Reciprocal inhibition between wrist flexors and extensors in man: a new set of interneurones?

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1. Interneurones mediating reciprocal inhibition between wrist flexors and extensors in man are characterized using both Renshaw cells and transarticular group I afferent activation.

2. Renshaw cells were activated by reflex discharges evoked by a tendon tap. The tendon tap was applied to the tendon of the muscles from which the Ia fibres responsible for the reciprocal inhibition originated. Contrary to what was observed both in the cat hindlimb and in human elbow muscles, this Renshaw cell activation never resulted in a long depression of the reciprocal inhibition between wrist flexors and extensors.

3. Convergence from group I elbow muscle afferents and antagonistic group I afferents onto interneurones mediating reciprocal inhibition between wrist muscles was revealed in post-stimulus time histogram (PSTH) experiments using the technique of spatial facilitation.

4. The characteristics of the interneurones mediating reciprocal inhibition between wrist flexors and extensors could therefore be summarized as follows: (a) they are fed by antagonistic group I afferents and group I afferents originating from both flexor and extensor elbow muscles; (b) they are not inhibited by Renshaw cells; (c) they are not excited by low threshold cutaneous afferents; and (d) they are probably interposed in a disynaptic pathway.

5. It is therefore concluded that interneurones mediating reciprocal inhibition between wrist flexors and extensors in man differ both from Ia interneurones and from interneurones interposed in the Ib reflex pathways and these characteristics are related to the complex circumduction movements developed in the wrist.

Inhibition of a motoneuronal pool during contraction of an antagonist muscle is one of the most thoroughly studied physiological mechanisms in animals and humans. Sherrington (1906) introduced the concept of reciprocal inhibition and numerous experiments performed in animals (for references, see Baldissera, Hultborn & Illert, 1981) have demonstrated that reciprocal inhibition is evoked disynaptically through neurones fed by Ia afferents and called 'Ia interneurones'. Studies of reciprocal inhibition in human ankles (Mizuno, Tanaka & Yanagisawa, 1971), wrists (Day, Marsden, Obeso & Rothwell, 1984) and elbows (Katz, Pénicaud & Rossi, 1991) led likewise to the conclusion that Ia fibres are involved and that the inhibition is mediated via a disynaptic pathway. These studies also suggested that the same category of interneurones mediate reciprocal inhibition of hindlimb motoneurones in animals and between various flexors and extensors in humans. However, Jankowska & McCrea (1983) have described another group of interneurones mediating inhibition of both antagonistic and non-antagonistic motoneurones and co-excited by Ia and Ib afferents. The relative contribution of these two groups of interneurones and of the 'Ia reciprocal' and 'Ia non-reciprocal' inhibition remains to be defined. Recurrent inhibition and selective input from group Ia afferents provide the most reliable criteria of identification of Ia inhibitory interneurones because there are only two groups of spinal interneurones inhibited by Renshaw cells: Ia inhibitory interneurones (Hultborn, Jankowska & Lindström, 1971) and Renshaw cells themselves (Ryall, 1970). In a previous paper, Katz *et al.* (1991) introduced a method for counteracting reciprocal inhibition by activation of Renshaw cells in man. Using this method, they demonstrated that inhibition between human elbow flexors and extensors is mediated primarily by Ia inhibitory interneurones. However, the anatomy and physiology of the wrist joint differ greatly from those of the elbow, in particular by the greater number of degrees of freedom and by the fact that wrist flexors and extensors may behave both as antagonists (during flexion and extension) and as synergists (during abduction). The aim of

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the present study was therefore to determine whether these differences correlate with differences in the neural circuitry mediating inhibition between wrist flexors and extensors.

METHODS

General experimental arrangement

The experiments were performed on eight healthy volunteers from the departmental staff (aged 25–47 years; 3 men, 5 women), all of whom gave their informed consent to the procedures, which were approved by the appropriate institutional ethics committee. The subjects were seated comfortably in an armchair. The examined (right) arm lay on an armrest with the shoulder abducted about 60 deg, elbow semi-flexed and wrist extended. The surface electromyogram (EMG) was recorded by two non-polarizable disc electrodes (0·9 cm diameter) placed 1·5 cm apart over the bellies of the corresponding muscles.

Test reflexes

Percutaneous electrical stimulation of the median nerve through bipolar electrodes placed just above the elbow (rectangular shocks of 1 ms duration, every 3·5 s) was used to evoke an H reflex in the wrist flexors. The recording electrodes were placed over the belly of the flexor carpi radialis (FCR). A marked increase in the H reflex during wrist flexion but not during pronation or finger flexion was the criterion that the reflex originated mainly from FCR. As stressed in the literature, it is more difficult to obtain a reasonably large, stable monosynaptic reflex in extensor carpi radialis (ECR) than in FCR. Nevertheless, in three subjects, stimulation of the radial nerve through bipolar electrodes placed a few centimetres above the elbow resulted in a satisfactory H reflex in the wrist extensors. When the H reflex increased markedly with a wrist extension but not with a finger extension, it was considered to originate mainly from ECR. In the other subjects the ECR test reflex was evoked by a mechanical tap applied to the distal tendon of the muscle by an electromagnetic hammer (model 4809; Brüel & Kjaer, Naerum, Denmark), which produced a quick transient stretch (8 mm in 5 ms). The intensity of percussion was graded using a power amplifier and expressed in multiples of the threshold for the tendon-jerk reflex (×TT). Special care was taken to ensure that the hammer struck the tendon in the same position throughout the experiment.

Conditioning stimuli

Different kinds of conditioning stimuli were used, as follows. (1) Electrical pulses of 1 ms duration were delivered to the median and the radial nerves through the same electrodes used to elicit the test reflexes. (2) In some experiments the radial branch innervating the ECR was stimulated at the motor point just below the elbow, to ensure that mainly group I afferents originating from the ECR were involved by the conditioning stimulus, and it was carefully verified that, even using the maximum intensity of the stimulators, the ECR was the only contracting muscle. In such conditions the maximum value reached by the direct motor response was taken as the ECR maximum motor response (M_{max}) and it should be noticed that there was, in most cases, no cutaneous irradiation. (3) Electrical pulses of 1 ms duration were delivered percutaneously to the musculocutaneous nerve and the radial branch innervating the triceps (triceps nerve) through stimulation electrodes placed a few centimetres below the shoulder in accordance with the experimental protocol described by Katz *et al.* (1991) and it was carefully checked that there was no spread to other nerve branches. In all these cases, the efficacy of the conditioning electrical stimulus in exciting I a fibres was verified by its ability to increase the firing probability of a homonymous voluntarily activated motor unit (see below). (4) Since percutaneous stimulation of nerves also activated cutaneous afferents, as indicated by local pricking under the stimulation electrodes and/or paraesthesia irradiating along the nerve trajectory, similar cutaneous sensations were evoked without stimulating the nerve trunk. The local pricking was reproduced by displacing the electrodes laterally on the arm, 2–3 cm away from the nerve trajectory, so that the stimulus was applied only to the skin. To reproduce the irradiating paraesthesia, large plate electrodes were placed on the skin in the nerve projection area, or the cutaneous branch of the radial nerve was stimulated at the wrist. The conduction time for the cutaneous afferent volley from the electrodes placed on the skin to the sites of the electrical conditioning stimuli described above was determined, and the part of the conditioning–test interval corresponding to this extra peripheral conduction time was subtracted. The current delivered by the stimulators was measured by a current probe (Tektronix 6021, OR, USA) and the stimulus intensity was expressed in multiples of the threshold intensity for the direct motor wave (×MT). (5) Mechanical stimulation of the distal tendon of the ECR was applied with the same electromagnetic hammer used to elicit ECR and FCR test reflexes.

Special care was taken to detect the appearance of a muscle contraction in response to electrical and mechanical stimuli. The threshold of the muscle response was determinated both by EMG recordings and by muscle palpation and it was verified that the motor (or reflex) response exhibited a steep increase when the intensity of the stimulus increased. In those conditions when the intensity of the stimulus was decreased until the disappearance of the muscle contraction, it was considered that no motor unit was activated.

Experimental protocol and analysis of results

In each experimental run, unconditioned and conditioned reflexes were randomly presented. By convention, the timing of the pulse triggering the test stimulus is referred to that of the conditioning electrical shock. When the simultaneous arrival of the conditioning and test volleys to the spinal cord was obtained with the conditioning stimulus delivered after the test, the conditioning–test interval was said to be negative. A total of twenty control and twenty conditioned reflexes was used in each sequence. Variance analysis was used for testing the significance of the changes in the test reflex amplitudes.

Study of single motor units

The effects of a conditioning stimulus on a voluntarily activated motor unit can be determined by constructing a post-stimulus time histogram (PSTH) of the occurrence of motor unit spikes following repeated presentation of the stimulus. The ability of the PSTH to detect small postsynaptic potentials in motoneurones has been established by intracellular recording (Fetz & Gustafsson, 1983).

