Autogenetic inhibition of motoneurons by impulses in group Ia muscle spindle afferents

Article *in* The Journal of Physiology · August 1979

DOI: 10.1113/jphysiol.1979.sp012884 · Source: PubMed

J. Physiol. (1979), **293**, *pp.* 173–195
With 10 *text-figures*
Printed in Great Britain

AUTOGENETIC INHIBITION OF MOTONEURONES BY IMPULSES IN GROUP Ia MUSCLE SPINDLE AFFERENTS

BY EBERHARD E. FETZ*, ELŻBIETA JANKOWSKA, TOMAS JOHANNISSON AND JANUSZ LIPSKI†

From the Department of Physiology, University of Göteborg, Göteborg, Sweden

(*Received 25 September 1978*)

SUMMARY

1. Inhibitory post-synaptic potentials evoked by adequate stimulation of group Ia muscle spindle afferents of homonymous and synergistic muscles and by selective electrical stimulation of tendon organ afferents were analysed in motoneurones of triceps surae and plantaris.

2. Selective activation of Ia afferents was verified to occur with brief stretches of triceps surae and plantaris 35 μm or less in amplitude with an initial muscle tension of 5 N; stretches of 30–35 μm were estimated to activate 80–90 % of Ia afferents in these muscles. Under the same conditions the lowest thresholds for group Ib tendon organ afferents were about 40 μm.

3. Stretches $\leqslant 30$ μm evoked i.p.s.p.s in 80 % of triceps surae and plantaris motoneurones; lowest thresholds for evoking i.p.s.p.s were 10 μm or less. However, such low thresholds for stretch-evoked i.p.s.p.s, lower than the thresholds for activation of Ib afferents, were found mainly in spinalized, unanaesthetized (after decerebration) or lightly anaesthetized animals. The latencies of these i.p.s.p.s indicated disynaptic and trisynaptic coupling between Ia afferents and motoneurones. The i.p.s.p.s were evoked (i) from the homonymous and synergistic muscles stretched together, (ii) from the homonymous muscles alone and (iii) from the synergistic muscles alone.

4. Control experiments showed that i.p.s.p.s could be evoked by stretches subthreshold for discharging motoneurones, thus showing that those i.p.s.p.s were not mediated by Renshaw cells. The stretch-evoked i.p.s.p.s disappeared after sectioning the nerves from the corresponding muscles, further excluding their mediation by afferents other than group Ia afferents from the stretched muscle.

5. In order to selectively activate tendon organ afferents, thresholds for excitation of Ia afferents by electrical stimuli were increased to a level above the threshold for Ib afferents by prolonged muscle vibration (Coppin, Jack & MacLennan, 1970). I.p.s.p.s evoked by stimuli near threshold for Ib afferents appeared with latencies

* Present address: Department of Physiology and Biophysics, University of Washington School of Medicine, Seattle, Washington 98195, U.S.A. Supported by a Josiah Macy Faculty Scholar Award.

† Present address: Department of Physiology, Medical Faculty, 00–927 Warsaw 64, Poland. IBRO/UNESCO Fellow.

0022-3751/79/4260-0749 $01.50

indicating disynaptic coupling. Later (trisynaptic) components of Ib i.p.s.p.s required somewhat stronger stimuli.

6. Amplitudes of Ia i.p.s.p.s evoked by muscle stretches activating about 80 % of muscle spindle afferents were compared with amplitudes of Ib i.p.s.p.s due to less than 50 % of tendon organ afferents of the same muscles. The Ia i.p.s.p.s were much smaller (16–36 %) than the Ib i.p.s.p.s. The amplitudes of such Ia and Ib i.p.s.p.s constituted about 10 and 25–66 %, respectively, of the maximal i.p.s.p.s evoked by electrical stimulation of all group I afferents.

7. We conclude that inhibition of motoneurones may be evoked from Ia muscle spindle afferents from homonymous and synergistic muscles as well as from Ib tendon organ afferents. In view of much stronger inhibitory effects of Ib afferents alone, the Ia inhibition may operate primarily to support inhibition evoked from tendon organs and in conjunction with the latter.

INTRODUCTION

Previous studies of synaptic actions of group I muscle afferents revealed that both the group Ia muscle spindle afferents and the group Ib tendon organ afferents evoke inhibition of spinal motoneurones. However, the motoneurones inhibited by these two groups of afferents appeared to have different functional relations with the muscles of their origin. Impulses in Ia afferents from a given muscle were found to inhibit motoneurones of antagonistic muscles operating at the same joint (the Ia reciprocal inhibition between flexors and extensors; Lloyd, 1946; Eccles, Eccles & Lundberg, 1957*a*; Eccles & Lundberg, 1958), and only impulses in Ib afferents were thought to be responsible for inhibition of motoneurones of homonymous and synergistic muscles (the autogenetic inhibition; Laporte & Lloyd, 1952; Granit, 1950; Hunt, 1952; Eccles *et al.* 1957*a*; Eccles, Eccles & Lundberg, 1957*c*; see also Haase, Cleveland & Ross, 1975).

Using adequate stimulation of muscle spindle afferents, different selection of motoneurone species and more sensitive detection techniques we have found that both Ia and Ib afferents contribute to the autogenetic inhibition. The present paper describes evidence for inhibitory post-synaptic actions of impulses in group Ia muscle spindle afferents from homonymous and synergistic muscles on motoneurones of ankle extensors and compares them with inhibition evoked by selective activation of Ib afferents as described by Coppin *et al.* (1970). The papers to follow (J. Czarkowska, E. Jankowska & E. Sybirska, in preparation; E. Jankowska, T. Johannisson & J. Lipski, in preparation) will show that the Ia and Ib autogenetic inhibition may be mediated by the same interneurones. Some of the preliminary results were briefly reported (Fetz, Jankowska, Johannisson & Lipski, 1978).

METHODS

Preparation. The experiments were performed on twenty-five cats. In all animals the preliminary surgical preparation, including tracheal, venous and arterial cannulations, dissection of peripheral nerves and muscles, and laminectomy was done under ether anaesthesia. Seventeen cats were subsequently anaesthetized with chloralose (40–50 mg/kg I.V. initial dose, supplemented once or twice with 10 mg/kg) or with both chloralose (40–60 mg/kg) and sodium pentobarbitone (Nembutal, Abbot, 10–20 mg/kg, supplemented with 1–2 mg/kg.hr). Three cats were anaemically decerebrated (Pollock & Davis, 1930) and five cats anaemically decorticated as described by Andén, Jukes, Lundberg & Vyklický (1966), 2–3 h before terminating ether anaesthesia; in these cats small amounts of chloralose were also subsequently administered. In the main series of experiments all the cats were spinalized at Th13-L1 level to remove any supraspinal inhibitory control of interneuronal transmission (Holmqvist & Lundberg, 1961).

The animals were paralysed with gallamine triethiodide (Flaxedil, Rhodia) and artificial ventilation was adjusted to keep the end-tidal PCO_2 close to 4 %. The mean arterial blood pressure was continuously monitored and its decrease below 90 mmHg during later stages of the experiments was counteracted by slow infusion of Dextran and/or norepinephrine. The temperature of the animals (oesophagal) and of paraffin pools over the exposed spinal cord and the dissected nerves was maintained between 37 and 38 °C by a servo-controlled heating lamp.

Recording. The main results to be presented were obtained while recording intracellularly from motoneurones in L7 and S1 spinal segments. Micropipettes filled with 3 M-KCl or 2 M-K citrate solution, with tips broken to 1·5–2·0 μm and resistance of 1·5–4·0 MΩ were used. The postsynaptic potentials were photographed from the oscilloscope; records included both superimposed single responses and averages of sixty-four to 256 responses compiled by a Hewlett-Packard (type 8480A) averager.

Selective stimulation of Ia afferents. Adequate stimulation of Ia muscle spindle afferents by brief stretches of muscles was used in the main part of the experiments. Four ankle extensors (medial and lateral gastrocnemius, soleus and plantaris muscles) were usually simultaneously stretched to activate a maximal total number of Ia afferents and thus to optimally excite those interneurones which mediate the group Ia i.p.s.p.s to motoneurones. In two experiments medial gastrocnemius and plantaris were dissected free from each other and from lateral gastrocnemius and soleus and each stretched separately.

After rigid fixation of the left hind limb, the muscles were stretched longitudinally by an electromagnetic puller attached through a stainless-steel wire to the peripherally cut tendons of triceps surae and plantaris; the position of the puller could be changed to adjust the initial length of the muscles. The displacement of the tendons was measured by an optical bridge circuit. Since the system had some compliance (0·01 mm/N) and there was a linear relationship between the force and the displacement, this circuit also measured the longitudinal tension exerted on the puller by the stretched muscles. The initial tension of 5 N corresponded to an increase in the length of the muscles of 8–12 mm, depending on the size of the animals. The stretch used as a phasic stimulus resembled a triangular wave form with a duration of 3–5 msec and the amplitude up to 70 μm (at 5 N); slightly larger stretch amplitudes could be produced at lower initial tensions. The stretched muscles were dissected free over approximately the distal half of their length, taking particular care not to compromise their blood supply. The nerves to medial gastrocnemius, lateral gastrocnemius and soleus and plantaris were dissected free in continuity to allow the electrical as well as adequate stimulation of muscle afferents.

Since the effect of a stretch of a muscle on muscle spindles and Golgi tendon organs may depend on numerous experimental variables (e.g. number of simultaneously stretched muscles, initial tension used, the limb fixation etc., cf. Brown, Engberg & Matthews, 1967; Matthews, 1972), we first investigated the optimal stimulus parameters for activating each type of receptor under our experimental conditions. In three non-paralysed cats, the activity of ninety-seven single afferent fibres from triceps surae and plantaris was analysed while recording from split filaments of dorsal roots, or intra-axonally. Muscle spindle primary endings (Ia afferents) were identified by a conduction velocity $\geqslant$ 75 m/sec, and a pause in their discharge during muscle contractions evoked by electrical stimulation of its nerve; muscle spindle secondary endings (group II afferents) by conduction velocity $\leqslant$ 70 m/sec and a similar pause during muscle contractions; tendon organ afferents (group Ib afferents) by conduction velocity $\geqslant$ 75 m/sec and increase in

firing rate during muscle contraction. Fig. 1A shows changes in thresholds of Ia and Ib afferents as a function of the initial muscle tension. The percentages of the afferents excited by stretches of different amplitude for five different initial tensions are given in Fig. 1*B*. In contrast to results obtained with single muscles (cf. Brown *et al.* 1967; Stuart, Moscher, Gerlach & Reinking, 1970) we found that when all four muscles were stretched, the lowest thresholds for Ia afferents were attained only when the initial tension was greater than 4 N. At the initial tension of 5 N, which was routinely used in the main series of the experiments, the majority of Ia afferents (75 %, $n = 51$) had thresholds below 10 μm and stretches 30–35 μm activated about 90 % of these fibres (Fig. 1*B*); only single spike discharges were observed. None of thirty-nine Ib fibres were activated by stretches 40 μm or less at 5N but 44 % responded to 45–60 μm stretches, i.e. with thresholds similar to those reported by Stuart *et al.* (1970) and Ellaway & Trott (1978). It is worth noting that an increase of muscle tension from 3 to 5 N did not markedly decrease the thresholds for Ib afferents (Fig. 1*A*, *B*) but did allow activation of a much higher proportion of Ia afferents with stretches subthreshold for Ib afferents.

