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RECIPROCAL INHIBITION DURING THE TONIC STRETCH REFLEX IN THE DECEREBRATE CAT

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SUMMARY

1. The aim of this study was to investigate post-synaptic reciprocal Ia inhibition during the stretch reflex; particularly the extent to which an increased Ia excitation of the Ia inhibitory interneurones will be counteracted by recurrent inhibition from motor axon collaterals. For this purpose we investigated depression of monosynaptic test reflexes to antagonist flexors (reciprocal inhibition) during static stretch of quadriceps or triceps surae in unanaesthetized decerebrate cats.

2. With increasing stretch of the extensor muscle there was first a linear augmentation of reciprocal inhibition, but along with the stretch reflex in the extensor a plateau appeared in the inhibition of the flexors, although the extensor stretch reflex (judged by the e.m.g.) increased with further stretching. Within the range of stretching of triceps surae which gave increased stretch reflexes the plateau in the reciprocal inhibition was usually maintained, while during stretching of quadriceps a second phase of augmenting reciprocal inhibition often appeared. Stretch beyond the level which increased the stretch reflex activity gave augmenting reciprocal inhibition both in case of quadriceps and triceps surae.

3. Excitability measurements from central terminals of Ia afferents revealed that the increasing reciprocal inhibition during increasing stretch reflex activity in quadriceps was associated with a primary afferent depolarization in knee flexor Ia afferents; there was no corresponding effect in ankle flexor Ia afferents during stretch reflexes in triceps surae.

4. The primary afferent depolarization evoked in knee flexor Ia afferents by electrical nerve stimulation was then compared with the presynaptic inhibition of knee flexor monosynaptic test reflexes produced by the same stimuli. The results suggest that the second phase of increasing reciprocal inhibition in knee flexors is due to presynaptic inhibition and accordingly that the depth of post-synaptic reciprocal inhibition remains constant at different degrees of stretch reflex activity in both knee and ankle extensors.

5. It is postulated that during increasing stretch reflex activity the increment in Ia excitation and recurrent inhibition on to the Ia inhibitory interneurones almost exactly balance each other. It is suggested that recurrent inhibition of Ia inhibitory

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interneurones may serve as a segmental autoregulatory mechanism to keep 'α-γ-linked reciprocal inhibition' at a constant depth during different levels of agonist activity.

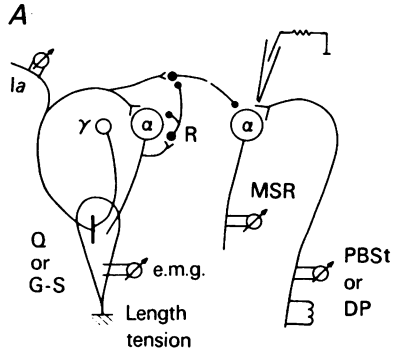
INTRODUCTION

It is established that nerve impulses in large muscle spindle (I*a*) afferents cause a monosynaptic excitation of motoneurones innervating the homonymous and synergic muscles and a concomitant disynaptic inhibition of motoneurones to antagonists (see Matthews, 1972, for a review). It was shown several years ago (Hultborn, Jankowska & Lindström, 1971*a*, *b*) that antidromic stimulation of ventral roots can depress transmission in the I*a* inhibitory pathway to motoneurones by an inhibition of the interposed interneurone. The strongest depression of I*a* i.p.s.p.s in motoneurones was invariably evoked from motor fibres to those muscles whose I*a* afferents produced the i.p.s.p.s (Hultborn, Jankoswska & Lindström, 1971*c*). From experiments with single electrical shocks applied to peripheral nerves and to ventral roots we thus know that activity in I*a* afferents from a given muscle will cause direct monosynaptic excitation of I*a* inhibitory interneurones and recurrent inhibition of the same interneurones if homonymous motoneurones are activated (cf. Fig. 1*A*). It is not known, however, to what an extent an increment in I*a* excitation will be counteracted by augmented recurrent inhibition. We have now approached this problem by investigating effects on monosynaptic reflexes from knee and ankle flexors during tonic stretch reflexes in the knee extensor quadriceps and ankle extensor triceps surae.

The stretch reflex has been extensively investigated (cf. Granit, 1970; Matthews, 1972) but less attention has been given in recent time to stretch evoked reciprocal inhibition. Liddell & Sherrington (1925) found that stretch of the hamstring muscles effectively inhibited the stretch reflex in quadriceps. It is likely that this inhibition was largely of presynaptic origin because it proved to be resistant to strychnine which is now known to block post-synaptic inhibition (Bradley, Easton & Eccles, 1953*a*). In the present experiments we investigated stretch of extensors on monosynaptic reflexes from flexors. This combination should be more favourable in order to reveal the role of post-synaptic reciprocal inhibition because presynaptic inhibition of transmission from I*a* afferents appears to be particularly powerful from flexors but is generally weaker from extensors (Eccles, 1964). However, among the extensors, quadriceps is somewhat exceptional (Eccles, Schmidt & Willis, 1962*b*) and it will be shown that part of the depression of the knee flexor monosynaptic reflex during stretch of quadriceps is of presynaptic origin, while reciprocal inhibition of ankle flexors appears to be entirely post-synaptic. The degree of presynaptic inhibition from quadriceps has been evaluated in order to obtain a measure of post-synaptic I*a* inhibition of the knee flexors. Our results suggest that the depth of post-synaptic reciprocal I*a* inhibition is kept relatively constant at different degrees of agonist stretch reflex activation. These findings lead us to propose that recurrent inhibition of I*a* inhibitory interneurones may serve as a segmental autoregulatory mechanism that prevents reciprocal I*a* inhibition from getting too deep during increased α-γ-linked excitation of agonists. A preliminary report of some of the findings has been published (Hultborn & Lundberg, 1972).

METHODS

Preparation. The experiments were performed on twenty-two cats decerebrated by intercollicular section. Ether anaesthesia was used during dissection, but was withdrawn at least 2 hr before any recording. The blood pressure was monitored continuously and a drop below 80 mmHg was counteracted by a slow intravenous infusion of dextran and noradrenaline. The rectal temperature was kept within 36–38 °C. Two different series of experiments were performed. In the first series (eleven cats) the left hind limb was denervated except the nerves to the knee extensor vasto-crureus (the nerve to the double joint muscle, rectus femoris was severed). The quadriceps muscle was then carefully dissected free from surrounding muscles and connective tissue. The patellar ligament was cut and a hole drilled through the patella. Following this dissection the skin was sutured to protect the muscle. On the dorsal side of the limb the



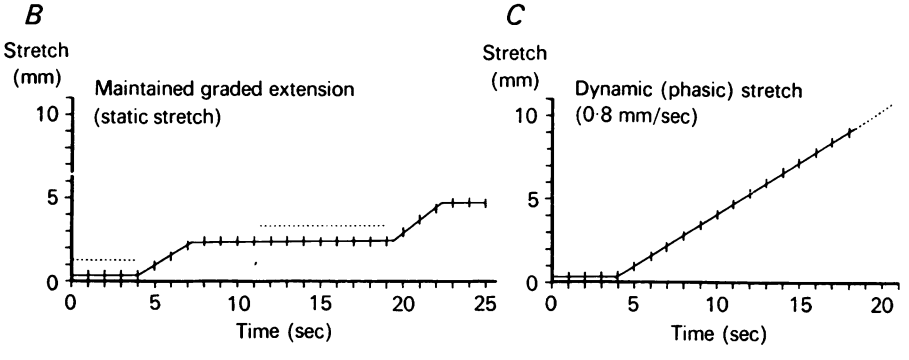


Fig. 1. Schematic drawings of neuronal connexions and experimental arrangements. *A*, experimental arrangement. See further in text. *B*, illustration of the experimental situation referred to as 'maintained graded extension'. The interrupted lines indicate the periods during which the monosynaptic text reflex (MSR) was measured, i.e. a few seconds after the end of the dynamic stretch. *C*, illustration of the experimental situation referred to as 'dynamic stretch'. In this case the monosynaptic text reflexes were recorded during the dynamic phase.

skin flaps were sewn up to form a pool which was filled with warm paraffin oil. Several muscle nerves (always including the nerves from the antagonists posterior biceps and semitendinosus muscles) were mounted on bipolar silver electrodes for stimulation and recording. Stretch of the quadriceps was applied via a hook fixed in the patella and a steel wire of low compliance which was connected to a strain gauge mounted on a puller. The femur was fixed rigidly by steel pins. In the second series of experiments (eleven cats) the left hind limb was denervated

except the triceps surae (soleus and gastrocnemius) which was freed from surrounding tissue. The tibia was fixed rigidly by steel pins, and the Achilles tendon with its bony insertion was separated from the calcaneus and connected to the strain gauge and puller. Several nerves were mounted for stimulation (always including the nerves from the antagonist ankle dorsi-flexors tibialis anterior and extensor digitorum longus).

Lumbar spinal segments were exposed by a laminectomy from L4 to L7. In the first series the S1 and L7 ventral roots were transected and their central parts were mounted on silver wire electrodes for recording the monosynaptic reflex evoked by stimulation of the nerve from posterior biceps and semitendinosus. In the second series the L6 and the most rostral part of the L7 ventral roots were cut and mounted for recording the monosynaptic reflex evoked from ankle dorsi-flexor nerves. Thin dorsal root filaments were dissected for recording afferent activity during muscle extension. The skin flaps around exposed areas of the cord were sewn up to form a pool filled with warm paraffin oil.

Recording and stimulation (*see Fig.* 1*A–D*). The muscle was stretched by an accurate manipulator allowing only one speed (0·8 mm/sec). Several parameters were monitored during extension (Fig. 1*A*); firing frequency of an isolated I*a* fibre, e.m.g., tension and a monosynaptic test reflex. Measurements were either made during periods starting 1·5–2·0 sec after completion of the dynamic phase of the stretch (maintained graded extension – static stretch, Fig. 1*B*) or during the dynamic phase (dynamic or phasic stretch, Fig. 1*C*). The monosynaptic test reflexes were evoked twice per second and five to ten responses were usually averaged (during static stretch). The I*a* afferents were identified by their response to passive stretch, muscle twitch and stimulation of the muscle nerve. The motoneuronal activity was monitored by recording the e.m.g. with thin copper wires inserted in the muscle. The e.m.g. was sometimes rectified and integrated to obtain a quantitative measure of the activity. Such measurements do not have any simple quantitative relationship with the motoneuronal activity (number of recruited motor units × firing frequency), since (1) there is a large variation of amplitudes between different motor units and (2) an 'occlusion' of the recorded activity may occur at high e.m.g. activity. Nevertheless, an increase of the integrated e.m.g. shows an increased motoneuronal activity while an apparently unchanged level does not exclude actual variations. Monosynaptic test reflexes, recorded from the ventral roots, were used to monitor reciprocal inhibition during muscle extension. The monosynaptic reflex from the pretibial flexors is weak in the decerebrate state and several animals were discarded because no monosynaptic text reflex could be evoked from the deep peroneal nerve even when double volleys were used. The active tension in the extensor muscles (plotted in most Figures) was obtained by subtracting the passive tension from the total tension measured at each muscle length.

