

## Human spinal lateralization assessed from motoneurone synchronization: dependence on handedness and motor unit type

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1. Motoneurone synchronization as a means of investigating synaptic connectivity was studied in the extensor carpi radialis muscles of the preferred and non-preferred arms of healthy right- and left-handed human subjects. The activities of pairs of motor units recorded during voluntary isometric contractions were analysed by cross-correlation to detect any synchronous motor unit firing in the form of central peaks in the cross-correlation histograms.
2. The synchronization peaks were compared first in the case of 273 motor unit pairs tested in the preferred and non-preferred arms of two left-handed subjects and two right-handed subjects. The percentage of synchronized motor unit pairs was found to be significantly higher in the preferred arm with synchronization peaks significantly larger and broader than in the non-preferred arm. The narrow peaks (< 7.5 ms) likely to reflect the activity of common inputs to motoneurons were also found to be significantly larger in the preferred arm of all four subjects.
3. The handedness-related differences in synchronization were definitely confirmed in a total of 275 pairs of motor units tested in the left extensor carpi radialis muscles of fourteen right-handed subjects using their non-preferred arm and six left-handed subjects using their preferred arm. In order to determine whether the differences in synchronization were dependent on the motor unit type, each motor unit was characterized on the basis of its recruitment threshold and on the basis of the contraction time of its twitch extracted from the overall muscle force using the spike-triggered averaging method. Two populations of motor units were distinguished, namely the 'slow' motor units (recruitment thresholds < 0.4 N, contraction times > 40 ms) and the 'fast' motor units (recruitment thresholds > 0.6 N, contraction times ≤ 40 ms).
4. In the non-preferred arm, the synchronization peaks were always fairly narrow, whatever the motor unit's biomechanical properties; whereas in the preferred arm, broad peaks were found to be particularly common among the pairs including one or two fast motor units, which also showed the largest rate of synchronization occurrence.
5. The narrow peaks (< 7.5 ms) were found to be consistently larger in the preferred than the non-preferred arm whatever the categories of motor unit pairs. In both arms, however, the amplitude of the narrow peaks tended to increase as the recruitment threshold of the motor unit decreased and as their contraction time increased. This suggests the involvement of common inputs acting on the various types of motoneurons in much the same way as shown in the case of the muscle spindle primary afferents in animals.
6. The idea is put forward that the general enhancement of the motor unit discharge synchronization observed in the arm preferentially used by the subjects may reflect, in the first place, an enhancement of the efficiency of the motoneurons' common inputs, particularly in the case of the slow motor units, and, in the second place, an enhancement of the presynaptic synchronization of the motoneurone inputs, particularly in the case of the fast motor units, which require a strong drive to be recruited.

The common view that motoneurone discharges on the whole are asynchronous during muscle contraction had to be revised when cross-correlation analyses of the temporal coupling between single motor unit discharges consistently demonstrated that synchronous firing occurred with a probability higher than chance level during the voluntary contraction of various human muscles (Buchthal & Madsen, 1950; Milner-Brown, Stein & Lee, 1975; Dengler, Wolf, Birk & Struppler, 1984; Adams, Datta & Guz, 1989; Datta & Stephens, 1990; Davey, Ellaway, Friedland & Short, 1990; Nordstrom, Miles & Türker, 1990; Bremner, Baker & Stephens, 1991).

Synchronous activity is reflected in cross-correlation histograms in the form of central peaks, the time course of which depends on the synaptic processes involved in the synchronization (Kirkwood, 1979; Kirkwood, Sears, Tuck & Westgaard, 1982; Kirkwood & Sears, 1991). In the short-term synchronization process described by Sears & Stagg (1976), common excitatory inputs that innervate the motoneurons via branching axons can produce rather narrow synchronization peaks, which are thought to be closely related to the rising phase of the common inputs' postsynaptic potentials (cf. Kirkwood & Sears, 1991).

Another process, referred to as broad-peak synchronization (cf. Kirkwood *et al.* 1982), involves the synchronization of the motoneurone inputs by their own common inputs, at some pre-motoneuronal (presynaptic) level. This process is generally thought to produce less tightly coupled synchronous firing, resulting in broader cross-correlogram peaks than those reflecting short-term synchrony.

As thoroughly discussed in a recent review (Kirkwood & Sears, 1991), no clear-cut boundary can be set, however, between the maximum duration typical of short-term synchrony and the minimum duration typical of broad-peak synchrony. According to these authors, the peaks commonly wider than 6 ms, which have been observed on human motor unit activity, are likely to reflect the combined action of common branched-axon inputs and presynaptically synchronized inputs.

The muscle spindle Ia fibres which innervate virtually all the motoneurons of their muscle (Mendell & Henneman, 1971) are the best-known source of common inputs. In cats, these afferents have been shown to generate the largest EPSPs in the motoneurons corresponding to the first recruited motor units, which produce small slow-rising contractile forces and, conversely, much smaller Ia EPSPs are generated in motoneurons corresponding to the high-threshold motor units, which produce fast-rising and large twitches (Burke, Rymer & Walsh, 1976). A similar differential action might be expected in the case of other motoneurone afferents such as the cortico-spinal inputs, the distribution of which has been found, in the monkey, to closely match that of the Ia afferents among the forearm motoneurone pools (Clough, Kernell & Phillips, 1968; Mantel & Lemon, 1987).

If inputs distributed similarly to Ia afferents contribute to motoneurone activity during muscle voluntary contraction in humans, they are liable to induce short-term synchronization and the largest peaks can be expected to occur between the low-threshold, slow-contracting motor units that presumably receive the largest EPSPs.

An increase in the degree of synchronization assessed at the level of the whole EMG activity has been reported to occur after a few weeks of intensive muscular training (Milner-Brown *et al.* 1975). This suggested that the synaptic efficiency of motoneuronal inputs may depend on muscle use.

The present study was aimed at investigating the motoneuronal synaptic connectivity in the wrist extensor muscles assessed from the synchronization of the motor unit activities in relation to the subject's handedness and in relation to the motor unit types.

A preliminary report of these data has been presented (Schmied, Vedel & Pagni, 1992).

## METHODS

Experiments were performed on twenty healthy male human subjects aged 18–30 years, with the approval of the Ethics Committee of the local Medical University (CCPPRB-Marseille I, approval No. 92/74). All the subjects gave their informed consent to the experimental procedure, as required by the Helsinki Declaration (1964).

Single motor unit activities were recorded in the wrist extensor muscles of left- and right-handed subjects, as defined by the Edinburgh Inventory test (Oldfield, 1971).

### Instructions to subjects

The subjects were seated in an adjustable armchair. Their right or left forearm was placed in a cushioned groove to ensure that a stereotyped position was maintained from one experiment to another. The distal end of the forearm was immobilized in a device leaving the wrist joint free and maintaining the hand in a semi-prone position, flexed at an angle of 10 deg, the back of the hand being maintained in contact with an isometric force transducer.

The amplified and filtered (bandpass, 300–3000 Hz) motor unit activities were continuously monitored on loud speakers to provide the subjects with auditory feedback.

The subjects were asked to perform selective contractions of the wrist extensor muscles by pushing on the force transducer device with the back of their hand and had to maintain the two motor units firing tonically for 3–5 min, in order to produce up to 3000 impulses from each unit.

### Muscle force recording

The net force produced by the wrist extension was calibrated in newtons and recorded as a direct (DC) signal and as a filtered (AC) signal (bandpass, 0.1 Hz to 1 kHz), which was used off-line to extract the motor unit twitch by means of the spike-triggered averaging method.

### Muscle activity recording

The overall EMG activity of the extensor carpi radialis (ECR) longus and brevis muscles was recorded by means of paired surface electrodes 2 cm apart.

Single motor unit activities were recorded in the ECR muscles by means of two sterilized metal semi-microelectrodes (impedance 12 M $\Omega$  tested at 1 kHz, Frederick Haer & Co., Brunswick, ME, USA). The microelectrodes were inserted transcutaneously (1–2 cm apart) and then moved in tiny steps until a stable recording of a clearly identifiable single motor unit activity was obtained.

In some cases (<10% of all the motor unit pairs tested), when the action potentials of two motor units were clearly identifiable on one electrode, cross-correlograms were computed between each of these motor units and the motor unit recorded with the second electrode.

The surface electrodes and microelectrodes were connected to amplifiers through probes with an isolated ground for optimum subject protection (current leakage < 3  $\mu$ A).

The force signals (direct and filtered), the EMG and the microelectrode recordings were stored on digital tape and analysed off-line.

### Data analysis

The analysis of single motor unit activities was performed off-line using dual window discriminators (BAK Electronics Inc., Germantown, MD, USA). To avoid any spurious firing of other motor units the autocorrelograms of the two motor unit discharges were systematically computed.

At the first experimental session, motor unit synchronization was investigated in the right and left ECR muscles of two left- and two right-handed subjects. The data were analysed in the case of each subject and subsequently pooled.

At the second experimental session, motor unit synchronization was investigated on the basis of the motor units' functional properties, i.e. the force recruitment thresholds and twitch contraction times. Data were obtained on the left forearm with a manipulandum equipped with a highly sensitive DC and AC force transducer in the case of six left-handed subjects (using their preferred arm) and fourteen right-handed subjects (using their non-preferred arm).

### Synchronization analysis

The probability of synchronization occurring above chance level between the impulses produced by two simultaneously recorded motor units was evaluated by performing a cross-correlation analysis. Given the fact that the patterns of the two motor unit discharges were usually different, two cross-correlation histograms were systematically computed for each pair, using each motor unit alternately as the trigger. In each pair, the synchronization characteristics were assessed from the mean value of the peak parameters obtained from the two cross-correlograms. More than 70% of the cross-correlograms were computed with a minimum of 3000 action potentials from at least one of the motor units. The distribution of the impulses of one of the motor units was analysed in the bins (1.5 ms) of a cross-correlation histogram (75 ms before and after the trigger impulses) with respect to the firing of the trigger motor unit.

