Exp. Brain Res. 29, 57–74 (1977)

Experimental Brain Research

Differential Control of Fast and Slow Twitch Motor Units in the Decerebrate Cat

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Summary. In approximately 3/4 of precollicular decerebrate (unanesthetized) cats, tetanic electrical stimulation of the sural nerve, or pinching the ankle skin innervated by the sural nerve, produced predominant excitation (overall increased force output and EMG activity) in the mixed medical gastrocnemius (MG) muscle and simultaneous inhibition in its slow twitch synergist, soleus (Sol). The present experiments were designed to test whether, as this and other evidence suggests, certain sets of cutaneous afferents can produce activation of particular groups of motor units and simultaneous inhibition of other groups within the same motor unit pool (i.e., units belonging to a single muscle).

We recorded, in decerebrate cats, the activity of restricted sets of MG motor units using either fine bipolar EMG wire electrodes or bipolar hook electrodes on small natural filaments of the MG muscle nerve. In preparations exhibiting the differential effect of sural input noted above, we usually found that some low threshold MG motor units (i.e., those responding to stretch or vibration of the MG muscle) exhibited slowing of discharge or complete inhibition at the same time that higher threshold MG units, not responsive to stretch or vibration, were powerfully recruited by either electrical or natural stimulation of sural nerve afferents. The net balance of synaptic effects within the MG motoneuron population may thus be excitatory in some cells and simultaneously inhibitory in others. This finding, together with earlier evidence, suggests the existence of at least two patterns of organization of synaptic input to the MG motoneuron pool.

Key words: Motor units – Synaptic control – Cutaneous reflexes – Decerebrate cat

Introduction

In both animals and human subjects, motoneurons within a motor unit pool (i.e., units belonging to a given muscle) are usually recruited in a stereotyped and

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repeatable order (e.g., Henneman et al., 1965; Milner-Brown et al., 1973; Freund et al., 1975; Tanji and Kato, 1973). Although exceptions to fixed recruitment patterns have been described (e.g., Grimby and Hannerz, 1968, 1974, 1976; Tanji and Kato, 1973; Kernell and Sjöholm, 1975; Wyman et al., 1974), interpretation of such results is sometimes difficult because of a lack of information about relative "threshold" of different units, difficulty in repeating observations (i.e., lack of stereotypy), and a variety of technical limitations.

The existence of alternative patterns of motor unit recruitment could well provide new insights for investigation of the spinal mechanisms that govern the output from motoneuron pools. Early observations from Sherrington's laboratory are of particular interest in this regard. Denny-Brown (1929) found that some labyrinthine reflexes excited fast, pale muscles such as gastrocnemius as much or more than the slow, red soleus. Further, certain peripheral inputs could facilitate muscle tension in the gastrocnemius while simultaneously inhibiting reflex tension in the soleus (Creed et al., 1932, see esp. their Fig. 37). These patterns were quite different from those usually found in other postural reflexes (Denny-Brown, 1929).

The medial gastrocnemius muscle (MG) of the cat is composed of a mixture of motor unit types, including several varieties of fast twitch (called types FF, F(int) and FR) and a single variety of slow twitch (type S) motor units (Burke, 1967; Burke et al., 1973a). The soleus (Sol) muscle, on the other hand, contains only type S units (Burke et al., 1974). Soleus type S motor units are similar to MG type S units in a number of respects, including the fact that polysynaptic potentials produced in their motoneurons upon electrical stimulation of the ipsilateral sural nerve are dominated by inhibitory PSP components. In contrast, the polysynaptic PSPs produced by sural nerve stimulation in cells innervating fast twitch units are dominated by early excitatory components and inhibition is usually much less prominent (Burke et al., 1970, 1973b). The present experiments were designed to test whether the different balance of excitation to inhibition in sural PSPs might produce simultaneous inhibition of some MG motor units and excitation of others. This result was indeed found under some conditions and the implications of this finding for motor unit control are discussed. A preliminary report of some of this material has appeared elsewhere (Kanda et al., 1976).

Material and Methods

Experiments were performed on 21 adult cats (2.0–3.8 kg), which were anesthetized with halothane in nitrous oxide-oxygen (60%–40%) during surgical preparation. The distal portions of the MG and Sol muscles were carefully dissected free of surrounding tissues and the MG was separated from the lateral gastrocnemius (LG) muscle without interrupting blood supply. The tendons of each muscle were cut near their insertion on the calcaneus and were attached to a muscle puller or to a strain gauge through heavy silk sutures and small steel hooks. The left hind limb and hip were widely denervated by cutting the following nerves: hamstring, gluteal, common peroneal, quadriceps, obturator, posterior tibial, posterior femoral cutaneous and pudendal. Only the sural (in some experiments), LG-Sol and MG nerves were left intact. The left hind limb was rigidly fixed with bone clamps to a frame holding vertebrae and hips. Afterwards, all cats save one were decerebrated by precollicular section and the anesthetic discontinued. In one experiment, halothane anesthesia was

maintained without decerebration at a very light level such that stretch and vibration reflexes could be elicited from MG and Sol.

Exposed tissues were covered with warm mineral oil. Blood pressure, expired CO_2 and the temperatures of rectum and oil pools were monitored continuously. Temperatures of body and spinal cord pools (when present) were kept at 37–38° C (35–37° C for leg oil pools) using radiant heat and heating pads.

Reflex activity was produced in MG and Sol motoneurons by muscle stretch or by longitudinal vibration at 160 Hz and 60–160 μm (usually 80–100 μm) amplitude. Vibration was applied for 5.5 sec every 20 sec and initial tension and vibration amplitude were adjusted so that plateau tensions during the tonic vibration reflex (TVR) reached 100–400 gm. When only one muscle was vibrated (e.g., MG), the other (e.g., Sol) was connected to a strain gauge (Grass FT-10) under moderate stretch to generate a stretch reflex (active force 200–700 gm).

A variety of experimental approaches were attempted to solve the problem of recording simultaneously from small numbers of individual MG motor units during massive activity. The effects on the MG motor unit pool produced by electrical stimulation of a number of hindlimb skin and muscle nerves (saphenous, superficial peroneal, sural and extensor digitorum longus – tibialis anterior) were examined. After considerable testing, the final experimental designs described below were used.