In addition to group Ia afferents, stretches of about 30 μm excited two of ten group II afferents. Impulses in these afferents arrived at the dorsal root entry zone 6 and 9 msec after the stimulus, respectively, later than impulses in Ia afferents ($4{\cdot}7 \pm 0{\cdot}9$ msec, S.D.) or Ib afferents ($5{\cdot}1 \pm 0{\cdot}6$ msec, S.D.) (cf. Stuart *et al.* 1970). Thus if any disynaptic i.p.s.p.s were evoked from group II afferents they should not be confused with the disynaptic group I i.p.s.p.s, although possible contribution of group II afferents to the trisynaptic or later i.p.s.p.s could not be excluded.

The effectiveness of small muscle stretches in activating Ia afferents was also tested in a series of experiments in which monosynaptic e.p.s.p.s evoked by stretches of increasing magnitude were compared with e.p.s.p.s evoked by electrical stimulation of the nerves. According to Mendell & Henneman (1971) and Scott & Mendell (1976), nearly all or a great majority of group I spindle afferents from a homonymous muscle converge onto each motoneurone. The size of the e.p.s.p should thus be a reasonably good measure of the proportion of the activated spindles. This comparison was made for medial gastrocnemius and plantaris motoneurones, for e.p.s.p.s evoked by stretches of their homonymous muscles (other muscles were dissected free and left slack) and by electrical stimulation of the corresponding nerve maximal for all group I afferents. The e.p.s.p.s to be compared were recorded in rapid succession with the same level of membrane polarization. The areas under the e.p.s.p.s evoked by stretches were expressed as a per cent of the areas of the electrically evoked e.p.s.p.s. As shown in Fig. 1*G*, e.p.s.p.s evoked by stretches within the range of 30–35 μm reached $79{\cdot}2\ \% \pm 19{\cdot}9$ S.D. of their reference e.p.s.p.s. This confirms that the effectiveness of the activation of Ia afferents by stretches just below Ib threshold was quite high, although this estimate appeared to be lower than the estimate based on records from single group Ia afferents.

Taking into account that not all the Ia afferents terminate on individual motoneurones, that there are considerable differences between amplitudes of the unitary e.p.s.p.s, and that the electrically evoked e.p.s.p.s might be more likely to include group II monosynaptic e.p.s.p.s (Kirkwood & Sears, 1975; Taylor, Watt, Stauffer, Reinking & Stuart 1976) and group I i.p.s.p.s than the stretch-evoked e.p.s.p.s, the latter e.p.s.p.s were further analysed as illustrated in Fig. 1C–F. In these measurements both the amplitudes and the areas of e.p.s.p.s evoked by maximal stretches were taken as 100 % and those evoked by smaller stretches were compared with them. In this comparison the e.p.s.p.s evoked by 30–35 μm stretches were also about 80 % of the maximal ones, both for the amplitude (*C*, *D*) and area (*E*, *F*) measurements. Similar relations between amplitudes of muscle stretches and the resulting e.p.s.p.s were found for those evoked from single muscles (Fig. 1*D*, *F*) and from all four muscles pulled together (Fig. 1*C*, *E*).

In order to restrict the effect of stretches of triceps surae and plantaris to afferents of these muscles, other muscles of the leg and of the thigh, the skin and the joints were denervated by cutting the following nerves: femoral, gracilis, adductor femoris and longus, cutaneous femoris lateralis, hamstring, sural, common peroneal and all branches of the tibial except those to triceps surae and plantaris.

Selective stimulation of Ib afferents. The tendon organ afferents were stimulated electrically using method of Coppin *et al.* (1970). Thresholds of Ia afferents from triceps surae to electrical stimuli were increased above thresholds for Ib afferents by prolonged (30–60 min) vibration applied to Achilles tendon (200–250 Hz, amplitude about 50–70 μm). After such

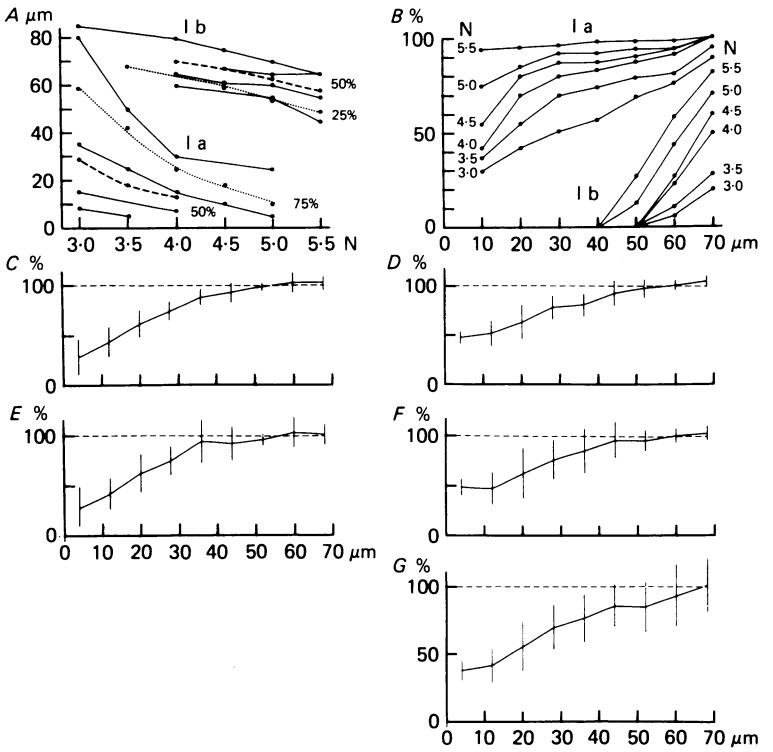

Fig. 1. Effectiveness of different amplitudes of stretches of triceps surae and plantaris in activating Ia and Ib afferents. *A*, thresholds for activating single Ia and Ib afferents as a function of initial muscle tension. Representative data for four Ia and three Ib fibres are plotted with continuous lines; the median (50 %) and quartile (25 and 75 %) values for all tested fibres (fifty-one Ia and thirty-nine Ib) are given by dashed and dotted lines, respectively. *B*, percentage of Ia and Ib afferents excited by stretches of different amplitudes at different initial muscle tensions. *C–G*, size of monosynaptic e.p.s.p.s recorded in motoneurones, as a measure of activation of Ia afferents by stretches of different amplitudes. *C*, *E*, data for twelve motoneurones of triceps surae with e.p.s.p.s evoked by stretches of triceps surae and plantaris at the initial tension of 5 N, with the nerve to plantaris muscle cut. *D*, *F*, *G*, data for twenty motoneurones (thirteen of plantaris and seven of medial gastrocnemius) with e.p.s.p.s evoked by stretches of their homonymous muscles only; initial tension at 3 N. Both the amplitudes (*C*, *D*) and areas (*E*, *F*) of e.p.s.p.s are expressed as a percentage of the mean values obtained for stretches of 50–70 μm, calculated for the whole sample. In *G* the e.p.s.p. areas are expressed as a percentage of the areas of e.p.s.p. evoked by electrical stimulation of the corresponding nerve with an intensity maximal for group I afferents. Most of the motoneurones were slightly hyperpolarized (5–15 nA) to prevent their firing by the largest stimuli. The measurements and calculations were done with Hewlett-Packard digitizer (type 9864A) and calculator (type 9830A).

vibration thresholds for evoking Ia e.p.s.p.s in triceps surae motoneurones increased to 1·2–1·4 their original level. The excitability of Ia afferents was monitored by recording from a triceps surae motoneurone with a microelectrode inserted in S1 or caudal L7. Such a motoneurone was penetrated before or during the vibration which was continued until no monosynaptic e.p.s.p.s were evoked in it by electrical stimuli up to about 1·3 times previous threshold. Leaving the electrode in this motoneurone, a plantaris motoneurone was penetrated with a second micro-

electrode. The latter was previously positioned in the plantaris motor nucleus in rostral L7 to allow impalement of a motoneurone within a few minutes after terminating vibration. If more than 15–20 min elapsed, muscle vibration was resumed for another 10–15 min before records from the selected motoneurone were taken and thresholds for Ia afferents were tested again in the same or another triceps surae motoneurone. The intensity of electrical stimuli used to evoke Ib i.p.s.p.s was just below threshold for Ia afferents. According to Coppin *et al.* (1970) such stimuli should activate not more than about half of Ib afferents.

RESULTS

The autogenetic inhibition of motoneurones *sensu stricto* would be that evoked by afferents from the same muscle which is innervated by those motoneurones; however, the term has also been applied to inhibition evoked from both the same muscle and its synergists. We are using the term 'autogenetic inhibition' in this broader sense in order to relate inhibition from Ia afferents to the inhibition from Ib afferents, usually referred to as the autogenetic (see Granit, 1950, 1955 and Haase, Cleveland & Ross, 1975). There are, however, good reasons to restrict this term to effects evoked from homonymous muscles (see Eccles *et al.* 1957*c* and the Discussion) and to use another term, e.g. 'synergistic inhibition', to denote synaptic actions from synergists.

As the evidence for inhibition of motoneurones by Ia afferents from homonymous and synergistic muscles it will be shown: (i) that i.p.s.p.s are evoked in motoneurones of ankle extensors, medial and lateral gastrocnemius, soleus and plantaris by brief stretches of these muscles, subthreshold for exciting tendon organ afferents, (ii) that such i.p.s.p.s may appear even when impulses in muscle spindle afferents do not fire any motoneurones, excluding their mediation via Renshaw cells, and (iii) that the stretches of triceps surae and plantaris are effective in evoking i.p.s.p.s only when the nerves from these muscles are intact, excluding their mediation by afferents other than group Ia afferents of the stretched muscles.