Synchronization was characterized by an increase in the bin counts around the triggering impulse generating a central peak in the histogram.

To determine the presence and the significance of the peaks, the mean value (baseline) of the activity of the motor unit analysed was computed during 60 ms on the left and right sides of the histogram, not including a period of 30 ms around the origin of the cross-correlograms where the synchronous firing could be expected to occur. The same 60 ms

baseline was used in all the histograms in order to standardize the analyses. Two cumulative sums (cusum, Ellaway, 1978) were computed, working first from the left to the right of the histogram and second from the right to the left. On the basis of the confidence limits of the cusums (Davey *et al.* 1986), the peak onset and offset were determined as the first bin which was significantly higher than the baseline in the two cusums. The only peaks taken into account were those that could be delimited on the basis of the confidence limits of the two cusums and those for which one limit could be determined taking the confidence limits of one cusum, the other one being positioned visually on the basis of the cusum inflexions.

The significance of the synchronization peaks was further assessed at a level of  $P < 0.001$  by means of the  $z$  test ( $z > 3.27$ ; Garnett & Stephens, 1980) and the critical value of the synchronization index (Wiegner & Wierzbicka, 1987). The peak width ( $W$ ) was calculated on the basis of the peak onset and offset.

The amplitude of the peaks was assessed by two parameters. (1) The 'synchrony probability per trigger' (SP/T) was given by the number of impulses in the peak above the baseline divided by the number of trigger impulses (i.e. the number of synchronized impulses per trigger impulse). This parameter was chosen because it is potentially correlated with the size of the EPSPs generated by the common inputs (Kirkwood, 1979; Cope, Fetz & Matsumura, 1987). (2) The 'synchronous impulse frequency' (SIF) was calculated by dividing the number of impulses in the peak by the duration of the motor unit discharge recording. This parameter corresponds to the 'common input strength' (CIS) recently proposed by Nordstrom, Fugelvand & Enoka (1992) as liable to be less dependent on the motor unit firing frequency than any of the parameters used in previous studies, including the 'synchrony probability per trigger'.

The firing properties of each motor unit pair were given by the geometric mean of the firing rates, the geometric mean of the coefficient of variation of the interspike intervals and the difference between the firing rates of the two motor units.

### Motor unit biomechanical properties

In order to determine the motor unit recruitment threshold the subjects were asked to perform stereotyped ramp contractions (0.25 N s<sup>-1</sup>) at the beginning of each recording. The level of force at which each motor unit started to fire was taken to constitute its recruitment threshold. Since other muscles, such as the extensor carpi ulnaris, can contribute to voluntary wrist extension, it was impossible, however, to express the motor unit recruitment threshold in terms of the percentage of the maximal force produced by the selective contraction of the ECR muscles.

In order to evaluate the motor unit contraction time, the force change or twitch selectively associated with the firing of each motor unit was extracted by spike-triggered averaging the net extension force (bandpass filtered at 0.1 Hz to 1 kHz), using the method developed by Stein, French, Mannard & Yemm (1972). To minimize the distortion resulting from the partial fusion of successive twitches, any spikes occurring with an interspike interval of less than 80 ms (both before and after the spike) were excluded from the analysis. Whenever possible, spike-triggered averaging was performed on two or three different periods in the recording, including a minimum number of one hundred action potentials. The mean rise time of the two or three twitches elicited with each motor unit was calculated and taken as an index to its contraction time.

The biomechanical properties of the motor unit pairs were expressed in two ways: first, on the basis of the type-identification of the motor units, i.e. low-threshold, slow-contracting motor units ('slow') or high-threshold, fast-contracting motor units ('fast') suggested by the distribution of the contraction times and the recruitment thresholds established in the extensor carpi radialis muscles in this study as well as in a previous one (Romaiguère, Vedel, Pagni & Zenatti, 1989). The second method was based on the calculation of the mean recruitment threshold and the mean contraction time of the two motor units constituting each pair.

#### Statistical analysis

Regression analyses were performed between the peak parameters and the biomechanical properties or the firing characteristics of the motor unit pairs. Comparisons of the discharge and synchronization characteristics were performed using an analysis of variance (ANOVA). *Post hoc* unpaired comparisons were performed using Fisher's protected least significant difference (or PLSD) test.

## RESULTS

### General characteristics of the motor unit synchronization in the ECR muscles

In a total of 409 pairs of motor units tested in the extensor carpi radialis longus and brevis, during isometric contractions lasting for 3–5 min, motoneuronal synchronous activity in the form of significant central peaks in cross-correlation histograms was observed in the case of 72.8% of the motor unit pairs. Among these synchronization peaks, 54.9% were delimited by the confidence limits of the two cusums, and 45% were delimited by one cusum limit and one visual limit.

Rather narrow peaks (<7.5 ms) were observed in the case of 59% of the motor unit pairs, while broader peaks lasting from 7.5 to 28.5 ms were observed in the case of 39.2% of synchronized pairs. In some cases (1.6%; 5 motor unit pairs), very long asymmetrical peaks were observed, with durations of up to 48.7 ms, always when the subjects were using their preferred arm.

Considering the whole significant peak population, the mean ( $\pm$  s.d.) peak duration was  $7.7 \pm 5.8$  ms (range: 1.5–24.7 ms), the mean SP/T was  $0.045 \pm 0.036$  (range: 0.01–0.33) and the mean SIF was  $0.40 \pm 0.26$  impulses  $s^{-1}$  (range: 0.10–2.14).

### Relationships between the motor unit discharge characteristics and the synchronization level in the motor unit pairs

The discharge frequency was found to be slightly but significantly lower in the preferred than in the non-preferred arm of the two left-handers and the two right-

handers (Table 1). No differences were observed, however, in the case of the difference between the firing rates of the two motor units constituting each pair or in the case of the geometric mean coefficients of variation of their discharge.

In the preferred arm only, a weak negative correlation was observed between the SP/T and the geometric mean discharge frequency ( $r = -0.18$ ,  $P = 0.05$ ). Whatever the subject's handedness, however, no significant correlations could be found between the mean discharge frequency and the SIF, as shown in Fig. 1A and B.

In both arms, a negative correlation was observed, showing that the SP/T ( $r = -0.24$ ,  $P = 0.02$  and  $r = -0.43$ ,  $P < 0.0001$ ) as well as the SIF (Fig. 1C and D) tended to increase as the difference between the firing rates decreased.

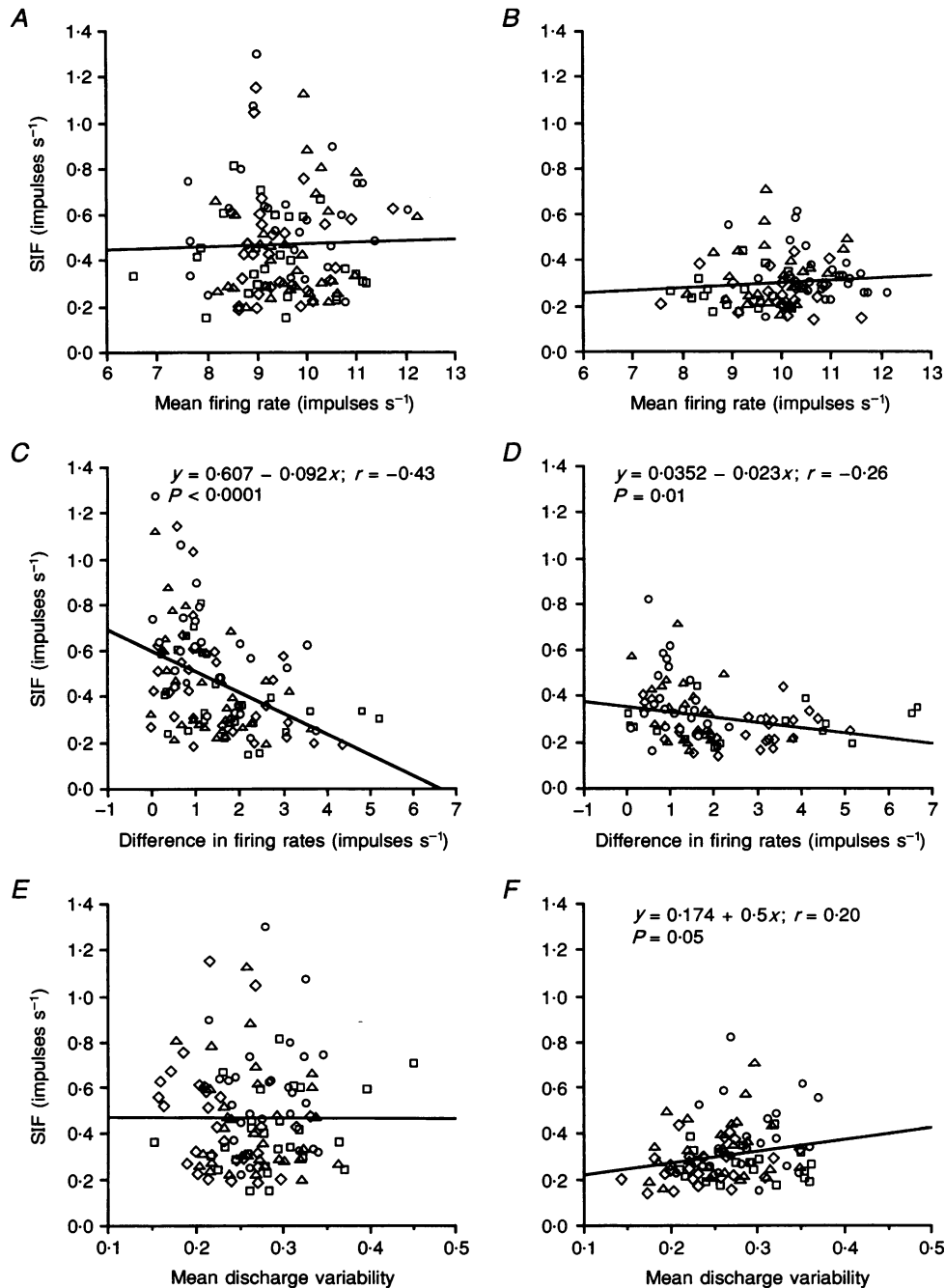
In the non-preferred arm only, a weak positive correlation was found to exist between the strength of synchronization measured in terms of either the SP/T ( $r = 0.27$ ,  $P = 0.007$ ) or the SIF (Fig. 1F;  $r = 0.20$ ,  $P = 0.05$ ) and the geometric mean of the coefficient of variation of the interspike intervals in the motor unit discharges.