Variation 1. A small laminectomy to the left side of the L5 and L6 vertebrae was performed. A ball electrode was placed on the intact dura over the entry of the L7 dorsal root to monitor incoming volleys. The cut nerves noted above were placed on bipolar stimulating electrodes. Fine bipolar electromyographic (EMG) electrodes were made by twisting insulated fine (36 ga) stainless steel wires together, with cut tips separated by 200–300 μm. These were inserted into the MG muscle with a hypodermic needle. Coarse monopolar EMG electrodes (multi-stranded stainless steel insulated wires with large exposed tips) were also inserted into MG and Sol. Electrical stimulation of peripheral nerves (10–100 Hz trains lasting 2 sec, pulse duration 0.05 msec and strength 1.1 to 15 times electrical threshold) was superimposed on stretch reflexes or TVR responses; the stimulus trains started 2 sec after onset of vibration (see Fig. 2). All data were recorded on an FM tape recorder with bandwidth 0–5 kHz.

Variation 2. The sural nerve was left intact throughout its length. No laminectomy was performed. A small natural filament of the MG nerve was dissected free, cut at its entry into the muscle and placed on bipolar platinum recording electrodes. The whole MG nerve was carefully separated from the sciatic trunk proximally without disturbing its blood supply and lifted in continuity onto another pair of platinum wire electrodes (see Fig. 1). Cutaneous afferent input was generated by pinching the skin innervated by the sural nerve (lateral aspect of the ankle and upper foot) with plain or toothed forceps; the sural nerve was not electrically stimulated (see Figs. 4–7).

The activity of small numbers of MG efferent axons was recorded from the MG nerve filament. Individual unit spikes were separated using a spike discriminator sensitive to both amplitude and wave shape (Bak and Schmidt, 1977a). The conduction velocity of individual axons was determined by passing the signal recorded from the proximal MG nerve or from the small distal filament through an analog delay line (Bak and Schmidt, 1977b; delay approximately 2 msec) and then to a signal averaging computer (Nicolet 1070). The signal averager was triggered by the acceptance pulse of the spike discriminator adjusted to identify one or another efferent spike (Fig. 1, inset). The signal produced by the target unit at the proximal electrode could thus be retrieved by spike triggered averaging. The conduction time was estimated by the delay between the first deflection of each signal (Fig. 1, inset) and the conduction distance between the more proximal electrode in each recording pair (20–37.2 mm) was measured by laying a fine suture along the nerve.

Results

Differential Effect of Sural Nerve Input on MG and Sol Muscles

After testing various skin and muscle nerves in the ipsilateral leg (see Methods; Variation No. 1), we found that the sural nerve quite consistently (i.e., in 16 of

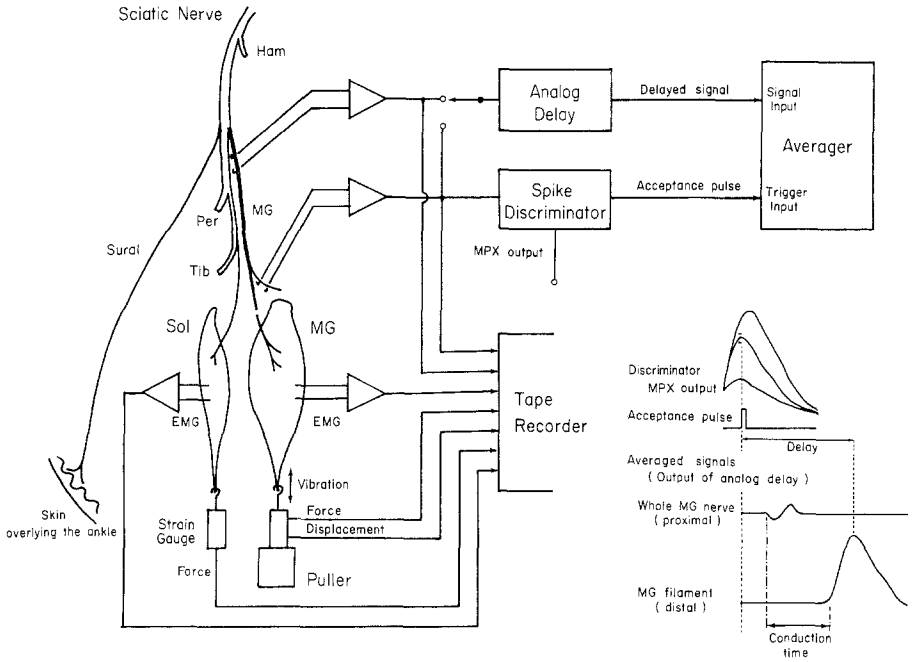

Fig. 1. Diagram of experimental arrangement (specifically Variation No. 2). See text for explanation

21 animals) produced simultaneous facilitation of the whole MG muscle and inhibition of Sol when the sural tetanus was superimposed on a stretch reflex and/or a TVR (Fig. 2). In 4 of the other 5 cats, sural stimulation produced simultaneous excitation of both MG and Sol at low strengths ($<5\times$T) and inhibition at higher strengths. In only one cat was sural nerve input inhibitory throughout the range of stimulus strengths tested. Other leg nerves produced effects on MG and Sol which were quite variable from one preparation to another, and we therefore concentrated on the sural nerve input. These results are in accord with those of Hagbarth's early study (1952) of topographical specificity in reflex effects from skin afferents to ankle extensor motoneurons.

The records in Figure 2 show the differential effect on force and EMG activity from MG and Sol during vibration of MG and stretch of Sol (preparation as in Variation No. 1 in Methods). A substantial TVR response was obtained in MG (Fig. 2A) and a small heteronymous TVR was also apparent in Sol. Superimposition of a weak tetanic stimulus (100 Hz; 1.7 times threshold for the most excitable fibers in the nerve; Fig. 2B) produced a small increase in force and EMG activity in both MG and Sol. However, as the stimulus strength was increased, the overall response in Sol became increasingly inhibitory such that, at $5.6\times$T (record F), Sol force and EMG activity virtually disappeared during the sural tetanus. At the same time, the response in MG consisted of progressively greater overall excitation, with increases in both force output and EMG.