A. Inhibitory post-synaptic potentials evoked by brief muscle stretches of small amplitudes

Any i.p.s.p.s evoked in a motoneurone by stretches of its homonymous muscle and its close synergists would obviously be superimposed on and to a great extent masked by monosynaptic e.p.s.p.s. However, hyperpolarization of the motoneurone membrane and chloride injection may be used to reverse the i.p.s.p.s, making them more evident as humps just before or after the summit of the e.p.s.p.s (Eccles *et al.* 1957*c*). Conversely, depolarization of motoneurones may be used to increase the amplitude of the i.p.s.p.s, resulting in a faster decay of the e.p.s.p.s. We have therefore routinely injected chloride into the motoneurones under investigation and hyperpolarized them with currents of 20–70 nA, usually 30–40 nA. The records from the hyperpolarized motoneurones were then compared with the records taken after depolarization of their membrane potential, taking into account that some reversal of the i.p.s.p. could have resulted from diffusion of chloride from the electrode even prior to passing any hyperpolarizing current. The intensity of the depolarizing current depended on the state of the neurones; it was either below the threshold for their firing (5–20 nA) or above the level for inactivating the spike generation mechanism (50–80 nA).

As the onset of the i.p.s.p.s revealed in this way was taken the point of deviation

between post-synaptic potentials evoked in hyperpolarized and depolarized motoneurones. Changes in the time course of the e.p.s.p.s due to changes in membrane properties induced by polarization, which were most convincingly shown for unitary e.p.s.p.s (Edwards, Redman & Walmsley, 1976) were not taken into account in these comparisons because they could not be quantified without abolishing the i.p.s.p.s. The error in defining the onset of the i.p.s.p.s due to this factor was estimated to be ± 0·1–0·2 msec, as judged from a comparison of the latencies of the i.p.s.p.s after

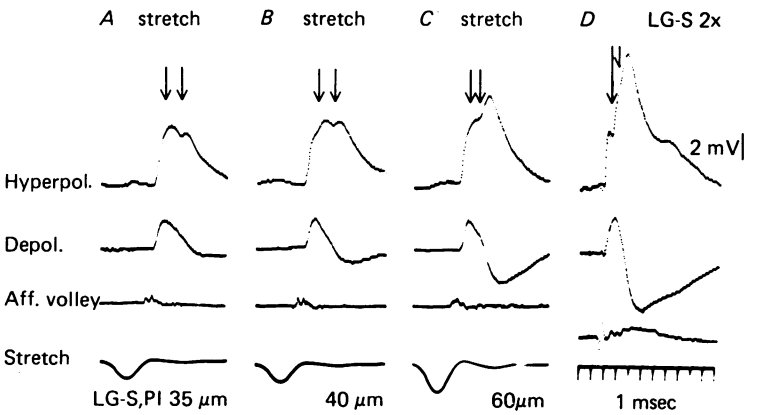

Fig. 2. Post-synaptic potentials evoked in a lateral gastrocnemius motoneurone by muscle stretches and by electrical stimuli. From top to bottom: averaged p.s.p.s recorded in the motoneurone during its hyperpolarization (50 nA) and depolarization (40 nA), averaged incoming afferent volleys recorded from the surface of the spinal cord near the dorsal root entry zone and changes in muscle length. Records in each column were taken simultaneously (except the p.s.p.s taken during membrane depolarization) but the output of the length transducer was displayed on another oscilloscope screen and combined to preserve the timing between changes in the muscle length and postsynaptic potentials. Averaged records were taken with a temporal resolution of 40 μsec per address. *A–C*, responses to increasing amplitudes of stretches of lateral gastrocnemius-soleus and plantaris muscles. *D*, responses to electrical stimulation of afferents of lateral gastrocnemius supramaximal for group I afferents. Arrows indicate onsets of two components of i.p.s.p.s. Note similar amplitudes of e.p.s.p.s recorded during depolarization and increasing amplitudes of i.p.s.p.s. The following abbreviations are used in this and the other figures: LG-S, lateral gastrocnemius-soleus; MG, medial gastrocnemius; Pl, plantaris; VRs, ventral roots.

different degrees of polarization. Since the presence or absence of the Ia i.p.s.p.s was the main point of interest, they were maximally enhanced by polarization of the neurones and their absolute amplitudes were analysed only in some special cases (see below).

The stretch-evoked i.p.s.p.s were analysed in three main experimental variants: (i) while recording from motoneurones of the triceps surae and plantaris muscles and stretching all the four muscles together (initial tension 5 N) with their nerves intact, (ii) while recording from plantaris and medial gastrocnemius motoneurones and stretching separately either the plantaris or medial gastrocnemius muscles (initial tension 3·0–3·5 N) and (iii) while recording from plantaris motoneurones and stretching all the four muscles together, but with plantaris nerve cut (initial tension 5 N). These variants allowed demonstration of i.p.s.p.s evoked by Ia afferents from

only homonymous muscles (ii), from only synergists (iii) and from both (i). It was expected that the first variant should provide the strongest excitation of the interposed interneurones, assuming convergence of afferents from several muscles onto them, and the most pronounced Ia i.p.s.p.s in motoneurones. The second variant was necessary to demonstrate the existence of Ia autogenetic inhibition *sensu stricto*, despite the expected weaker effects. The greatest advantage of the third variant was the possibility of recording i.p.s.p.s practically uncontaminated by simultaneously

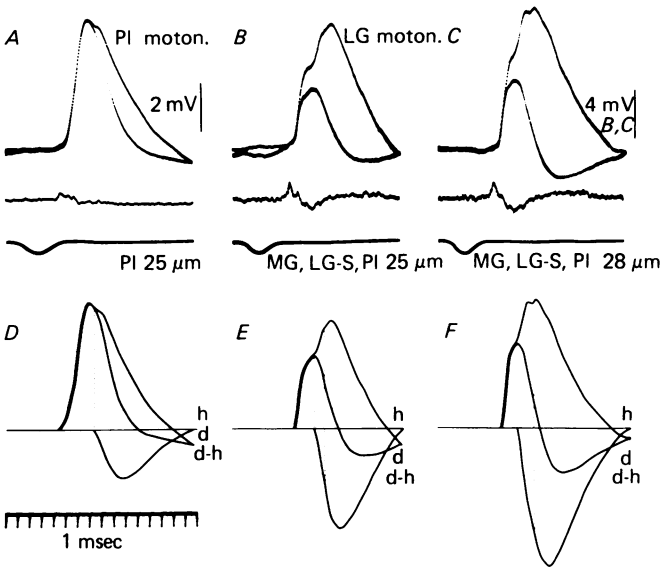

Fig. 3. Post-synaptic potentials evoked by stretches of only a homonymous muscle and by stretches of a homonymous and synergistic muscles. *A–C* from top to bottom: Superimposed records of averaged p.s.p.s recorded during hyperpolarization (40 nA) and depolarization (20 nA) of a plantaris (*A*) and of a lateral gastrocnemius (*B*, *C*) motoneurone, averaged records of afferent volleys and changes in muscle length. Same amplification for p.s.p.s recorded during hyperpolarization and depolarization. *D–F*, tracings of intracellular records in *A–C* (d, h) and their algebraic difference (d-h); the amplification for traces in *E*, *F* was adjusted to equalize the amplitudes of the monosynaptic e.p.s.p.s. The differences between each pair of records were calculated with Hewlett-Packard digitizer (type 9864A) and calculator (type 9830A) with resolution 110 μsec per address. Dashed lines indicate onset of the earlier and later components of the i.p.s.p.s.

evoked e.p.s.p.s; these will be referred to as 'pure i.p.s.p.s'. Within motoneurones of the four ankle extensors, Eccles, Eccles & Lundberg (1957*b*) found the ratio of heteronymous to homonymous e.p.s.p.s to be lowest in plantaris motoneurones and therefore mainly these motoneurones were used in the third variant.

Fig. 2 (top records) shows examples of reversed i.p.s.p.s following monosynaptic e.p.s.p.s in a lateral gastrocnemius motoneurone. These responses were evoked by simultaneous stretches of the lateral gastrocnemius, soleus and plantaris muscles (*A*, *B*, *C*) and by electrical stimulation of the nerve to the lateral gastrocnemius (*D*). Responses recorded during depolarization of the motoneurone, evoked by the same stimuli, are shown just below. A 35 μm stretch evoked an e.p.s.p. followed by small

but distinct i.p.s.p.s, which were seen also with 25 μm stretches. Larger stretches and electrical stimulation of the nerve evoked larger i.p.s.p.s, occurring at somewhat shorter latencies (arrows). Since stretches below 40 μm were subthreshold for Ib afferents (Fig. 1*A*) the i.p.s.p.s in *A* must be attributed to muscle spindle afferents alone, those in *B* to spindle afferents with a possible small contribution from Ib afferents and those in *C* and *D* to the combined actions of Ia and Ib afferents.

Fig. 3*A* shows that Ia i.p.s.p.s can be evoked also by stretches of single muscles, in this case a homonymous one. The records taken during hyperpolarization and depolarization of the motoneurone, labelled h and d, were superimposed to facilitate their direct comparison. The difference between these curves is shown as lowest trace

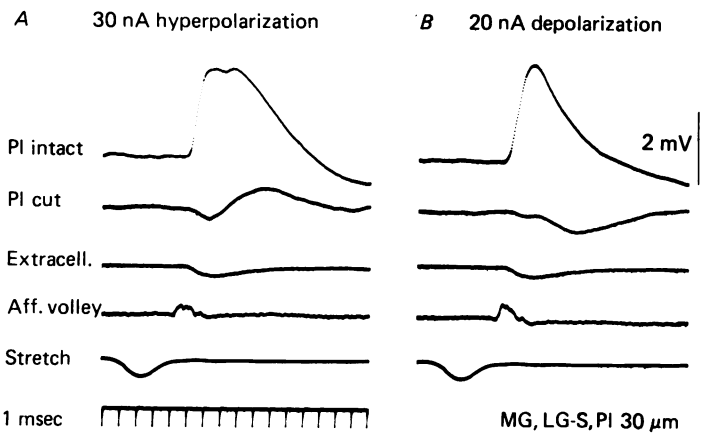

Fig. 4. Post-synaptic potentials evoked by stretches of a homonymous and synergistic muscles and of only synergistic muscles. Two upper traces: intracellular records from a plantaris motoneurone just before and after cutting the nerve to plantaris; note disappearance of monosynaptic e.p.s.p.s and appearance of Ia i.p.s.p.s in a 'pure' form. Other records as indicated. *A* and *B*, during hyperpolarization and during depolarization of the motoneurone, respectively.

in D. The time course of this i.p.s.p. was similar to the time course of the i.p.s.p. evoked by a weaker stretch of all four muscles (Fig. 3*B*, *E*); only a stronger stretch evoked the second component of the i.p.s.p.s (Fig. 3*C*, *F*) in the latter motoneurone.