The excitability of I*a* primary afferent terminals were tested by stimulation in the motor nuclei *ad modum* Wall (1958). Single stimuli were delivered through fine tungsten microelectrodes of low impedance (50–100 kΩ) or in case of pretibial flexors through low resistance glass capillary electrodes filled with 2 M-K citrate solution. The antidromic potentials were recorded from the peripheral nerve (Fig. 1*A*). When the quadriceps muscle was extended the spinal cord was often dislodged as much as 1 mm. It was therefore necessary to arrange a 'floating electrode' system. During insertion of the micro-electrode into the spinal cord it was fixed to the manipulator by solid stearin. When the electrode was placed in the spinal cord, the stearin was melted by current passage through a heating coil. The electrode then smoothly followed the movements of the spinal cord.

The nerves were stimulated with square-wave pulses of 0·1 msec duration and strength of stimulation is expressed in multiples of threshold (× *T*). Nerve volleys were recorded monopolarly from the dorsum of the spinal cord close to the dorsal root entry zone against an indifferent electrode in back muscles. Differentiation between afferent fibre groups was done as described by Bradley & Eccles (1953*b*) and Eccles, Eccles & Lundberg (1957*a*).

RESULTS

Section 1. Reciprocal inhibition during maintained graded extension

The results in this section were obtained from twelve cats in which seventy-three full stretch sequences were analysed. All data presented here were obtained from

animals with typical decerebrate tonic inhibition of transmission in I*b* and flexor reflex afferent pathways (R. M. Eccles & Lundberg, 1959). The active operation of this system was confirmed intermittently during the course of an experiment as the lack of effect on a flexor monosynaptic reflex (posterior biceps and semitendinosus or deep peroneus) by single conditioning volleys in high threshold muscle afferents. The consequence of a failing tonic inhibitory control of transmission in these pathways will be illustrated in section 3.

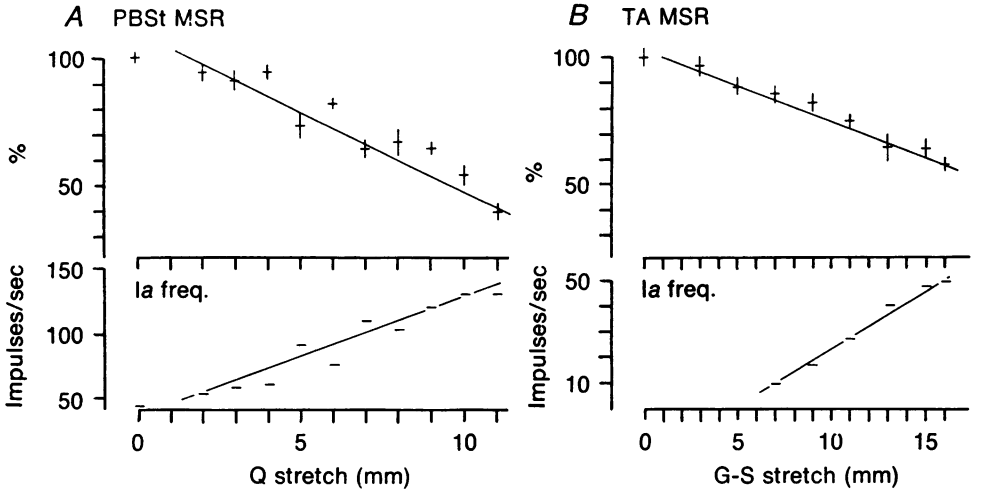


Fig. 2. Depression of 'antagonist' monosynaptic test reflex during muscle extension without a stretch reflex. *A*, upper diagram illustrates the decrease of a posterior biceps and semitendinosus monosynaptic test reflex (PBSt MSR) during extension of the quadriceps (Q) muscle (abscissa). The size of the reflex, ordinate, is expressed in per cent of the amplitude recorded with slack muscle (0 mm). The horizontal bars show the mean values and the vertical bars the S.E. of the means. Lower diagram shows the firing frequency of a monitored I*a* fibre. The abscissa is common for both upper and lower diagrams. *B*, similar arrangement as in *A* but with a tibialis anterior test reflex (TA MSR) and extension of triceps surae (G-S).

In the decerebrate cat a graded extension of the quadriceps or triceps surae muscles usually causes the development of a stretch reflex. Occasionally there is, however, a lack of reflex discharge despite the presence of an efficient static γ-bias. Though such examples are exceptional they make up a good starting point in this presentation since the reciprocal inhibition resulting from stretch is not then complicated by recurrent inhibition of the interneurones from motoneurones. Typical effects under these circumstances on a posterior biceps and semitendinosus monosynaptic reflex by stretch of the quadriceps and on a tibialis anterior reflex by stretch of the triceps surae are illustrated in Fig. 2*A* and *B*, respectively. The upper graphs show the decrease in monosynaptic test reflex amplitude (mean value and standard error of the mean) with increasing extension, while the lower graphs show the concomitant discharge frequency of monitored I*a* fibres to graded extension of respective muscles (common abscissa for upper and lower graphs). The lower graphs in both *A* and *B* reveal the expected linear relationship between extension and I*a* frequency (Eldred, Granit & Merton, 1953; Granit, 1958; Harvey & Matthews, 1961; Jansen & Matthews, 1962).

The decline of amplitude of the monosynaptic test reflex with increasing muscle extensions (upper graphs) was easily fitted by straight lines. Repeated stretch sequences confirmed that the deviations from the straight line in the upper graph of *A* depended on slow random fluctuation of these amplitudes. A close inspection of the relation between I*a* frequency and the posterior biceps and semitendinosus reflex amplitudes in Fig. 2*A* (e.g. the extensions of 4, 5, 6 and 7 mm) indeed suggests that this fluctuation is, at least partly, caused by a drifting γ-bias of the muscle spindles.

To summarize, in experiments in which a stretch reflex did not develop there is a linear relation between muscle length and depression of the test reflex of antagonists. It follows that when no recurrent inhibition is generated, there is a simple linear relation between the I*a* discharge from the extended muscle and the reciprocal inhibition of antagonists.

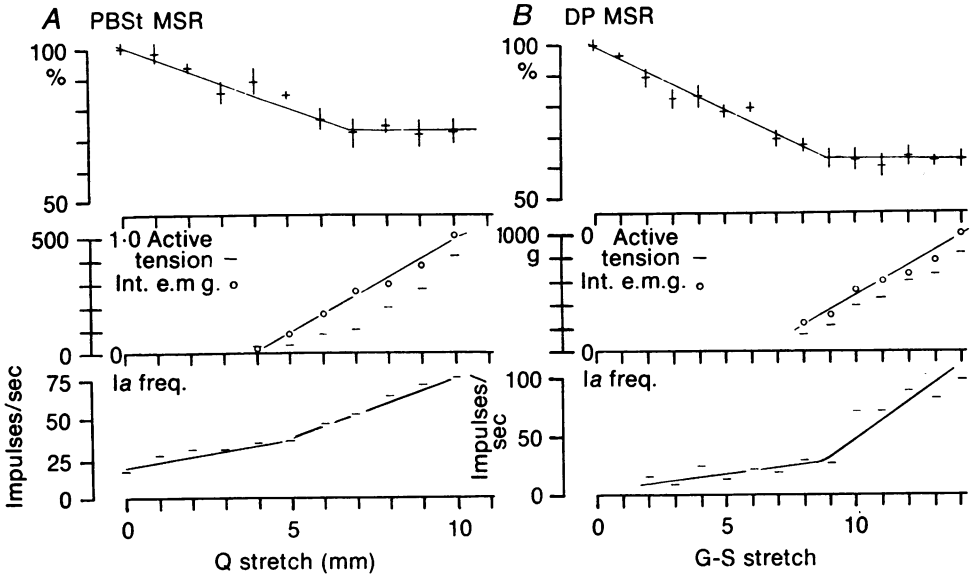


Fig. 3. Depression of 'antagonist' monosynaptic test reflex during muscle extension with continuously increasing e.m.g. activity. The general arrangement is similar to Fig. 2. *A*, upper graph illustrates decrease of a posterior biceps and semitendinosus monosynaptic test reflex (PBSt MSR) during extension of the quadriceps (Q) muscle (common abscissa for all three diagrams). The middle graph shows both rectified integrated e.m.g. (○) and active tension (—) during muscle extension. Lowermost diagram shows firing frequency of a monitored I*a* fibre. *B*, similar arrangement to *A* but with a deep peroneus (DP) monosynaptic test reflex and extension of triceps surae (G-S). In both *A* and *B* the slope of the firing rate in the I*a* fibre by coincidence increased at the threshold for the stretch reflex. Although a linear relationship between extension and firing frequency was the rule, exceptions like those illustrated in this Figure may be easily explained by the precise location of the muscle spindle in relation to the contracting motor units.

Fig. 3. illustrates one type of behaviour of 'antagonist' monosynaptic reflexes during quadriceps (*A*) or triceps surae (*B*) extensions. Initially during the extension there is a linear relationship between muscle extension and reciprocal inhibition just as for the previous examples from preparations without stretch reflexes. However,

with the appearance of a static stretch reflex at 4–5 mm in quadriceps (middle graph in *A*), the reflex soon ceased to decrease further with additional extensions though both the I*a* frequency (cf. legend) and the stretch reflex (active tension and e.m.g.) continued to increase. The same feature is displayed in *B* on stretching the triceps surae. As exemplified in Fig. 3 the plateau of reciprocal inhibition regularly developed after one or a few millimeters stretch beyond the threshold for the static stretch reflex. The plateau never appeared before the e.m.g. onset. The simplest explanation of this regular behaviour is to assume that increments of I*a* excitation and recurrent inhibition in the I*a* inhibitory interneurones almost exactly balance each other at successive muscle extensions beyond the threshold for reflex discharge.