A detailed description of the method used in these experiments has been published (Fournier, Meunier, Pierrot-Deseilligny & Shindo, 1986) and will be only summarized here. The EMG from single motor units was recorded by conventional surface electrodes while the subject performed a very weak (below 5% of maximal

voluntary force) and steady contraction. The EMG potentials of single motor units were converted into standard pulses by a discriminator with variable trigger levels, and they were used to trigger first a computer (Mac II) and then the stimulators delivering nerve stimulations. The motor unit potential and the trigger pulse were continuously monitored to detect false triggers due to other active units and to ensure that the motor unit shape and trigger position remained constant within and between the sequences. In the method described by Fournier *et al.* (1986) the nerve stimulation is delivered at a fixed interval after a previous motor unit discharge, thus allowing a choice of the delay at which the probability for a new discharge is high and a reduction of the number of trials necessary to reveal obvious changes in the PSTH. The PSTHs of the motor unit discharges were constructed for the period of 15–75 ms following the stimulation, using bins of 1 ms. While using this method the probability of discharges in the PSTH depends not only on the postsynaptic potentials evoked by the stimulation, but also on the motoneurone membrane trajectory during the interspike interval. To take account of the latter, a control histogram of firing probability, was constructed in the absence of stimulation. The control and the different conditioning situations were randomly used within a sequence. The control histogram represented the background firing probability, to which the results following stimulation were compared. To clarify the stimulus-induced changes, the control value in each bin was subtracted from that obtained after stimulation.

Within different time interval windows a χ^2 test was used to determine to what extent the distribution of firing probability after stimulation differed from that obtained in the control situation. Such an analysis was only performed after having checked that in the control situation the firing probability within the window of analysis did not differ from the mean probability of discharge of this unit. The onset of the changes in firing probability following the conditioning stimulation was visually identified. It was then required: (1) that the number of counts in the bins following the onset was significantly greater or lesser than the control values; and (2) that the number of counts in the bins preceding this onset did not differ significantly with and without stimulation. To perform the statistical analysis the duration of the bin window was increased by summing individual bins so that there were at least five counts (validity conditions for χ^2 test).

RESULTS

Baldissera, Campadelli & Cavallari (1983) and Day *et al.* (1984), using a reflex technique in man, demonstrated that reciprocal inhibition between wrist flexors and extensors is mediated through only one interneurone activated by group Ia afferents. The method used here to counteract reciprocal inhibition by Renshaw cell activation needed, as a first step, an investigation of the time courses of the variations of amplitude of wrist muscle monosynaptic reflexes following antagonistic electrical nerve stimulation, in order to determine the time interval at which the reciprocal inhibition was maximum. Similarly, the method used to determine the afferent fibres converging upon the interneurones mediating inhibition between wrist muscles needed, as a first step, an investigation of the reciprocal inhibition using the PSTH technique.

Reciprocal inhibition between wrist flexors and extensors

Figure 1*A* illustrates the time course of the changes in an FCR H reflex amplitude when conditioned by stimulation of the radial nerve at 0·95 MT, 6 cm above the elbow. In this example, the inhibition became apparent at a conditioning–test interval of −0·5 ms, reached a peak at 0 ms, and ended at 2 ms. When the inhibition was maximal, the test reflex amplitude was 50% of its control value. Such a time course closely resembles those previously described in similar experimental conditions by Baldissera *et al.* (1983) and by Day *et al.* (1984). It was found in all seven subjects.

Figure 1*B* shows the time course of the changes in an ECR H reflex when conditioned by stimulation of the median nerve at 0·95 MT at elbow level. The inhibition of the ECR reflex started at 1 ms, peaked at 1·5 ms (48% of its control value) and then declined progressively during the following 2 ms. This time course closely resembled those published by Day *et al.* (1984) and Baldissera, Cavallari, Fournier, Pierrot-Deseilligny & Shindo (1987); it was found in the three subjects exhibiting a satisfactory ECR H reflex. Similar time courses, but shifted from −6 to −9 ms depending upon the length of the brachial segment and the mechanical delay introduced by the electromagnetic coupling of the hammer, were found with an ECR tendon reflex in the four other subjects.

In similar experimental conditions, i.e. when the test H reflexes were evoked in FCR (or in ECR) and conditioned by electrical stimuli just below motor threshold applied to antagonistic nerves, Baldissera *et al.* (1983, 1987) Day *et al.* (1984) and Cavallari (1988) provided evidence that the early inhibition is due to activation of group Ia afferents and that the central delay is compatible with a disynaptic pathway.

Figure 1*C* and *D* illustrates the modifications of firing probability of a voluntarily activated motor unit of the FCR (Fig. 1*C*) and of the ECR (Fig. 1*D*) following conditioning stimuli at 0·95 MT applied to the homonymous and the antagonistic nerves. The histograms show the distribution of the differences obtained by subtracting values of histograms without stimulation (see Methods and open columns in Fig. 2) from histograms following stimulation (see Methods and hatched columns in Fig. 2).

The early increases following homonymous stimulation are shown in Fig. 1*C* (first column) for the FCR motor unit and in Fig. 1*D* (first column) for the ECR motor unit. The early decreases following antagonistic nerve stimulations at an intensity of 0·95 MT are shown in the second column of Fig. 1*C* for the FCR motor unit and in the second column of Fig. 1*D* for the ECR motor unit. Fifteen FCR motor units were studied in five subjects and a decrease in firing probability (as illustrated in Fig. 1*C*) was observed in 53% of the cases. Eleven ECR motor units were studied in three

subjects and a decrease in firing probability (as illustrated in Fig. 1*D*) was observed in 54% of the cases. In both situations the duration of the decrease in firing probability was short, 5·6 ms on average (range, 3–8 ms). Although it has already been shown in reflex experiments that the activation of cutaneous fibres was not responsible for the early inhibition induced by the conditioning stimulation, it was verified in PSTH experiments that purely cutaneous stimulations mimicking the sensation associated with the median and the radial nerve stimuli did not decrease the firing probability of the test motor units at the appropriate latencies.

In 1987, Hultborn, Meurnier, Morin & Peirrot-Deseilligny introduced, in PSTH experiments, a technique allowing calculation of the conduction velocity in the fastest Ia fibres and so comparison of the latency of the earliest response elicited in a given motor unit by an homonymous and heteronymous nerve stimulation. This method relies on the stimulation at two different sites of the homonymous nerve, whose effects are tested on a given motor unit with bins of 0·2 ms. When the effects of the homonymous and antagonistic nerve stimulation are tested in the same motor unit (for example a given FCR (or ECR) motor unit, as in Fig. 1*C* (or *D*)), the efferent conduction times are identical