Fig. 4 illustrates responses evoked in a plantaris motoneurone by stretches of triceps surae and plantaris before and after sectioning the plantaris nerve. With the nerves to all four muscles intact the i.p.s.p.s followed the e.p.s.p.s (uppermost traces) as in Figs. 2 and 3. Cutting the plantaris nerve abolished the homonymous e.p.s.p.s and allowed pure i.p.s.p.s to be evoked from Ia afferents from synergists; these appeared in a depolarizing (*A*) or a hyperpolarizing (*B*) direction depending on the membrane potential.

Latencies. The earliest stretch-evoked Ia i.p.s.p.s appeared with latencies of 0·9–1·0 msec after the onset of the monosynaptic e.p.s.p.s and 1·2–1·4 msec after the arrival of the afferent volleys to the spinal cord. The later components of these i.p.s.p.s had latencies up to 4·0–4·2 msec. The distribution of the latencies of all the distinct components of i.p.s.p.s evoked by stretches $\leqslant$ 30 μm is shown in Fig. 5*C*. The latencies distributed fairly uniformly within the range between 1·2 and 3·7 msec, with

only a hint of possible subgroups below and above 2·6 msec. Comparing the latencies of Ia i.p.s.p.s evoked in motoneurones and of stretch-evoked Ia e.p.s.p.s in interneurones (Fig. 5*A*) shows a difference of 0·8–1·0 msec between their shortest values. A similar difference was found between stretch-evoked Ia e.p.s.p.s and Ia i.p.s.p.s recorded in interneurones (Fig. 5*A* and *B*). Since most of the latter were positively

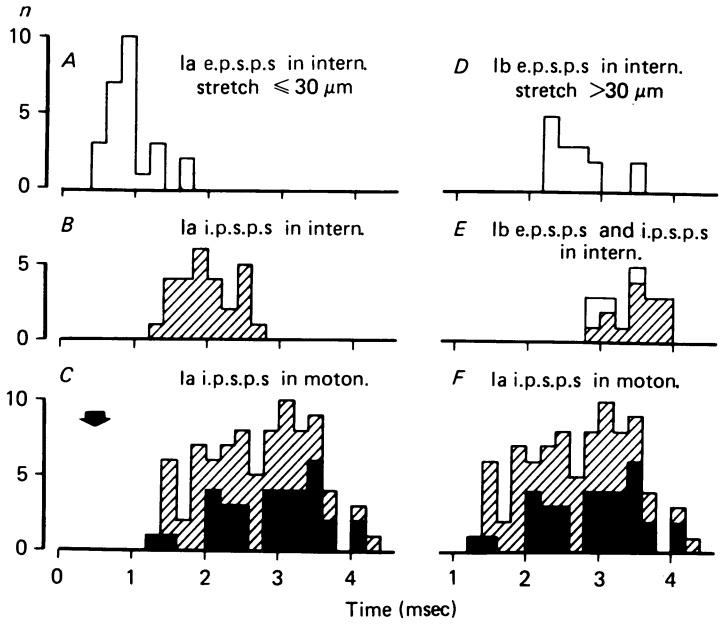

Fig. 5. Latencies of Ia i.p.s.p.s evoked by muscle stretches in the whole sample of motoneurones and latencies of post-synaptic potentials evoked in interneurones under comparable conditions. *C* and *F*, distribution of latencies of i.p.s.p.s evoked in motoneurones. ⊠, i.p.s.p.s preceded by e.p.s.p.s, evoked from homonymous and synergistic muscles in twelve plantaris, nine medial gastrocnemius and eight lateral gastrocnemius-soleus motoneurones. ■, pure i.p.s.p.s evoked in twenty-six plantaris motoneurones from triceps surae. Same histogram in *C* and *F*. *A* and *D*, distribution of latencies of monosynaptic e.p.s.p.s evoked by Ia and Ib afferents, respectively, in laminae V-VI interneurones. *B* and *E*, distribution of latencies of disynaptic i.p.s.p.s (⊠) and e.p.s.p.s (□) evoked by Ia and Ib afferents, respectively, in laminae V–VI interneurones. *A*, *B*, *D* and *E* data from E. Jankowska, T. Johannisson and J. Lipski in preparation for publication. Arrow in *C* indicates latencies of stretch-evoked monosynaptic e.p.s.p.s in motoneurones (0·54 ± 0·06 msec).

identified as disynaptic, we conclude that the i.p.s.p.s appearing with similar latencies in motoneurones would also be disynaptic. The longer latency i.p.s.p.s would probably be trisynaptic. Comparing the latencies of Ia i.p.s.p.s evoked in motoneurones by muscle stretches and by electrical stimulation of group I afferents (Fig. 6*A*, *B*) leads to the same conclusion. The electrically evoked i.p.s.p.s appeared with latencies 1·1–1·8 and 2·5–3·2 msec, similar to those of i.p.s.p.s classified as di- and trisynaptic (Fig. 6*C*) by Eccles *et al.* (1957*c*). The latencies of stretch- and electrically-evoked i.p.s.p.s were distributed over a similar range, although the values for the stretch evoked i.p.s.p.s tended to be slightly greater and were more evenly distributed.

A comparison between the latencies of Ia autogenetic i.p.s.p.s in motoneurones (Fig. 5*C*, *F*) and of monosynaptic Ib e.p.s.p.s in interneurones, both evoked by muscle stretch (Fig. 5*D*) shows that the shortest latencies of the latter were either longer or the same as the latencies of the former. Thus the Ib excited interneurones could not be responsible for the earliest i.p.s.p.s evoked in motoneurones by stretches $\leqslant 30\ \mu$m even if such stretches had activated Ib afferents. The latencies of Ib e.p.s.p.s evoked in interneurones by larger stretches and positively identified as disynaptic were also longer than the latencies of the disynaptic Ia i.p.s.p. in motoneurones.

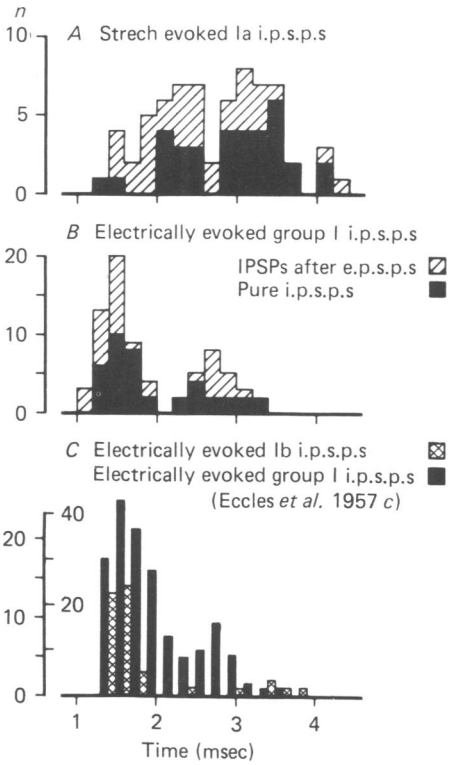

Fig. 6. Latencies of i.p.s.p.s evoked in motoneurones by muscle stretches and by electrical stimulation of Ia and Ib afferents. *A*, distribution of latencies of stretch-evoked i.p.s.p.s as in Fig. 5*C* for those motoneurones in which these i.p.s.p.s were compared with i.p.s.p.s evoked electrically. *B*, distribution of latencies of i.p.s.p.s evoked by electrical stimuli applied to medial gastrocnemius, lateral gastrocnemius-soleus or plantaris nerves, maximal or supramaximal for group I afferents. *C*, distribution of latencies of i.p.s.p.s evoked by electrical stimulation of group I afferents according to Eccles *et al.* (1957*c*; scale 0–40) and of i.p.s.p.s evoked by stimulation selective for Ib afferents after increasing threshold for Ia afferents by a prolonged vibration of the muscle.

Thresholds. Ia i.p.s.p.s evoked by muscle stretches $\leqslant 30\ \mu$m were found in 55 (80%) of sixty-nine motoneurones in which i.p.s.p.s were evoked by both muscle stretches and electrical stimulation of group I afferents. The sample included forty-seven plantaris, fourteen medial gastrocnemius and eight lateral gastrocnemius-soleus motoneurones recorded in spinalized animals. Whenever tested (in about half of the motoneurones, usually plantaris motoneurones with pure i.p.s.p.s evoked from

triceps surae) the i.p.s.p.s could also be evoked by stretches $\leqslant 20$ μm. The lowest thresholds for these i.p.s.p.s were about 10 μm (in six out of eleven motoneurones tested with a series of graded stretches (see Fig. 7)). Stretches $\leqslant 30$ μm evoked i.p.s.p.s in a greater proportion of motoneurones when three or four muscles were simultaneously stretched (in forty-four of fifty-two motoneurones, 85 %) than when only one (homonymous) muscle was stretched (in eleven of seventeen motoneurones, 65 %). Ia i.p.s.p.s evoked from only homonymous muscles were also much smaller.

The proportion of motoneurones with Ia i.p.s.p.s was somewhat higher (91 %) in preparations with less than 20 mg/kg of chloralose anaesthesia, or none, than under deeper anaesthesia (60 %). In contrast to observations in spinalized cats only two of fifteen motoneurones recorded in five non-spinalized preparations exhibited i.p.s.p.s evoked by 30 μm stretches.

B. Comparison of thresholds for evoking i.p.s.p.s and for activating motoneurones by muscle stretch

The results in Fig. 1 *C–G* show that 30–35 μm stretches evoked nearly maximal e.p.s.p.s in some motoneurones. We therefore considered the possibility that stretches in this range might fire some motoneurones and that the observed i.p.s.p.s might in part be mediated by Renshaw cells excited by these motoneurones. This might, however, be the case only for stretch-evoked trisynaptic i.p.s.p.s.