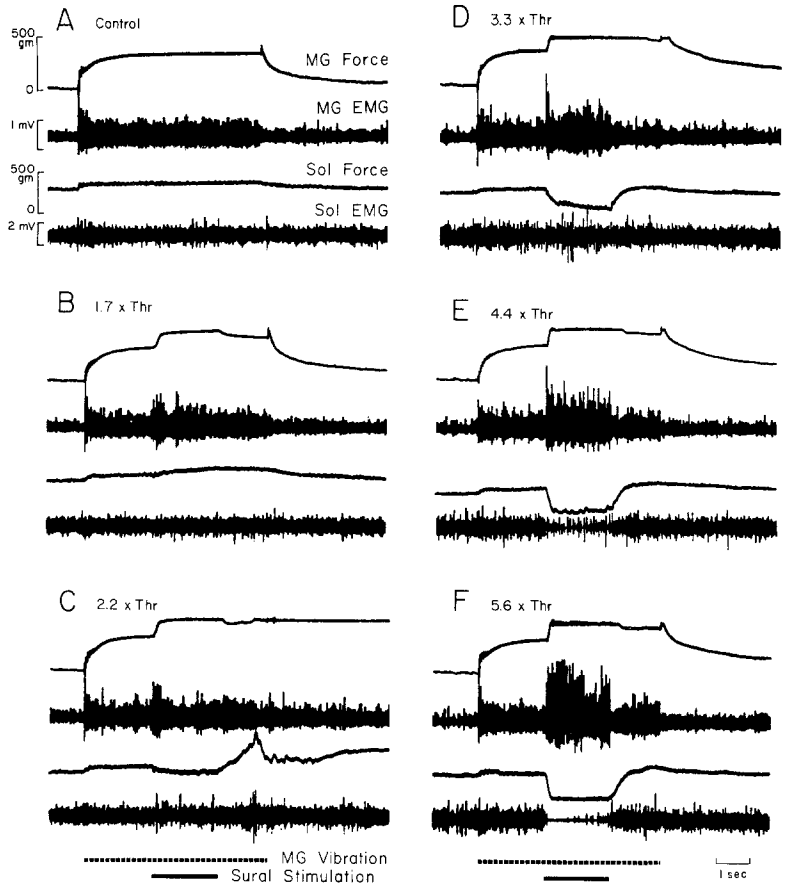

Fig. 2. Differential effect of sural nerve stimulation at various strengths on force output and electromyographic (EMG) activity in MG and Sol muscles when superimposed on tonic vibration reflexes. (Variation No. 1: see Methods). Duration of MG vibration indicated below by dashed lines; sural tetanic stimulation indicated by solid lines. Strength of sural stimulation indicated in multiples of threshold for the most excitable fibers in the nerve. Sustained MG and Sol force in record C was due to spontaneous movement in this active decerebrate preparation

Differential Control Within the MG Motor Unit Population

The differential response in MG and Sol shown in Figure 2 raised the question whether some motor units within the MG population (specifically the type S units) might also exhibit inhibition during sural stimulation, while other (presumably fast twitch) units are simultaneously excited. To examine this possibility, we initially recorded the activity of small numbers of individual MG motor units using fine EMG electrodes (see Methods, Variation No. 1). In the case shown in Figure 3, weak (2×T) sural stimulation superimposed on a TVR generated by vibrating both MG and Sol together caused complete inhibition of

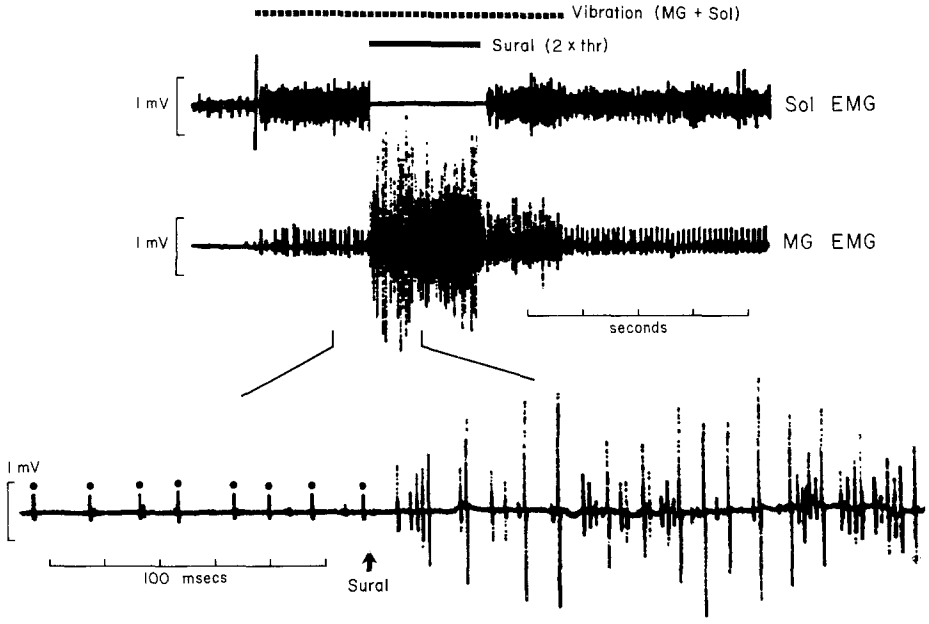

Fig. 3. Differential effect of sural nerve stimulation on EMG activity in Sol and MG muscles when superimposed on vibration (160 Hz; 80 μm amplitude) of both muscles. Durations of vibration and sural tetanus indicated above. Sol EMG recorded with large wire electrode; MG EMG recorded with fine bipolar wires (see Methods). Activity of individual MG motor units is seen in the MG EMG trace. A small amplitude unit (marked with dots) was excited by vibration but this unit spike apparently disappeared during the sural tetanus (lowermost fast time base record) and was replaced by marked activity in other, larger amplitude MG units. Unit identification was checked on very fast time base records (not illustrated). The disappearance of the small amplitude MG unit spike was similar to the behavior of the whole Sol muscle, which exhibited complete suppression of activity during the sural tetanus (uppermost trace)

Sol activity and a large extra burst in the MG EMG. The MG EMG trace, when examined on a greatly expanded time base (Fig. 3, lowest trace, for example) showed that a relatively small amplitude unit recruited during vibration (unit marked with dots) disappeared from the record after the start of the sural nerve tetanus (arrow); it was replaced by activity in other motor units with generally much larger amplitude spikes. The small target unit reappeared in the record with the same shape and amplitude only after the sural tetanus had ended.