### Comparisons of the motor unit synchronization between the preferred and non-preferred arms

In the first experimental session, comparisons were carried out on the rate of occurrence and the parameters of the peaks of the motor unit pairs recorded in the preferred and non-preferred arms of two left-handed subjects (Subjects 1 and 2 in Figs 2, 3 and 4) and two right-handed subjects (Subjects 3 and 4 in Figs 2, 3 and 4).

An enhancement of the broad-peak synchronization in the preferred arm was observed in the case of each subject upon examining the covariation between the peak width and the SIF in the preferred and non-preferred arms with each motor unit pair. Figure 2 clearly shows that in both the two left-handed subjects (Fig. 2A) and the two right-handed subjects (Fig. 2B), the peak width and amplitude consistently shifted towards higher values in the case of the preferred arm.

Among the 273 motor unit pairs tested in both arms of the two right- and two left-handed subjects, 214 (79.1%) produced significant synchronization peaks. Figure 3A illustrates the overall rate of occurrence of the significant peaks in each subject's preferred and non-preferred arms. In the case of each subject, the number of synchronized motor unit pairs was higher in the preferred arm. Given the rather small samples studied in each arm of each subject (20 to 33 pairs), however, the contingency table showed the existence of a significant difference ( $0.01 < P < 0.05$ ) only in Subjects 2 and 3, one of whom was left- and the other right-handed.



**Figure 1.** Correlations between the amplitude of the synchronization peaks and the firing characteristics of the motor unit pairs

Correlations (regression analysis) between the geometric mean frequency (A and B), the difference in firing rates (C and D), the geometric mean discharge variability (E and F) and the amplitude of the synchronization peak parameters expressed by the synchronous impulse frequency (SIF), in the preferred and non-preferred arms of two right- and two left-handed subjects. The SIF was found to be closely correlated with the difference in the firing rates (C and D) in the preferred ( $r = -0.43$ ,  $P = 0.0001$ ) and in the non-preferred arm ( $r = -0.26$ ,  $P = 0.01$ ), whereas correlation with the mean discharge variability was only significant in the non-preferred arm (F,  $r = 0.20$ ,  $P = 0.05$ ). Equations for the regression lines are given only where the correlations were significant. ○, □, left-handed subjects; ◇, △, right-handed subjects.

The differences in the rate of synchronization of the motor unit were nevertheless definitely confirmed by pooling separately the data obtained on the preferred or on the non-preferred arm, in the case of the two left-handed subjects and in the case of the two right-handed subjects. In both cases, the peak rate of occurrence was higher in the preferred arm, yielding  $\chi^2$  values of 8.9 ( $P < 0.005$ ) and 4.5 ( $P < 0.05$ ), respectively.

Upon pooling the data obtained on all four subjects (Fig. 3E), 88.4% (115/130) of the motor unit pairs tested in the preferred arm were found to have significant synchronization peaks, compared with 69.2% (99/143) of the pairs recorded in the non-preferred arm ( $\chi^2 = 13$ ,  $P < 0.001$ ).

In each subject, the peak width, the SP/T and the SIF (Fig. 3B, C and D) were all much higher in the preferred arm, with a level of significance ranging from  $P < 0.01$  to  $P < 0.001$ .

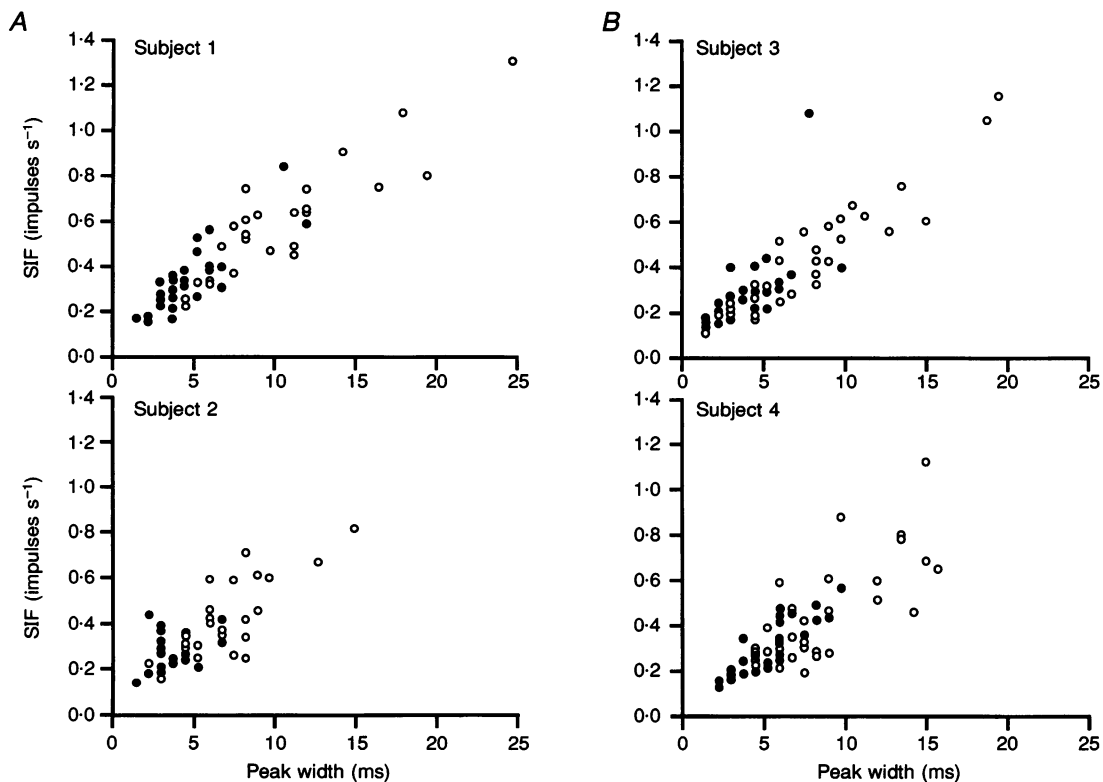
Table 1A gives the mean values and the ranges of the peak parameters observed in both the preferred and the non-preferred arms of all four subjects. The strength of synchronization, assessed by either the SP/T or the SIF, was much higher in the case of the preferred arm (Fig. 3E).

With a view to investigating more closely the distribution and the strength of the putative common motoneurone inputs in terms of handedness, we analysed separately the characteristics of the narrowest of the peaks that were most liable to reflect short-term synchronization. A limit of 7.5 ms was chosen as constituting an intermediate value between the two modes, one at 6 ms and the other at 10.5 ms, observed in the distribution of peak widths upon pooling the data obtained in the preferred and non-preferred arms.

The characteristics of the synchronization peaks lasting less than 7.5 ms were compared between the preferred and non-preferred arms first, on each subject individually (Fig. 4A, B and C) and second after pooling the data on the preferred arms and those on the non-preferred arms (132 peaks  $< 7.5$  ms) of the four subjects (Fig. 4D).

The narrow peaks amounted to 43.4% (50/115) in the preferred arm, compared with 81.2% (82/101) in the non-preferred arm.

In each subject the amplitude of the narrow peaks assessed by either the SP/T or the SIF was larger in the preferred than in the non-preferred arm (Fig. 4A and B).

