gamma loop is both essential for it and in command of considerable power. In Merton's (1951) elaboration of the servo concept the possibility of linked alpha-gamma reflexes was considered but there was hardly enough evidence for this idea at the time.

The simplest version of the servo concept regards the sense organ as a detector of the difference in length between the intra- and extrafusal muscles thereby keeping a set point of muscle length by means of the stretch reflex, in the manner envisaged by Liddell & Sherrington (1924, 1925). Grodins (1963) prefers to call this performance a mere regulation. He wants to restrict the servo concept to a closed loop feed-back circuit capable of following a varying command signal, Merton's (1951) 'follow-up length servo'. This implies that the fusimotor gamma impulses contract the intrafusal muscle fibres to a definite wanted length and that the extrafusal fibres are forced by the subsequent stretch reflex to follow suit. In this manner intrafusal shortening will produce extrafusal tension (= shortening). Eldred *et al.* (1953) supported this notion by showing that strong reflexes to head tilt disappeared when the dorsal roots were cut, although the gamma-spindle loop still was as active as before root section. In their experiments loop activity in terms of afferent spike frequencies proved very powerful. The intracellular work which I discussed in the introduction has now shown what stretch reflexes can do to a firing motoneurone, thereby supporting the servo hypothesis in a highly significant manner. We cannot, of course, produce a demanded length setting with a decerebrate animal – only its caricature – but this is what the respiratory centre is called on to do when it responds to the composition of the blood gases. This is why the work on respiration has been so valuable for the theory. Automatic load compensation is another and most important

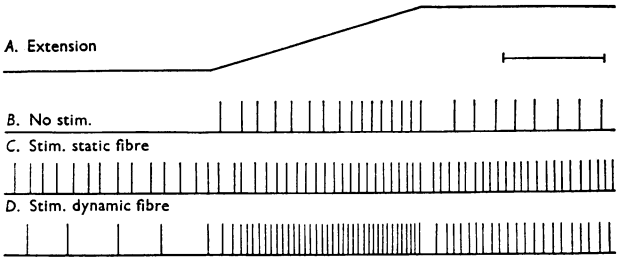

Fig 6 *Cat. The effects of stimulating separately static and dynamic fusimotor gamma fibres. Re-drawn experimental values of spindle discharge in single afferent. Static fibre in* C *and dynamic in* D *stimulated at rate 70/sec. Muscle extended 6 mm at 30 mm/sec. (Reproduced from Crowe & Matthews 1964*a*, by kind permission)*

aspect of the same process, based on alpha-gamma co-activation. Load compensation is by no means restricted to respiration. It will follow movement like a shadow and whenever muscles go from a more isotonic to a more isometric form of contraction in carrying weights – lifting limbs alone or limbs with weights added – automatically the alpha output is likely to be adjusted by the length servo for optimum compensation.

Dynamic-static Differentiation

Sir Bryan Matthews (1933) showed that the spindle primaries are sensitive to velocity of stretch after which their frequency of discharge adapts and settles for a lower maintained or static rate. His son, P B C Matthews (1962), working alone and with Jansen (Jansen & Matthews 1962*a*, *b*) on these end organs thirty years later, in the present era of fusimotor gamma interest, discovered that the dynamic and static discharges of the spindles are governed by separate gamma fibres. Fig 6 (Crowe & Matthews 1964*a*) shows in a schematic fashion what the two kinds of fusimotor gamma fibres do when a muscle is stretched. Stimulation of the static fibre elevates the rate of spindle firing to a higher maintained level. The dynamic fibres do that to some extent but, in addition, increase the rate of discharge of the initial phase that is basically sensitive to velocity of pull. It has been shown for a variety of muscles (Crowe & Matthews 1964*b*, Brown *et al.* 1965, Bessou *et al.* 1966) that once a gamma fibre is either static or dynamic for any spindle, it has an equivalent action on all the other spindles to which its terminals are distributed. (For a very recent discussion of the peripheral nervous and muscular structures in the spindle that mediate these effects, *see* papers by Barker, Boyd & Davey, Smith, Bessou & Laporte, Jansen, and Discussion (pp 115–119), in Granit 1966).