Although this type of EMG record suggested the existence of differential control within the MG unit pool, we could not exclude the possibility that an already active unit might have continued to discharge during sural tetanus in perfect synchrony with one or more of the larger motor units, and was thus undetected during the massive activity. In order to avoid this ambiguity, we turned to a method that permits recording the activity of individual motor axons with known destination, i.e., those present in small natural filaments of a peripheral muscle nerve (see Methods, Variation No. 2). This technique produced records in which the activity of small numbers of MG motor axons

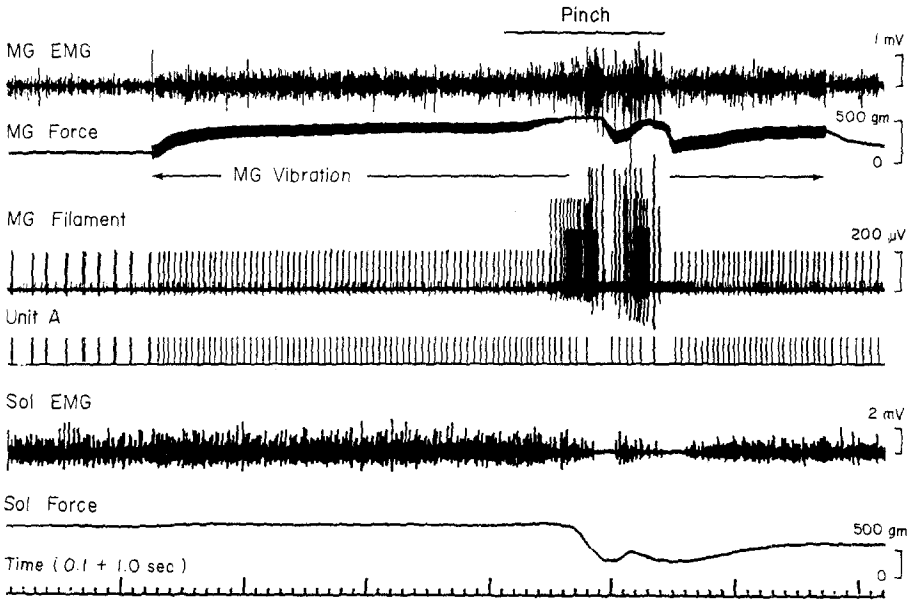

Fig. 4. Records of EMG activity and force output of MG (two uppermost traces) and Sol (two lowermost traces) muscles, together with simultaneous record of activity of a small number of MG motor axons in a natural filament of MG muscle nerve (third trace; see Methods, Variation No. 2). During MG vibration (160 Hz, 90 μm), activity in whole MG increased (TVR) and that in Sol showed a smaller increase. Pinching the skin over the lateral ankle (pinch) with toothed forceps produced two bursts of MG activity, with recruitment of large amplitude motor axons in the MG filament, but caused quite complete suppression of Sol activity. Trace labeled "unit A" shows isolated activity of medium amplitude motoneuron spike evident in the original filament record. Note that activity of unit A parallels that in whole Sol

could be followed reliably even during intense whole MG activity. We also used natural stimulation of the skin innervated by the sural nerve (see Methods) to circumvent the problem of possible synchronization of efferent discharge. Pinching the skin over the lateral and dorsal aspects of the ankle proved to be a very effective stimulus (see Hagbarth, 1952).

A particularly clear example of the results obtained in 3 cats is shown in Figure 4. Skin pinch to the lateral ankle skin was superimposed on vibration of MG and stretch of Sol. Note that the response in the whole MG muscle during pinch consisted of two bursts of increased activity, while in the Sol muscle inhibition clearly predominated (cf. Fig. 2). The MG filament record (3rd trace) shows that a motor axon with a moderate spike amplitude fired slowly before vibration (this unit was extremely responsive to passive stretch), then increased in discharge rate during MG tendon vibration. The 4th trace ("Unit A") shows the output of a spike discriminator adjusted to recognize this target unit. During ankle skin pinch, discharges were recruited in other MG motor units, all with larger spike amplitudes, but unit A, already firing, showed only inhibition. The pattern of activity in unit A was similar to that evident in the whole Sol muscle.

The same response is shown in Figure 5 on a faster time base. In this figure the discharge patterns of all of the responding motoneurons are shown separately. In each case, the accuracy of spike recognition was checked against photographic traces of the MG filament record taken on a very fast time base, permitting unambiguous identification of the individual unit spikes. Responses in 5 different motoneurons were clearly present and these are labeled A through E in the rank order of their recruitment during repeated trials of skin pinch. This order correspond closely to the rank order of their axonal conduction velocities (Table 1), estimated as described under methods. The conduction velocity measurements established that units A through E were all alpha motoneurons.

In these records (Figs. 4 and 5) the MG response to the pinch stimulus was complex, including two bursts of increased activity (with possible inhibition after each) in both filament motor axons and in the whole MG response (upper traces). However, the expanded records show clearly that activity in the lowest threshold unit (unit A) slowed and then ceased during the period when the higher threshold units (units B–E) were recruited. In the first burst sequence (Fig. 5), units D and E began to fire only during a long pause in the activity of unit A. Thus, while the firing behavior of unit A was similar to the activity pattern in the whole Sol muscle, the spike patterns in the higher threshold MG units (B–E) were quite unlike those of either Sol motoneurons or unit A. This seems a clear and unambiguous example of differential control of alpha motoneurons within a single motor unit pool.

In the animals exhibiting the differential activity pattern in MG and Sol (Fig. 2), small MG nerve filaments showing motoneuron activity patterns such as in Figures 4 and 5 were found rather readily. This was in fact a requirement of the experiment. Since we depended on a relatively intact homonymous afferent discharge to maintain MG motor pool excitability, only a few MG nerve filaments could be cut in any one cat. The present experiments did not test how widespread the differential recruitment pattern may be within the MG motoneuron pool, but these results suggest that it is not unusual.

It was not possible to identify unit A in terms of its motor unit type. However, its axonal conduction velocity was relatively slow (Table 1) and it exhibited a vigorous response to stretch, tendon tap and vibration. All of these observations suggest that unit A was very likely a type S, or slow twitch, motor unit. In an earlier study of MG motor units in the decerebrate cat (Burke, 1968b), all MG type S units encountered responded to MG stretch with sustained firing, but less than 37% of fast twitch units fired at all during MG stretch. Thus at least some of the higher threshold units in Figures 4 and 5 were probably fast twitch units, particularly those with the fastest axonal conduction velocities (Table 1).

The conduction velocity estimates for the MG efferents illustrated in Figures 4 through 7 are shown in Table 1. The several sets of figures resulted from estimates made at different conduction distances by varying the position of the proximal electrode, keeping the distal pair fixed (see Methods and Fig. 1). It is of interest that the velocities measured at the longest conduction distance (37.2 mm) were consistently 10–13% faster than those at the shorter, more peripheral distances. Although it is impossible to dismiss measurement error as an explanation, the data suggest that there may be some systematic slowing of motor axon conduction velocity in the 1–2 cm of nerve immediately before entry into the muscle, perhaps due at least in part to axonal branching (Eccles and Sherrington, 1930).