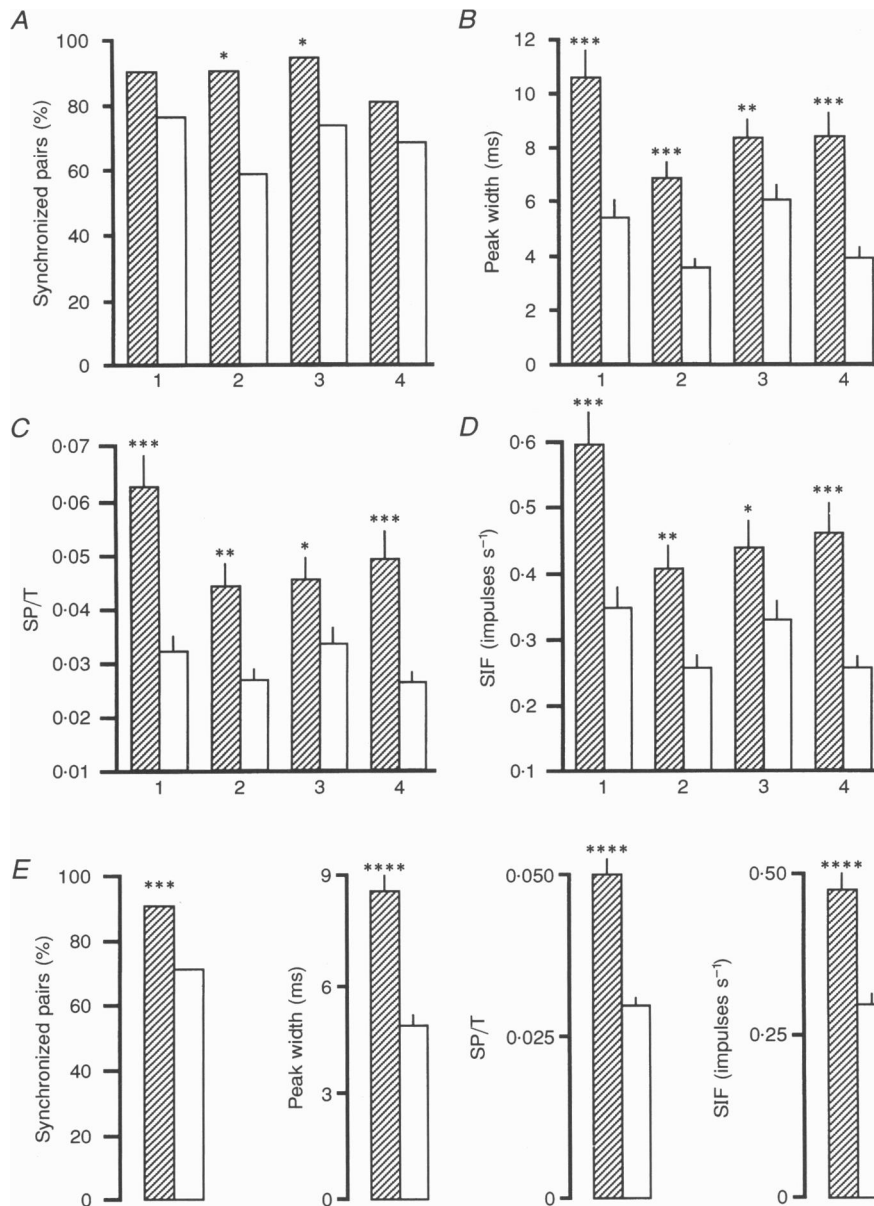


**Figure 2.** Covariation between the amplitude and the width of the synchronization peaks in the preferred and non-preferred arms

Changes in the time course of the synchronization peaks in the preferred arm assessed from the covariation between the SIF and the peak width of all the peaks observed in two left-handed subjects (1 and 2, A) and two right-handed subjects (3 and 4, B). For each subject, motor unit pairs were recorded in the non-preferred arm (●) and the preferred arm (○). The degree of synchronization of the motor unit discharge can be seen to be greater in the preferred arm from the fact that large, broad peaks occur much more frequently.

Upon analysing the larger population of motor unit pairs obtained by pooling the data on the preferred arms and those on the non-preferred arms of either the two left-handers, the two right-handers, or all four subjects combined (Fig. 4*C* and *D*), it was confirmed that both the SP/T and the SIF of the narrow peaks were significantly

larger in the preferred arm. Table 1*B* summarizes the mean values and the ranges of the amplitudes of the narrow peaks together with the characteristics of the motor unit discharge observed in the preferred and the non-preferred arms of all four subjects.



**Figure 3. Rate of occurrence, width and amplitude of the synchronization peaks in the preferred and non-preferred arms**

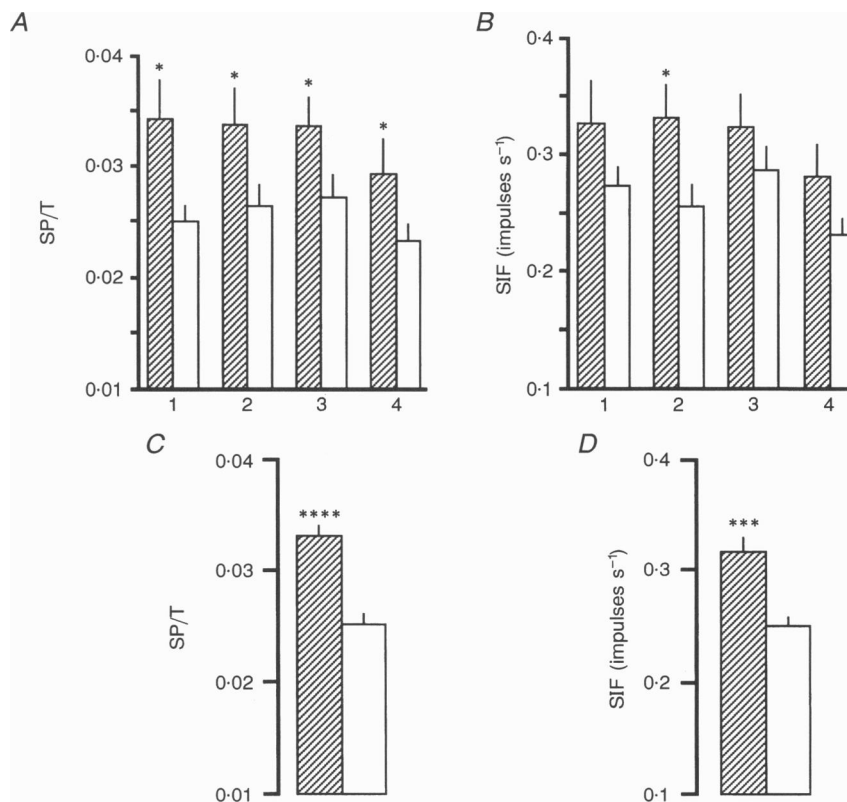
Synchronization characteristics in the preferred (▨) and non-preferred (□) arms of two left-handed subjects (1 and 2) and two right-handed subjects (3 and 4) in the case of 273 pairs of motor units recorded during isometric contraction of the extensor carpi radialis muscles. The peak occurrence rate (*A*) was higher in the preferred arm of all four subjects, reaching significance level in the case of two subjects (Subjects 2 and 3,  $0.01 < P < 0.05$ ). In each subject, comparative analysis of the peak width (*B*) and the peak amplitude as given by the SP/T (*C*) and the SIF (*D*) showed that the peaks were consistently larger in the preferred arm. Analysis of the pooled data on the preferred *versus* non-preferred arms of all four subjects (*E*) confirmed that a larger number of motor unit pairs was synchronized and that the peak width and amplitude values were higher in the preferred arm ( $P < 0.001$  to  $P < 0.0001$ ). In this and subsequent figures: \* $0.01 < P < 0.05$ ; \*\* $0.001 < P < 0.01$ ; \*\*\* $P < 0.01$ ; \*\*\*\* $P < 0.0001$ .

Table 1. Significant cross-correlogram peaks and motor unit discharge characteristics

	Peak occurrence (%)	Peak parameters (means $\pm$ s.d. and range)			Firing parameters (means $\pm$ s.d. and range)	
		Width (ms)	SP/T	SIF (impulses s <sup>-1</sup> )	Frequency (impulses s <sup>-1</sup> )	Coefficient of variation
<b>A. Whole peak population</b>						
Preferred arm	88 ( <i>n</i> = 115/130)	8.50 $\pm$ 4.09 2.25–24.75	0.050 $\pm$ 0.025 0.016–0.144	0.47 $\pm$ 0.23 0.15–1.30	9.56 $\pm$ 0.99 6.50–12.20	0.26 $\pm$ 0.05 0.15–0.45
Non-preferred arm	69**** ( <i>n</i> = 101/143)	4.75 $\pm$ 2.52**** 1.50–14.25	0.030 $\pm$ 0.012**** 0.030–0.120	0.30 $\pm$ 0.12**** 0.13–0.82	10.09 $\pm$ 1.02 7.59–12.72	0.27 $\pm$ 0.05 0.14–0.40
<b>B. Narrow peaks: width &lt; 7.5 ms</b>						
Preferred arm	43 ( <i>n</i> = 50/115)	—	0.033 $\pm$ 0.011 0.016–0.062	0.31 $\pm$ 0.10 0.15–0.59	9.72 $\pm$ 1.00 7.65–12.33	0.26 $\pm$ 0.05 0.15–0.40
Non-preferred arm	81**** ( <i>n</i> = 82/101)	—	0.025 $\pm$ 0.007**** 0.013–0.047	0.25 $\pm$ 0.07*** 0.13–0.46	10.06 $\pm$ 0.97 7.59–12.70	0.27 $\pm$ 0.05 0.14–0.40

Level of significance in the difference between the data groups of preferred and non-preferred arms:

\*\*\**P* < 0.001; \*\*\*\**P* < 0.0001.



**Figure 4.** Comparison of the amplitude of the narrow synchronization peaks in the preferred and non-preferred arms

Analysis of the amplitude of the short synchronization peaks (< 7.5 ms) in the preferred (▨) and non-preferred (□) arms of two left-handed subjects (1 and 2) and two right-handed subjects (3 and 4). The SP/T was significantly higher in the preferred than in the non-preferred arm (A,  $0.01 < P < 0.05$ ). The SIF was also found to be higher in the preferred arm, but significance level was reached only in the case of subject 2 (B). Analysis of the pooled data on the preferred *versus* non-preferred arms of the four subjects showed that the differences in the SP/T (C) and in the SIF (D) were highly significant ( $P < 0.001$  to  $P < 0.0001$ ).