To check this possibility the thresholds for discharging motoneurones by muscle stretches were tested in eight experiments by recording from L7 and S1 ventral roots (whole roots, mounted on two pairs of electrodes, separately tested) and averaging responses to stretches of different amplitudes. Thresholds for monosynaptic reflexes were between 10 and 45 μm in six cats and above 50 μm in two cats. In two other cats no monosynaptic reflexes were evoked even by maximal electrical stimuli which were otherwise more effective than muscle stretches. With the exception of one cat with threshold for firing the motoneurones about 10 μm, the threshold amplitudes of stretches giving rise to the i.p.s.p.s were always less than threshold stretches for evoking ventral root discharges (Fig. 7); in addition the 30 μm stretches were below the threshold for activating motoneurones in five out of ten cats.

Control experiments confirmed that our ventral root recording was sufficiently sensitive to detect action potentials in one or a few axons. Single motoneurones were activated by intracellularly applied depolarizing current pulses while recording simultaneously from the ventral roots. Action potentials in the axons of all (nine) tested motoneurones were easily seen after averaging (Fig. 7*F*, *H*) and usually also in single sweep records (Fig. 7*E*, *G*). In all cases they were detected both when strong and weak intracellular pulses were used and when motoneurone discharges were well synchronized or temporally dispersed. Randomly penetrated motoneurones were used for these tests. As potentials in their axons in the ventral roots were very distinct, no attempt was made to compare responses of smaller and larger motoneurones. Similar tests made under even less favourable recording conditions (for single fibres in the intact lateral funiculus, cf. Jankowska, Padel & Tanaka, 1975) showed clear averaged responses also in the cases when they could not be seen in single sweep records.

To what extent Renshaw cells may have contributed to trisynaptic i.p.s.p.s evoked by muscle stretches suprathreshold for discharging motoneurones is difficult to evaluate. It is relevant to note in this regard that in several motoneurones the amplitude and time course of i.p.s.p.s evoked by stretches below and above the threshold for motoneuronal discharges were virtually identical and that stretches of 30 μm or less activated only a few motoneurones.

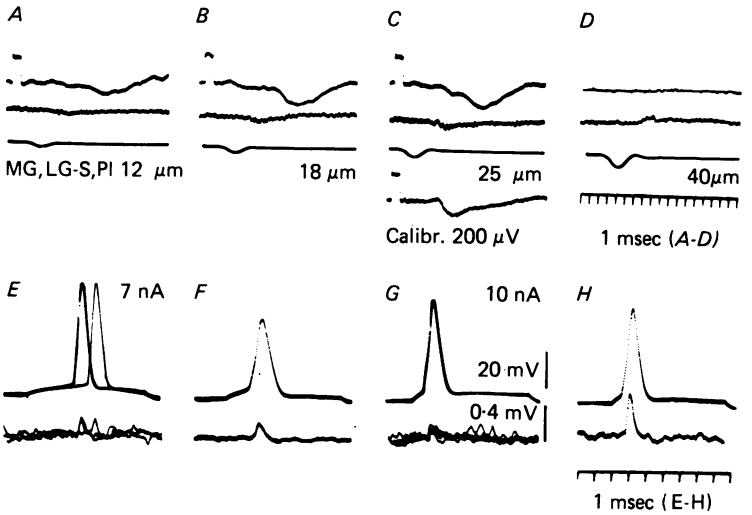

Fig. 7. Stretch-evoked i.p.s.p.s without concomitant discharges of motoneurones: 'pure' i.p.s.p.s evoked in a plantaris motoneurone by stretches of triceps surae and plantaris after cutting the plantaris nerve, recorded during depolarization of the motoneurone (50 nA). Lowermost trace in *C* shows extracellular field potential just outside the motoneurone, evoked by 40 μm stretches. Afferent volleys and changes in muscle length are in the remaining traces in *A–C* and in two lower traces in *D*. Upper trace in *D*, records from L7 ventral root during 40 μm stretches of the same muscles. *E–H*, simultaneous records from a motoneurone and from L7 ventral root during activation of the motoneurone by intracellularly applied depolarizing pulses of 7 nA (*E*, *F*) and 10 nA (*G*, *H*). *A–D*, *F* and *H*, averaged records; *E* and *G*, three superimposed single sweep records. Voltage calibrations in *G* are for intracellular and ventral root records in *E–H*, respectively.

C. Control experiments on the selectivity of effects of the applied muscle stretches

Although most of the muscles of the hind limb were denervated it remained possible that the observed effects could be due partially to mechanical transmission of vibration activating some other receptors with intact innervation. To test this the nerves to the stretched muscles were cut while recording from a motoneurone showing an i.p.s.p before the section was performed. In each of three such tests the stretch-evoked i.p.s.p.s were abolished by denervating the muscles. Fig. 8 illustrates this for i.p.s.p.s evoked in plantaris motoneurones by stretches of all four muscles; the nerve of plantaris muscle had been cut previously to provide a pure i.p.s.p. After sectioning the nerves of triceps surae even much larger stretches (60–70 μm) did not evoke any post-synaptic potentials in the motoneurone (Fig. 8*C*).

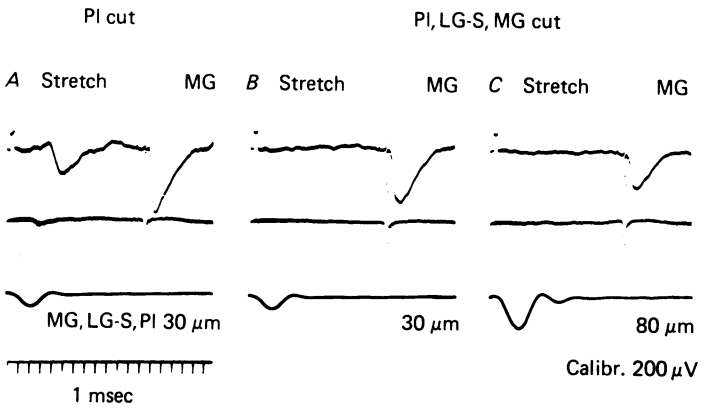

Fig. 8. Triceps surae origin of stretch-evoked i.p.s.p.s. Responses of a plantaris motoneurone, depolarized with 20 nA, to successively applied stretches of triceps surae and plantaris and to electrical stimulation of medial gastrocnemius nerve at 2 times threshold. Averaged records. *A*, with plantaris nerve cut and medial gastrocnemius and lateral gastrocnemius-soleus nerves intact. *B* and *C*, with all the three nerves cut distally to the stimulating electrodes; note disappearance of stretch-evoked i.p.s.p.s and continued presence of electrically evoked i.p.s.p.

D. Comparison between Ia and Ib i.p.s.p.s

To estimate relative contribution of Ia and Ib afferents from synergists to the inhibition of motoneurones we compared amplitudes of i.p.s.p.s evoked by about 80 % of Ia afferents of triceps surae (30–35 μm stretches) and by electrical stimulation of nerves to these muscles, just subthreshold for Ia afferents after tonic vibration for 30–60 min (Coppin *et al.* 1970); depending on the preparation the muscle vibration increased the threshold for Ia afferents to 1·2–1·4 times the original threshold and the data of Coppin *et al.* (1970) suggest that such electrical stimuli should have activated less than 50 % of Ib afferents.

As illustrated in Fig. 9*A–E* distinct i.p.s.p.s were already evoked by stimuli near threshold for Ib afferents. The weakest stimuli evoked i.p.s.p.s with a simple time course and latencies consistent with a disynaptic coupling (Fig. 6*C*▨). These latencies clearly fell within the range of the earliest i.p.s.p.s evoked by electrical stimuli maximal for group I afferents (Fig. 6*B*, Fig. 6*C*, ■). Stronger stimuli, but still subthreshold for Ia e.p.s.p.s, evoked a second component of the Ib i.p.s.p.s and increased their amplitude.

Amplitudes of Ib i.p.s.p.s evoked by stimuli 1·1–1·3 times the original group I thresholds constituted about 50 % (range 25–66 %) of amplitudes of maximal group I i.p.s.p.s evoked from the same nerves in eighteen motoneurones (fifteen of plantaris and three of triceps surae muscles).

The stretch-evoked Ia i.p.s.p.s were much smaller (100–400 μV, about 200 μV on the average) than the maximal group I i.p.s.p.s evoked from the same nerves and than the Ib i.p.s.p.s, as illustrated in Fig. 9*F*. In six plantaris motoneurones selected for analysis because Ia i.p.s.p.s evoked in them from triceps surae were minimally contaminated by monosynaptic e.p.s.p.s, the amplitudes of these Ia i.p.s.p.s were 9–12 % of group I i.p.s.p.s (see Fig. 9*G*) and 16–35 % of group Ib i.p.s.p.s (the latter evoked by a much smaller proportion of tendon organ afferents).