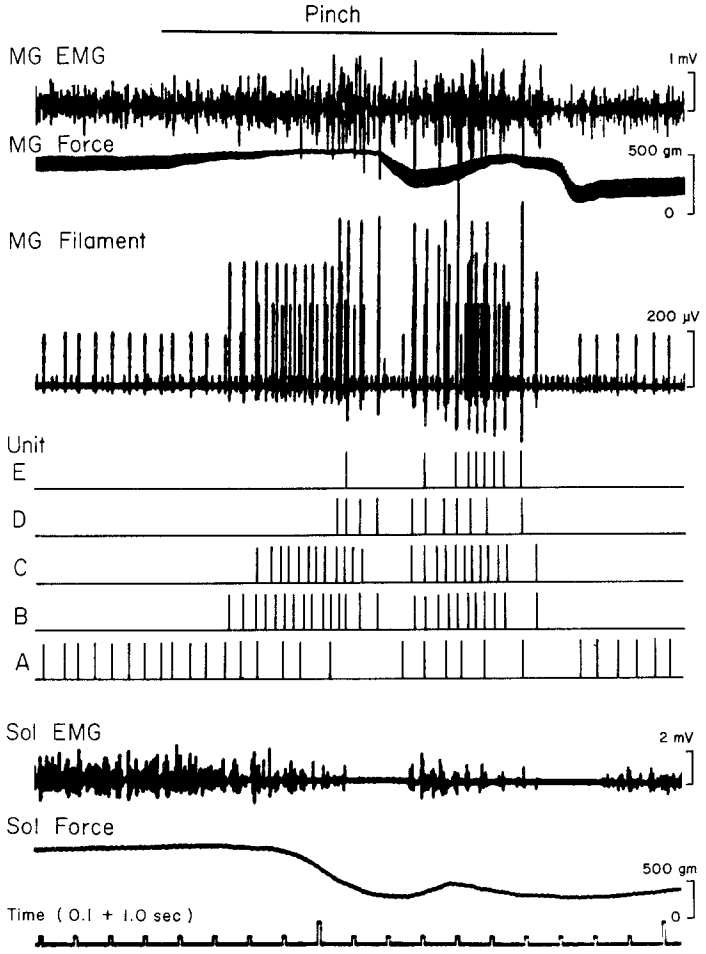

Fig. 5. Same response as in Figure 4, but shown on a faster time base. Isolated activity of five identifiable MG motoneuron axons is shown in the middle set of traces. Note slowing of unit **A** discharge during each burst of activity in the higher threshold units. **B–E**

Table 1. Motor axon conduction velocities measured at three different conduction distances in the experiment (Cat TVR 21) shown in Figures 4–7

Unit	Conduction distances		
	22 mm	24 mm	37.2 mm
E	88 m/sec	–	–
D	88 m/sec	80 m/sec	97 m/sec
C	85 m/sec	86 m/sec	–
B	79 m/sec	80 m/sec	89 m/sec
A	73 m/sec	70 m/sec	81 m/sec
Gamma	–	28 m/sec	–

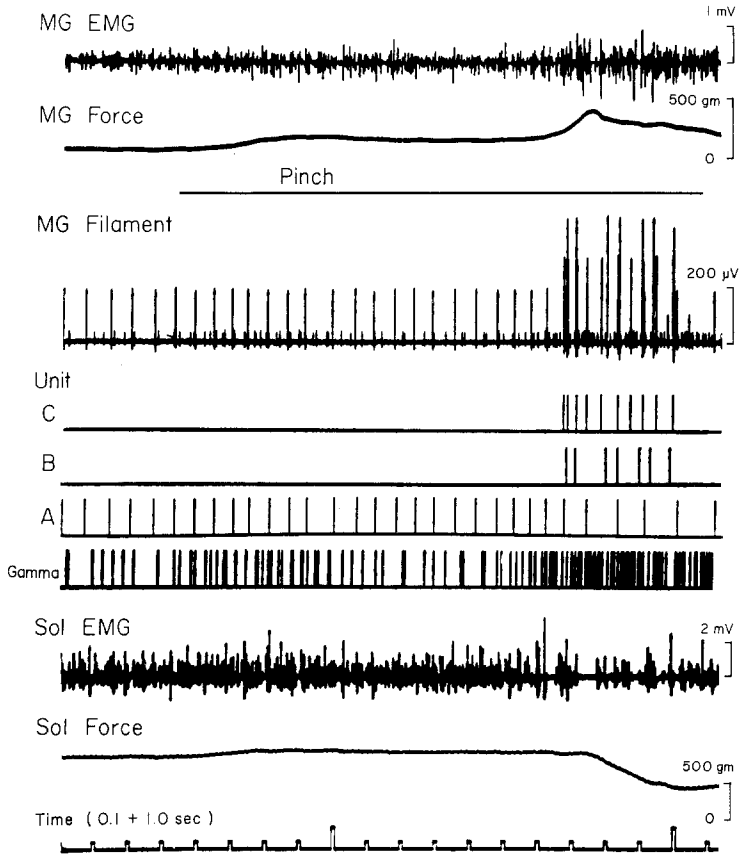

Fig. 6. Effect of much weaker pinch to ankle skin in same preparation as shown in Figures 4 and 5. MG EMG and force traces exhibit only excitation but Sol was inhibited, albeit incompletely. Activity in MG unit **A** was inhibited (also incompletely) at the same time that the higher threshold units (**B** and **C**) were recruited. The original filament record shows a small amplitude spike with irregular discharge and the isolated activity of this unit (conduction velocity 28 m/sec; see Table 1) is labeled "Gamma". Note purely excitatory response in this unit

As shown in Figure 6 (same experiment as Figs. 4 and 5), a relatively light pinch to the ankle skin produced apparently uncomplicated overall excitation in MG force and EMG, although inhibition was clearly present in the Sol records (lower traces). In this case, skin pinch was superimposed on MG and Sol stretch alone, without vibration. During the initial part of this light pinch, the low threshold unit A exhibited some increase in discharge rate but later, when the stimulus was increased to cause recruitment of the higher threshold units B and C, unit A was clearly inhibited, again in parallel with the incomplete inhibition evident in the Sol force and EMG traces. In another trial under the same conditions but with stronger pinch (Fig. 7), there were two clear sequences of excitation followed by inhibition in MG, while Sol exhibited only profound