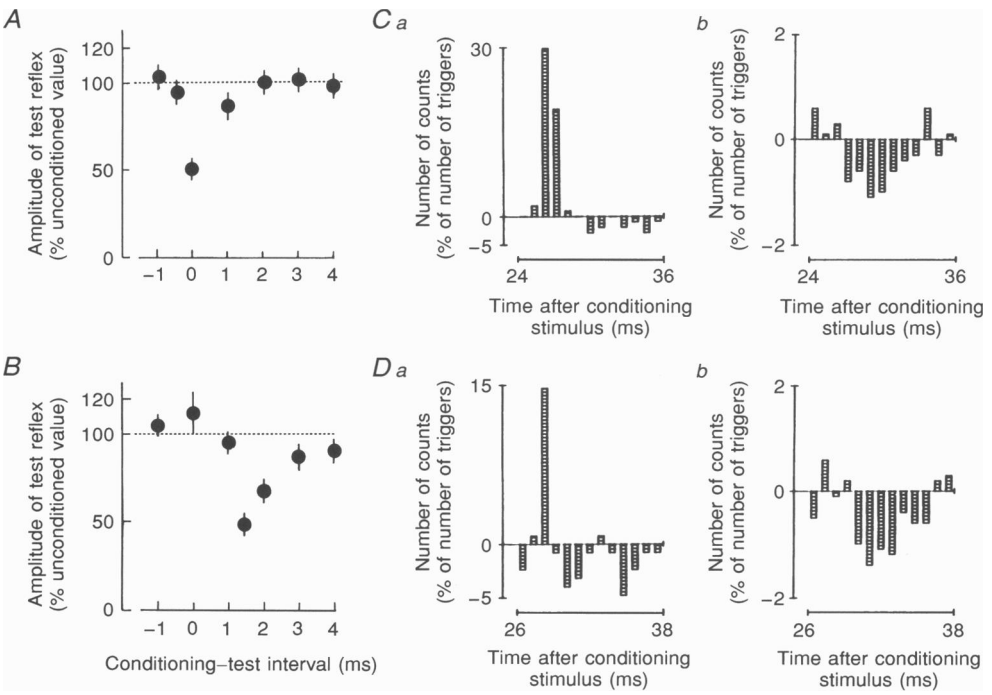

Figure 1. Reciprocal inhibition between wrist flexors and extensors

A and *B* show the time courses of the variations of wrist muscle H reflexes following antagonistic electrical nerve stimulation. In *A*, the test reflex was evoked in the FCR. The conditioning stimulus was applied to the radial nerve (intensity, 0·95 MT). By convention the timing of the test stimulus is referred to that of the conditioning stimulus. Negative time intervals correspond to cases in which the test stimulus was given first. In *B*, the test reflex was evoked in the ECR and the conditioning electrical stimulus applied to the median nerve (intensity, 0·95 MT). Each symbol represents the mean of 20 measurements. Vertical bars indicate S.E.M. *C* and *D* show changes in firing probability in a voluntarily activated FCR (*C*) and ECR (*D*) motor unit in response to homonymous (*Ca* and *Da*) and antagonistic (*Cb* and *Db*) nerve stimulations. Histograms (1 ms bins) were obtained in control conditions (i.e. without stimulation) and in response to nerve stimulation (see Fig. 2). The columns (▤) in *C* and *D* represent the difference between these two histograms; in each bin the control value was subtracted from that obtained after stimulation. The onset of the homonymous increase in firing probability (26 ms for the FCR motor unit and 28 ms for the ECR motor unit) and of the antagonistic decrease (26 ms for the FCR motor unit and 30 ms for the ECR motor unit) was visually identified and statistical analyses were performed to determine to what extent the distribution of firing probability after stimulation differed from that in the control situation. No significant differences between controls and those after stimulation were seen in the 3 bins preceding the onsets of the effects (χ^2 varied from 0·71 to 1·15 according to the configuration), while it was highly significant during the peak ($\chi^2 = 16{\cdot}72$, $P < 0{\cdot}001$ for the FCR motor unit; $\chi^2 = 16{\cdot}50$, $P < 0{\cdot}001$ for the ECR motor unit) and during the 7 ms following the onset of the antagonistic decrease in firing probability ($\chi^2 = 17{\cdot}92$, $P < 0{\cdot}001$ for the FCR motor unit and $\chi^2 = 13{\cdot}41$, $P < 0{\cdot}001$ for the ECR motor unit). Number of triggers: *Ca*, 105; *Cb*, 985; *Da*, 105; *Db*, 830.

and the differences between the latencies of the two effects must reflect the differences in afferent conduction time and in central delay. This procedure has already been used with the median, radial and musculocutaneous nerves by Cavallari & Katz (1989) to estimate the central delay of the facilitation induced in a biceps motor unit by radial and median nerve stimulation, and by Nielsen & Pierrot-Deseilligny (1991) to compare the afferent conduction time of a median Ia afferent volley and of a cutaneous afferent volley. In Fig. 1*C* the latency of the homonymous peak was 26 ms and that of the antagonistic decrease in firing probability was 27 ms. In this experiment the distance from the site of stimulation of the radial nerve and of the median nerve to the spinal cord was roughly similar (the two nerves were stimulated at elbow level), as was the conduction velocity in the fastest median and radial Ia fibres (as already shown by Cavallari & Katz, 1989). In Fig. 1*D* the latency of the homonymous peak was 28 ms and that of the antagonistic decrease in firing probability was 30 ms. In this experiment the median nerve was stimulated at elbow level and the radial nerve 10 cm above; the difference between the two afferent conduction times was 1·2 ms. In all cases, the central delay of the onset of the inhibition was about 1 ms longer than that of that of the monosynaptic facilitation, in agreement with the results obtained by Day *et al.* (1984) in test reflex experiments.

Moreover, Katz *et al.* (1991) introduced the method described by Day *et al.* (1984) in reflex experiments into PSTH experiments in order to demonstrate the central delay of the reciprocal inhibition between wrist flexors and extensors. The method relies on the assumption that the same afferent fibres are responsible for homonymous facilitation and reciprocal inhibition and requires no calculation of peripheral conduction times. Homonymous and antagonistic effects were studied in the same FCR (or ECR) motor unit, so the efferent conduction time was the same in both cases for a given motor unit. In these conditions the characteristics of the conditioning stimuli (localization and intensity) were identical whatever the motor unit studied, so the afferent conduction times were the same for the FCR and ECR motor units. In such conditions, an estimate of the central delay of the reciprocal inhibition in excess of the monosynaptic delay requires only the measurement, for each motor unit, of the latencies of the homonymous and antagonistic effects using the equation:

$$2TS = (LF_{FCR} - LI_{FCR}) + (LF_{ECR} - LI_{ECR}),$$

where *TS* is the central delay in excess of the monosynaptic delay; *LF*, the latency of the onset of the homonymous facilitatory effects; and *LI*, the latency of the onset of the antagonistic inhibitory effects (from Katz *et al.* 1991). In Fig. 2 the modifications of firing probability of a FCR (Fig. 2*A*) and ECR (Fig. 2*B*) motor unit following homonymous nerve stimulation (left-hand side) and antagonistic nerve stimulation (right-hand side) were constructed using 0·5 ms bins. The onset of the homonymous peak and the onsets of the antagonistic decreases were visually identified and it was verified that: (1) there was no difference in the distribution of firing probability between controls and following stimulation in the three bins preceding the arrows (Fig. 2*A b* and *d* and *B b* and *d*), and (2) a significant increase (or decrease) was seen in at least three subsequent bins, including that indicated by the arrows. The onset of facilitation was 25·5 ms for the FCR motor unit (Fig. 2*A b*) and 22 ms for the ECR motor unit (Fig. 2*B b*). The onset of the inhibition was 26 ms for the FCR motor unit (Fig. 2*A d*) and 23 ms for the ECR motor unit (Fig. 2*B d*). The differences between the homonymous and the antagonistic effects were 0·5 ms and 1 ms, respectively. The central delay was thus 0·75 ms longer than the monosynaptic delay and was therefore compatible with an inhibition mediated through one interneurone. Such an experiment is technically difficult, since it requires the subject to keep the same motor unit for the determination of the onset of the homonymous increase as well as the antagonistic decrease in firing probability and to activate successively a FCR and an ECR motor unit. When such a procedure was not possible, the central inhibitory delay was demonstrated using the protocol described in the preceding paragraph.

Depression of inhibition between antagonistic wrist muscles following Renshaw cell activation

Katz *et al.* (1991) have described a technique allowing effects of Renshaw cell activation on inhibition between antagonistic muscles to be studied in man. Figure 3*A* is a schematic representation of the connections between the interneurones mediating reciprocal inhibition and Renshaw cells. In this figure the main features of the technique are also indicated. Two conditioning stimuli were used. First, a mechanical tap applied to the distal tendon of the muscle antagonistic to that involved in the test (to the ECR tendon in the case schematized in this figure), which gave rise to a monosynaptic reflex. The amplitude of this tendon monosynaptic reflex varied betwen the subjects from 4 to 20% of the maximum direct motor response. Second, an electrical conditioning stimulus (0·95 MT) applied to the nerve innervating the muscle involved by the tendon tap (the radial nerve in the case schematized in this figure). The time interval between the test stimulus and the conditioning stimulus eliciting the reciprocal inhibition was kept constant and chosen so that the reciprocal inhibition was maximum. The time interval between the first and the second conditioning stimulus was systematically varied in order to study the effects of the first conditioning volley (giving rise to recurrent inhibition) upon the second one (giving rise to the reciprocal inhibition). A critical point of this method is the efficacy of the monosynaptic tendon reflex to activate Renshaw cells. To ensure that a given tendon tap applied to the distal ECR tendon was effectively activating ECR Renshaw cells when its effects upon reciprocal inhibition were studied, a special experimental design was set up (Fig. 4). Créange, Faist, Katz & Pénicaud