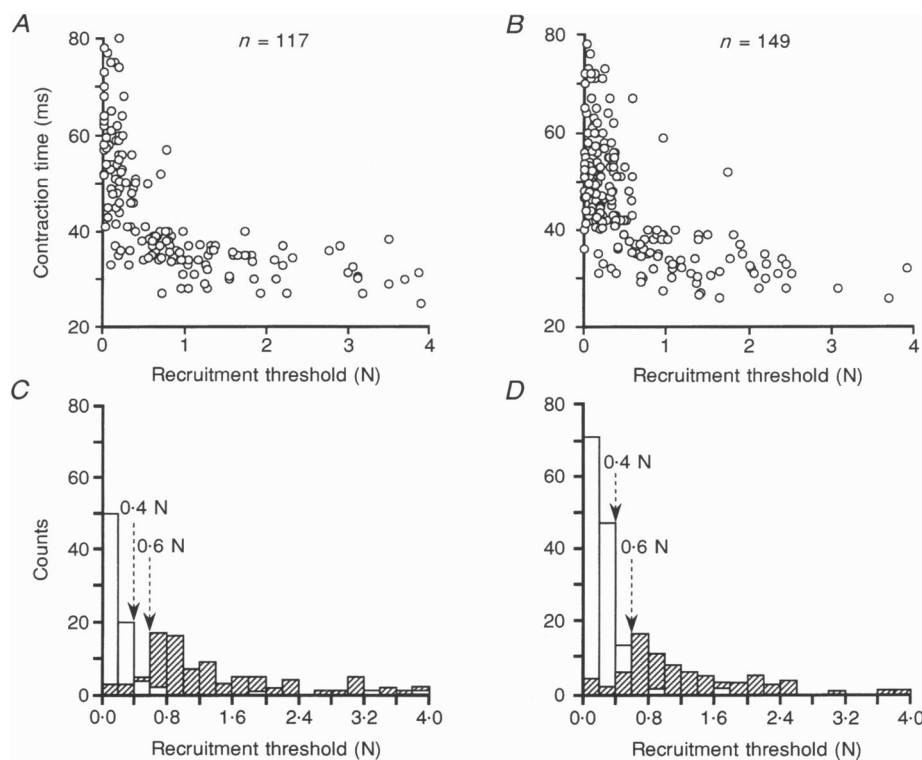
## Synchronization with regard to the motor unit biomechanical characteristics

At the second experimental session, synchronization was investigated in the left ECR muscles in the case of 158 motor unit pairs tested in fourteen right-handed subjects (i.e. in the non-preferred arm), and in the case of the 117 pairs tested in six left-handed subjects (i.e. in the preferred arm). As observed previously, the characteristics of the motor unit synchronization differed significantly depending on the subject arm preference. These handedness-related differences in synchronization will now be examined in terms of the biomechanical characteristics of the pairs of motor units.

## Motor unit biomechanical properties

The motor unit recruitment threshold and contraction time values were found to have similar ranges in both the preferred (0.01–3.9 N, 25–78 ms) and the non-preferred arm (0.01–3.6 N, 24–80 ms).

The relationship between the force recruitment threshold and the contraction time was examined in the preferred (Fig. 5A) and the non-preferred arm (Fig. 5B). In both cases, it was observed that most of the recruitment thresholds of the motor units with contraction times longer than 40 ms (Fig. 5C and D, open bars) were lower than 0.4 N and, conversely, most of the recruitment thresholds of the motor units with contraction times  $\leq 40$  ms (Fig. 5C and D, hatched bars) were higher than 0.6 N. Consequently, these values were used as criteria to distinguish the low-threshold ( $\leq 0.4$  N), slow-contracting ( $> 40$  ms) motor units referred to as 'slow' (S) from the high-threshold ( $\geq 0.6$  N), fast-contracting ( $\leq 40$  ms) motor units referred to as 'fast' (F). On this basis, seventy and eighty motor units were identified as 'fast' in the preferred and non-preferred arms, respectively; and eighty-four and seventy-two motor units were identified as 'slow' in the preferred and non-preferred arms, respectively. Motor units were taken to be unidentified and were denoted as '?' when their contraction times or their recruitment



**Figure 5.** Relationships between the contraction times and the recruitment thresholds of the wrist extensor motor units

Biomechanical properties of the motor units recorded in the left ECR muscles of left-handed (A and C) and right-handed subjects (B and D). In the scattergrams A and B, each symbol gives the recruitment threshold (abscissa) versus the contraction time (ordinate) of one motor unit. The contraction times had similar ranges in both the preferred (A) and the non-preferred arm (B). The histograms C and D show the distributions of the recruitment thresholds of the motor units with contraction times shorter (hatched) or longer (open) than 40 ms. The fact that these distributions overlapped very little suggested the presence of two types of motor units, which were characterized as 'slow' (recruitment thresholds  $\leq 0.6$  N and contraction times  $> 40$  ms) and 'fast' (recruitment thresholds  $> 0.6$  N and contraction times  $\leq 40$  ms).

Table 2. Cross-correlogram peaks of the different categories of motor unit pairs

Motor unit pairs	A. Whole peak population				B. Narrow peaks < 7.5 ms			
	Peak parameters (means $\pm$ s.d.)				Peak parameters (means $\pm$ s.d.)			
	<i>n</i>	Width (ms)	SP/T	SIF (impulses s <sup>-1</sup> )	<i>n</i>	Width (ms)	SP/T	SIF (impulses s <sup>-1</sup> )
Preferred arm (left-handers)								
SS ( <i>n</i> = 27)	18	7.1 $\pm$ 2.2 (* vs. FF) (* vs. SF)	0.055 $\pm$ 0.02	0.48 $\pm$ 0.22	11	5.5 $\pm$ 1.1	0.044 $\pm$ 0.01 (* vs. FF) (* vs. SF)	0.37 $\pm$ 0.15 (* vs. FF) (* vs. SF)
FF ( <i>n</i> = 35)	31	13.1 $\pm$ 10.4	0.073 $\pm$ 0.08	0.56 $\pm$ 0.42	10	5.3 $\pm$ 1.4	0.032 $\pm$ 0.01	0.23 $\pm$ 0.08
SF ( <i>n</i> = 34)	27	11.7 $\pm$ 7.1	0.068 $\pm$ 0.05	0.51 $\pm$ 0.35	10	5.4 $\pm$ 1.3	0.032 $\pm$ 0.01	0.25 $\pm$ 0.11
'??' ( <i>n</i> = 22)	21	9.1 $\pm$ 7.8	0.059 $\pm$ 0.06	0.55 $\pm$ 0.41	11	4.8 $\pm$ 1.2	0.034 $\pm$ 0.01	0.35 $\pm$ 0.09
Non-preferred arm (right-handers)								
SS ( <i>n</i> = 24)	25	5.8 $\pm$ 3.1	0.039 $\pm$ 0.02	0.34 $\pm$ 0.22	19	4.3 $\pm$ 1.3	0.029 $\pm$ 0.01 (* vs. FF)	0.28 $\pm$ 0.09 (* vs. FF) (** vs. SF)
FF ( <i>n</i> = 24)	16	6.1 $\pm$ 2.9	0.031 $\pm$ 0.02	0.29 $\pm$ 0.16	10	4.1 $\pm$ 1.1	0.022 $\pm$ 0.06	0.20 $\pm$ 0.06
SF ( <i>n</i> = 38)	18	6.4 $\pm$ 3.2	0.031 $\pm$ 0.01	0.25 $\pm$ 0.12	12	4.5 $\pm$ 1.4	0.025 $\pm$ 0.01	0.20 $\pm$ 0.06
'??' ( <i>n</i> = 50)	31	5.4 $\pm$ 2.7	0.030 $\pm$ 0.01	0.27 $\pm$ 0.09	24	4.3 $\pm$ 1.4	0.025 $\pm$ 0.01	0.25 $\pm$ 0.08

Level of significance in the difference between the SS, SF and FF data groups tested in the preferred and non-preferred arms, respectively: \**P* < 0.05; \*\**P* < 0.01.

thresholds did not fit the above criteria (this was so in the case of 15 motor units in the preferred arm and 24 motor units in the non-preferred arm) or when their contraction times and/or their recruitment thresholds could not be determined because of a failure in either the spike-triggered averaging or the force recording process itself (this occurred in the case of 23 motor units in the preferred arm and 34 motor units in the non-preferred arm).

Each pair of motor units was characterized biomechanically using either the mean recruitment thresholds and contraction times of the two constitutive motor units or the identification of motor units as 'slow' or 'fast'. On this basis, four groups of motor unit pairs could be differentiated: the pairs denoted 'SS' included two 'slow' motor units, those denoted 'FF' included two 'fast' motor units, the mixed pairs denoted 'SF' included one motor unit of each type and the question marks '??' stand for pairs including either one or two unidentified motor units. The distributions of these various categories in the preferred and non-preferred arms are shown in Table 2A.

The slight difference in firing rate observed above between the preferred and the non-preferred arms, in the case of the two left-handed and the two right-handed subjects, was again observed with all the categories of motor unit pairs, but the *P*  $\leq$  0.05 significance level was reached in the case of the pairs SF and FF only.

In the non-preferred arm, no significant differences in the firing rate were observed between the categories SS, SF and FF. In the preferred arm, however, the SF pairs

tended to discharge at a lower frequency than the SS pairs.

The variability of the discharges of the motor unit pairs, expressed in terms of the geometric mean of the coefficient of variation of the two motor units' interspike intervals, did not differ significantly in any category between the preferred and the non-preferred arm, or between the various categories of motor unit pairs in either the preferred or the non-preferred arm.

The difference between the firing rates of the motor units constituting each pair did not differ significantly depending on either the motor unit category or on whether the arm used was the preferential one. On the basis of a regression analysis, however, it was observed that the largest differences in firing rate tended to occur among pairs which showed the largest differences between their recruitment thresholds, in both the preferred and the non-preferred arms (*r* = 0.24, *P* = 0.03 and *r* = 0.31, *P* = 0.02). It was also observed, but in the non-preferred arm only, that the pairs of motor units which discharged with the largest differences in frequency tended also to show the largest differences between their contraction times (*r* = 0.24, *P* = 0.02).