The difference between the effects of dynamic and static fibres on a spindle emerges with particular clarity from Fig 7 in which different rates of stimulation of a dynamic and static fibre have been combined with increasing velocities of pull (on the abscissa). The ratio of impulse frequency to unit change of length defines the sensitivity of the spindle and clearly dynamic fusimotor action is capable of greatly increasing spindle sensitivity. We realize now what this signifies for the depolarization of the motoneurones. There is also a considerable body of evidence to the effect that dynamic and static fibres are acted upon differentially from various stations in the brain as well as in some reflexes (Jansen & Matthews 1962*a*, *b*, Alnaes *et al.* 1965, Appelberg & Emonet-Denand 1965, Jansen & Rudjord 1965). Thus both the response to velocity of pull as well as that to maintained stretch can be adjusted by the organism in response to its needs and this, of course, invites speculation and further experimentation to explore these various 'needs'.

Let us begin by considering movement of a movable part of a limb, again remembering that

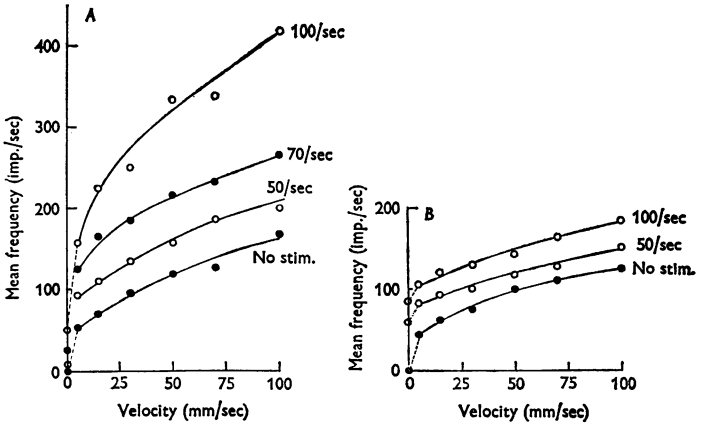

Fig 7 *Cat. The effect of stimulation of dynamic gamma fibre in* A, *of static one in* B, *as averaged over the whole of the dynamic phase of stretching at the velocities given by the absicissæ. (Reproduced from Crowe & Matthews 1964*a*, by kind permission)*

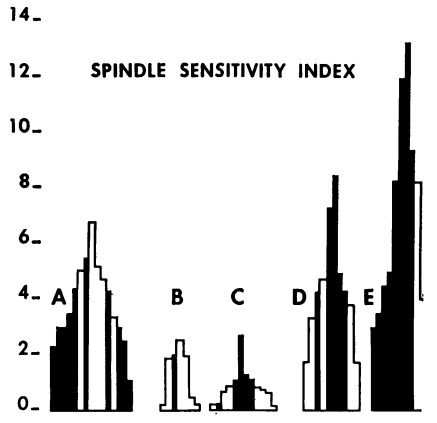

Fig 8 *Histogram of spindle sensitivity index of all spindle afferents studied in decerebrate cat with* (A) *cerebellum intact;* (B) *acute total cerebellectomy;* (C) *chronic total cerebellectomy before return of proprioceptive positive supporting;* (D) *chronic total cerebellectomy after return of maintained proprioceptive positive supporting;* (E) *chronic anterior lobe cerebellar ablation after return of hopping and ambulation. Each spindle afferent represented by one vertical bar. Extensor muscles, clear bars; flexor muscles, filled bars. Spindle sensitivity index represented in hundreds on vertical scale. (Reproduced from Van Der Meulen & Gilman 1965, by kind permission)*

the stretch reflex should be regarded as a component in contraction and not be thought of as an isolated event. Force is applied and, even if the weight merely is that of the muscles and piece of skeleton to be moved, force is always a product of mass and acceleration. The spindles do not record acceleration as such (Lennerstrand & Thoden 1967). But acceleration is a change of velocity and looking at Fig 7A it is seen that the dynamic instrument is admirably suited for taking care of changes of velocity. One can imagine, for instance, an increase of dynamic sensitivity leading to a recruitment of fresh motoneurones to compensate for a loss of speed in contraction when speed is required. I would like to carry speculation a little further. Considering that speed of movement is such an essential function in the organism and knowing how the brain tends to localize important functions to specific structures, it seems to me altogether probable that it would possess a special organization for taking care of speed of movement by linking up alphas with dynamic gammas. One used to think that fast movements were pure alpha movements and that the spindle apparatus was restricted to regulating slow postural contractions. This attitude to the gamma problem was partly a reflection of Sherrington's authority which drew attention to the postural reflexes and that remarkable preparation, the decerebrate animal. Partly and evidently the same conclusion also was suggested by the fact that the gamma fibres conduct slowly and so seemed admirably fitted for dealing with tone, as had been suggested by Rossi (1927) as a possibility. Their role in tone became well established in the early 1950s (Granit 1955) and need not now be recapitulated. From the clinical point of view this problem has been considered by Denny-Brown (1966).