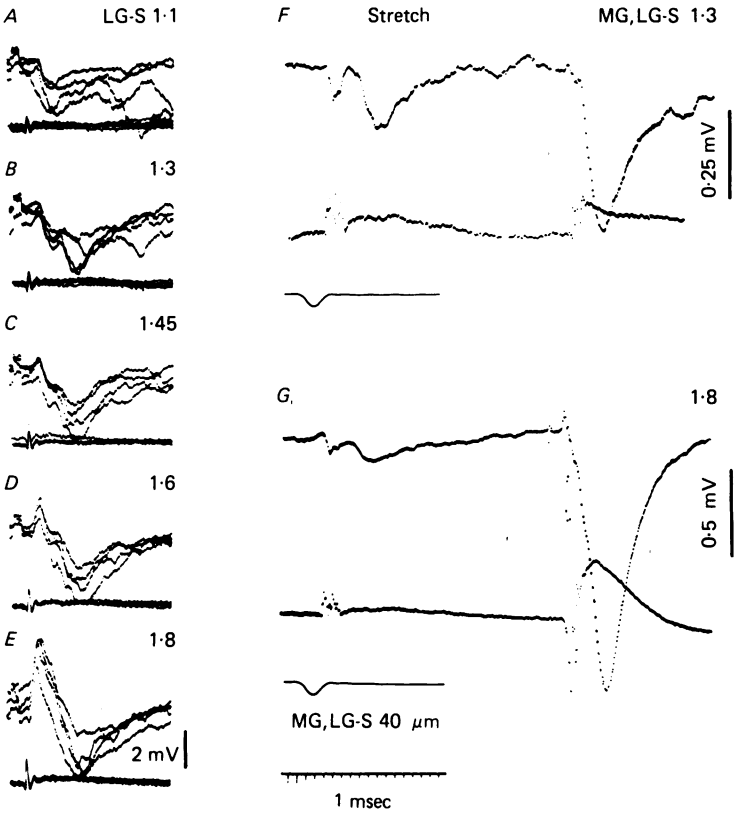

Fig. 9. Comparison of i.p.s.p.s evoked from Ia, Ib and all group I afferents. *A–E*, i.p.s.p.s evoked in a medial gastrocnemius motoneurone by selective stimulation of Ib afferents after prolonged vibration of lateral gastrocnemius and soleus. Note that the later component of i.p.s.p.s appeared with stimuli of 1·3 times threshold for group Ia afferents before the vibration and that the monosynaptic Ia e.p.s.p.s appeared with stimulus intensities 1·3–1·45 times threshold. *F*, *G*, averaged records from a plantaris motoneurone. To the left are i.p.s.p.s evoked by 40 μm stretches of medial gastrocnemius and lateral gastrocnemius-soleus. To the right are i.p.s.p.s evoked by a selective stimulation of Ib afferents just below threshold for Ia afferents (*F*) and by stimulation maximal for group I afferents (*G*) in medial gastrocnemius and lateral gastrocnemius-soleus nerves. Note lower amplification in *G*. The stretch-evoked i.p.s.p.s were preceded by a large extracellular field potential and by a small monosynaptic Ia e.p.s.p. Time calibration 1 msec for all records.

In twenty other plantaris motoneurones Ia i.p.s.p.s evoked by 30–35 μm stretches of triceps surae were compared with i.p.s.p.s evoked by electrical stimulation of all group I afferents in only lateral gastrocnemius-soleus. The amplitudes of these Ia i.p.s.p.s were also much smaller (7–35 %, mean 19 %).

In view of the relatively small amplitudes of the above described stretch-evoked Ia i.p.s.p.s one might hesitate to ascribe them any essential functional role. We therefore tested the effect of small stretches of synergistic muscles on monosynaptic reflex discharges of a larger population of motoneurones. The test monosynaptic reflex was evoked from plantaris and preceded by conditioning stretches of triceps surae. Vibration of triceps surae was previously reported to increase the monosynaptic

reflex from plantaris (Magherini, Pompeiano & Thodén, 1972) showing that the small heteronymous e.p.s.p.s (Eccles *et al.* 1957*b*) could have some effect counteracting the Ia autogenetic inhibition. In two of five tested cats both facilitation and inhibition of the test monosynaptic reflex was observed, depending on the parameters of the test

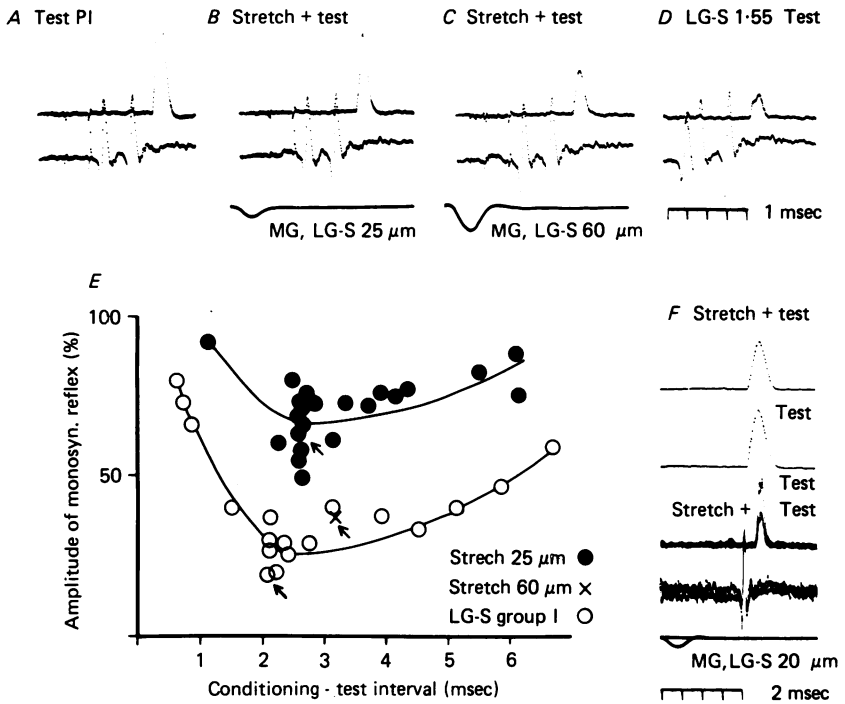

Fig. 10. Stretch-evoked inhibition of monosynaptic reflexes. *A–E*, inhibition of a monosynaptic reflex from plantaris. Upper traces: records from L7 ventral root. Lower traces: records from the surface of the spinal cord and changes in muscle length. *A*, monosynaptic reflex evoked by two stimuli applied to the cut plantaris nerve (1·3 times threshold and supramaximal for group I afferents). *B–D*, test monosynaptic reflex preceded by stretches of triceps surae (MG and LG-S), with amplitudes below and above threshold for Ib afferents, and by electrical stimulation of lateral gastrocnemius-soleus maximal for group I afferents. *E*, amplitude of the test monosynaptic reflex illustrated in *A–D* as a function of the interval between afferent volleys evoked by muscle stretch and the second stimulus applied to plantaris nerve. Arrows indicate data points for records in *B–D*. *F*, inhibition of a monosynaptic reflex from plantaris evoked in another cat by single test stimuli. Conditioning-testing interval: 3·5–msec. From top to bottom: averages of conditioned responses and test responses, superimposed traces of two conditioned and two test responses, cord dorsum potential and changes in muscle length. 1 msec time calibration is for all averaged records and 2 msec time calibration for the remaining ones.

and conditioning stimuli. In two other cats the conditioning Ia volley depressed the reflex by up to 15–20 %, as illustrated in Fig. 10*F*. Only in one cat was the maximal stretch-evoked depression more significant, as illustrated in Fig. 10*A–E*; the test reflex was decreased by 30–40 % by a Ia volley compared to 83 % decrease by the lateral gastrocnemius-soleus group I volley.

In this cat two stimuli were used to evoke the test monosynaptic reflex. Since the first stimulus (1·3 times threshold) was likely to excite a certain proportion of Ib afferents it might have affected some interneurones mediating Ib inhibition of motoneurones. The particular effectiveness of Ia conditioning volley at conditioning testing intervals of 2–4 msec (0·5–2·5 msec between the Ia volley and the first test stimulus) might therefore be accounted for by a mutual facilitation of effects from Ia and Ib afferents. A mutual facilitation of stretch-evoked effects of Ia afferents of lateral gastrocnemius-soleus and Ia afferents of medial gastrocnemius activated by the first electrical stimulus should also be taken into account.

DISCUSSION

Results of our experiments show that both Ib tendon organ afferents and Ia muscle spindle afferents from synergists may inhibit motoneurones. When activated in isolation, the Ia afferents were found to evoke distinct i.p.s.p.s in a considerable proportion of the analysed motoneurones. However, amplitudes of these i.p.s.p.s were much smaller than amplitudes of i.p.s.p.s evoked from Ib afferents; the differences were particularly marked in view of a higher proportion of Ia than of Ib afferents which were selectively stimulated under our experimental conditions. Also, fewer motoneurones were inhibited by volleys in Ia afferents alone as compared to those in which Ib i.p.s.p.s were evoked. It is thus possible that the main function of the Ia inhibition from synergists would be to support the Ib inhibition rather than to control the excitability of motoneurones independently of the tendon organ afferents.

In evaluating these results it should be noted that our observations were made on a limited number of motoneurone species and that so far they are valid primarily for motoneurones innervating triceps surae and plantaris. These motoneurones were selected for two reasons. First because afferents from ankle and toe extensors are among the most potent in evoking the autogenetic and synergistic inhibition (Eccles *et al.* 1957*c*) and second because adequate stimulation of muscle spindle afferents in these muscles by stretch and vibration is technically the easiest and was used in several previous studies (e.g. Granit & Henatsch, 1956; Lundberg & Windsbury, 1960; Brown *et al.* 1967; Stuart *et al.* 1970, 1971; Ellaway & Trott, 1978), thus allowing comparison with their results. In supplementing the results obtained on triceps surae and plantaris we might add that Ia i.p.s.p.s were also found in four out of ten tested knee flexors, posterior biceps-semitendinosus motoneurones (E. E. Fetz, E. Jankowska, T. Johannisson and J. Lipski, unpublished). These were evoked by electrical stimulation of the nerves to these muscles by stimuli clearly below threshold for the second (Ib) component of the incoming afferent volley, with intensities 1·08–1·3 times threshold for Ia afferents. I.p.s.p.s from similarly low threshold afferents from knee extensors, quadriceps, were previously observed in a number of ankle and toe extensors by Eccles *et al.* (1957*a*) and Lundberg, Malmgren & Schomburg (1977; see below). Thus the Ia inhibition from synergists may be quite a common phenomenon. However, before generalizing the conclusions of this study its occurrence in other motoneurone species should be systematically confirmed.

Previous observations relevant to the Ia origin of autogenetic and synergistic inhibition

(i) In the first systematic study of inhibition evoked from group I afferents in motoneurones of synergistic muscles, using the technique of conditioning monosynaptic reflexes, Laporte & Lloyd (1951) stated that 'clearly threshold to brief shocks of the afferent fibres mediating the inhibitory action is closely similar to that of the afferent fibres mediating monosynaptic facilitation'. They considered that the small differences might depend on 'presence in the inhibitory pathway of an internuncial relay requiring a degree of summation for response', but finally attributed the inhibition of motoneurones of homonymous and of synergistic muscles to tendon organ afferents. The main reason for this conclusion was that the pattern of the observed inhibitory actions was opposite to that of the reciprocal inhibition evoked from muscle spindle afferents (Lloyd, 1946) and was similar to the effect from tendon organ afferents previously described by Granit (1950) and Hunt (1952). Similar thresholds for monosynaptic facilitation and for disynaptic inhibition of synergists found by Laporte & Lloyd might, however, be taken as indicating Ia autogenetic inhibition only in the case of vastus lateralis, posterior biceps and semitendinosus, because Ia and Ib afferents in other nerves do not show comparable differences in their sensitivity to electrical stimuli (see Jack, 1978). Recording intracellularly from motoneurones, Eccles *et al.* (1957*a*) also observed inhibition from low threshold afferents from synergistic muscles stimulated electrically. Stimulation of quadriceps nerve (with intensities 1·17–1·39 times threshold for Ia afferents and below threshold for the second (Ib) component of the incoming afferent volleys) produced i.p.s.p.s in gastrocnemius-soleus motoneurones. However, since such low threshold inhibition appeared in only one cat it was considered an exception and attributed to contamination of the first (Ia) component of the incoming volley by Ib impulses. Lundberg *et al.* (1977) found i.p.s.p.s evoked in some extensor motoneurones by similarly low or even lower (1·1–1·15) threshold quadriceps afferents, which also evoked facilitation of Ib i.p.s.p.s (see their Fig. 5). In view of these and other observations they reconsidered the contribution of Ia afferents to the inhibition of synergistic motoneurones as an alternative possibility.