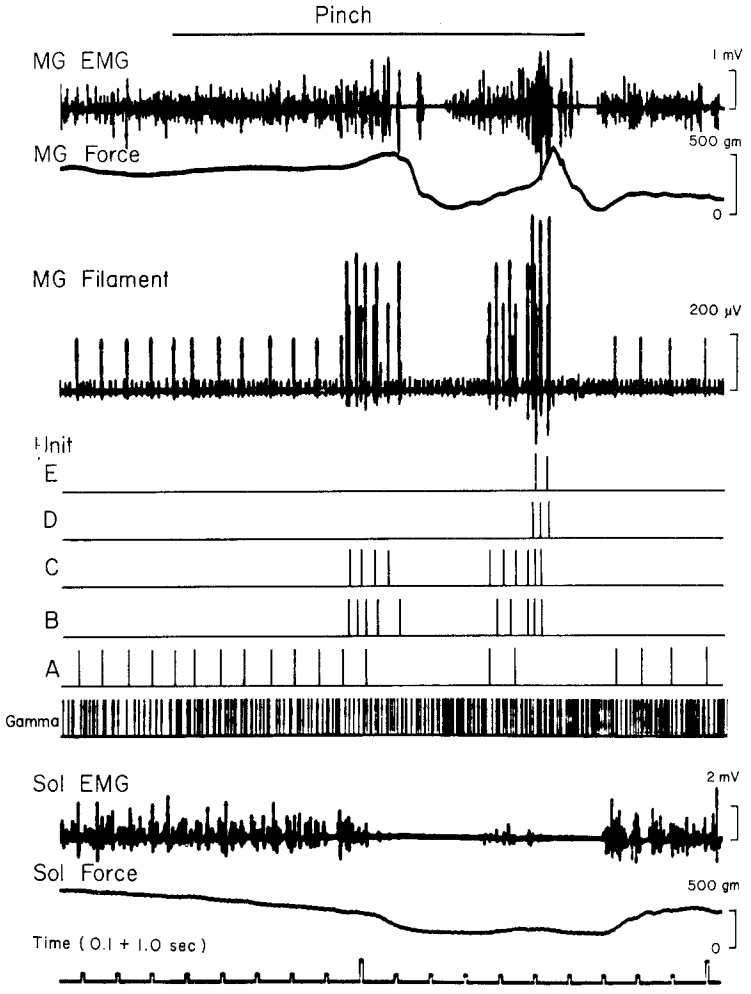

Fig. 7. Same preparation and conditions as in Figure 6, but with stronger pinch to ankle skin. Note marked excitation-inhibition sequences in MG records and pure inhibition in Sol. In the second burst, recruitment of the highest threshold MG units (**D** and **E**) occured only after apparent complete suppression of discharge in the low threshold unit **A** which again exhibited a pattern similar to that in the whole Sol. The gamma axon spike showed no trace of an inhibitory effect, despite virtually complete although brief periods of suppression of MG alpha activity (see MG EMG trace)

inhibition. The highest threshold units (D and E) were recruited during the second MG burst only after discharge in unit A had ceased.

Figures 6 and 7 show spike discriminator pulses triggered from a small efferent spike in the MG filament (labeled "Gamma"), visible in the filament trace in these figures although very much smaller than the unit A spike. The conduction velocity of this axon was estimated as 28 m/sec (Table 1), clearly identifying it as belonging to a gamma motoneuron. Note in Figure 6 that the

discharge pattern of this gamma efferent was quite irregular but that it responded with excitation to very light pinch, in parallel with the alpha unit A. Later, with increasing pinch input, unit A showed inhibition but the gamma efferent continued to show increased discharge. Even more striking, during the excitation-inhibition bursts in the MG alpha units (and indeed in the whole MG muscle) in Figure 7, the MG gamma motoneuron showed no clear evidence of inhibition despite complete cessation of extrafusal activity (see also the filament record in Fig. 5). The parallel excitation of the alpha and gamma efferents at some points in these complex responses is consistent with expectations of alpha-gamma coactivation (see Granit, 1970). However, the apparent lack of parallel inhibition suggests that whatever inhibitory mechanisms suppress alpha motoneurons under these conditions, they do not reach those gamma motoneurons that we have observed.

Discussion

The present experiments demonstrate that MG motoneurons with relatively low thresholds for reflex activation (i.e., during stretch and/or tonic vibration reflexes) can, under certain conditions, be inhibited by a system of cutaneous afferents at the same time that higher threshold (i.e., unresponsive to stretch or vibration) MG motoneurons are powerfully excited. This result, taken together with previous evidence, suggests that fast and slow twitch motor units in the cat MG pool are subject to differential control under some conditions.

From the most general point of view, the existence of differential control of groups of motor units within a given pool indicates clearly that the factors controlling excitability differences among motoneurons within the pool cannot be entirely intrinsic to the neurons themselves (e.g., cell size, membrane resistance, absolute voltage threshold, etc., or any combination of such intrinsic neuronal properties). Rather, as has been discussed elsewhere (Burke, 1973), the organization of the synaptic inputs projecting to individual motoneurons within the pool must play a critical role in controlling excitability patterns under varying input conditions. The differential control observed in the present results suggests the existence of at least two different patterns of input organization. This conclusion in no way implies that motor unit recruitment is at times chaotic (cf. Henneman et al., 1974). Rather, it suggests that at least different activity patterns, each intrinsically orderly, may occur in a mixed population of motor units such as that making up the MG muscle in the cat.

In a previous study of MG motor unit firing patterns in decerebrate cats (Burke, 1968b), all of the slow twitch (type S) units encountered responded to MG stretch with sustained firing but only about 37% of the MG fast twitch units studied responded at all to MG stretch. It is probable that MG type S units are also readily activated by homonymous muscle vibration (e.g., Anastasijevic et al., 1968). Thus, it seems very likely that the low threshold, stretch and vibration responsive units in results such as in Figures 3–7 were type S units, particularly unit A in Figures 4–7, with its slow axonal conduction velocity (Table 1). On the other hand, the higher threshold units that were unresponsive to stretch or vibration were very likely fast twitch units. Because of the necessarily limited

unit samples in these experiments and the lack of direct motor unit type identification, it is not possible to conclude that the MG motor unit groups subject to differential control are strictly equivalent to the fast and slow twitch groups identified directly (Burke, 1968b). However, the similarity in firing behavior of the low threshold MG units and that in the whole Sol unit population is consistent with this conclusion. Comparison of reflex behaviors between different muscles requires cautious interpretation, but MG type S units and Sol units are qualitatively similar in the organization of the relevant synaptic systems (group Ia monosynaptic excitation, see Burke, 1968a; and the lack of strong polysynaptic excitation from sural nerve afferents, see Burke et al., 1970, 1973b). Thus, we assume that sural nerve input under the present conditions can, at certain periods during the response, produce differential excitation of fast twitch and inhibition of slow twitch MG motor units.