Fresh aspects on the dynamic activity of the spindle primaries also come from the steadily growing evidence for a faster fusimotor alpha innervation of some spindles, at least in flexor muscles (Granit *et al.* 1959*a*, *b*, Rutledge & Haase 1961, Bessou *et al.* 1965, Brown *et al.* 1965, Green & Kellerth 1966, Haase *et al.* 1966). The workers at Toulouse and Oxford have shown these alpha fibres to be of the dynamic type. Their conduction velocities (α or β rate) are faster than those of the gamma fibres (γ rate). In fast synchronous action the extrafusal alpha fibres also mobilize spindles by direct electrical cross-excitation. We call such an effect ephaptic (Granit *et al.* 1959*b*). For all these reasons we cannot any more restrict the role of the spindles' fusimotor fibres to slow tonic reflexes alone, even though some tonic muscles in the cat have more spindles per gram than their phasic synergists.

On the servo theory, as pointed out by Merton (1951) and by Matthews (1964), sensitivity to velocity of stretch is required to counteract the consequences of time lag in the circuit. The response to a stretch will be delayed in traversing the reflex arc and for this reason emerge undamped and in the wrong phase relative to the pull initiating it, unless the lag can be compensated by the phase advance which sensitivity to velocity provides. Without this compensation by phase advance the stretch reflex would overshoot and easily start oscillating, especially when facilitated by high activity on the part of the static gamma fibres. Tremor has been observed by Henatsch (1966) after intracerebral perfusion of cats (in hydroxydione sodium succinate anæsthesia) with tubocurarine and in these experiments analysis of dynamic and static gamma activity showed the ratio of the two to be shifted in the direction of decreased dynamic and increased static effects.

Experimental Destruction of Alpha-gamma Linkage

At an early date we (Granit *et al.* 1955) succeeded in finding a case of breakdown of alpha-gamma linkage, indicating at the same time that the linkage was both functional as well as important. Acute destruction of the anterior cerebellum which is well known to cause rigidity of the alpha type (which is restricted to release of the alpha motoneurones in contrast to the gamma release in decerebrate rigidity, Granit 1955) led to passive behaviour of the spindles as if the gamma fibres had been paralysed by cocaine (cf. above). This

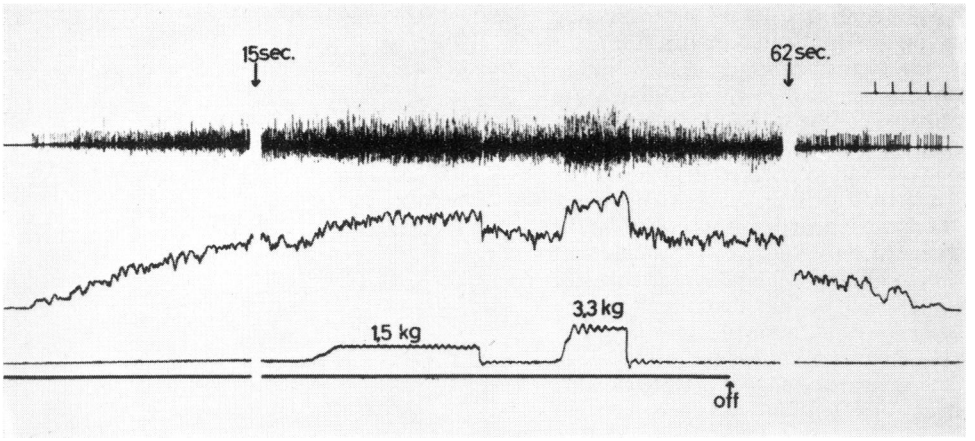

Fig 9 *Man. Electromyogram (above) and integrated electromyogram (below it) to show response of vibration at 100 c/s of the tendon of tibialis anterior, started 20 sec before beginning of record. Bottom of record shows moments of loading by weights 1·5 and 3·3 kg respectively and duration of vibration. These weights now gave stretch reflexes, absent before vibration. (Reproduced from Hagbarth & Eklund 1966a, by kind permission)*

work has been developed by Glaser and his colleagues at Yale (for a summary *see* Glaser & Higgins 1966) and by Van Der Meulen *et al.* (1966) at Harvard.