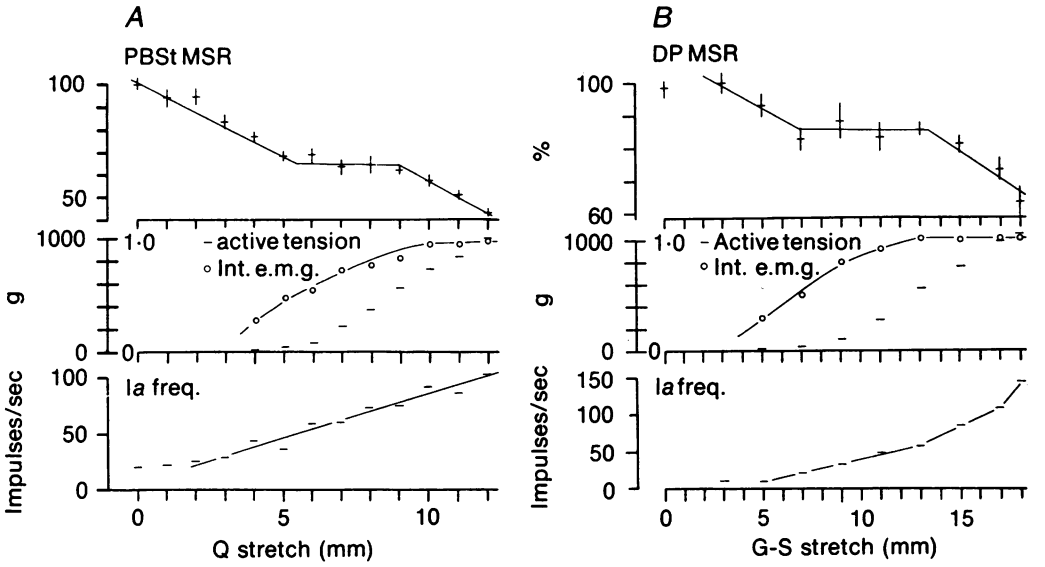


Fig. 4. Depression of 'antagonist' monosynaptic test reflex during muscle extension with saturating e.m.g. activity. The arrangement and abbreviations of the Figure are identical with Fig. 3.

In several experiments the plateau of the monosynaptic test reflex decline was maintained only over a certain range of extension and with further stretch of the muscle the inhibition again increased. This feature is illustrated and analysed in Figs. 4 and 5. Fig. 4 shows the results of stretching quadriceps (*A*) and triceps surae (*B*). In both cases the initial events conform with the results discussed in relation to the previous Figure (Fig. 3); with increasing extension there was first a linear increase in reciprocal inhibition (i.e. decrease of 'antagonist' test amplitudes), but when the stretch reflex commenced, and grew, the curve levelled off and the inhibition reached a plateau. Further extension, however, caused a second phase with linear increase of inhibition. For interpretation of the second phase of inhibition during stretch reflexes in some cats it is relevant that Grillner & Udo (1971*a*, *b*) have demonstrated a pronounced non-linearity in motoneuronal activity during 'good' stretch reflexes in the soleus muscle. At increasing lengths the recruitment of new motoneurones was successively reduced and each individual motoneurone stabilized its firing frequency soon after recruitment. The often linear relation between length and

tension at greater lengths was instead largely due to stiffness of already active muscle fibres. The middle graphs in Fig. 4 indeed suggest that such a saturation of motoneuronal activity occurred in those experiments since the rectified integrated e.m.g. levelled off at the largest extensions. It should be observed that this saturation occurs despite an increase of firing frequences in the Ia afferents (lower graphs). In this situation one would expect an imbalance between the two opposing processes controlling the Ia inhibitory interneurones with increasing muscle lengths. The linear increase in Ia excitatory action would be met with successively decreased increments in recurrent inhibition which would result in an increased reciprocal inhibition with higher degrees of extension.

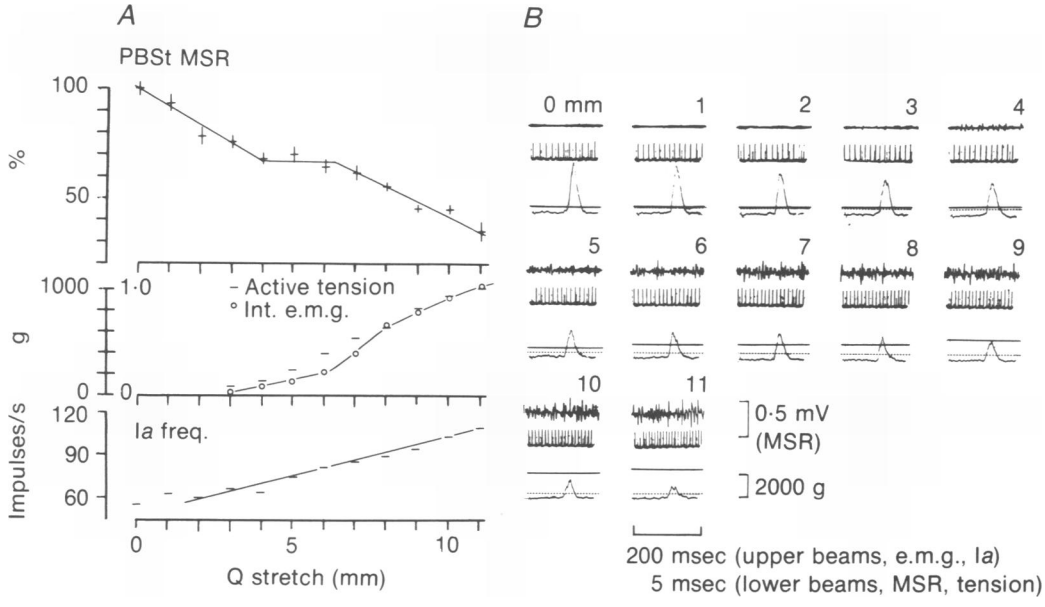


Fig. 5. Depression of 'antagonist' monosynaptic test reflex during muscle extension with continuously increasing e.m.g. activity. *A*, the arrangement and abbreviations of the Figure are identical with Fig. 3. *B*, specimen records from different extensions (0–11 mm). The traces (from top to bottom) record e.m.g. activity, firing in a Ia fibre, posterior biceps and semitendinosus monosynaptic test reflex and total tension. The interrupted line shows tension at 0 mm. Note that the sweep speeds are different for upper and lower traces. Spikes have been retouched.

The interpretation given above cannot always (or not alone) explain the increased reciprocal inhibition with large extensions as is evident from results exemplified in Fig. 5. The phases of declining and constant 'antagonist' test reflex amplitudes during muscle extension was very similar to that shown in Fig. 4. The additional decrease of the test reflex at large extension is, however, *not* correlated with any e.m.g. saturation as seen both from the middle graph (in *A*) and specimen records (in *B*). Another example of augmenting reciprocal inhibition without e.m.g. saturation is given in Fig. 7. In this case the inhibitory curve has no clear interposed plateau in relation to the onset of the agonist e.m.g. activity. Consequently the inhibitory curve resembles that found in experiments without agonist stretch reflex

activity (Fig. 2). Experiments to establish possible mechanisms for the second phase of depression in such cases will be presented in the next section.

A quantitative presentation of all the results is given in Fig. 6. Every analysed stretch sequence was classified in respect to the development of e.m.g. (no e.m.g., continuously increasing e.m.g., saturating e.m.g.) and reciprocal inhibition of the 'antagonist' test reflex (linear increase of the depression, linear increase followed by a plateau and linear increases in the beginning and the end with an interposed plateau).

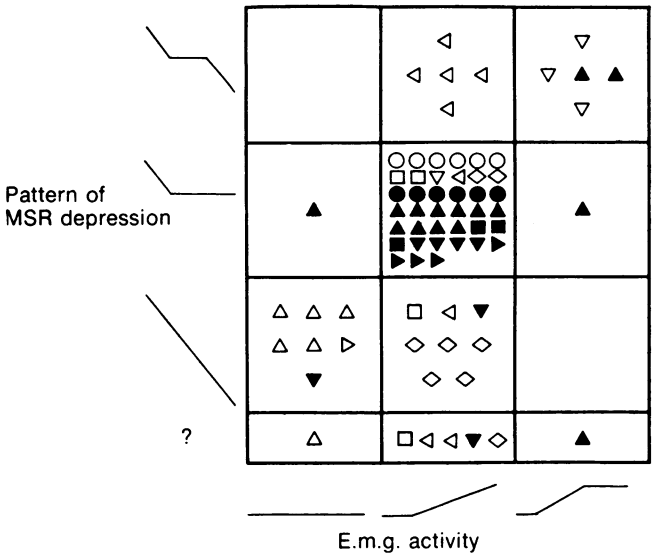


Fig. 6. Comparison between e.m.g. development of the extended muscle and the pattern of depression of 'antagonist' monosynaptic reflex. For each of the seventy-three analysed stretch sequences the type of e.m.g. development (no e.m.g., continuously increasing e.m.g., saturating e.m.g.) was plotted against the pattern of monosynaptic test reflex (MSR) depression (linear increase of the depression, linear increase followed by a plateau and linear increase in the beginning and the end with an interposed plateau). A fourth group (lowermost row denoted by a question mark) was for cases where judgement was impossible. Open and filled symbols refer to experiments on quadriceps and triceps surae, respectively. Symbols of different shapes are used to discriminate between different cats within the former grouping.

The degree of arbitrariness that goes into such a classification can be appreciated from an examination of Figs. 2–5 and 7. As appears from these examples the progressive decline of the monosynaptic test reflex amplitude is never absolutely smooth, neither is the plateau absolutely horizontal. Rather than to 'force fit' all our results into the above three groups a fourth group was instituted for cases which were difficult to judge. It is worth mentioning that this questionable group includes no example of a decreased depression in the test reflex during increased extension.

Each sign in Fig. 6 represents one full stretch sequence. Open and filled symbols are used to distinguish between experiments with the quadriceps and triceps muscles while different shapes are used to discriminate between different cats within the former grouping. When no e.m.g. developed during muscle extension a linear decline

of the monosynaptic test reflex amplitudes was confirmed in all but two cases. When a continuous increase in the e.m.g. occurred with extensions beyond threshold (second column), the linear decrease of the test reflex seen before reaching that threshold levelled off in the upper two groups resulting in an interposed or a fairly well maintained plateau. The large middle group in the second column includes some examples (particularly for the quadriceps) with rather 'bad' stretch reflexes, i.e. small active tension even at large extensions (cf. Fig. 3*A* and case illustrated by Hultborn & Lundberg, 1972). The maintained plateau in these cases may correspond to the interposed plateau in experiments when high active tension developed during the stretch reflex. The lower group in the second column may be related to the upper one and the absence of interposed plateau merely indicates a low threshold for the