### Rate of occurrence of significant peaks depending on motor units' biomechanical properties

Figure 6A shows the percentage of significant peaks observed in each category of motor unit pair tested in the preferred (hatched bars) and the non-preferred arms (open

bars). On the basis of the contingency table, the higher rate of synchronization observed in the preferred compared with the non-preferred arm was found to involve the categories SF and FF ( $\chi^2 = 6.58$  and  $7.21$ , respectively), but not the category SS ( $\chi^2 = 1.50$ ).

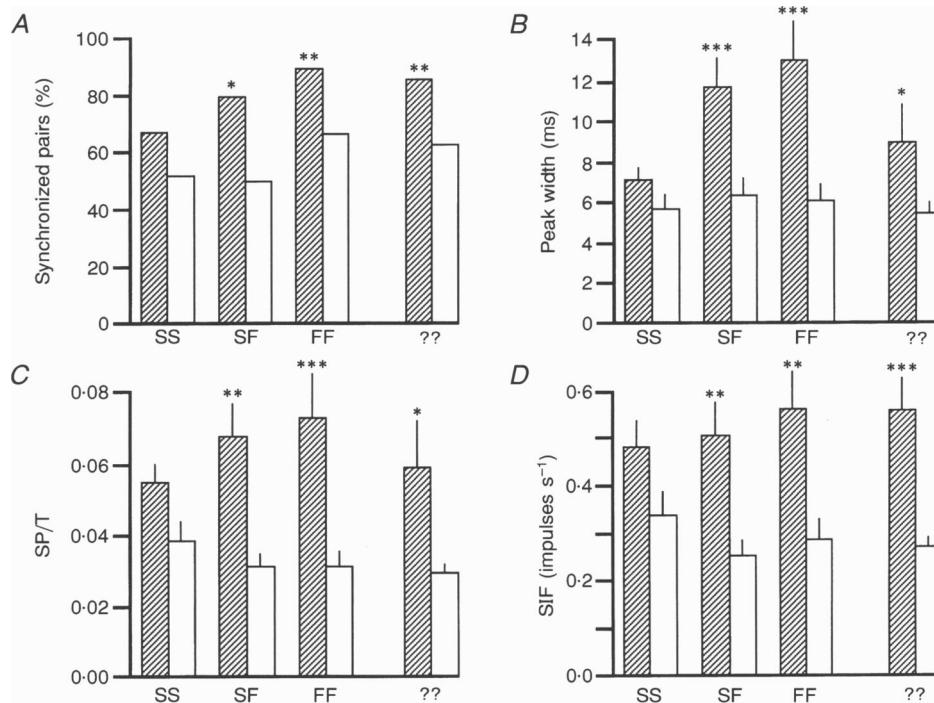
On comparing the rate of synchronization among the various categories of motor unit pairs tested on the same side, a gradient in the percentage of significant peaks was found to occur in both the preferred and in the non-preferred arms: the highest percentages of significant peaks were observed in the case of the FF pairs (88.6 and 66.7%, respectively) compared with the percentages observed in the case of the SF pairs (79.4 and 50%, respectively) and the SS pairs (66.7 and 52.1%, respectively). On the basis of the contingency table, however, this gradient did not reach the  $P \leq 0.05$  significance level in either the preferred ( $\chi^2 = 3.9$ ) or the non-preferred arm ( $\chi^2 = 1.9$ ).

### Differences in the synchronization time course depending on motor units' biomechanical properties

The mean values of the peak width ( $\pm$  s.e.m.) have been plotted in Fig. 6B, taking each category, SS, SF, FF and '??', tested in the preferred (hatched bars) and the non-preferred arm (open bars). Comparisons showed that the peak broadening observed in the preferred arm involved mainly the SF and FF pairs.

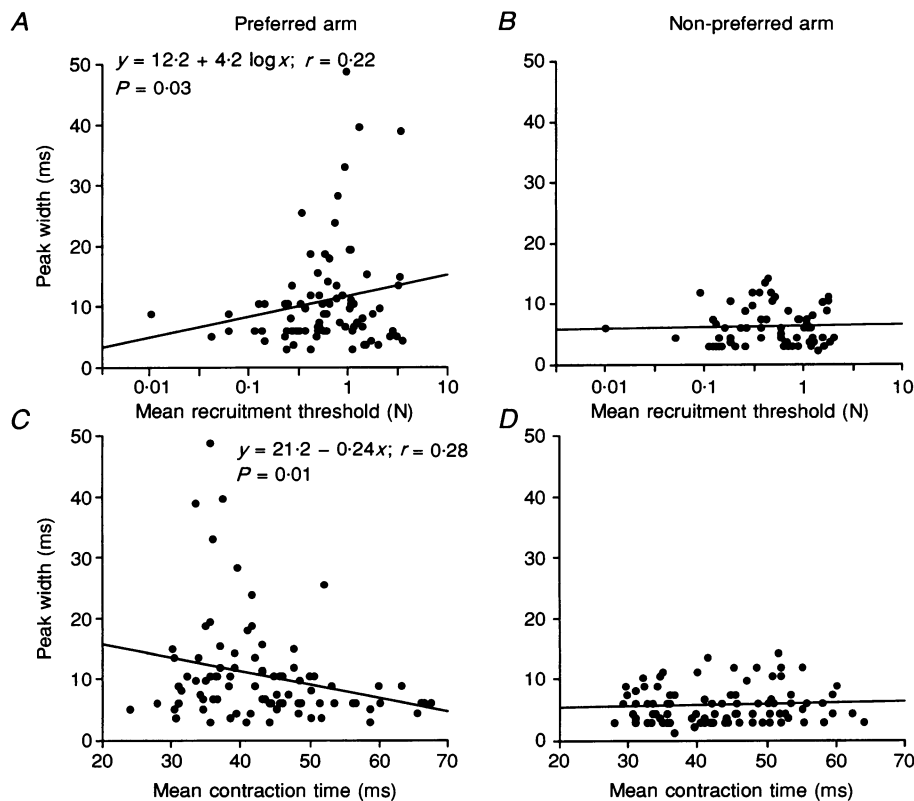
No differences in the mean peak duration values were observed in the non-preferred arm between the categories SS, SF and FF, whereas in the preferred arm, the peaks observed among the FF and SF pairs were significantly broader than those among the SS pairs.

In order to assess the correlation between the synchronization time course and the motor units'



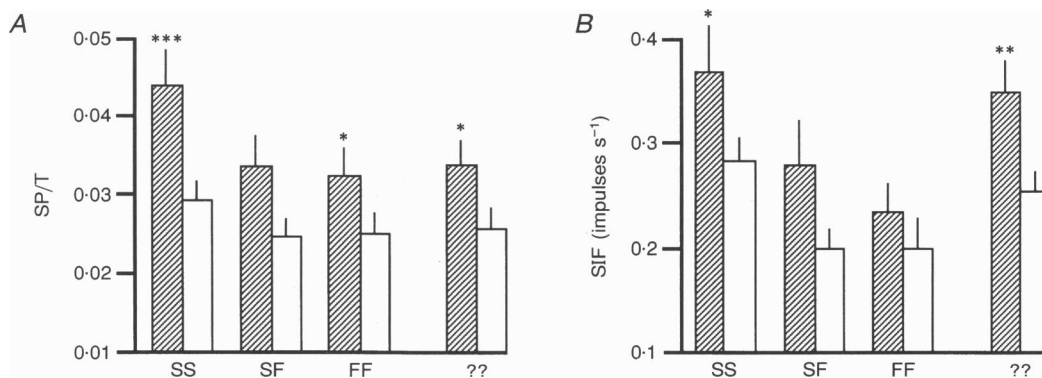
**Figure 6. Rate of occurrence, width and amplitude of the synchronization peaks in relation to the motor unit types in the preferred and non-preferred arms**

Synchronization characteristics in the left ECR muscles of right-handed ( $\square$ ) and left-handed subjects ( $\boxplus$ ) with respect to motor unit type. The percentage of significant peaks (A) and their mean durations (B) were plotted separately with the corresponding standard error for the pairs consisting of two low-threshold, slow-contracting motor units (SS), two high-threshold, fast-contracting motor units (FF), one motor unit of each type (SF), or non-identified motor units ('??'). In the preferred arm, the rates of synchronization and the peak widths were significantly larger in the FF and SF pairs. The degree of synchronization assessed from mean SP/T (C) and SIF values (D) was also plotted with the corresponding standard errors in the case of SS, SF and FF motor unit pairs and of the non-identified pairs, '??', in the preferred ( $\boxplus$ ) and the non-preferred arms ( $\square$ ). In the preferred arm, the SS, SF and FF pairs yielded peaks with larger amplitudes (C and D). The difference between the preferred and the non-preferred arms was particularly marked in the case of the SF and FF pairs. The asterisks show the level of significance obtained in the comparisons (ANOVA and Fisher's PLSD test) between the preferred and non-preferred arm for each category of motor unit pairs (see Fig. 3 legend for details).



**Figure 7. Correlations between the width of the synchronization peaks and the motor unit biomechanical characteristics**

Width of the cross-correlogram peaks as a function of the biomechanical properties of the pairs of motor units in the preferred (*A* and *C*) and non-preferred arm (*B* and *D*). Each dot gives the peak width *versus* the mean recruitment threshold (*A* and *B*) or the mean contraction time (*C* and *D*) of the two motor units constituting one pair. In the preferred arm, the peak width tended to increase as the mean recruitment threshold increased (*A*) and as the mean contraction time decreased (*C*).