(ii) Analysing the time course of monosynaptic e.p.s.p.s, Brock, Coombs & Eccles (1952) and Coombs, Eccles & Fatt (1955) described a slightly more rapid initial decay of some e.p.s.p.s with the largest amplitudes and a subsequent hyperpolarization. Such effects were illustrated both in gastrocnemius motoneurones and in posterior biceps-semitendinosus motoneurones, in the latter with stimuli below threshold for the Ib component of the afferent volley and under anaesthesia sufficiently deep to abolish reflex discharges of motoneurones. If the unusually rapid decay of such e.p.s.p.s was due to an i.p.s.p, evoked by impulses in Ia muscle spindle afferents, its relatively high threshold (within the Ia range), small amplitude (under barbiturate anaesthesia) and its temporal facilitation might be explained by properties of transmission at the interneuronal level; the prolonged duration of the hyperpolarization following the e.p.s.p.s would require some other explanations.

A differential sensitivity of the later phase of Ia e.p.s.p.s to depolarization (Smith, Wuerker & Frank, 1967; Kuno & Llinas, 1970; Shapovalov & Kurchavyj, 1974; Werman & Carlen, 1976) could likewise be interpreted as due to contamination of the

e.p.s.p.s by i.p.s.p.s. To avoid such possible contamination, Edwards *et al.* (1976) analysed unitary Ia e.p.s.p.s produced by impulses in single Ia afferent fibres. Polarizing currents shortened these e.p.s.p.s but never produced biphasic reversal. Such a reversal would therefore appear to be a feature of only compound e.p.s.p.s. Unfortunately, none of the reports of the biphasic reversal of the compound e.p.s.p.s provided complete information on all the following points: whether these were evoked by stimuli sub- or suprathreshold for tendon organ afferents and group II afferents, whether the hyperpolarization of the same motoneurones caused prolonged decay of the e.p.s.p.s, the intensity of the injected currents and the kind of electrolyte filling the micropipettes. Therefore, even assuming that a given e.p.s.p. (e.g. that in Fig. 2 of Smith *et al.* 1967) was followed by an i.p.s.p., it is not possible to determine whether it originated from muscle spindle or tendon organ afferents.

(iii) Adequate stimuli which undoubtedly activated Ia muscle spindle afferents (static stretch and vibration of muscles and muscle contractions accompanied by an early Ia discharge) have been reported to inhibit monosynaptic reflexes from synergists under various experimental conditions. However, the experiments were not designed to differentiate between Ia and Ib or group II effects (Granit, 1950; Bianconi, Granit & Reis, 1964) and between short latency postsynaptic and longer latency and long-lasting presynaptic actions of Ia afferents (Magherini *et al.* 1972; Magherini, Pompeiano & Seguin, 1973). Consequently the contribution of Ia afferents to the inhibition attributed to other afferents or to the primary afferent depolarization remains unresolved.

(iv) Brown, Lawrence & Matthews (1968) found that Ia afferents activated by vibration and stretch inhibited some spontaneously discharging motoneurones but were uncertain whether these were α- or γ-motoneurones. If they were γ-motoneurones these observations would agree with the subsequent studies by Fromm & Noth (1976) and Ellaway & Trott (1978). If some of these motoneurones were α-motoneurones, their inhibition could represent the Ia inhibition now described. In the interpretation of the stretch-evoked inhibition of γ-motoneurones the possibility of its mediation by Renshaw cells via stretch-activated α-motoneurones was strongly emphasized (for references see Ellaway & Trott, 1978). However, there is evidence for an alternative mechanism of this inhibition. Recording intracellularly from γ-motoneurones, Grillner, Hongo & Lund (1969) found that the latencies and time course of i.p.s.p.s evoked in them from group I afferents closely resembled those of i.p.s.p.s evoked in α-motoneurones. Ellaway & Trott (1976, 1978) also found evidence that Ib afferents contribute to the autogenetic control of γ-motoneurones. Thus, γ-inhibition of group I origin might well be evoked by the same system of interneurones which mediate inhibition of α-motoneurones.

Factors favouring and preventing appearance of inhibition from Ia muscle spindle afferents from synergists

Since i.p.s.p.s evoked from these afferents appear to be relayed both di- and trisynaptically, the occurrence of these i.p.s.p.s must primarily depend on the excitability of the interposed interneurones. The Ia autogenetic and synergistic inhibition should therefore appear more readily in unanaesthetized preparations than in those under deep anaesthesia, after removing the supraspinal inhibitory

control of interneurones by spinalization (Eccles & Lundberg, 1959; Holmqvist & Lundberg, 1961; Engberg, Lundberg & Ryall, 1968), and in circumstances in which afferents from several muscles are activated. Accordingly, in the present experiments the most pronounced and lowest threshold effects were found in spinalized decerebrate or decorticated preparations, which were unanaesthetized or only very lightly anaesthetized, and in which both triceps surae and plantaris muscles were simultaneously stretched. Under deeper chloralose and barbiturate anaesthesia and with the spinal cord intact the Ia i.p.s.p.s were weaker and required much stronger stimulation of muscle spindle afferents. Consequently they could not be differentiated from Ib i.p.s.p.s. The i.p.s.p.s could be further enhanced by polarization of the motoneurone membrane, hyperpolarization and chloride injection making them most conspicuous.

Relations between autogenetic inhibition evoked from muscle spindle and tendon organ afferents

The finding that inhibition of motoneurones from homonymous and synergistic muscles is evoked from both group Ia muscle spindle afferents and from Ib tendon organ afferents necessitates reconsideration of both its function and the way it is mediated. Regarding the interposed interneurones there are indications that the autogenetic inhibition may be mediated by interneurones of laminae V–VI excited by group I afferents. Originally these interneurones were thought to be monosynaptically excited by either Ia or Ib afferents (Eccles, Eccles & Lundberg, 1960) but subsequent studies revealed a convergence of both of these groups of afferents on many of them. Such a convergence was first found when Ia and Ib afferents from knee flexors and extensors were stimulated electrically (Hongo, Jankowska & Lundberg, 1966; see also Jankowska, 1979) and will be reported for adequately stimulated Ia afferents from ankle extensors (see Jankowska, 1979). Several of the laminae V–VI interneurones co-excited by Ia and Ib afferents have in addition shown terminal branching within the motor nuclei (Czarkowska *et al.* 1976; see Jankowska, 1979). These interneurones might thus mediate inhibition of motoneurones both from Ia and Ib afferents. Mutual facilitation of inhibitory actions of these afferents on motoneurones has been recently observed: i.p.s.p.s evoked from group I (Lundberg *et al.* 1977), or from Ib afferents selectively stimulated (E. E. Fetz, E. Jankowska and J. Lipski, unpublished) could be facilitated by conditioning volleys in Ia afferents.

If the autogenetic inhibition from triceps surae and plantaris is mediated by interneurones in laminae V and VI, which we consider most likely, the Ia autogenetic inhibition could be due to interneurones co-excited by Ia and Ib afferents, since none of the intermediate zone interneurones have so far been found to be selectively activated by Ia afferents. However, some of the laminae V and VI interneurones are excited only by Ib afferents; these could also contribute to the Ib autogenetic inhibition.

Linked reflex actions of muscle spindle and tendon organ afferents may be secured by peripheral as well as central mechanisms. Functionally the most important would be those producing co-activation of Ia and Ib afferents during muscle contractions. The recently analysed system of skeleto-fusimotor β-fibres (see Laporte & Emonet-

Dénand, 1976) can produce such a co-activation directly. Since β-fibres constitute a high proportion of those innervating extrafusal muscle fibres and supply a considerable number of muscle spindles (Emonet-Dénand & Laporte, 1975), these fibres might excite Ia afferents as effectively as Ib afferents. The role of γ-fusimotor system for ensuring firing of Ia afferents during muscle contraction is well known (see Granit, 1955; Matthews, 1972), and a parallel activation of α-and γ-motoneurones would have as an obvious consequence a co-activation of Ia and Ib afferents.

Finally it should be stressed that neither Ib nor Ia inhibition described in this paper provides only a local feed-back. This was previously shown by demonstrating that stimulation of group I afferents from one muscle evokes inhibition of motoneurones of both the same and other muscles (Laporte & Lloyd, 1952; Eccles *et al.* 1957*c*; Hongo *et al.* 1969; for further references see Granit, 1955 and Haase *et al.* 1975). Inhibition of an individual motoneurone is accordingly evoked from afferents from a number of muscles as has also been found to be the case for inhibition selectively evoked from Ia afferents.

We wish to thank Professor A. Lundberg for many helpful discussions, Engineer E. Eide for construction of muscle puller and Mrs Rauni Larsson, Miss Berit Nilsson and Mr Thomas Palm for their help during the experiments and in the preparation of the manuscript. This work was supported by the Swedish Medical Research Council (project no. 94).

REFERENCES

ANDÉN, N.-E., JUKES, M. G. M., LUNDBERG, A. & VYKLICKÝ, L. (1966). The effect of DOPA on the spinal cord. 1. Influence on transmission from primary afferents. *Acta physiol. scand.* **67**, 373–386.

BIANCONI, R., GRANIT, R. & REIS, D. J. (1964). The effects of extensor muscle spindles and tendon organs on homonymous motoneurones in relation to γ-bias and curarization. *Acta physiol. scand.* **61**, 331–347.