Glaser & Higgins, using sinusoidal stretch and interpreting their results on the servo theory, showed that in the decerebrate spastic animal this mode of stretching induced tension responses which were leading the concomitant length changes in phase. Removal of the anterior cerebellum induced a considerable diminution of this effect for up to 7 or 10 days or as long as functional decompensation was observed. Recovery led to re-establishment of the lost function closely correlated with restoration of the animal's ability to stand and walk. In similar experiments Van Der Meulen & Gilman (1965) studied spindle function with the aid of an elaborate 'spindle sensitivity index' which latter, as shown in Fig 8, was reduced after removal of the cerebellum and increased in parallel with recovery, even to the extent of producing some overcompensation. The recovery of ambulation, the positive supporting reaction and the hopping and tendon reflexes was parallel with spindle recovery. The success of these experiments, which required several weeks of animal care, was largely due to a new technique of cryogenic decerebration (Gilman & Van Der Meulen 1965).

Means of Clinical Analysis

It is not my intention to discuss the various attempts that have been made to fit spindle function into diagnostics (*see* e.g. Rushworth 1960, Jansen 1962). Much work has made use of the silent period of Hoffmann (1922) which by itself seems to me a rather equivocal index. Interpretation of the H-reflex is beset with pitfalls (*see* e.g. Granit, Kellerth & Szumski 1966*a*). The Jendrassik manœuvre can hardly be regarded as a pure test of spindle facilitation (Gassel & Diamantopoulos 1964).

Clearly we need something very definite to begin with, rather than a large number of indirect approaches. Recent developments promise to satisfy this demand. It was shown some ten years ago (Granit & Henatsch 1956) that the spindle primaries can follow very high frequencies of vibration, especially when activated by their fusimotor fibres, and a later systematic comparison by Bianconi & Van Der Meulen (1963) between the primaries and the so-called spindle secondaries showed that the latter did not partake of this property. Here is thus the much wanted and reasonably selective method of mobilizing the spindle primaries, and lately it has been applied to man with considerable success (Yamanaka 1964, De Gail *et al.* 1966, Eklund & Hagbarth 1966, Hagbarth & Eklund 1966*a*, *b*, Rushworth & Young 1966). High-frequency vibration of the tendon seems to be the best mode of application. It elicits a large autogenetic reflex, shown in Fig 9, and has already been used by Hagbarth's group with some success in the clinic. The properties of this reflex with respect to stretch, contraction, and the reciprocal inhibition of the antagonist, support the conclusion that it is wholly determined by the afferent barrage of the spindle primaries. In addition Hagbarth & Vallbo (1967*a*, *b*) have succeeded in obtaining micro-electrode records of impulses in fairly good isolation from their own nerves, sometimes also from spindle primaries, and shown them to be activated by vibration. Direct recording may yet develop into a valuable method of checking up on the role of

spindles in volitional acts. It has independently been worked out by Knutsson & Widén (1967).

Another great advantage of the vibration method is that motoneurones which definitely are driven by spindles can be studied for comparison by the indirect methods mentioned above, adding also volitional activation of different degrees. The reader is referred to the papers mentioned, especially those of Hagbarth's group which at the moment seems to have the greatest amount of experience, both of normal and diseased subjects. A very useful indirect method, that of unloading a muscle holding a weight, originally introduced by Hansen & Hoffmann (1922), has the advantage of excluding the contribution of the Golgi tendon organs which are tension recorders. It has recently been used by Hufschmidt (1966), Struppler & Schenck (1958) and Hoffmann & Angel (1968) and could now be improved a great deal by systematic comparisons with the vibration test, as Hagbarth & Eklund (1966*a*) have shown. We are apparently entering upon a phase of real advance in spindle diagnostics and I hope that you do not think me over-confident when I predict that the spindles soon will be shown to have a good share in most of the volitional motor acts that are accessible to analysis. This, at least, is what Vallbo's (1967) experiments, making use of microrecording of proprioceptive impulses in man, seem to indicate.

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