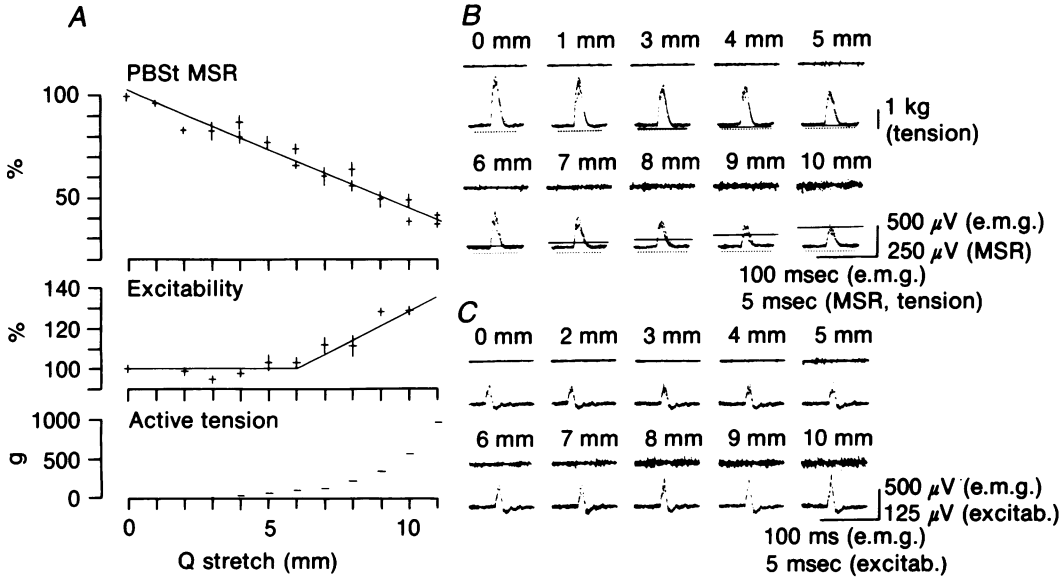


Fig. 7. Depression of a posterior-biceps and semitendinosus test reflex and increased excitability of Ia terminals during extension of quadriceps. *A*, upper graph illustrates the decrease of a posterior biceps and semitendinosus reflex during extension of the quadriceps muscle. Lowermost graph displays the active tension from the same stretch. The middle graph shows the increased excitability of posterior-biceps and semitendinosus Ia terminals, i.e. the increased amplitude of the antidromic volley in Ia afferents, during a stretch sequence just following the one from which the upper graph was obtained. *B*, specimen records related to the upper graph in *A*, the traces (from top to bottom) record e.m.g., posterior biceps and semitendinosus monosynaptic test reflex and total tension. The interrupted line shows the tension at 0 mm. *C*, specimen records related to the middle graph in *A*. The upper traces show e.m.g. and the lower traces the antidromic response in posterior biceps and semitendinosus Ia afferents recorded in the nerve following stimulation in the motor nucleus. Abbreviations as in Fig. 3.

second phase of incrementing inhibition. The different results obtained on stretch of quadriceps and triceps surae (middle column) and the role of presynaptic inhibition of the test reflex will be considered in the next section. When the e.m.g. saturated (third column) there was only one exception to the rule of a second phase of reflex reduction with larger extension.

In several cases the depression of the amplitudes of 'antagonist' monosynaptic test reflexes was studied during slow phasic stretch (0·8 mm/sec, see Methods) in addition to the maintained static extensions discussed above. The rational of that experiment was to 'dissect' the influence of the different muscle receptors which might influence the stretch reflex (Houk, Singer & Goldman, 1970; Matthews, 1972) and the reciprocal reflex depression. Even for the modest speed of 0·8 mm/sec the dynamic sensitivity of the primary endings was large enough to give firing frequencies corresponding to an additional static extension of 2–3 mm. Since the secondary endings rather lack dynamic sensitivity (Matthews, 1963) it follows that the firing of group I*a* and group II fibres have been 'separated' corresponding to an extension of about 2–3 mm. Firing frequency in I*b* afferents from Golgi tendon organs is mainly a function of active tension (in series with the receptor, Stauffer & Stephens, 1975). Because of the well known relation between muscle length and active tension the same amount of motoneuronal activity will cause less active tension at shorter muscle lengths (see Grillner & Udo, 1971*a*; Grillner, 1972). Since the e.m.g. activity starts and develops with less extensions during dynamic stretch (the dynamic sensitivity of the primary endings) it follows that the I*b* frequency would be less under dynamic than static stretch when related to the amount of e.m.g. activity. When the data obtained from the dynamic stretch situation were plotted in graphs similar to those presented in Figs. 2–5 and compared with those from equivalent static stretch, there was usually a simple shift to the left by several millimetres for I*a* frequency, integrated e.m.g. and 'antagonist' test reflex amplitudes. These observations suggest that the reciprocal decrease of test reflexes is governed mainly by I*a* frequency from and motoneuronal activity to the extended muscle and also that the latter depends mainly on the I*a* activity. The modest velocity of 0·8 mm/sec does not permit any optimal 'dissection' of activity from different receptor afferents, but higher velocities, on the other hand, would not permit sufficient resolution in the measurement of reciprocal inhibition (the test reflexes were elicited at 2 Hz). Higher and systematically changed velocities of the dynamic stretch with simultaneous direct recording from the I*a* inhibitory interneurons (cf. Benecke, Böttcher, Henatsch, Meyer-Lohmann & Schmidt, 1975) may, however, exploit the possibility to judge the relative importance of the various proprioceptors.

Section 2. Contribution of presynaptic inhibition to depression of the monosynaptic test reflex to antagonists

There are several examples in Fig. 6 of stretch sequences with continuously increasing e.m.g. activity (middle column) that were accompanied by a second decline of the monosynaptic test reflex at large extensions (exemplified in Fig. 5) or by a continuous decrease during the development of the stretch reflex (Fig. 7). Such results are seemingly contrary to our hypothesis of a balance between I*a* excitation and recurrent inhibition at the level of the I*a* inhibitory interneurones. It must, however, be recalled that transmission in group I pathways mediating presynaptic inhibition is *not* depressed in the decerebrate preparation (Carpenter, Engberg, Funkenstein & Lundberg, 1963) in contrast to I*b* and flexor reflex pathways to motoneurones. It is therefore conceivable that muscle stretch will cause a presynaptic inhibition at the terminals of the I*a* afferents from the antagonist flexor muscle which then would contribute to the decreased amplitudes of the monosynaptic test reflex.

Presynaptic inhibition of I*a* transmission is particularly powerful from flexors but some effects are evoked also from extensors. In the original investigation by Eccles *et al.* (1962*b*), employing electrical stimulation of nerves, it was found that significant effects could be evoked from quadriceps but not from triceps surae. Accordingly, if presynaptic inhibition contributes to the reciprocal depression of the monosynaptic test reflex some differences in effects from these two muscles would rather be expected. Inspection of the second column in Fig. 6 reveals that in no single case did stretch

of triceps surae give augmentation of the test reflex depression after an interposed plateau (upper group) and there is only one exception among the eight examples in the lower group. Triceps surae, on the other hand, dominates in the middle group with maintained plateaux. In order to test if there was a corresponding difference in presynaptic inhibition excitability measurements were made. Figs. 7 and 12 show

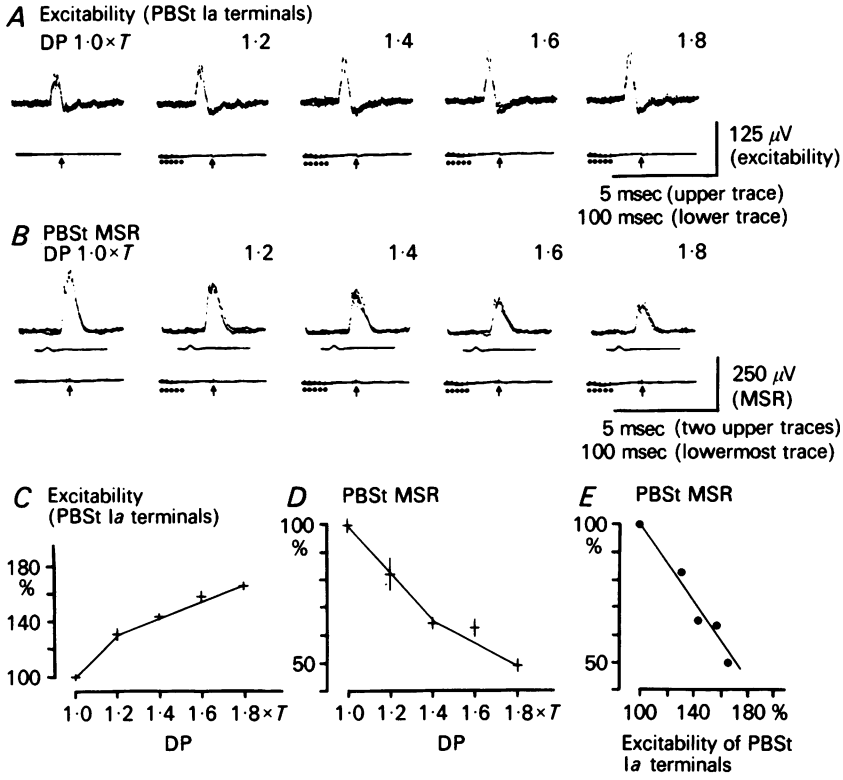


Fig. 8. Relation between increased excitability of posterior biceps and semitendinosus Ia terminals and depression of the test reflex mediated by these afferents. *A*, upper traces show the antidromic response in the posterior biceps and semitendinosus nerve to constant stimulation of the Ia terminals in the motor nucleus, when preceded by graded group I volleys in the deep peroneus nerve. Lower traces are recorded from the dorsal root entry zone and show the timing of the deep peroneus stimuli (dots) and the test stimulus to the Ia terminals (arrow). Note that the sweep speed is much slower for the lower records. *B*, upper traces show the amplitude of posterior biceps and semitendinosus monosynaptic test reflexes when preceded by graded group I volleys in the deep peroneus nerve. Middle traces are records from the dorsal root entry zone. Lowermost traces are also records from the dorsal root entry zone, but with a slower sweep speed in order to show the timing of the deep peroneus stimuli (dots) and the posterior biceps and semitendinosus test stimulus (arrow). *C*, diagram showing the relation between the amplitude of the antidromic response in the nerve to a constant stimulus in its motor nucleus (mean values and S.E. of the means) and the stimulus strength of the conditioning deep peroneus train. *D*, diagram showing the relation between the reflex amplitude and the stimulus strength of the conditioning deep peroneus train. *E*, diagram showing the relation between the decrease of the posterior biceps and semitendinosus monosynaptie test reflex and the increased excitability of the Ia terminals (obtained by a combination of diagrams in *C* and *D*). Abbreviations as in Fig. 3.

that a depolarization was indeed evoked in posterior biceps and semitendinosus I*a* terminals during stretch reflex in quadriceps (three experiments), but not in deep peroneus I*a* terminals during a stretch reflex in triceps surae (two experiments). We will describe how the degree of presynaptic inhibition could be evaluated from these excitability measurements. The results suggest that in experiments with continuously increasing e.m.g. the second phase of depression of the monosynaptic test reflex from the posterior biceps and semitendinosus is caused by presynaptic inhibition of the test.