There is abundant evidence, dating from now classical studies of Denny-Brown (1929), that recruitment of motoneurons in reflexes studied in experimental animals, and in voluntary muscle activation in human subjects, is usually an orderly and more or less stereotyped process. Activation of a motor unit pool in such cases begins with the most excitable motoneurons that innervate relatively small tension, slow twitch muscle units (Burke, 1968b; Henneman and Olson, 1965; Milner-Brown et al., 1973). The process continues, with increasing excitatory drive, to involve motoneurons with progressively higher thresholds of activation that are very likely correlated with the properties of the innervated muscle units, such that the highest threshold cells (the last to be activated) innervate large tension, fast twitch, easily fatigued muscle units. This pattern of activation has a number of functional advantages, particularly in relation to muscle unit fatigue resistance, and these are discussed elsewhere (see e.g., Burke and Edgerton, 1975; Burke et al., 1973b, 1976; Henneman and Olson, 1965). It is highly likely that this recruitment sequence occurs in most mammalian movements (see Burke and Edgerton, 1975) and it will be referred to here as the "usual" sequence.

Henneman and coworkers have reported that the order of recruitment of ankle extensor motoneurons is precisely fixed in a variety of reflexes (Clamann and Henneman, 1976; Henneman et al., 1965, 1974), and that de-recruitment occurs in exactly the reverse order (Clamann et al., 1965). With increasing excitatory input, a unit begins to fire when its input reaches a "critical firing level" and it ceases to fire when the synaptic drive falls below this level because of either decreasing excitation or increasing inhibition (cf. Rall and Hunt, 1956). This process results in sets of spike sequences such as shown in the upper portion of Figure 8, where the units A through D are ordered according to increasing relative thresholds. Such spike sequences can be produced if *all the active* synaptic systems are weighted (i.e., vary in synaptic efficacy) in accord with the width of the shaded arrows in the diagram in Figure 8. A discussion of the complex interplay between the presynaptic and the intrinsic motoneuronal factors that control synaptic efficacy is beyond the scope of this report, but the density and spatial distribution of synaptic terminals from a given functional system on the motoneuron membrane appear to be key variables (see e.g., Burke, 1973).

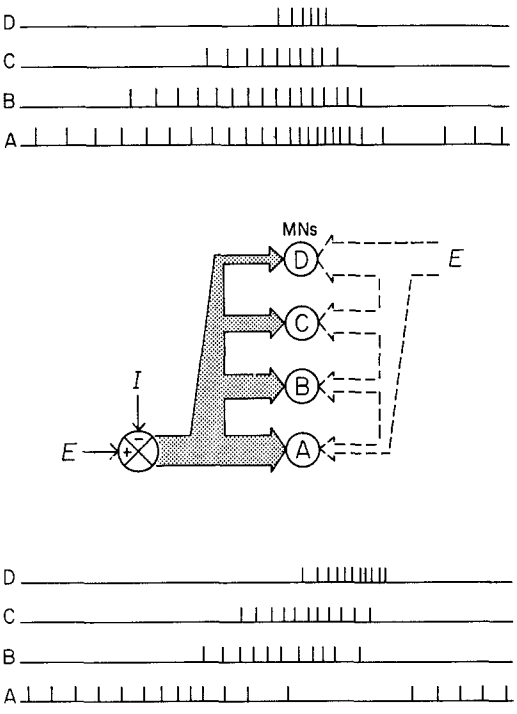

Fig. 8. Diagram of model formulation to explain the present results. See text for discussion and explanation

In the cat MG motor unit pool, synaptic efficacies of at least two defined systems, one excitatory (monosynaptic excitation from homonymous group Ia afferents) and one inhibitory (disynaptic inhibition from antagonist group Ia afferents) are ordered in the above way in relation to motor unit type (Burke et al., 1976). Cell A in Figure 8 would represent type S motor units and B through D would denote, respectively, the identifiable categories of fast twitch units (type FR, type F(int), type FF). It is significant that the ordering of group Ia synaptic efficacy is directly correlated with relative fatigue resistant in the innervated muscle units (Burke et al., 1973a, 1976).

The "usual" recruitment order is also correlated with the amplitude of the extracellular motor axon spike (Henneman et al., 1965, 1974), from which conduction velocity and axonal diameter can be estimated (Clamann and Henneman, 1976). By inference, the order of motoneuron recruitment is assumed to be closely correlated with anatomical motoneuron size, although the relation between axonal conduction velocity and total cell membrane area in motoneurons is not very precise (see Barrett and Crill, 1974). The "usual" recruitment process has therefore sometimes been referred to as a "size principle". This term is a convenient shorthand designation for the interrelated physiological, histochemical and morphological characteristics of motor units. It is, however, potentially misleading because motoneuron size per se is almost certainly not a critical factor in determining either relative excitability or synaptic efficacy (Burke, 1973; Zucker, 1973). The term "size principle" is perhaps a useful description of, but certainly not an explanation for, the usual recruitment process.

If all of the synaptic systems projecting to the alpha motoneurons of a particular motor pool were weighted as denoted by the shaded arrows in Figure 8, the cells would be recruited invariably in the same sequence and de-recruited

in exactly the reverse sequence (upper set of spike trains), irrespective of the source of input drive. Consequently, whenever a given motor unit in the population is active, all of the units receiving greater synaptic weights (therefore exhibiting lower reflex thresholds) would necessarily also be active. Henneman and colleagues (1974) have referred to this as a "law of combination". However, the present results include spike sequences like those in the lower set in Figure 8 (see Figs. 5, 6 and 7). In these, there are periods when marked activation of high threshold motoneurons coexists with slowing or even cessation of discharge in the lowest threshold units. This result requires the existence of at least one pattern of input organization different from that denoted by the shaded arrows in Figure 8.

Several possible other patterns of synaptic input organization could produce the present observations. For example, if recurrent inhibition via the Renshaw cell loop were activated primarily by the higher threshold motoneurons and affected the lower threshold cells most strongly, a differential inhibition of low threshold units might result. Such an organization for the Renshaw loop has in fact been proposed (Ryall et al., 1972) and may play some part in the present results. However, if recurrent inhibition were alone responsible for such inhibitory effects as in Figures 5–7, it should operate irrespective of input source and the firing pattern shown in the lower part of Figure 8 should be the rule rather than the exception. The fact that differential control is unusual and hard to demonstrate, and the apparent specificity of sural nerve input in producing it, when taken together with other observations on sural afferent PSPs in MG motoneurons, all lead us to postulate that an excitatory input system organized as shown by the dashed arrows in Figure 8 is predominately responsible for the present results.