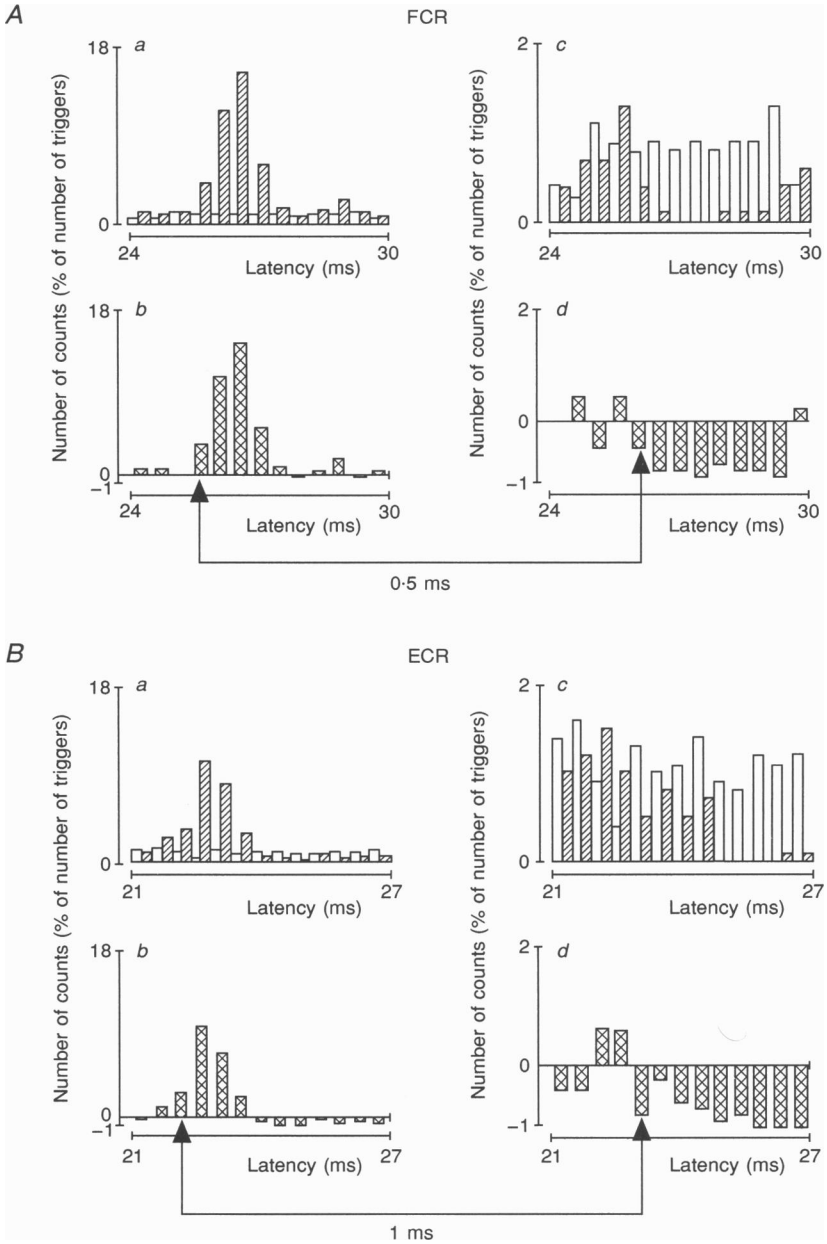

Figure 2. Determination of the central delay of reciprocal inhibition between wrist muscles

Comparison between the latencies of the increase in firing probability in response to homonymous nerve stimulation (left) and of the decrease in firing probability in response to antagonistic nerve stimulation (right). *A*, PSTHs of the discharge of a voluntarily activated FCR motor unit. *B*, PSTHs of the discharge of a voluntarily activated ECR motor unit. In *Aa*, *Ac*, *Ba* and *Bc*, open columns represent the values obtained in control conditions (i.e. without stimulation) while hatched columns represent the histograms obtained in response to nerve stimulation. In *Ab*, *Ad*, *Bb* and *Bd*, cross-hatched columns represent the difference between the control situation and that after stimulation. The vertical arrows indicate the bin corresponding to the onset of the increase (*Ab* and *Bb*) or the decrease (*Ad* and *Bd*) in firing probability. This bin was visually identified and statistical analysis was performed to determine to what extent the distribution of firing probability after stimulation differed from that in the control situation. No significant differences between the control situation and that after stimulation was seen in the 3 bins preceding the onsets of the increases of homonymous facilitation ($\chi^2 = 0{\cdot}8$ in *Ab* and 1·9 in *Bb*) and in the 3 bins preceding the onset of the decrease of the reciprocal inhibition ($\chi^2 = 0{\cdot}4$ in *Ad* and 0·5 in *Bd*) whereas the increase in each bin of the peak in firing probability was highly significant ($\chi^2 > 35$, $P < 0{\cdot}001$ in *Ab*; and $\chi^2 > 19{\cdot}2$, $P < 0{\cdot}001$ in *Bb*). In *Ad*, the decrease in the window 26–27 ms was highly significant ($\chi^2 = 10{\cdot}9$, $P < 0{\cdot}001$) and in *Bd* the decrease in the window 23–24 ms was also significant ($\chi^2 = 5{\cdot}59$, $P < 0{\cdot}05$). Number of triggers: 805 for the FCR motor unit and 1005 for the ECR motor unit. Same co-ordinates as in Fig. 1.

(1992) showed that heteronymous recurrent inhibition is elicited in the deltoid motoneurones by reflex discharge evoked in the ECR. An example of this finding is illustrated in Fig. 4: when the mechanical tap applied to the ECR tendon was just subthreshold for the ECR tendon reflex (Fig. 4*B*) only a small increase in firing probability appeared in the deltoid motor unit (Fig. 4*A*). When the strength of the conditioning mechanical tap was increased and gave rise to an ECR monosynaptic reflex (4% of M_{max} in the example illustrated in Fig. 4*D*, it resulted in a long decrease in firing probability of the deltoid motor unit (Fig. 4*C*). This decrease in firing probability, which appeared as soon as the ECR reflex appeared and whose amount increased with the size of the ECR reflex, is in all likelihood caused by the activation of Renshaw cells (Meunier *et al.* 1990; Créange *et al.* 1992; Katz, Mazzochio, Pénicaud & Rossi, 1993). After having verified that, in a given experimental session, an ECR monosynaptic tendon reflex was sufficient to evoke a heteronymous recurrent inhibition, the experimental procedure (described in full in the following paragraph) allowing investigation of the effects of the activation of ECR Renshaw cells on reciprocal inhibition from ECR to FCR was applied using an ECR tendon tap, whose amplitude was equal to or greater than that necessary to evoke the heteronymous recurrent inhibition in the deltoid motoneurones (Fig. 4*E* and *F*).

It is obvious, however, that the effects of the conditioning mechanical tap were not restricted to those on the interneurones mediating reciprocal inhibition. The tendon tap resulted in the following. (1) The activation of homonymous group I afferents. (2) The possible activation of cutaneous afferents from the skin where the mechanical tap was applied. (3) The activation, via the monosynaptic reflex loop, of some motoneurones. This activation of motoneurones resulted, in turn, in the activation of some Renshaw cells

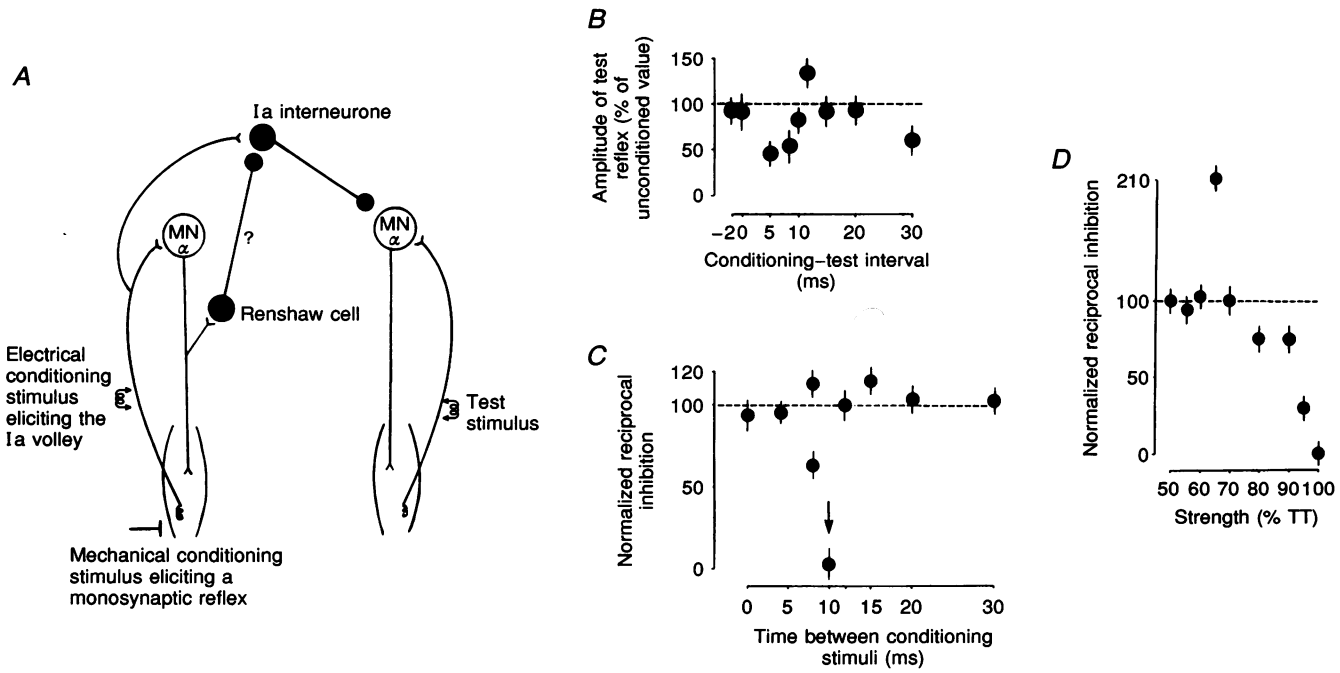

Figure 3. Effects of Renshaw cell activation on reciprocal inhibition between wrist muscles