Fig. 7 illustrates a continuous decline of the test reflex from the posterior biceps and semitendinosus with increasing extension of quadriceps despite a continuously growing e.m.g. activity beyond the threshold at 5 mm (see specimen records in *B*). When the excitability of posterior biceps and semitendinosus I*a* terminals was tested at

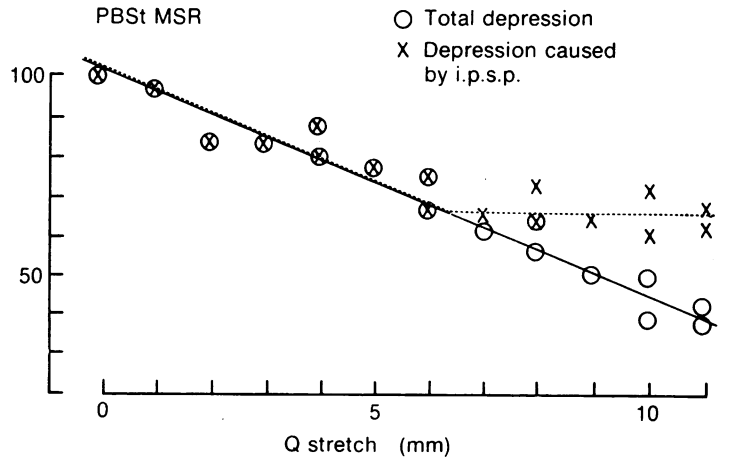


Fig. 9. Pre- and post-synaptic components in the depression of a posterior biceps and semitendinosus monosynaptic test reflex during quadriceps extension. Open circles are identical with the mean values for depression of the test reflex in the upper graph of Fig. 7*A*. The crosses show the depression which is left after a subtraction of the presynaptic component estimated from the increased excitability of the posterior biceps and semitendinosus I*a* terminals during muscle extension (middle graphs Fig. 7*A*) and the relation between excitability increase and test reflex depression (Fig. 8*E*). Abbreviations as in Fig. 3.

corresponding extensions, a large excitability increase occurred along with the development of active tension (middle and lower graphs in *A* and specimen records in *C*). Fig. 8 illustrates the procedure which was used to quantify to which extent the depression of the monosynaptic test reflex (upper graph in Fig. 7*A*) was due to presynaptic inhibition. Different degrees of excitability increase in the posterior biceps and semitendinosus I*a* terminals were elicited by a train of graded group I volleys in the deep peroneal nerve (Fig. 8*A*; cf. Eccles, Magni & Willis, 1962*a*). The relation between the size of compound antidromic response and strength of conditioning stimulation is shown in Fig. 8*C*. The effect of the same conditioning stimuli on the posterior biceps and semitendinosus test reflex, adjusted to the same size as that used in the measurements of reciprocal inhibition during the stretch reflex, was then registered (records in *B*) and plotted (Fig. 8*D*).

Since it can be assumed that the inhibitory effect of this conditioning stimulation is of purely presynaptic nature (cf. Eccles, Eccles & Lundberg, 1957*b*; R. M. Eccles & Lundberg, 1959) it was possible to use the graphs in *C* and *D* to obtain a relation between the increased excitability of posterior biceps and semitendinosus Ia terminals and the resulting presynaptic inhibition of the test reflex (graph *E* in Fig. 8). From this relationship the part of the inhibition which was caused by primary afferent depolarization during the stretch reflex may be subtracted from the total inhibition.

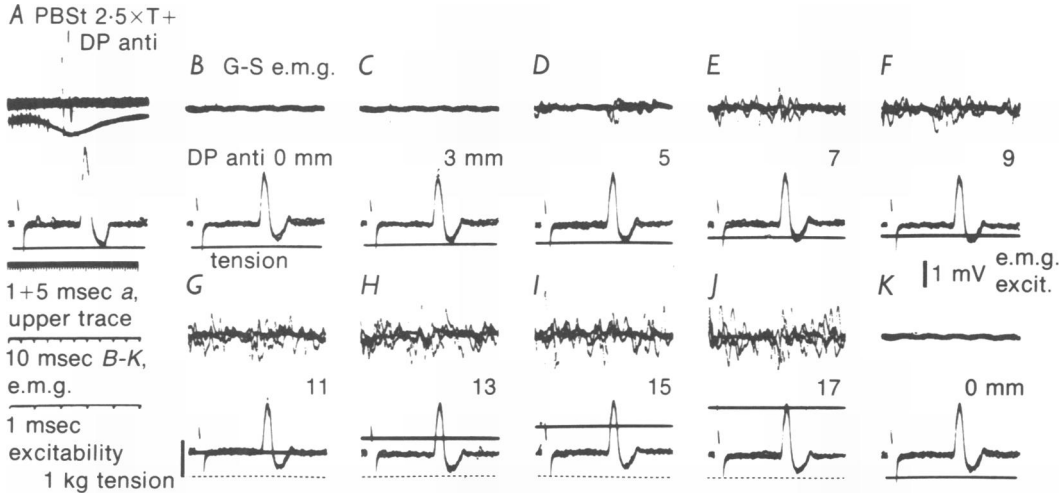


Fig. 10. Absence of increased excitability in the deep peroneus Ia afferents during a stretch reflex in triceps surae. The traces in *B–K* are records of e.m.g., antidromic response in deep peroneus Ia afferents and tension; zero tension is indicated by interrupted lines in *G–J*. Compare the unchanged excitability in *D–J* with the large increase in *A* evoked by a train of volleys in the posterior biceps and semitendinosus nerve at maximal group I strength, 2·5 times threshold. Upper and lower pair of traces in *A* were taken simultaneously at different speeds. Upper records in each pair in *A* is the antidromic response in deep peroneus Ia afferents. The second trace in *A* shows the group I volleys from the posterior biceps and semitendinosus recorded at the L7 dorsal root entry zone. Abbreviations as in Fig. 3.

The outcome of this subtraction for the present example is illustrated in Fig. 9. The circles are the mean values for the depression of the test reflex shown in the upper graph of Fig. 7*A*. The crosses (approximated by the interrupted line) show the resulting curve after subtraction and should represent the *post*-synaptic inhibition only. It is evident that this estimated post-synaptic inhibition levels off and stays virtually constant during increased stretch reflex activity with extension beyond 4–5 mm. Even this example, which at the first sight appeared to contradict the hypothesis, suggests a reasonable balance between the two opposing systems (Ia excitation and recurrent inhibition) controlling the excitability of Ia inhibitory interneurones. Turning back to Fig. 6, it is seen that increasing depression during extensions with growing e.m.g. was encountered at thirteen occasions. Five of these cases were tested for presynaptic inhibition as described above and in all of them the estimated presynaptic inhibition was of the same order of magnitude as the late depression, i.e. that the computed *post*-synaptic inhibition was kept at a fairly constant level.

Fig. 10 illustrates corresponding excitability measurements from the deep peroneus I*a* afferents during static stretch of triceps surae. Threshold for the stretch reflex was at 5 mm extension (*D*) and *E–J* show that the e.m.g. increased continuously when the muscle was stretched up to 12 mm beyond this level. Note the absence of an excitability change at all lengths while the short train of group I volleys in the posterior biceps and semitendinosus nerve evoked a very large excitability increase (lower traces *A*, *B*). Accordingly, the difference in reciprocal effects from quadriceps and triceps surae (second column in Fig. 6) appears to be well explained by the differences in presynaptic effect on the terminals of I*a* afferents from the antagonist.

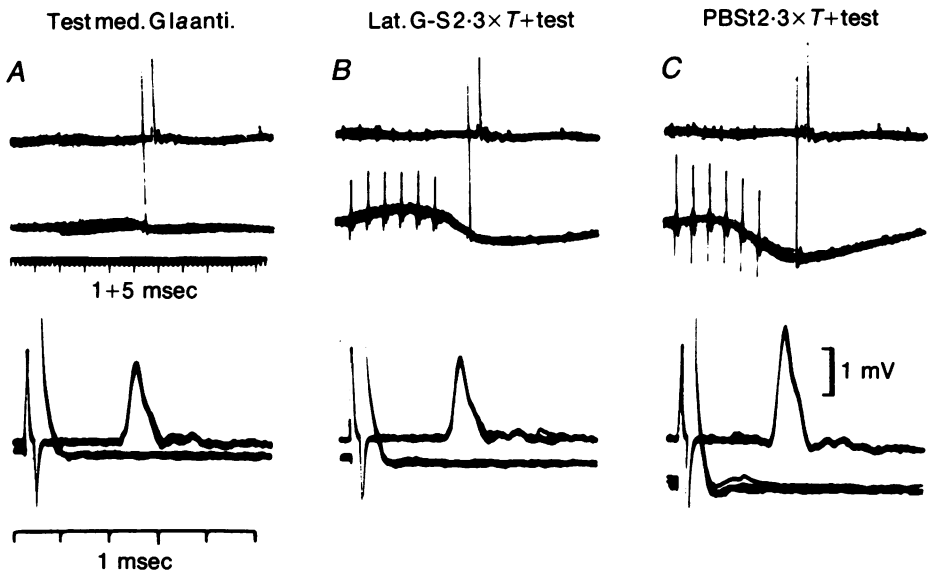


Fig. 11. Effect of a train of group I volleys from the posterior biceps-semitendinosus and lateral gastrocnemius-soleus on the excitability of medial gastrocnemius I*a* afferents. Upper and lower pairs of records were taken simultaneously at different sweep speed. Upper traces in each pair of records show the antidromic response in the medial gastrocnemius nerve (med. G) to stimulation of the I*a* terminals in the motor nucleus. Lower traces are records from the dorsal root entry zone. Strength of conditioning stimulation of the posterior biceps and semitendinosus and lateral gastrocnemius-soleus (lat. G–S) nerves are indicated in multiples of threshold. These records were obtained in an experiment on a low spinal cat anaesthetized with chloralose (40 mg/kg). The body temperature was 38 °C which may be relevant for comparison with results obtained by Decandia *et al.* (1967) in similar experiments but with a body temperature of 35 °C.

It must be kept in mind that presynaptic inhibition evoked by the stretch reflex might influence the measurements not only by the effect on the antagonist monosynaptic test reflex but also by the effect on transmission from homonymous I*a* afferents to motoneurones and I*a* inhibitory interneurones. The lack of widespread effects from triceps surae (Eccles *et al.* 1962*b*) cannot be taken to suggest that its own I*a* afferent terminals are uninfluenced. Experiments with strong adequate stimulation have indeed revealed such effects (Barnes & Pompeiano, 1970) and Decandia, Provini & Táboříková (1967) reported that medial gastrocnemius I*a* afferent terminals were as effectively depolarized by a short train of nerve volleys from lateral gastrocnemius-soleus as from the posterior biceps and semitendinosus. We have repeated the experiments by Decandia *et al.* (1967) on unanaesthetized decerebrate cats and on chloralose

anaesthetized spinal cats but failed to confirm their results; compare in Fig. 11 the large effect evoked by six posterior biceps and semitendinosus volleys with the lack of effect during similar conditioning stimulation of the nerve to lateral gastrocnemius-soleus. Accordingly, it seems unlikely that the interpretation of our results is complicated by presynaptic inhibition back onto Ia afferents belonging to triceps surae.