**Figure 8. Amplitude of the narrow synchronization peaks in relation to the motor unit types in the preferred and non-preferred arms**

Degree of short-term synchronization assessed from the amplitude of the peaks shorter than 7.5 ms, in the preferred (▨) and the non-preferred arm (□). Means  $\pm$  s.e.m. are plotted for the pairs consisting of two low-threshold, slow-contracting motor units (SS), two high-threshold, fast-contracting motor units (FF), one motor unit of each type (SF) and non-identified motor units ('??'). In the preferred arm, the narrow peaks had consistently larger amplitudes in each category of motor unit pairs, whatever the parameter examined. The difference between the preferred and non-preferred arms was particularly conspicuous in the case of the SS pairs, as indicated by the asterisks showing the level of significance obtained in the comparisons (ANOVA and Fisher's PLSD test).

biomechanical properties further, a regression analysis was performed between the peak width and the mean recruitment threshold or the mean contraction time in each motor unit pair tested in the preferred (Fig. 7A and C) and the non-preferred arm (Fig. 7B and D). In the non-preferred arm, the rather narrow durations of the peaks, ranging from 1.5 to 12 ms, showed no consistent correlation with either the mean recruitment thresholds (Fig. 7B) or the mean contraction times (Fig. 7D). In the preferred arm, where the range of peak widths was found to be much wider (3–48.7 ms), the peak width tended to increase as the mean recruitment threshold increased (Fig. 7A) and as the mean contraction time decreased (Fig. 7C).

### Differences in the synchronization strength depending on the motor units' biomechanical properties

As reported above in the case of the peak duration, the handedness-related differences in the amplitudes of the synchronization peaks were also found to depend on the motor unit type.

In the case of the SS pairs, the relative increase in the SP/T (40%) and in the SIF (42%) in the preferred arm compared with the non-preferred arm did not reach the  $P < 0.05$  significance level. In the case of both the FF and SF pairs, however, the relative increase in both the SP/T (135 and 71%, respectively) and the SIF (95 and 100%, respectively) in the preferred arm, was highly significant (Fig. 6C and D).

Table 2A gives the mean peak durations and amplitudes (SP/T, SIF) of the various categories of motor unit pairs, SS, SF, FF and '??', tested in either the preferred or the non-preferred arm. The asterisks indicate the level of significance obtained upon comparing the synchronization parameters between the SS and FF pairs, between the SS and SF pairs and between the SF and FF pairs tested on the same side.

In the non-preferred arm, both the SP/T and the SIF were found to be larger in the category SS than in SF and FF, but the differences did not reach significance level at  $P \leq 0.05$ . The opposite situation was observed in the preferred arm, where both the SP/T and the SIF were slightly larger in the case of the FF and SF pairs than in that of the SS pairs, although the differences again did not reach significance level.

In order to investigate further the relationships between the strength of the synchronization and the biomechanical properties of the motor units in the preferred and the non-preferred arms, regression analyses were performed between the SP/T and the SIF and the mean contraction times in each pair of motor units. In the non-preferred arm, the SP/T and the SIF were weakly but significantly correlated with the mean contraction times of the motor unit pairs: the largest peaks tended to occur among the pairs with the slowest mean contraction times. In the preferred arm, the largest SP/T and SIF values

tended to occur, on the contrary, among the pairs with the fastest mean contraction times, in keeping with the presence of broad peaks among these pairs of motor units. This trend did not, however, reach the  $P \leq 0.05$  significance level.

Opposite trends were again observed in the regression analyses performed with the mean recruitment thresholds of the motor unit pairs. In the non-preferred arm, the largest SIFs tended to occur among the pairs with the smallest mean recruitment thresholds; weak negative trends were likewise observed between the mean recruitment threshold and the SP/T. In the preferred arm, however, a slightly positive but non-significant trend was observed between the mean recruitment threshold and either the SP/T ( $r = 0.14$ ,  $P = 0.17$ ) or the SIF ( $r = 0.14$ ,  $P = 0.18$ ); the largest SP/T and SIF values tended to occur among the pairs with the highest mean recruitment thresholds also having the broadest peaks.

### Differences in the amplitudes of the narrow synchronization peaks depending on the motor units' biomechanical properties

As stated above in the case of the two right- and the two left-handed subjects, the amplitude of the narrow peaks (lasting less than 7.5 ms) was consistently higher in the preferred than in the non-preferred arm. Figure 8 gives the mean values of the SP/T and the SIF of the narrow peaks observed among the pairs SS, SF, FF and '??' in the preferred (hatched bars) and the non-preferred arm (open bars). The asterisks indicate the level of significance reached upon comparing the amplitudes of the narrow synchronization peaks observed in each category of motor unit pairs between the preferred and the non-preferred arms.

In all categories, the amplitudes of the narrow peaks assessed from either the SP/T or the SIF turned out to be larger in the preferred than in the non-preferred arm. The most conspicuous and most significant arm-related difference in these two parameters was observed in the case of the SS pairs.

It is noteworthy that the changes in the narrow peak amplitudes observed between the preferred and non-preferred arms were not consistently associated with any significant changes in the motor units' mean firing rates or variability.

Table 2B gives the mean width and the mean amplitudes (SP/T, SIF) of the narrow peaks of the various categories of motor unit pairs tested in the preferred and the non-preferred arm. The asterisks indicate the level of significance reached in comparisons between the firing and synchronization parameters of SS and FF pairs, those of SS and SF pairs and those of SF and FF pairs tested on the same side.

It emerged that whatever the subject's arm preference, the narrow peaks tended to be larger among the SS pairs. In both the non-preferred and the preferred arm, the SS

pairs showed significantly larger narrow peaks than the FF pairs, as shown by the larger values of the SP/T and the SIF. The SS pairs also showed significantly larger narrow peaks than the SF pairs in the preferred arm, in terms of SP/T or SIF, whereas in the non-preferred arm, the difference between the SS and SF pairs reached significance only in the case of the SIF.

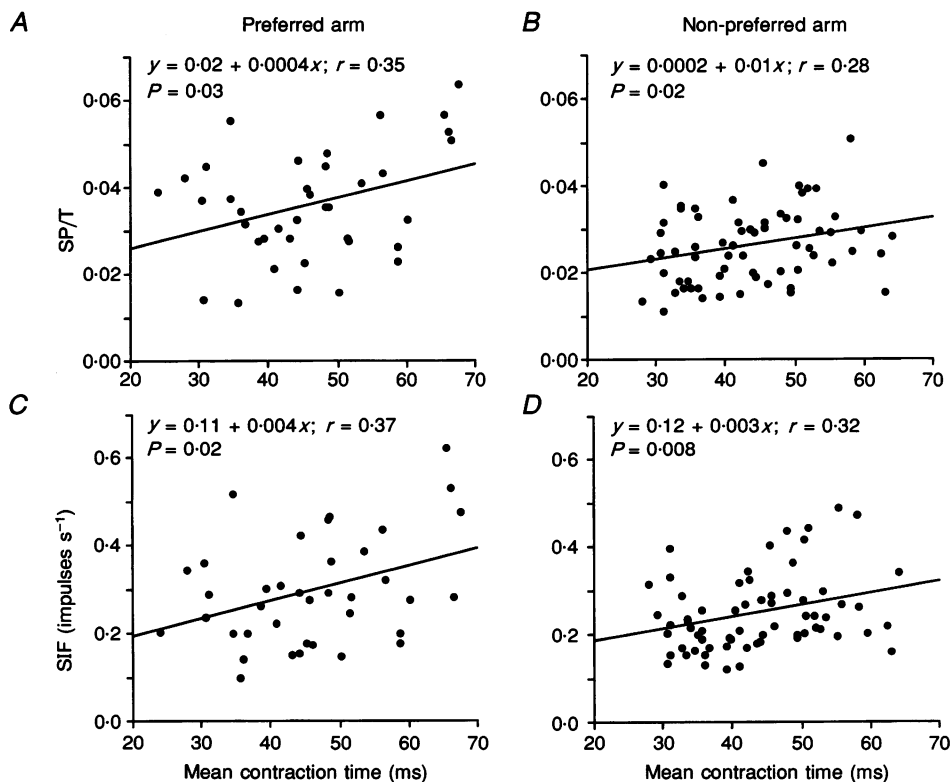
In both the preferred and the non-preferred arms, the narrow peaks of the SF and FF pairs did not differ significantly in amplitude.

The dependence of the narrow peak amplitude on the motor units' biomechanical properties was confirmed by the significant correlations obtained in the regression analysis of the SP/T and the SIF of the narrow peaks as a function of the mean contraction time and the mean recruitment threshold of each pair of motor units. Whatever the subject's arm preference, the SP/T and the SIF of the narrow peak tended to increase as the mean threshold recruitment decreased (Fig. 9) and as the mean contraction time increased (Fig. 10).

## DISCUSSION

The present data show that during an isometric voluntary contraction maintained for several minutes, the motor unit pairs studied in the wrist extensor muscles discharged with a higher degree of synchronization in the arm preferentially used in most everyday motor tasks compared with the non-preferred arm. All in all, these findings demonstrate that motor lateralization as far as handedness is concerned is expressed at the spinal level by significant differences in the synaptic processes revealed by the synchronization of the motor unit activity.

In previous studies on motor unit synchronization, the subject's handedness has not been taken into account. Since the synchronization peak rates and durations previously reported in the arm muscles (Davey *et al.* 1990; Bremner *et al.* 1991) were quite similar to those observed here in the case of the preferred arm, it could be assumed that most of the data published up to now have been obtained on the arm preferentially used by the subjects.