A, schematic representation of the connections between Ia interneurones and Renshaw cells (after Hultborn *et al.* 1971). The Ia interneurone is fed by Ia fibres, inhibited by Renshaw cells and inhibits the antagonistic α-motoneurones (MN α). *B*, time course of the variations of the FCR test reflex induced by a tendon reflex discharge evoked in the ECR. Ordinate, amplitude of the test reflex expressed as a percentage of its unconditioned value. Abscissa, time interval between test and conditioning stimuli. *C*, time course of the modifications of reciprocal inhibition induced by the mechanical conditioning stimulus. The test reflex was evoked in the FCR, a conditioning electrical stimulus applied to the radial nerve gave rise to the reciprocal inhibition and the Renshaw cells were activated by an ECR reflex discharge. Ordinate, amount of reciprocal inhibition (conditioned by the antagonistic tendon reflex) expressed as a ratio of its unconditioned value and normalized in order to have $y = 100\%$ (dashed line) when the reciprocal inhibition was not modified by the conditioning tendon reflex and $y = 0$ when the reciprocal inhibition was completely blocked. Abscissa, time interval between the two conditioning stimuli. *D*, changes in the amount of reciprocal inhibition following changes in the strength of the mechanical conditioning stimulus at a fixed time interval (10 ms between the two conditioning stimuli, arrow in *C*). Same ordinate as in *C*. Abscissa, strength of the mechanical tap expressed as a percentage of tendon threshold (%TT). Each symbol represents the mean of 20 measurements.

and in a consequent afferent discharge. (4) The possible activation, via the spread of the vibration wave (Katz, Morin, Pierrot-Deseilligny & Hibino, 1977; Katz *et al.* 1991) of *test* muscle spindle endings.

In order to distinguish between the effects induced by the first conditioning stimulus (the tendon tap) on the interneurones mediating reciprocal inhibition from all its other effects, the following protocol was set up. Four configurations were randomly used. First, twenty test reflexes alone. Second, twenty test reflexes plus the first conditioning stimulus (the tendon tap). The comparison between the first and second configuration allowed appreciation of the effects of the antagonistic tendon tap on the test reflex, as illustrated in Fig. 3*B*. The amplitude of the test reflex when preceded by the first conditioning stimulus was then adjusted to be in the same range as that of the test reflex alone in order to avoid the effects linked to the amplitudes of the test reflex *per se* (Crone, Hultborn, Mazières, Morin, Nielsen & Pierrot-Deseilligny, 1990). Third, twenty test reflexes plus the second conditioning stimulus (eliciting reciprocal inhibition). Comparison between the first and third configuration revealed the amount of reciprocal inhibition in control conditions. Fourth, twenty test reflexes plus the first conditioning stimulus plus the second conditioning stimulus (Figs 3*C* and 4*E*). Comparison between the fourth and second configurations allowed appreciation of the amount of reciprocal inhibition when conditioned by the tendon tap. Comparison between the ratio of the fourth to the second configuration, and the ratio of the third to the first configurations allowed appreciation of the modifications of reciprocal inhibition by the tendon tap.

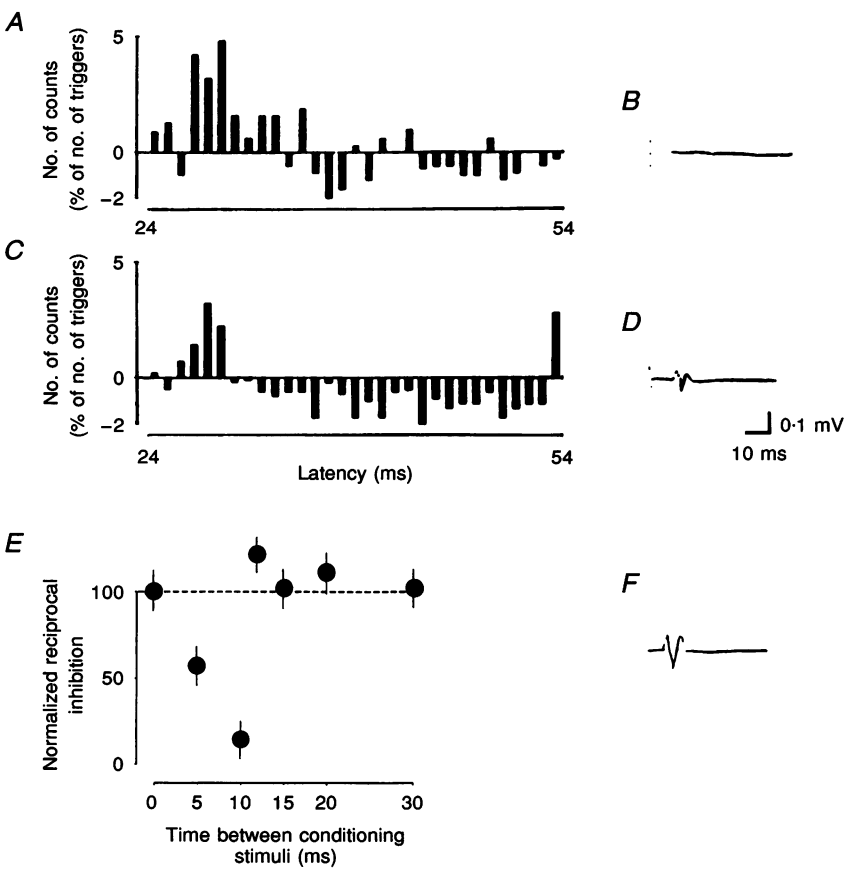

Figure 4. Control of activation of Renshaw cells by an ECR reflex discharge

A–D, changes in firing probability evoked in a voluntarily activated deltoid motor unit by an ECR tendon tap. PSTHs were obtained in the control situation and after stimulation; each bar represents the difference between the two histograms (see Fig. 2). *A* and *C*, PSTHs of the discharge of the unit in response to the ECR tendon tap. Number of triggers: *A*, 310; *C*, 460). *B* and *D*, averaged reflex response in the ECR. In *B*, the strength of the tendon tap was just subthreshold for the ECR tendon reflex. In *D*, the tap gave rise to a reflex equal to 4% of M_{max}. *E*, time course of the modification of reciprocal inhibition induced by the mechanical stimulus. The test reflex was evoked in the FCR, the conditioning electrical stimulus applied to the radial nerve gave rise to reciprocal inhibition and the Renshaw cells were activated by the ECR reflex discharge represented in *F* (6% of M_{max}). Co-ordinates as in Fig. 3. All the data were obtained from the same experimental session. Each symbol represents the mean of 20 measurements.

Figure 5*C* and *D* summarizes the results obtained by Katz *et al.* (1991) concerning the depression of the reciprocal inhibition between elbow flexors and extensors induced by Renshaw cell activation. A typical example of their results is represented in Fig. 5*C*: the reciprocal inhibition was deeply depressed during 30 ms, and a similar result was found in all the subjects studied (Fig. 5*D*) when the conditioning mechanical tap evoked a reflex discharge (● in Fig. 5*D*). When the strength of the conditioning mechanical tap was slightly reduced to be just below tendon reflex threshold (around 0·95 TT), no modifications of reciprocal inhibition between elbow antagonistic muscle were seen (△ in Fig. 5*D*). These results therefore suggest that the reciprocal inhibition between elbow flexors and extensors is mediated by Ia inhibitory interneurones inhibited by Renshaw cells (Hultborn *et al.* 1971).

Exactly the same experimental protocol was used for the wrist. In the examples presented in Figs 3*C* and 4*E*, the test reflex was evoked in the FCR. The first conditioning stimulus was a tendon tap applied to the distal tendon of the ECR. It gave rise to an ECR monosynaptic reflex liable to activate Renshaw cells (Fig. 4). The second conditioning stimulus (evoking the reciprocal inhibition from ECR to FCR) was an electrical stimulus (0·95 MT) applied to the radial nerve at a site where mainly ECR afferent fibres were activated (see Methods). The delay between the second conditioning stimulus and the test reflex was kept constant and corresponded to that at which the reciprocal inhibition was maximum. The delay between the first conditioning stimulus and the test reflex was systematically varied between 0 and 30 ms.