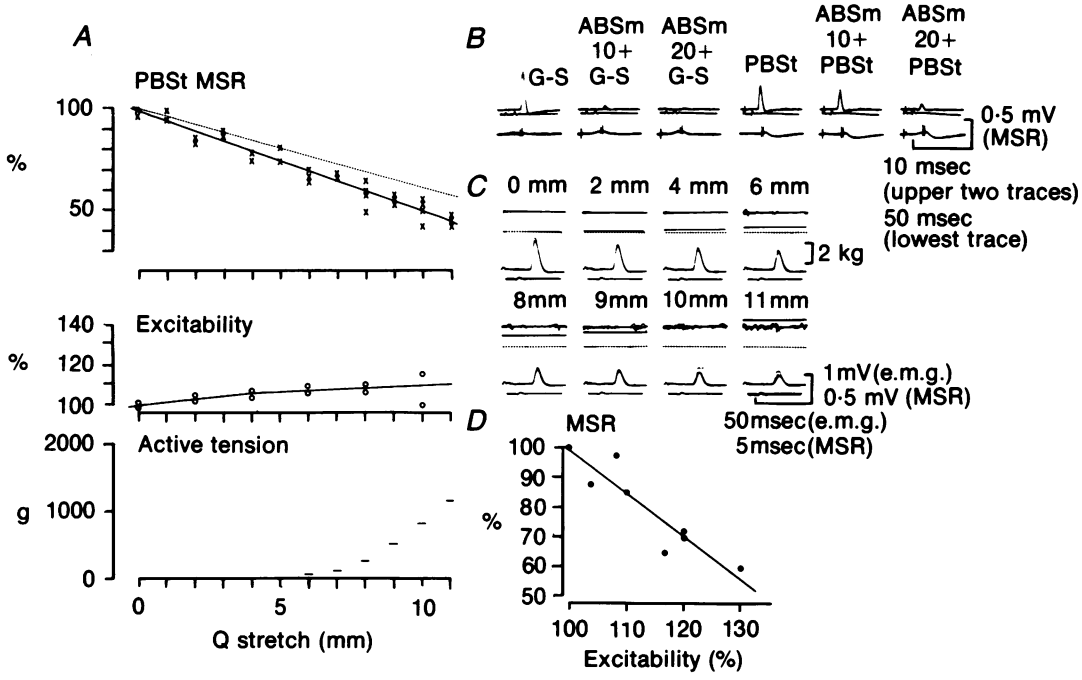


Fig. 12. Depression of a posterior biceps and semitendinosus monosynaptic test reflex during quadriceps extension in a preparation with failing decerebrate control of reflex transmission. *A*, upper graph shows the decrease of a test reflex during repeated extensions of the quadriceps muscle (each cross is the mean value of five to ten responses). The interrupted line represents the depression which is caused by *post*-synaptic inhibition. Lower graph shows the development of active tension at one of the stretch sequences. The middle graph illustrates the excitability increase of the posterior biceps and semitendinosus Ia terminals obtained from another stretch sequence. *B*, upper traces: monosynaptic test reflexes (from gastrocnemius-soleus and posterior biceps and semidendinosus) and their inhibition by preceding single volleys in high threshold afferents in the nerve of the anterior biceps and semimembranosus, ABSm, 10 and 20 × *T*). Lower traces are records from the dorsal root entry zone; the middle trace taken at the same sweep speed as the monosynaptic test reflex, the lower at a slower speed to show the interval between conditioning and testing volleys. *C*, specimen records related to the upper graph in *A*. The traces (from top to bottom) record e.m.g., total tension (interrupted lines show the tension at 0 mm), monosynaptic test reflex and the cord dorsum potential. *D*, diagram showing the relation between the decrease of the test reflex and the increased excitability of nerve terminals.

Section 3. The effect of failing decerebrate tonic inhibition of transmission in flexor reflex pathways

All data presented in sections 1 and 2 were obtained under conditions with typical decerebrate tonic inhibition of transmission in Ib and flexor reflex pathways. Sometimes this tonic inhibition started to fail during the course of an experiment. In Fig. 12 this was confirmed by an efficient inhibition of monosynaptic test reflexes to gastro-

cnemius-soleus as well as posterior biceps and semitendinosus by single conditioning volleys to the anterior biceps and semimembranosus nerve (10 and $20 \times T$, Fig. 12*B*). Despite this deteriorating condition a stretch reflex developed when the quadriceps muscle was extended (lowest graph). The 'antagonist' posterior biceps and semitendinosus test reflex then displayed a continuous decline in amplitude throughout the extension (upper graph). This pattern may look very similar to that in Fig. 7 but in contrast compensation for presynaptic inhibition indicates that even the *post*-synaptic inhibition grows linearly during the whole muscle extension (interrupted line in the upper graph; subtraction of presynaptic component was done as illustrated in Figs. 7–9). It is suggested that the continuous increase of the calculated post-synaptic inhibition of posterior biceps and semitendinosus motoneurones under these conditions is due to the contribution of afferents other than I*a* afferents.

It is seen that the magnitude of presynaptic inhibition in Fig. 12, i.e. when a release of flexor reflex afferent inhibition occurred, is much smaller than in the example of Fig. 9. It was noticed several times that when such a release occurred, the presynaptic inhibition tended to be weak even when large active tensions were produced during the stretch reflex. This observation may be correlated with earlier findings that activity in the flexor reflex afferents effectively inhibits transmission in the pathways giving primary afferent depolarization in the terminals of I*a* afferents (Lund, Lundberg & Vyklický, 1965).

DISCUSSION

Reciprocal Ia inhibition during the stretch reflex

It may appear hopeless to reach simple and unequivocal answers regarding post-synaptic reciprocal I*a* inhibition from results obtained when stretching the antagonist muscle. Not only are several species of muscle afferents activated during stretch or contraction but all of them may affect antagonist motoneurones via different pathways. However, in the present investigation we have taken advantage of the fact that reflex pathways to motoneurones from other muscle afferents than I*a* afferents are tonically inhibited at an interneuronal level in the decerebrate state (R. M. Eccles & Lundberg, 1959). This tonic inhibition may vary in effectiveness between different decerebrate cats (cf. section 3) but when it is pronounced there is complete inhibition not only of transmission from single primary afferent volleys to motoneurones but also of the effects evoked by very strong adequate receptor stimulation (Holmqvist & Lundberg, 1961). The assessment of interaction between I*a* excitation and recurrent inhibition in the control of the reciprocal I*a* inhibitory pathway was made on decerebrate cats in which the descending inhibition of reflex transmission to motoneurones operated effectively. Nevertheless, our interpretation of the results must be based on some assumptions given in the small print section below. Also, it must be kept in mind that inhibition of the antagonist monosynaptic test reflex may be evoked not only post-synaptically but also presynaptically by depolarization of the I*a* terminals conveying the test reflex. Transmission in the pathway mediating primary afferent depolarization to I*a* afferent terminals is not tonically inhibited in the decerebrate cat (Carpenter *et al.* 1963) and volleys in group I afferents from the knee extensors do indeed give presynaptic inhibition of transmission from posterior biceps and semitendinosus I*a* afferents (Eccles *et al.* 1962*b*). Accordingly, it was not unexpected to find significant presynaptic inhibition of the posterior biceps and

semitendinosus test reflex during the stretch-evoked contraction in quadriceps and in order to study the role of post-synaptic reciprocal Ia inhibition it was necessary to measure and subtract the monosynaptic test reflex depression contributed by presynaptic inhibition. In the case of triceps surae, on the other hand, our measurements show that the interpretation of the results is not complicated by presynaptic inhibition of the deep peroneal test reflex.

Primary afferents other than Ia afferents may influence reflex actions evoked by muscle stretch not only via reflex paths to motoneurones but also via their interneuronal pathways to the interneurones mediating reciprocal Ia inhibition; they are known to receive convergence of interneuronal paths from primary afferents (Fedina & Hultborn, 1972; Fedina, Hultborn & Illert, 1975). The interpretation of the present results is based on the assumption of a parallel descending tonic inhibitory control of the interneuronal pathways to motoneurones and Ia inhibitory interneurones, implying that the existence of an effective tonic control of reflex transmission to motoneurones indicates a similar control of corresponding interneuronal pathways to the Ia inhibitory interneurones. This assumption seems a reasonable one as there is now extensive evidence for a parallelism in projection to motoneurones and Ia inhibitory interneurones (see Hultborn, 1976). It does in fact have some experimental support since it has been shown that interneuronal paths from the flexor reflex afferent to Ia inhibitory interneurones are tonically inhibited in the decerebrate state (L. Fedina & H. Hultborn, 1972, and unpublished observations).

Recent investigations have shown that also secondary afferents have a monosynaptic projection to motoneurones (Kirkwood & Sears, 1975; Stauffer, Watt, Taylor, Reinking & Stuart, 1976) and thus may contribute to the stretch reflex as originally proposed from indirect evidence (Matthews, 1972; cf. however Jack & Roberts, 1978). The amount of monosynaptic action from secondary afferents is still a matter of controversy and it may well be marginal (cf. Lundberg, Malmgren & Schomburg, 1977). In any case we assume that there is a corresponding projection to the Ia inhibitory interneurones as has been found for other afferent systems (Hultborn, 1976). If so, the effect from secondary afferents can be disregarded in the present context.

It is also necessary to make certain assumptions regarding the role of presynaptic inhibition of Ia transmission during the stretch reflex. As part of the widespread effect from quadriceps (Eccles *et al.* 1962*b*) it must be expected that during the stretch reflex in this muscle a depolarization is also evoked back in its own Ia afferent terminals. It seems reasonable to assume that Ia afferent terminals on motoneurones and Ia inhibitory interneurones receive a parallel primary afferent depolarization and that the ensuing presynaptic inhibition reduces the synaptic efficacy of Ia transmission proportionally. This assumption implies that presynaptic inhibition does not cause an asymmetry in the degree of agonist activation and the depth of reciprocal inhibition; i.e. it would have the same effect as a decrease in Ia firing frequency. Since the e.m.g. activity continues to increase when the muscle is extended beyond threshold for the stretch reflex it follows that presynaptic inhibition in this phase only very partially counteracts the increasing Ia excitation. Eccles *et al.* (1962*b*) showed that widespread effects on Ia afferent terminals are not evoked by a train of group I volleys from triceps surae, but other results (Decandia *et al.* 1967; Barnes & Pompeiano, 1970) have raised the question whether there exists a more specific restricted action from triceps surae on its own Ia afferent terminals. However, since we failed to confirm the findings by Decandia *et al.* (1967) we find no reason to assume that the stretch reflex in triceps surae is associated with a depolarization of its own Ia afferent terminals. The effects obtained with massive synchronous adequate activation (Barnes & Pompeiano, 1970) may have been transmitted through functionally marginal connexions from triceps surae to the system giving widespread depolarization of Ia afferent terminals (Eccles *et al.* 1962*b*). The lack of effect on deep peroneal Ia afferent terminals suggests that the more asynchronous adequate receptor activation during the stretch reflex does not suffice to activate the widespread system.