Electrical stimulation of the sural nerve in anesthetized cats elicits polysynaptic potentials in ankle extensor motoneurons that differ in relation to motor unit type. The sural PSPs in most of the MG motoneurons that innervate fast twitch muscle units are dominated by early excitatory components that are much less apparent, and sometimes entirely absent, in the sural PSPs recorded in motoneurons that innervate slow twitch (type S) units in both MG and Sol (Burke et al., 1970, 1973b). Sural PSPs in type S units are predominately inhibitory. The intracellular records of sural PSPs shown in Figure 9 were obtained in an unanesthetized decerebrate cat and are qualitatively similar to sural PSPs found in anesthetized animals. Such results indicate that a system of interneurons organized to produce excitatory input more or less in the pattern shown by the dashed arrows in Figure 8 is in fact available in the decerebrate cat.

We suggest that motor unit firing such as shown in Figures 3 through 7 and in the lower spike sequences in Figure 8 can be produced by the *combined action* of synaptic input systems organized as indicated by *both* sets of arrows in Figure 8. MG stretch and vibration generate input from primary (group Ia) muscle spindle afferents that excite MG motoneurons belonging to the various motor unit types with efficacy weighted very much as indicated by the shaded arrows (type S > type FR > type F(int) > type FF; Burke et al., 1973b, 1976). The polysynaptic inhibition produced by sural nerve afferents is also distributed to

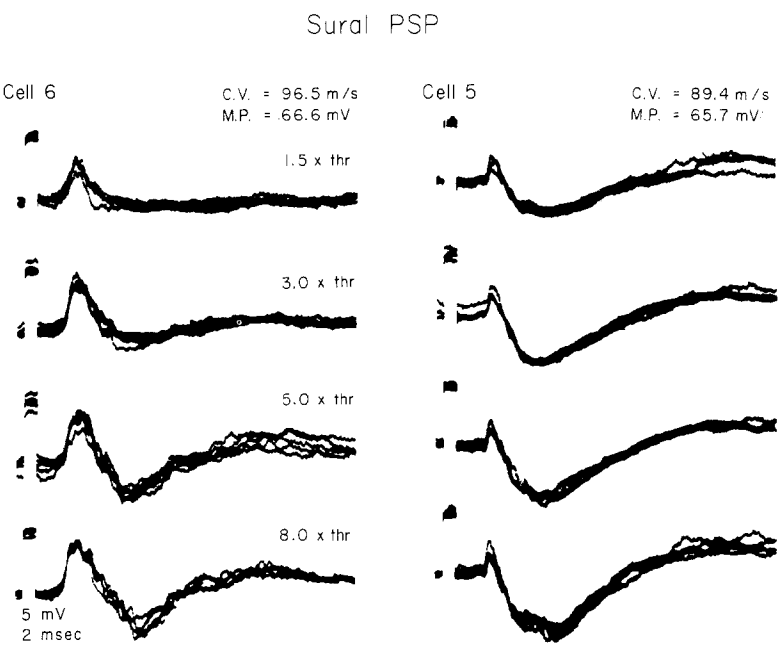

Fig. 9. Intracellular records of polysynaptic PSPs produced in two different MG alpha motoneurons by single shock stimulation of the cut ipsilateral sural nerve at various multiples of threshold strength. Decerebrate, unanesthetized cat (Variation No. 1 in Methods). Recording conditions were identical but the sural PSP patterns differed in the two cells. The PSPs in cell 6 (left set) were dominated by early excitatory components which were relatively small in cell 5, where the PSPs were predominately inhibitory. Resting membrane potentials were almost identical so that these responses can be compared with some assurance. Motor unit types were not identified for technical reasons but cell 5 had a slower axonal conduction velocity than cell 6

MG motoneurons roughly as indicated by the shaded arrows, although the available data suggest that the distribution pattern among fast twitch units is non-specific (i.e., type S > type FR = type F(int) = type FF; Burke et al., 1970, 1973b). The polysynaptic sural excitatory input is, however, distributed more or less according to the "reverse" pattern indicated by the dashed arrows (i.e., type FF = type F(int) = type FR > type S; Burke et al., 1970, 1973b). By combining the effects of all three of these input systems, superimposing sural afferent input (both excitatory and inhibitory) upon the excitation generated by stretch or vibration (e.g., Fig. 5), the observed patterns of MG motoneuron firing can be explained. The presence of the "reverse" input organization can generate combinations of active motor units that differ from those produced by the "usual" (i.e., shaded) input organization, depending on the balance of effects from these competing inputs in individual motoneurons within the MG pool.

Whether this or similarly organized input systems account for reported deviations from the "usual" recruitment pattern in human subjects (e.g., Grimby and Hannerz, 1968, 1974, 1976) or in animal studies (e.g., Kernell and Sjöholm, 1975; Wyman et al., 1974) is unclear. Nevertheless, such deviations

can be used, as in the present work, as clues for further investigation of the organization of synaptic input to defined groups of motoneurons.

It is impossible to say at present whether differential control of fast and slow motor units within a mixed population is functionally useful but it is intriguing that sural nerve afferents, carrying information from the skin of the ankle and lateral foot, are particularly effective in producing it. Hagbarth (1952) found that sural afferents of both large and small diameter produced overall excitation of ankle extensor motoneurons. The argument for a significant functional role for this system would be strengthened if it could be demonstrated that interneurons in the pathway are controlled by descending supraspinal axons (e.g., the rubrospinal tract; see Burke et al., 1970) as well as by restricted sets of cutaneous afferents.

It may be that the "reverse" excitatory system acting alone can activate preferentially some of the otherwise high threshold motoneurons that innervate fast twitch, large force muscle units. Such preferential control might be exerted during ballistic movements or actions requiring rapid alternation of agonists and antagonists, when motoneuron control by the usual segmental reflex organization could perhaps be disadvantageous. A second possibility is that the "reverse" excitatory system may be used to supplement the "usual" (e.g., group Ia excitatory) input organization in order to produce the rapid and synchronous activation of the entire motor unit pool that occurs in quick, forceful movements such as galloping or jumping. The functional dynamic range of large limb muscles such as the cat MG is so wide (e.g., Burke et al., 1976) that differential control of fast twitch motor units, operating either alone or in combination with the usual segmental reflex systems, may be required to cover it.

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Received January 26, 1977
Accepted February 28, 1977