Contrary to what was observed at elbow level (Fig. 5*C*), whatever the time interval between the two conditioning stimuli (except around 10 ms) the reciprocal inhibition was not depressed during the 30 ms following the mechanical stimulus giving rise to the monosynaptic reflex (Figs 3*C*, 4*E* and 5*A*, *B* and *E*). Whatever the strength of the tendon tap (slightly below or above tendon threshold), the results were identical (Fig. 5*E*).

Since the brief depression of reciprocal inhibition was also seen when the conditioning mechanical stimulus did not evoke any reflex discharge (and was not therefore able to activate a Renshaw cell), it is probably not due to recurrent inhibition. However, to specify the origin of this brief depression, complementary experiments were performed in five subjects. The time interval between the two conditioning stimuli was kept constant, equal to that at which the brief depression was maximum (arrow in Fig. 3*C*) and the strength of the mechanical tap was systematically varied from 50 to 100% tendon threshold. An example of the results of these experiments is represented in Fig. 3*D*. At low strengths (below 60% of tendon threshold) the mechanical tap applied to the distal tendon of the ECR did not modify the amount of reciprocal inhibition evoked in the FCR H reflex by a conditioning electrical stimulus applied to the radial nerve. When the strength of the mechanical stimulus was progressively increased, it resulted in a clear increase in the amount of reciprocal inhibition, followed by a decrease in the amount of reciprocal inhibition. This decrease became apparent for a strength of the mechanical tap of 80% of tendon threshold, i.e. in the absence of reflex discharge. Similar results, i.e. a biphasic curve with an increase of reciprocal inhibition followed by a decrease becoming apparent without any activation of motor axons, were found when the mechanical stimulus was replaced by an electrical stimulus applied to the radial nerve. Obviously those modifications of reciprocal inhibition which appeared for strengths of the mechanical tap clearly below reflex threshold could not be due to activation of Renshaw cells, but were probably caused by an interaction between the first and the second conditioning group I volleys. The reinforcement appearing at low conditioning intensities could be due to a summation of facilitatory inputs upon the interneurone mediating reciprocal inhibition and the depression seen at stronger conditioning intensities to occlusion at the interneuronal level or to refractoriness of the afferent fibres.

Similar results, i.e. that an antagonistic reflex discharge did not evoke a long-lasting inhibition of reciprocal inhibition and that the antagonistic mechanical stimulus resulted in the same modifications of reciprocal inhibition whether or not it evoked a monosynaptic reflex, were observed in the eight experiments performed in five subjects with an FCR test reflex and in the seven experiments performed in seven subjects with an ECR test reflex (in 3 subjects there was an H reflex and in 4 of them a tendon reflex). In Fig. 5*A* and *B*, the results obtained with an ECR test reflex are illustrated (and thus with an electrical conditioning stimulus applied to the median nerve and a mechanical tap applied to the distal tendon of the FCR muscle). In Fig. 5*A*, the test reflex was an ECR H reflex, while in Fig. 5*B* it was an ECR tendon reflex. No long-lasting depression of reciprocal inhibition from FCR to ECR was found following activation of Renshaw cells by an FCR reflex discharge.

To allow a better comparison between the results obtained at wrist and elbow level, the modifications of reciprocal inhibition induced by activation of Renshaw cells in all the subjects were plotted together for each joint against the duration of the depression of the reciprocal inhibition. In Fig. 5*D* the results obtained in five subjects at elbow level are plotted: the depression of reciprocal inhibition lasted at least 30 ms (●) and disappeared as soon as the strength of the mechanical tap was subthreshold for the reflex response (△).

In Fig. 5*E* the results obtained in eight subjects at wrist level are plotted (5 with an FCR test H reflex and 3 with an ECR test H reflex): the depression of reciprocal inhibition lasted in all the cases between 10 and 15 ms (●) and the reduction of the strength of the mechanical tap below the threshold of the tendon reflex did not modify the depression of reciprocal inhibition (△). Therefore, the main result is

the finding that the effects of the mechanical stimulus on reciprocal inhibition were the same whether or not it evoked a reflex discharge, i.e. with or without activation of Renshaw cells, and that it never resulted in a long-lasting depression of reciprocal inhibition resembling the time course of recurrent inhibition described in the cat by Renshaw (1946) or found in man at the level of the elbow (Katz *et al.* 1991).

Effects of combined stimulation of two nerves on reciprocal inhibition between wrist flexors and extensors

Cavallari, Katz & Pénicaud (1992) have shown that biceps and triceps Ia fibres inhibit FCR motoneurones through an oligo- (possibly di-)synaptic pathway. To characterize further the interneurone mediating reciprocal inhibition between

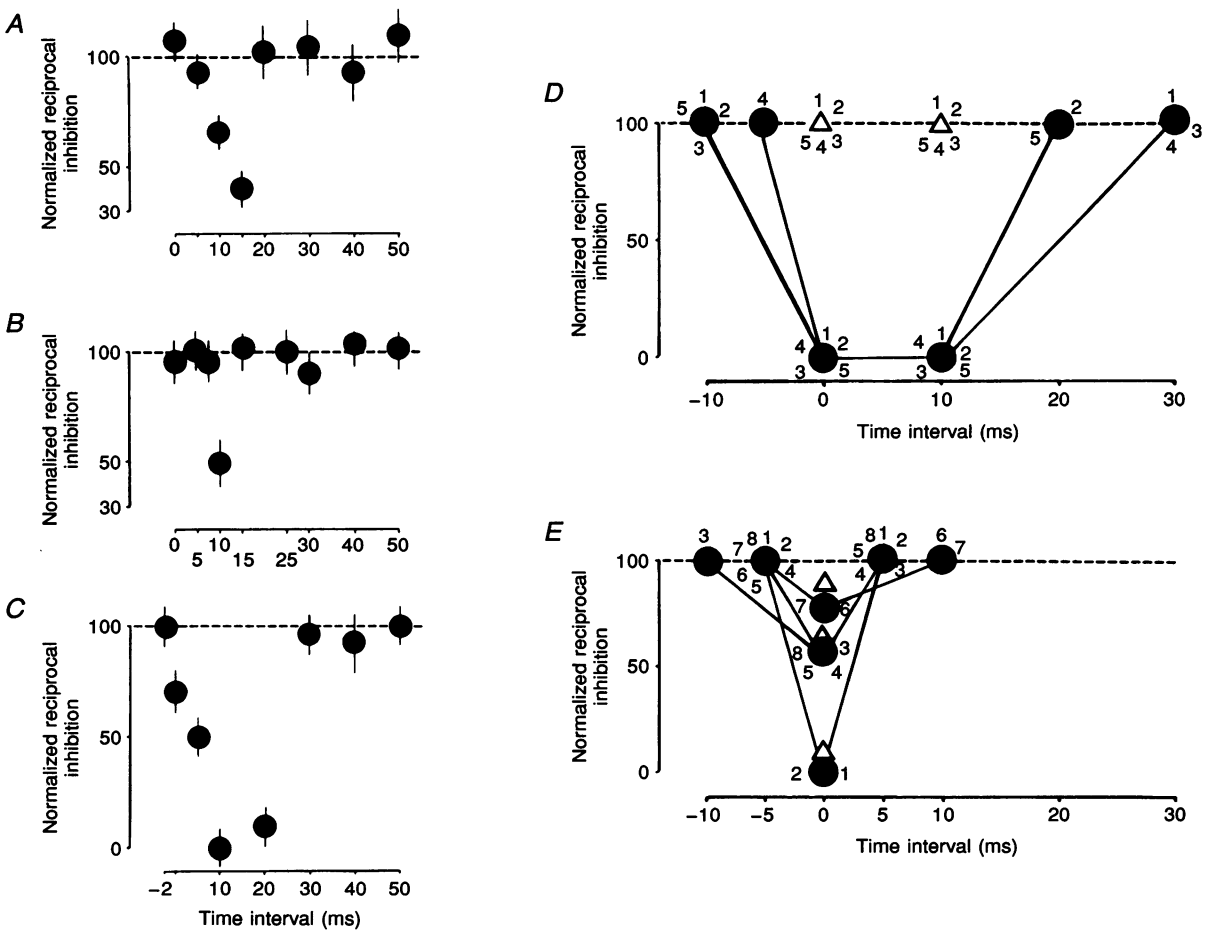

Figure 5. Summary of the effects of activation of Renshaw cells on reciprocal inhibition at the elbow and wrist