The experimental results have proved a linear relationship between reciprocal depression of monosynaptic test reflexes and firing frequency in Ia afferents below the threshold for the stretch reflex. We postulate that this inhibition is post-synap-

tically evoked via the reciprocal Ia inhibitory pathway. With the appearance of a static stretch reflex the inhibition often reached a plateau, although firing frequency of Ia afferents, e.m.g. and active tension all increased with further extension. We believe that this plateau is caused largely by recurrent inhibition from the active agonist motoneurones of transmission in the reciprocal Ia inhibitory pathway. The plateau sometimes appeared at the very threshold for the motoneuronal activity, but more typically it developed with some additional extension presumably because there is need for some excitatory summation onto Renshaw cells, i.e. the motoneuronal activity to the stretched muscle must reach a certain level before the Renshaw cells start to transmit recurrent inhibition and to level off further increase of reciprocal Ia inhibition. In some experiments, particularly with stretch of the knee extensors, the plateau was maintained only for a certain range of extensions and with further stretch the inhibition increased again. An important part of our analysis has aimed at disclosing the nature of this second phase of depression which appears to be contributed by two different mechanisms. First, the contraction of the stretched knee extensor evoked presynaptic inhibition of the antagonist monosynaptic test reflex used to test reciprocal inhibition; the absence of a corresponding presynaptic inhibition on stretch of the ankle extensors agrees well with the original findings regarding presynaptic inhibition from different extensors (Eccles *et al.* 1962*b*). Secondly, when the e.m.g. of the stretched muscle saturated at large extensions there was regularly a marked enhancement of reciprocal inhibition as would be expected since in this situation the excess of Ia excitation was not matched by a corresponding increase in recurrent inhibition. One or the other of these mechanisms may dominate in the individual experimental situation but it is noteworthy that under conditions of a reasonable linear e.m.g. increment during the entire range of extension tested, then the increment in depression of the test seemed to be rather well accounted for by presynaptic inhibition of the monosynaptic test reflex, as quantitatively assessed in special experiments. From these results we postulate that *the depth of the postsynaptic reciprocal Ia inhibition is kept relatively constant at different degrees of agonist stretch reflex activation*. Since the depth of reciprocal Ia inhibition depends on the activity in the Ia inhibitory interneurones the results suggest that their firing frequency during the initial stage of extension increases in direct relation to the increased firing rate in the Ia afferents from the extended muscle. After the onset of the stretch reflex, their firing is stabilized mainly because the incrementing Ia excitation is now counteracted by increasing recurrent inhibition.

The discussion above on the quantitative relation between Ia excitation and recurrent inhibition of Ia inhibitory interneurones rather assumes a linear relationship between motoneuronal activity and the amount of recurrent inhibition evoked by it. Such a relation, however, is far from selfevident since a gradually increased excitation of the pool of Renshaw cells may cause both a recruitment of fresh Renshaw cells and an increased firing frequency of those already recruited. Although the exact relationship between motoneuronal firing and Renshaw cell activity remains to be elucidated it seems that the very large recurrent i.p.s.p.s seen during intracellular recording from Ia inhibitory interneurones (Hultborn *et al.* 1971*b*; Hultborn, Illert & Santini, 1976*a*, *b*, *c*) are of the order of magnitude to cope with the equally very strong monosynaptic Ia excitation. Experiments by Benecke *et al.* (1975) have also shown that the increment in firing rate of individual Ia inhibitory interneurones (monosynaptically activated from the gastrocnemius-soleus nerve) during ramp stretch of triceps surae is considerably enhanced after administration of dihydro-β-erythroidine, a substance that blocks excitation of Renshaw cells

from motor axon collaterals. Unfortunately, Benecke *et al.* (1975) did not monitor the motoneuronal activity. It is therefore impossible to compare our quantitative data on the reciprocal inhibition with their direct recording from these interneurones. Since Benecke *et al.* (1975) often used anaesthetized and always curarized preparations it can be assumed that the primary endings were not very sensitive to static stretch and that a tonic stretch reflex may often be lacking in their animals. Their occasional recordings from Renshaw cells in response to ramp stretch indeed suggest that the motoneuronal discharge occurred mainly during the phasic stretch.

Function of reciprocal Ia inhibition in motor control

The significance of the present results must be viewed in light of the presumed role of the Ia stretch reflex and reciprocal inhibition in movements. Many neuronal systems evoke similar effects on α- and γ-motoneurones and it is believed that the γ-controlled stretch reflex gives servo-assistance in movements controlled by α-γ-linkage (Matthew, 1972). Extensive studies have revealed that the neuronal systems controlling α- and γ-motoneurones have parallel effects on the Ia inhibitory interneurones (for ref. see Hultborn, 1976) serving to give 'α-γ-linked reciprocal inhibition', i.e. a functional coupling of antagonist relaxation to the contraction of the agonist muscle (Hongo, Jankowska & Lundberg, 1969). To this scheme can now be added a segmental regulatory mechanism controlling the depth of reciprocal inhibition. We will first discuss its role in a simple flexion-extension movement without co-contraction but with complete relaxation of the antagonist and consider the expected events without this recurrent control. When shortening of the contracting agonist is opposed then the increased Ia discharge would produce not only increased motoneuronal activity but also acceleration of firing in the Ia inhibitory interneurones to the antagonist and a deepening of reciprocal inhibition. While increased motoneuronal activation gives load compensation, there does not seem to be any corresponding need for an enhancement of reciprocal inhibition beyond a level which prevents firing of antagonist motoneurones. There would even seem to be a distinct advantage in preventing an 'unnecessary' strong reciprocal inhibition. Rapid and accurate reversal of a movement is an important aim in motor regulation (compare deficiences occurring after cerebellar lesions). Since reciprocal inhibition provides the background against which a command for a reversal operates, it is likely that the task of higher centres ordering contraction of antagonists with a certain speed and force is simplified if the level of reciprocal inhibition is kept relatively constant. The recurrent inhibition by agonist motoneuronal activity of transmission in the reciprocal Ia inhibitory pathway appears to represent an ingenious mechanism to maintain a constant depth of reciprocal inhibition during increasing agonist contractions.

Some important limitations in applying the present results to movement control in general must be pointed out. First, the very same motor discharge may cause different amounts of recurrent inhibition under various conditions. This depends on the fact that Renshaw cells receive a synaptic input from other sources than the motor axon collaterals. Such segmental or supraspinal control (see Hultborn *et al.* 1971*c* for ref.) may enhance or depress transmission in the recurrent pathway and thus change the sensitivity of the recurrent regulation of Ia inhibition (cf. Hultborn, 1972). Secondly, our analysis deals with the problem of how increments in *Ia excitation* are counteracted by recurrent inhibition, but Ia afferents are but one, albeit a crucial one, of many excitatory systems which conjointly control agonist

motoneurones and Ia inhibitory interneurones. Although the balance between Ia excitation and recurrent inhibitory actions under our conditions appears to be so delicate that the depth of reciprocal inhibition is made virtually independent of agonist activity, it remains to show whether or not a similar balance exists for other excitatory systems to the Ia inhibitory interneurones. Application of the quantitative aspects of the present results to movement control in general requires the assumption that the relative strength of excitation of corresponding α-motoneurones and Ia inhibitory interneurones from other neuronal systems is similar to that from Ia afferents. The hypothesis of 'α-γ-linkage in reciprocal inhibition' rather presumes such a balance of the relative strengths and further quantitative studies of other systems than Ia afferents can thus serve both to test this hypothesis and the role of the recurrent control of reciprocal inhibition.

The present result bears on the hypothesis of 'α-γ-linkage in reciprocal inhibition' also from another point of view. This hypothesis was based on the idea that 'reciprocal inhibition should not occur as an independent event without excitation of agonists; nor should it precede neither outlast excitation of agonist motoneurones. In short, it would be an advantage if reciprocal inhibition, that is the excitation of the inhibitory interneurones was coupled, not to the synaptic depolarization of agonist α-motoneurones but to their excitation' (Lundberg, 1970). The general idea of a functional coupling of contraction of agonist and relaxation of antagonists is strongly supported by all the findings showing a parallel excitatory control of corresponding α-motoneurones and Ia inhibitory interneurones (cf. Hultborn, 1976), and studies on humans strongly suggest that the postulated co-activation does indeed occur during voluntary flexion-extension movements (Tanaka, 1974). The present results nevertheless show that there is no close coupling in excitation of these two neuronal systems in the decerebrate cat. Reciprocal inhibition does in fact occur as an independent event below threshold for agonist α-activation because motoneurones are usually recruited only when the muscle is stretched some mm from its resting length, while reciprocal inhibition appears below threshold for the stretch reflex and in this phase is linearly related to the impulse frequency in Ia afferents. Since many Ia inhibitory interneurones are known to have a resting discharge in the decerebrate state (Hultborn, Jankowska, Lindström & Roberts, 1971*d*) it is likely that growth of inhibition with increasing extension below threshold for the stretch reflex does not depend only on recruitment of fresh Ia inhibitory interneurones but more on an increased firing frequency in already active neurones. Only further investigations can reveal whether the decerebrate cat represents a special case or whether the appropriate function of reciprocal inhibition in some motor acts does indeed require that the Ia inhibitory interneurones have lower threshold than agonist motoneurones.

General role of recurrent inhibition from motor axon collaterals

Recurrent inhibition via motor axon collaterals and Renshaw cells acts in parallel onto corresponding α-motoneurones and Ia inhibitory interneurones and it seems reasonable to assume that the functions of these projections are inseparable (Hultborn *et al.* 1971*c*; Hultborn, 1976). How is it then possible to suggest that their inhibition of Ia inhibitory interneurones will more or less equalize additional Ia

excitation while their action on to motoneurones fails to prevent an increased motoneuronal activity with further muscle extensions? In order to make both ends meet it may seem necessary to postulate at least some quantitative differences in the projection of Renshaw cells on to these two types of neurones, which would be a concession from the postulate of an inseparable function of these parallel projections. We believe, however, that the difficulties are more apparent than real, and that they derive from the dubious description of recurrent inhibition of motoneurones as a negative feed-back. Although it is well known that the largest recurrent i.p.s.p.s are produced by antidromic stimulation of the autogenous nerve (Eccles, Eccles, Iggo & Ito, 1961; Hultborn *et al.* 1971*c*) there is little precise knowledge on the distribution *within* the motor nucleus. A true feed-back would imply recurrent inhibition evoked and received by a given population of motoneurones in a muscle, or else that recurrent inhibition is distributed diffusely among the motoneurones innervating the same muscle. The evidence, though incomplete and indirect points to another type or organization in that recurrent inhibition is *produced* mainly by large motoneurones which are recruited late, i.e. at high tensions (Ryall, Piercey, Polosa & Goldfarb, 1972) and *received* mainly by smaller tonic motoneurones activated with the weakest contractions (Granit, Pascoe & Steg, 1957). Note that large and small motoneurones do not refer only to two discrete populations with distinctly different properties; we rather assume a gradual scale corresponding to the recruitment order also found among the relatively homogeneous soleus motor units (the size order principle of Henneman, see Clamann & Henneman, 1976). Recurrent inhibition of motoneurones would then contribute to the stabilization of firing frequencies (see Granit, 1970) of already recruited motoneurones without compromising recruitment of fresh ones. It is noteworthy that Grillner & Udo (1971*a*) observed that during slow extension of the soleus muscle in decerebrate cats motor units reached their optimal firing frequency soon after their recruitment despite the fact that the increasing excitatory inflow caused recruitment of new motor units. Somewhat similar observations were made in humans (Gydikov & Kosarov, 1974); with increasing voluntary contractions there was first a frequency modulation of small tonic motor units, but when large 'phasic' units started to be recruited the discharge frequencies of the former remained at a more or less constant level.