BROCK, L. G., COOMBS, J. C. & ECCLES, J. C. (1952). Recording of potentials from motoneurones with an intracellular electrode. *J. Physiol.* **117**, 431–460.

BROWN, M. C., ENGBERG, I. & MATTHEWS, P. B. C. (1967). The relative sensitivity to vibration of muscle receptors of the cat. *J. Physiol.* **192**, 773–800.

BROWN, M. C., LAWRENCE, D. G. & MATTHEWS, P. B. C. (1968). Reflex inhibition by Ia afferent input of spontaneously discharging motoneurones in the decerebrate cat. *J. Physiol.* **198**, 5–7 P

COOMBS, J. S., ECCLES, J. C. & FATT, P. (1955). Excitatory synaptic action in motoneurones. *J. Physiol.* **130**, 374–395.

COPPIN, C. M. L., JACK, J. J. B. & MACLENNAN, C. R. (1970). A method for the selective activation of tendon organ afferent fibres from the cat soleus muscle. *J. Physiol.* **210**, 18–20.

CZARKOWSKA, J., JANKOWSKA, E. & SYBIRSKA, E. (1976). Axonal projections of spinal interneurones excited by group I afferents in the cat, revealed by intracellular staining with horseradish peroxidase. *Brain Res.* **118**, 115–118.

ECCLES, J. C., ECCLES, R. M. & LUNDBERG, A. (1957*a*). Synaptic actions on motoneurones in relation to the two components of the group I muscle afferent volley. *J. Physiol.* **136**, 527–546

ECCLES, J. C., ECCLES, R. M. & LUNDBERG, A. (1957*b*). The convergence of mono-synaptic excitatory afferents on to many different species of alpha motoneurones. *J. Physiol.* **137**, 22–50.

ECCLES, J. C., ECCLES, R. M. & LUNDBERG, A. (1957*c*). Synaptic actions on motoneurones caused by impulses in Golgi tendon organ afferents. *J. Physiol.* **138**, 227–252.

ECCLES, J. C., ECCLES, R. M. & LUNDBERG, A. (1960). Types of neurone in and around the intermediate nucleus of the lumbosacral cord. *J. Physiol.* **154**, 89–114.

ECCLES, R. M. & LUNDBERG, A. (1958). Integrative pattern of Ia synaptic actions on motoneurones of hip and knee muscles. *J. Physiol.* **144**, 271–298.

ECCLES, R. M. & LUNDBERG, A. (1959). Supraspinal control of interneurones mediating spinal reflexes. *J. Physiol.* **147**, 565–584.

EDWARDS, F. R., REDMAN, S. J. & WALMSLEY, B. (1976). The effect of polarizing currents on unitary Ia excitatory post-synaptic potentials evoked in spinal motoneurones. *J. Physiol.* **259**, 705–723.

ELLAWAY, P. H. & TROTT, J. R. (1976). Reflex connections from muscle stretch receptors to their own fusimotor neurones. *Prog. Brain Res.* **44**, 113–122.

ELLAWAY, P. H. & TROTT, J. R. (1978). Autogenetic reflex action on to gamma motoneurones by stretch of triceps surae in the decerebrated cat. *J. Physiol.* **276**, 49–66.

EMONET-DENAND, F. & LAPORTE, Y. (1975). Proportion of muscle spindles supplied by skeletofusimotor axons (β-axons) in peroneus brevis muscle of the cat. *J. Neurophysiol.* **38**, 1390–1394.

ENGBERG, I., LUNDBERG, A. & RYALL, E. W. (1968). Reticulospinal inhibition of transmission in reflex pathways. *J. Physiol.* **194**, 201–223.

FETZ, E., JANKOWSKA, E., JOHANNISSON, T. & LIPSKI, J. (1978). Autogenetic inhibition of motoneurones evoked by impulses in group Ia muscle spindle afferents. *Neuroscience Letters*, suppl. **1**, 593.

FROMM, Chr. & NOTH, J. (1976). Reflex responses of gamma-motoneurones to vibration of the muscle they innervate. *J. Physiol.* **256**, 117–136.

GRANIT, R. (1950). Reflex self-regulation of muscle contraction and autogenetic inhibition. *J. Neurophysiol.* **13**, 351–372.

GRANIT, R. (1956). *Receptors and Sensory Perception.* New Haven: Yale University Press.

GRANIT, R. & HENATSCH, H. D. (1956). Gamma control of dynamic properties of muscle spindles. *J. Neurophysiol.* **19**, 356–366.

GRILLNER, S., HONGO, T. & LUND, S. (1969). Descending monosynaptic and reflex control of γ-motoneurones. *Acta physiol. scand.* **75**, 592–613.

HAASE, J., CLEVELAND, S. & ROSS, H. G. (1975). Problems of postsynaptic autogenous and recurrent inhibition in the mammalian spinal cord. *Rev. Physiol. Biochem. Pharmacol.* **73** 73–129.

HOLMQVIST, B. & LUNDBERG, A. (1961). Differential supraspinal control of synaptic actions evoked by volleys in the flexion reflex afferents in alpha motoneurones. *Acta physiol. scand.* **54**, Suppl. 186, 1–51.

HONGO, T., JANKOWSKA, E. & LUNDBERG, A. (1966). Convergence of excitatory and inhibitory action on interneurones in the lumbosacral cord. *Expl Brain Res.* **1**, 338–358.

HULTBORN, H., JANKOWSKA, E. & LINDSTRÖM, S. (1971). Recurrent inhibition of interneurones monosynaptically activated from group Ia afferents. *J. Physiol.* **215**, 613–636.

HUNT, C. C. (1952). The effect of stretch receptors from muscle on the discharge of motoneurones. *J. Physiol.* **117**, 359–379.

JACK, J. J. B. (1978). Some methods for selective activation of muscle afferent fibres. In *Studies in Neurophysiology*, Essays in honour of Professor McIntyre, A. K. Cambridge: Cambridge University Press.

JANKOWSKA, E. (1979). New observations on neuronal organization of reflexes from tendon organ afferents and their relation to reflexes evoked from muscle spindle afferents. In *Reflex Control of Posture and Movement*, ed. POMPEIANO, O. Amsterdam: Elsevier (In the press).

JANKOWSKA, E., PADEL, Y. & TANAKA, R. (1975). The mode of activation of pyramidal tract cells by intracortical stimuli. *J. Physiol.* **249**, 617–636.

KIRKWOOD, P. A. & SEARS, T. A. (1975). Monosynaptic excitation of motoneurones from muscle spindle secondary endings of intercostal and triceps surae muscles in the cat. *J. Physiol.* **245**, 64–66*P*.

KUNO, M. & LLINAS, R. (1970). Alterations of synaptic actions in chromatolysed motoneurones of the cat. *J. Physiol.* **210**, 823–838.

LAPORTE, Y. & EMONET-DÉNAND, F. (1976). The skeleto-fusimotor innervation of cat muscle spindle. *Prog. Brain Res.* **44**, 99–106.

LAPORTE, Y. & LLOYD, D. P. C. (1952). Nature and significance of the reflex connections established by large afferent fibers of muscles. *Am. J. Physiol.* **169**, 609–621.

LLOYD, D. P. C. (1946). Integrative pattern of excitation and inhibition in two-neuron reflex arc *J. Neurophysiol.* **9**, 439–444.

LUCAS, M. E. & WILLIS, W. D. (1974). Identification of muscle afferents which activate interneurons in the intermediate nucleus. *J. Neurophysiol.* **37**, 282–293.

LUNDBERG, A., MALMGREN, K. & SCHOMBURG, E. D. (1977). Cutaneous facilitation of transmission in reflex pathways from Ib afferents to motoneurones. *J. Physiol.* **265**, 763–780.

LUNDBERG, A. & WINSBURY, G. (1960). Selective adequate activation of large afferents from muscle spindles and Golgi tendon organs. *Acta physiol. scand.* **49**, 155–164.

MAGHERINI, P. C., POMPEIANO, O. & THODÉN, H. (1972). The relative significance of presynaptic and postsynaptic effects on monosynaptic extensor reflexes during vibration of synergic muscles. *Arch ital. Biol.* **110**, 70–89.

MAGHERINI, P. C., POMPEIANO, O. & SEGUIN, J. J. (1973). The effect of stimulation of Golgi tendon organs and spindle receptors from hindlimb extensor muscles on supraspinal descending inhibitory mechanisms. *Arch ital. Biol.* **111**, 24–57.

MATTHEWS, P. B. C. (1972). *Mammalian Muscle Receptors and Their Central Actions*, pp. 1–630. London: Edward Arnold.

MENDELL, L. M. & HENNEMAN, E. (1971). Terminals of single Ia fibers: location, density and distribution within a pool of 300 homonymous motoneurons. *J. Neurophysiol.* **34**, 171–187.

POLLOCK, I. J. & DAVIS, L. (1930). The reflex activities of a decerebrate animal. *J. comp. Neurol.* **50**, 377–411.

SCOTT, J. G. & MENDELL, L. M. (1976). Individual EPSPs produced by single triceps surae Ia afferent fibers in homonymous and heteronymous motoneurons. *J. Neurophysiol.* **39**, 679–692.

SHAPOVALOV, A. I. & KURCHAVYJ, G. C. (1974). Effects of trans-membrane polarization and TEA injection on monosynaptic actions from motor cortex, red nucleus and group Ia afferents on lumbar motoneurons in the monkey. *Brain Res.* **82**, 49–67.

SMITH, T. G., WUERKER, R. B. & FRANK, K. (1967). Membrane impedance changes during synaptic transmission in cat spinal motoneurons. *J. Neurophysiol.* **30**, 1072–1096.

STUART, D. G., MOSCHER, C. G., GERLACH, R. L. and REINKING, R. M. (1970). Selective activation of Ia afferents by transient muscle stretch. *Expl Brain Res.* **10**, 477–487.

STUART, D. G., WILLIS, W. D. & REINKING, R. M. (1971). Stretch-evoked excitatory postsynaptic potentials in motoneurons. *Brain Res.* **33**, 115–125.

TAYLOR, A., WATT, D. G. D., STAUFFER, E. K., REINKING, R. M. & STUART, D. G. (1976). Use of afferent triggered averaging to study the central connections of muscle spindle afferents *Prog. Brain Res.* **44**, 171–183.

WERMAN, R. & CARLEN, P. L. (1976). Unusual behavior of the Ia EPSP in cat spinal motoneurons. *Brain Res.* **112**, 395–401.