A comparison between the results obtained at wrist and at elbow is shown for changes in reciprocal inhibition induced by a preceding reflex discharge. *A*, the test reflex was an ECR H test reflex. *B*, the test reflex was an ECR tendon reflex. In both cases, the electrical stimulus giving rise to the reciprocal inhibition was applied to the median nerve and the mechanical tap giving rise to an FCR tendon reflex was applied to the distal tendon of the FCR. *C*, the test reflex was a biceps brachii tendon reflex, the conditioning stimulus eliciting the reciprocal inhibition was applied to the triceps nerve and the Renshaw cells were activated by a triceps reflex discharge (after Katz *et al.* 1991). Same co-ordinates as in Fig. 3*C*. *D*, changes induced by a preceding reflex discharge in the reciprocal inhibition between antagonistic elbow muscles (●). The results obtained in 5 subjects are shown (subjects are labelled from 1 to 5). Abscissa: duration of the depression of the reciprocal inhibition; zero corresponds to the time interval at which the depression was maximal. Ordinate as in Fig. 3*C*. Open triangles represent results obtained when the mechanical tap was just subthreshold for the tendon reflex. *E*, changes induced by a preceding reflex discharge in the reciprocal inhibition between ECR and FCR. The results obtained in 8 subjects (subjects labelled from 1 to 8; 5 with a test FCR H reflex and 3 with a test ECR H reflex) are plotted together (●). Same co-ordinates as in *D*. Open triangles represent the results obtained when the mechanical tap was just subthreshold for the tendon reflex.

wrist muscles, the effects of combined stimulation of musculocutaneous (or triceps) and radial nerves onto FCR motoneurones were tested. First, the intensity of the conditioning stimuli applied to the musculocutaneous and the radial nerves was adjusted to 0·95 MT, and resulted in each case in an early and short-lasting decrease in firing probability (Fig. 6*B* and *C*). The conditioning electrical stimulation to the radial nerve was placed just below the elbow to activate mainly ECR group I fibres (see Methods). The intensities of the conditioning stimuli were then decreased to 0·6 MT for the radial nerve and to 0·65 MT for the musculocutaneous nerve. In such conditions, no change in firing probability was seen in the FCR motor unit (Fig. 6*D*, *G*, *E* and *H*) when the two nerves were stimulated separately. A clear change occurred with combined stimulation of the two nerves (Fig. 6*F* and *I*) when the interval between the two conditioning stimuli was such that the two afferent volleys reached the spinal cord simultaneously: an early and short-lasting decrease in firing probability appeared despite the fact that each conditioning stimulus alone was unable to decrease the firing probability of the test FCR motor unit. Nineteen motor units were recorded in five subjects. The spatial facilitation illustrated in Fig. 6*F* and *I* was found in eleven

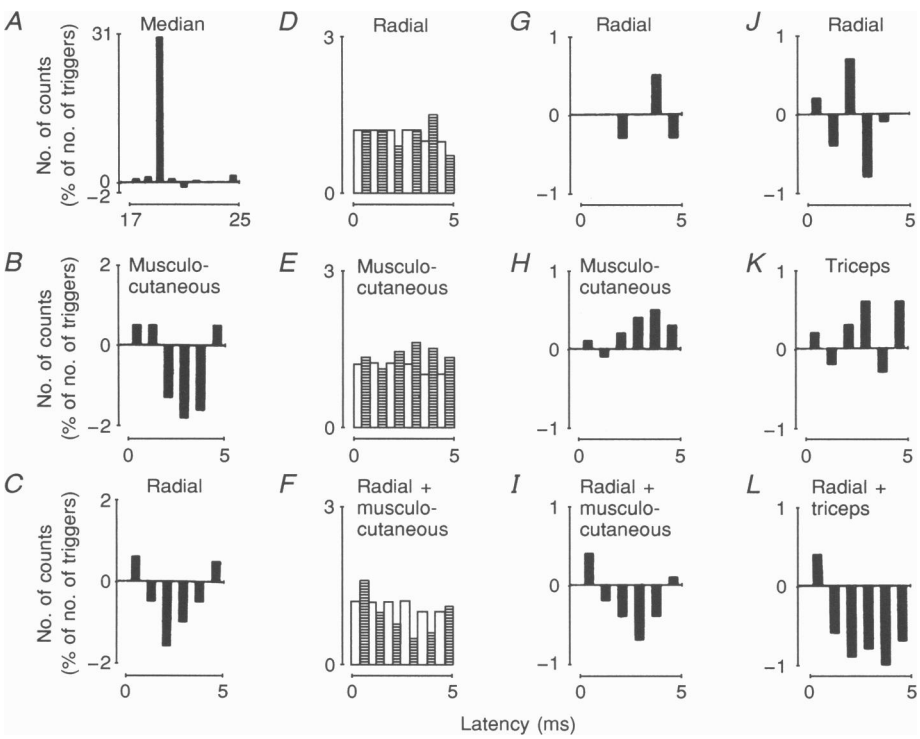

Figure 6. Convergence upon interneurones mediating reciprocal inhibition between wrist muscles

Effects of the electrical stimulation of median, radial, musculocutaneous and triceps nerves on a single FCR voluntarily activated motor unit. In *D*, *E* and *F*, open columns (□) represent the results obtained in control situation and shaded columns (▤) the results obtained after stimulation. In all the other histograms filled columns (■) represent the differences between the two situations. *A–C*, the intensity of the conditioning stimuli (median nerve in *A*, musculocutaneous nerve in *B* and radial nerve in *C*) was adjusted at 0·95 MT. *D*, *G* and *J*, effects evoked by the stimulation of the radial nerve alone (intensity 0·6 MT); *E* and *H*, effects evoked by the stimulation of the musculocutaneous nerve alone (intensity 0·65 MT). *F* and *I*, effects of stimulation of both the radial and the musculocutanous nerves. *K*, effect evoked by the stimulation of the triceps nerve alone (intensity 0·6 MT). *L*, effects of stimulation of both radial and triceps nerves. Abcissa: *A*, time elapsed since the occurrence of the conditioning stimulation; *B–L*, time elapsed since the occurrence of the monosynaptic peak represented in *A*. Same ordinates as in Fig. 1*C–D*. Number of triggers: *A*, 150; *B–L*, 1100. Statistical analysis as in Figs 1 and 2. No significant modification of firing probability was seen in *G*, *J*, *H* and *K*, and in the 3 bins preceding the effects in *A*, *B*, *C*, *I* and *L*, while the decrease in firing probability was significant, $0{\cdot}001 < P < 0{\cdot}05$ (according to the configurations) in *B*, *C*, *I* and *L*.

of these motor units. There were no significant changes in firing probability following the combined nerve stimulation in the remaining motor units. To rule out the possibility that cutaneous fibres alone were responsible for the decrease obtained with the combined stimulation, each of the conditioning stimuli was replaced by a purely cutaneous stimulus mimicking the sensation induced by the stimulation of the two nerves. No decrease in firing probability was seen when a cutaneous stimulus was combined with a nerve trunk stimulus.

Similar results were obtained in four experiments performed in two subjects when the two conditioning stimuli were applied to the radial nerve below the elbow and to the triceps nerve. After having verified that each conditioning stimulus at an intensity of 0·95 MT resulted in an early and short decrease in the firing probability of the tested FCR motor unit, each stimulus intensity was decreased to be just subthreshold for the inhibition when the stimuli were given separately (Fig. 6*J* and *K*). With combined stimulation there was, in all the cases, an early and short-lasting decrease in firing probability of the motor unit (Fig. 6*L*). In this experimental situation it was also shown that no spatial facilitation occurred when one of the conditioning nerve stimuli was replaced by a pure cutaneous stimulation.

DISCUSSION

In the present experiments, first, the disynaptic inhibition between wrist flexors and extensors was not depressed by activation of Renshaw cells and, second, group I afferents originating from antagonistic elbow muscles were found to facilitate actions of interneurones mediating inhibition between wrist flexors and extensors. These findings suggest that the interneurones mediating reciprocal Ia inhibition between wrist flexors and extensors, although fed by group I afferents and interposed in a disynaptic pathway, exhibited properties different from those of interneurones mediating reciprocal inhibition. In the following, the strength of arguments in favour of this hypothesis will be scrutinized and the functional consequences of the hypothesis discussed.

Reciprocal inhibition between wrist muscles is not depressed by recurrent inhibition

Inhibition of the Ia inhibitory interneurones by Renshaw cells (Hultborn *et al.* 1971) provides a unique means of their identification. Katz *et al.* (1991) proposed a technique allowing depression of reciprocal inhibition in man by the activation of Renshaw cells and demonstrated that the reciprocal inhibition between elbow flexors and extensors was depressed when a conditioning reflex discharge was elicited in the muscle from which the conditioning Ia fibres originate. The time course of this depression closely resembled the time course of recurrent inhibition described in the cat (Renshaw, 1946), and it was only observed when the mechanical stimulus conditioning the reciprocal inhibition evoked a monosynaptic reflex. It was therefore concluded that the inhibition between antagonistic elbow muscles was probably mediated through Ia inhibitory interneurones. Exactly the same experimental protocol was used in this study to characterize the interneurones mediating inhibition between wrist flexors and extensors. Contrary to what was observed for elbow antagonistic muscles, no long-lasting depression of reciprocal inhibition was observed and the brief modifications of reciprocal inhibition induced by the mechanical tap were identical whether or not this tap gave rise to a reflex discharge, i.e. whether or not Renshaw cells could have been activated.