Our findings regarding inhibition during the stretch reflex in the decerebrate cat thus suggest that the recurrent control of the I*a* inhibitory interneurones resembles that of small tonic α-motoneurones since in both cases the discharge frequency is stabilized by the stretch reflex. Burke, Rymer & Walsh (1976) recently concluded that reciprocal I*a* inhibition was particularly efficient in small tonic α-motoneurones (also when their high input resistance was compensated for) and it may therefore seem logical that also the recurrent inhibitory control is similar in case of small α-motoneurones and I*a* inhibitory interneurones.

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REFERENCES

BARNES, C. D. & POMPEIANO, O. (1970). Presynaptic and postsynaptic effects in the monosynaptic reflex pathway to extensor motoneurones following vibration of synergic muscles. *Archs ital. Biol.* **108**, 259–294.

BENECKE, R., BÖTTCHER, U., HENATSCH, H.-D., MEYER-LOHMANN, J. & SCHMIDT, J. (1975). Recurrent inhibition of individual Ia inhibitory interneurones and disinhibition of their target α-motoneurones during muscle stretches. *Expl. Brain Res.* **23**, 13–28.

BRADLEY, K., EASTON, D. M. & ECCLES, J. C. (1953*a*). An investigation of primary or direct inhibition. *J. Physiol.* **122**, 474–488.

BRADLEY, K. & ECCLES, J. C. (1953*b*). Analysis of the fast afferent impulses from thigh muscles. *J. Physiol.* **122**, 462–473.

BURKE, R. E., RYMER, W. Z. & WALSH, JR., J. V. (1976). Relative strength of synaptic input from short-latency pathways to motor units of defined type in cat medial gastrocnemius. *J. Neurophysiol.* **39**, 447–458.

CARPENTER, D., ENGBERG, I., FUNKENSTEIN, H. & LUNDBERG, A. (1963). Decerebrate control of reflexes to primary afferents. *Acta physiol. scand.* **59**, 424–437.

CLAMANN, H. P. & HENNEMAN, E. (1976). Electrical measurement of axon diameter and its use in relating motoneuron size to critical firing level. *J. Neurophysiol.* **39**, 844–851.

DECANDIA, M., PROVINI, L. & TÁBOŘÍKOVÁ (1967). Presynaptic inhibition of the monosynaptic reflex following the stimulation of nerves to extensor muscles of the ankle. *Expl. Brain Res.* **4**, 34–42.

ECCLES, J. C. (1964). Presynaptic inhibition in the spinal cord. In *Progress in Brain Research*, chap. **12**, pp. 65–89. Amsterdam: Elsevier.

ECCLES, J. C., ECCLES, R. M., IGGO, A. & ITO, M. (1961). Distribution of recurrent inhibition among motoneurones. *J. Physiol.* **159**, 479–499.

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*). Synaptic action on motoneurones caused by impulses in Golgi tendon organ afferents. *J. Physiol.* **138**, 227–252.

ECCLES, J. C., MAGNI, F. & WILLIS, W. D. (1962*a*). Depolarization of central terminals of group I afferent fibres from muscle. *J. Physiol.* **160**, 62–93.

ECCLES, J. C., SCHMIDT, R. F. & WILLIS, W. D. (1962*b*). Presynaptic inhibition of the spinal monosynaptic reflex pathway. *J. Physiol.* **161**, 282–297.

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

ELDRED, E., GRANIT, R. & MERTON, P. A. (1953). Supraspinal control of the muscle spindles and its significance. *J. Physiol.* **122**, 498–523.

FEDINA, L. & HULTBORN, H. (1972). Facilitation from ipsilateral primary afferents of interneuronal transmission in the Ia inhibitory pathway to motoneurones. *Acta physiol. scand.* **86**, 59–81.

FEDINA, L., HULTBORN, H. & ILLERT, M. (1975). Facilitation from contralateral primary afferents of interneuronal transmission in the Ia inhibitory pathway to motoneurones. *Acta physiol. scand.* **94**, 198–221.

GRANIT, R. (1958). Neuromuscular interaction in postural tone of the cat's isometric soleus muscle. *J. Physiol.* **143**, 387–402.

GRANIT, R. (1970). *The Basis of Motor Control*, pp. 1–346. London and New York: Academic.

GRANIT, R., PASCOE, J. E. & STEG, G. (1957). The behaviour of tonic α- and γ-motoneurones during stimulation of recurrent collaterals. *J. Physiol.* **138**, 381–400.

GRILLNER, S. (1972). The role of muscle stiffness in meeting the changing postural and locomotor requirements for force development by the ankle extensors. *Acta physiol. scand.* **86**, 92–108.

GRILLNER, S. & UDO, M. (1971*a*). Motor unit activity and stiffness of the contracting muscle fibres in the tonic stretch reflex. *Acta physiol. scand.* **81**, 422–424.

GRILLNER, S. & UDO, M. (1971*b*). Recruitment in the tonic stretch reflex. *Acta physiol. scand.* **81**, 571–573.

GYDIKOV, A. & KOSAROV, D. (1974). Some characteristics of different motor units in human m. biceps brachii. *Pflügers Arch.* **347**, 75–88.

HARVEY, R. J. & MATTHEWS, P. B. C. (1961). The response of de-efferented muscle spindle endings in the cat's soleus to slow extension of the muscle. *J. Physiol.* **157**, 370–392.

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. (1969). The rubrospinal tract. II. Facilitation of interneuronal transmission in reflex paths to motoneurones. *Expl. Brain Res.* **7**, 365–391.

HOUK, J. C., SINGER, J. & GOLDMAN, M. (1970). An evaluation of length and force feedback to soleus muscles of decerebrate cats. *J. Neurophysiol.* **33**, 784–811.

HULTBORN, H. (1972). Convergence on interneurones in the reciprocal Ia inhibitory pathway to motoneurones. *Acta physiol. scand.* **85**, Suppl. 375, 1–42.

HULTBORN, H. (1976). Transmission in the pathway of reciprocal Ia inhibition to motoneurones and its control during the tonic stretch reflex. In *Understanding the Stretch Reflex, Progress in Brain Research*, ed. HOMMA, S., pp. 235–255. Amsterdam: Elsevier.

HULTBORN, H., ILLERT, M. & SANTINI, M. (1976*a*). Convergence on interneurones mediating the reciprocal Ia inhibition of motoneurones. I. Disynaptic Ia inhibition of Ia inhibitory interneurones. *Acta physiol. scand.* **96**, 193–201.

HULTBORN, H., ILLERT, M. & SANTINI, M. (1976*b*). Convergence on interneurones mediating the reciprocal Ia inhibition of motoneurones. II. Effects from segmental flexor reflex pathways. *Acta physiol. scand.* **96**, 351–367.

HULTBORN, H., ILLERT, M. & SANTINI, M. (1976*c*). Convergence on interneurones mediating the reciprocal inhibition of motoneurones. III. Effects from supraspinal pathways. *Acta physiol. scand.* **96**, 368–391.

HULTBORN, H., JANKOWSKA, E. & LINDSTRÖM, S. (1971*a*). Recurrent inhibition from motor axon collaterals of transmission in the Ia inhibitory pathway to motoneurones. *J. Physiol.* **215**, 591–612.

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

HULTBORN, H., JANKOWSKA, E. & LINDSTRÖM, S. (1971*c*). Relative contribution from different nerves to recurrent depression of Ia IPSPs in motoneurones. *J. Physiol.* **215**, 637–664.

HULTBORN, H., JANKOWSKA, E., LINDSTRÖM, S. & ROBERTS, W. (1971*d*). Neuronal pathway of the recurrent facilitation of motoneurones. *J. Physiol.* **218**, 495–514.

HULTBORN, H. & LUNDBERG, A. (1972). Reciprocal inhibition during the stretch reflex. *Acta physiol. scand.* **85**, 136–138.

JACK, J. J. B. & ROBERTS, R. C. (1978). The role of muscle spindle afferents in stretch and vibration reflexes of the soleus muscle of the decerebrate cat. *Brain Res.* **146**, 366–372.

JANSEN, J. K. S. & MATTHEWS, P. B. C. (1962). The effects of fusimotor activity on the static responsiveness of primary and secondary endings of muscle spindles in the decerebrate cat. *Acta physiol. scand.* **55**, 376–386.

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*.

LIDDELL, E. G. T. & SHERRINGTON, C. S. (1925). Further observations on myotatic reflexes. *Proc. R. Soc.* B **97**, 267–283.

LUND, S., LUNDBERG, A. & VYKLICKÝ, L. (1965). Inhibitory action from the flexor reflex afferents on transmission to Ia afferents. *Acta physiol. scand.* **64**, 345–355.

LUNDBERG, A. (1970). The excitatory control of the Ia inhibitory pathway. In *Excitatory Synaptic Mechanisms*, ed. ANDERSEN, P. & JANSEN, J. K. S., pp. 333–340. Oslo: Universitetsforlaget.

LUNDBERG, A., MALMGREN, K. & SCHOMBURG, E. D. (1977). Comments on reflex actions evoked by electrical stimulation of group II muscle afferents. *Brain Res.* **122**, 551–555.

MATTHEWS, P. B. C. (1963). The response of de-efferented muscle spindle receptors to stretching at different velocities. *J. Physiol.* **168**, 660–678.

MATTHEWS, P. B. C. (1972). *Mammalian Muscle Receptors and their Central Actions*. London: Edward Arnold.

RYALL, R. W., PIERCEY, M. F., POLOSA, C. & GOLDFARB, J. (1972). Excitation of Renshaw cells in relation to orthodromic and antidromic excitation of motoneurones. *J. Neurophysiol.* **35**, 137–148.

STAUFFER, E. K. & STEPHENS, J. A. (1975). The tendon organs of cat soleus: static sensitivity to active force. *Expl. Brain Res.* **23**, 279–291.

STAUFFER, E. K., WATT, D. G. D., TAYLOR, A., REINKING, R. M. & STUART, D. G. (1976). Analysis of muscle receptor connections by spike-triggered averaging. 2. Spindle group II afferents *J. Neurophysiol.* **39**, 1393–1402.

TANAKA, R. (1974). Reciprocal Ia inhibition during voluntary movements in man. *Expl. Brain Res.* **21**, 529–540.

WALL, P. D. (1958). Excitability changes in afferent fibre terminations and their relation to slow potentials. *J. Physiol.* **142**, 1–21.