Inhibition between wrist flexor and extensor muscles therefore seems not to be affected by Renshaw cell activation. However, before reaching this conclusion one must be sure: (i) that activation of FCR and ECR motoneurones was followed by activation of Renshaw cells; and (ii) that the conditioning reflex discharge was sufficient to activate them.

In relation to the first point, Illert & Wietelmann (1989) have recently demonstrated the presence of homonymous recurrent inhibitory postsynaptic potentials (RIPSPs) in ECR and FCR motoneurones in the cat. In man, Katz *et al.* (1993), using the paired H reflex technique described by Bussel & Pierrot-Deseilligny (1977) coupled with a pharmacological study (Mazzocchio & Rossi, 1989), demonstrated the presence of homonymous recurrent inhibition in both FCR and ECR motoneurones. In 1993, Katz and co-workers, using the PSTH technique illustrated in Fig. 4, were able to evoke heteronymous recurrent inhibition in deltoid and biceps motoneurones with an ECR or a FCR reflex discharge.

In relation to the second point, Hultborn, Pierrot-Deseilligny & Wigström (1979) showed that in the cat even the lowest threshold motoneurones are efficient in producing recurrent inhibition and it is a general rule, at least in the cat (for references see Baldissera *et al.* 1981), that homonymous RIPSPs are larger than heteronymous ones. Therefore a reflex discharge powerful enough to elicit heteronymous recurrent inhibition should also be powerful enough to elicit homonymous recurrent inhibition. However, since the result of this series of experiments was a negative one (the reflex discharge evoked in the muscle from which originate the Ia afferents activated by the electrical conditioning stimulus failed to elicit a long-lasting depression of reciprocal inhibition), control experiments were performed to ensure that in the same experimental session, the same ECR reflex discharge was able to evoke heteronymous recurrent inhibition in a deltoid motoneurone and did not evoke a long-lasting depression of reciprocal inhibition. To favour the activation of Renshaw cells it was also verified in the same experimental session (Fig. 3) that even with larger reflex discharges no long-lasting depression was evoked in reciprocal inhibition.

Together these arguments lead to the conclusion that the reflex discharge elicited by the mechanical tap applied to

the wrist muscle tendon was efficient in activating Renshaw cells. Therefore, the fact that these reflex discharges failed to evoke a long-lasting depression of reciprocal inhibition between wrist flexors and extensors strongly suggests that the interneurones mediating reciprocal inhibition at wrist level are not inhibited by Renshaw cells and therefore are not homologues of Ia inhibitory interneurones.

Input to interneurones mediating reciprocal inhibition between wrist muscles

The indirect technique used in this study to investigate convergence upon interneurones mediating reciprocal inhibition between wrist flexors and extensors has been adapted from Lundberg (1975). The efficacy of each conditioning volley in biceps, triceps and ECR group I afferents was firstly verified and then the intensity of the conditioning stimuli was decreased until they no longer affected the firing probability of the tested motor unit, because they were subliminal for activation of the interposed interneurones. When combined stimulation of pairs of the muscle nerves modified the firing frequency of the tested motor unit, this was taken as an indication of spatial summation of subliminal actions from these nerves on common interneurones. Our experimental conditions obviously differ from those originally described by Lundberg (1975): (i) the modifications of firing probability of a motor unit rather than amplitude of postsynaptic potentials or monosynaptic reflexes were studied; and (ii) the conditioning stimulations were applied percutaneously to a nerve trunk and were therefore less selective for a specific afferent type.

Fetz & Gustafsson (1983) have shown that changes in firing probability in a PSTH reflect changes in postsynaptic potentials. If one of the conditioning stimuli applied alone had given rise to an inhibitory postsynaptic potential in a motoneurone, it should have resulted in a decrease in the firing probability of the tested motor unit. Since no such decrease occurred (Fig. 6*G*, *H*, *J* and *K*), it is likely that the stimuli were subliminal for affecting the motoneurones and that the decrease in firing probability of the tested motor unit by combined stimulation of the two nerves was due to spatial summation of synaptic actions of these nerves upon common interneurones. The strength of the conditioning volleys was below motor threshold, and it seems unlikely that cutaneous fibres alone play a major role, since no modifications of firing probability were seen following combined stimulation when one of them was a pure cutaneous volley. The afferents converging upon interneurones and co-exciting them are therefore likely to be group I afferents. The musculocutaneous nerve innervates only elbow flexors, and it has been shown (Cavallari *et al.* 1992) that it is possible selectively to activate the radial branch innervating the triceps. As stated in the Methods, it was also possible to find on the radial nerve trajectory a site at which, even when using the maximal intensity of the stimulation, the radial nerve stimulus resulted only in a wrist extension, with no finger extension, thus suggesting that it affected mainly ECR group I afferents. It seems likely, therefore, that interneurones interposed in the reciprocal Ia inhibitory pathway from ECR to FCR are also activated by group I afferents originating from biceps *and* triceps muscles. Convergence from more proximal muscle afferents onto Ia inhibitory interneurones is not uncommon in the cat hindlimb (Hultborn & Udo, 1972) but is characterized by a pattern which is often similar to that of Ia excitation of motoneurones. Convergence from antagonistic proximal muscles onto Ia inhibitory interneurones was never found in the cat hindlimb, contrary to our findings, since afferents coming from antagonistic elbow muscles both facilitate interneurones mediating inhibition from ECR to FCR. When the median nerve is stimulated, it is impossible to be sure that group I afferents coming from pronators or from digital flexors are not activated together with FCR group I afferents, and thus the reverse experiment (i.e. with an ECR test motor unit) was not performed. Nevertheless, we favour the hypothesis that the interneurones mediating inhibition from FCR to ECR would behave in the same manner as the interneurones mediating inhibition from ECR to FCR, taking into account the fact that all their characteristics (input, synaptic delay, initial inhibition and effect of cutaneous afferents) are similar.

Properties of interneurones mediating reciprocal inhibition between wrist flexors and extensors

The present results obtained with PSTH experiments are in accordance with those obtained using H reflexes (Baldissera *et al.* 1983; Day *et al.* 1984) showing that activation of group Ia afferent fibres induce inhibition of antagonistic motoneurones in wrist muscles through a disynaptic pathway. Cavallari, Fournier, Katz, Malmgren, Pierrot-Deseilligny & Shindo (1985) established that reciprocal inhibition between wrist muscles was not modified by activation of low-threshold cutaneous afferents and Baldissera *et al.* (1987) presented evidence for mutual inhibition between interneurones mediating inhibition of wrist flexors and extensors, respectively. Two other features of these interneurones are described in this study: (i) they are not inhibited by Renshaw cells; and (ii) they are co-excited by group I afferents originating from more proximal antagonistic muscles. The latter two features are at variance with those of the previously described interneurones, which mediate Ia reciprocal inhibition between hindlimb flexors and extensors in the cat and are referred to as Ia inhibitory interneurones (see Jankowska, 1992). Indeed, Ia inhibitory interneurones are inhibited by Renshaw cells, excited by group Ia afferent fibres originating from non-antagonistic muscles (Hultborn *et al.* 1971; Hultborn & Udo, 1972) and inhibited by group Ia afferent fibres of antagonists (Hultborn, Illert & Santini, 1976). However, these features do not seem to correspond to those of interneurones interposed in Ib reflex pathways and co-excited by group Ia and Ib afferent fibres (for references see Jankowska, 1992), because these

interneurones are strongly co-excited by low-threshold cutaneous afferents. The results of this study thus lead to the conclusion that interneurones mediating inhibition between wrist flexors and extensors in man have properties which distinguish them from both Ia inhibitory interneurones and Ib interneurones.

It must be pointed out, however, that the characterization of Ia and Ib interneurones has been performed in the cat lumbar spinal cord. Illert & Wietelmann (1989) summarized the knowledge about the cat cervical spinal cord. They indicated that, although there is no real information about the reflex connections, in the cat distal forelimb no direct evidence has been presented up to now for the presence of a disynaptic Ia inhibitory pathway from motor nuclei to distal forelimb muscles. Although certainly more limited in the cat than in man, the wrist movements differ greatly from those executed by hindlimb joints and it is tempting to suggest that the differences in interneuronal characteristics are related to the difference in joint performance. However, taking into account the absence at the present time (M. Illert, personal communication) of data concerning reciprocal inhibition between wrist flexors and extensors in the cat, it cannot be known whether the features exhibited by the interneurones mediating reciprocal inhibition between wrist flexors and extensors in man are peculiar to man or also exist in the cat cervical spinal cord.

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