**Figure 9.** Correlation between the strength of the short-term synchronization and the motor unit contraction time

Degree of short-term synchronization assessed from the amplitude of the peaks shorter than 7.5 ms as a function of the contraction times of the motor unit pairs tested in the preferred (A and C) and the non-preferred arm (B and D). Each dot gives the SP/T (A and B) or the SIF of a narrow peak (C and D) versus the mean contraction time of the corresponding motor units. In both the preferred and the non-preferred arms, the SP/T (A and B) and the SIF (C and D) of the narrow peaks increased with the mean contraction time.

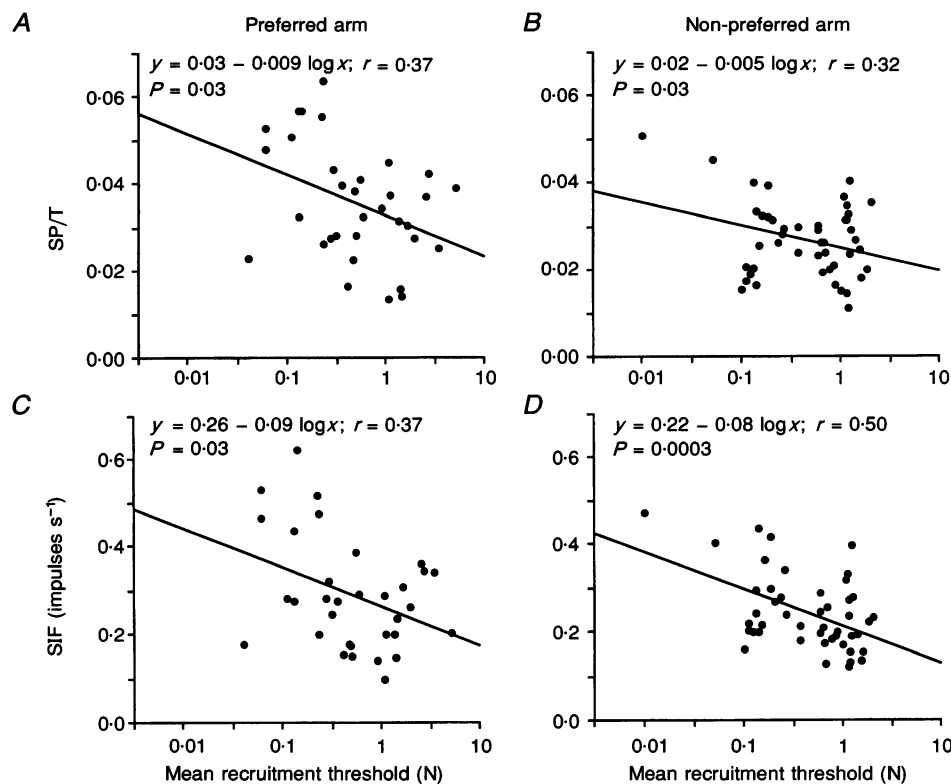
## Motor unit discharge characteristics and synchrony

In both the preferred and the non-preferred arms, the amplitude of the synchronization peaks, expressed in terms of synchrony probability per trigger or synchronous impulse frequency, was found to be poorly, if at all, correlated with the mean motor unit firing rate. Consequently, the larger SP/T and SIF values that were observed when the subjects were using their preferred arm cannot have been due to the fact that the firing rates of the motor units were slightly lower in the preferred arm.

Working on the first dorsal interosseus muscle of the left hand of subjects whose handedness was not determined, Nordstrom *et al.* (1992) reported that the strength of the synchrony increased as the variability of the interspike intervals in the motor unit discharge increased. This was confirmed in the present study in the case of both the SP/T and the SIF, but in the non-preferred arm only.

No significant differences were observed, however, in the variability of the motor unit discharges between the preferred and the non-preferred arms or between the different types of motor unit. The handedness-related difference observed in the strength of synchronization was therefore not attributable to any differences in the variability of the motor unit discharges.

The degree of synchronization, as estimated from the SP/T and SIF, increased significantly when the difference between the firing rates of the two units decreased, in both the preferred and the non-preferred arms. This finding is consistent with data obtained in the same muscles during physiological tremor by Logigian, Wierzbicka, Bruyninckx, Wiegner, Shahah & Young (1988), which showed that motor unit pairs which fired at nearly the same frequency (frequency difference < 1 Hz) were more fully synchronized than those which discharged at frequencies differing by more than 1 Hz. These authors suggested that the high level of synchronization observed in the case of motor units firing at similar rates might be due to the fact that



**Figure 10.** Correlation between the strength of short-term synchronization and the motor unit recruitment threshold

Degree of short-term synchronization assessed from the amplitude of the peaks shorter than 7.5 ms as a function of the recruitment thresholds of motor unit pairs tested in the preferred (A and C) and the non-preferred arm (B and D). Each dot gives the SP/T (A and B) or the SIF (C and D) of the peaks shorter than 7.5 ms *versus* the mean recruitment threshold of the corresponding motor units. In both the preferred and the non-preferred arms, the SP/T (A and B) and the SIF (C and D) of the narrow peaks increased as the mean recruitment threshold decreased.

the motor units firing at comparable frequencies have similar biomechanical properties and receive a larger number of common inputs. In keeping with this suggestion, the present data show a tendency for the pairs of motor units with the least differences between their recruitment thresholds and their contraction times to fire at the most similar frequencies.

The values of the differences in the firing rates of the motor unit pairs observed in the preferred and the non-preferred arm, however, were not found to differ. Consequently, the handedness-related differences in the strength of synchronization could not have resulted from differences in this parameter.

### Effect of the synchronization on the motor unit biomechanical characteristics

No consistent difference was observed in the distribution of the motor unit recruitment thresholds and the contraction times in relation to arm preference.

The reliability of the twitch extraction using the spike-triggered averaging method can be affected by the synchronization of the motor unit discharges (Milner-Brown, Stein & Yemm, 1973; Kirkwood, 1979; Nordstrom, Miles & Veale, 1989; Thomas, Bigland-Ritchie, Westling & Johansson, 1990; Dick, 1990). This might produce an artificial lengthening of the twitch rise times and might unify the twitch characteristics.

The mean values of SP/T observed in the non-preferred and preferred arms were 0.033 and 0.064, respectively. This corresponded to about three and six extraneous synchronous action potentials in the case of a twitch obtained by averaging one hundred triggers. Since any interspike intervals shorter than 80 ms were excluded, only 20–50% of the action potentials were actually used to trigger the averaging. Among the hundred triggers actually used for the spike-triggered averaging of each twitch, no more than three extraneous action potentials were therefore liable to have occurred in synchrony in the preferred arm and no more than 1.5 in the non-preferred arm.

In the present study, despite the fact that the level of synchronous activity was twice as high in the preferred than in the non-preferred arm, the ranges and the means of the twitch rise times of the motor units did not differ between the two arms (Fig. 5). Furthermore, despite the fact that many of the SF pairs discharged with a high level of synchronization, particularly in the preferred arm (Table 2), the twitches extracted with these pairs of motor units differed completely in their rise times and amplitudes.

This suggests that, although more than 66% of the motor unit pairs tested in the non-preferred arm and 77% in the preferred arm produced significant cross-correlogram peaks during sustained isometric contraction,

the synchronization processes appear to have operated at a fairly low stochastic level, in agreement with the lack of overlapping observed between the synchronous discharges of motor unit pairs tested simultaneously (Dengler *et al.* 1984).

### Changes in the synchronization processes depending on handedness, with regard to motor unit type

In the non-preferred arm, the peaks were fairly narrow whatever the motor units' biomechanical properties, whereas in the preferred arm, the peak duration increased as the mean contraction time decreased and as the mean recruitment threshold increased. This is consistent with previous data obtained on the right extensor digitorum communis muscle of right-handed subjects (using their preferred arm), which showed that the pairs consisting of two fast-contracting motor units had significantly broader peaks and that the peak width was negatively correlated with the mean contraction time (Schmied, Ivarsson & Fetz, 1993). In another study carried out on the first dorsal interosseus muscle (laterality not specified), significantly broader peaks were also found to occur in the case of the pairs consisting of two high-threshold motor units (Datta & Stephens, 1990).

The time course of the cross-correlogram synchronization peaks depends on the synaptic processes involved (cf. Kirkwood & Sears, 1991). Assuming that the synaptic noise and the EPSPs have constant characteristics, the motoneurons' inputs that are synchronized presynaptically with respect to the motoneurons might be expected to produce synchronous firings that are likely to be less tightly coupled than those produced by common inputs. This will generate smaller and broader peaks, unless the synchronized inputs are themselves common to the two motoneurons, in which case they will generate larger and broader peaks; this was what was observed in the present study in the case of the preferred arm.

Broad synchronization peaks might also result from common inhibitory inputs (Moore, Segundo, Perkel & Levitan, 1970), but the actual contribution of this process to the synchronization of motoneurone activity has not yet been elucidated.

In the non-preferred arm, peaks with short durations were predominantly observed. This suggests that when the muscles are not used preferentially in everyday motor tasks, short-term synchronization by common excitatory inputs might constitute the main form of synchronous activity, although the possible contribution of input synchronization and/or common inhibitory inputs cannot be ruled out.

In the preferred arm, short duration peaks were still predominant among the pairs of slow contracting, low-



threshold motor units, but they were larger than in the non-preferred arm. This suggests that the common inputs which innervate 'slow' motor units are more efficient on the muscles of the arm preferentially used by the subjects.

The peaks observed among the SF and FF pairs were significantly broader, however, in the preferred than in the non-preferred arm. This broadening, which was most prominent in the case of the 'FF' pairs, was associated with a larger peak amplitude. On the basis of the branched-axon common input hypothesis, broader and larger peaks might be attributable to broader and larger EPSPs and/or to marked changes in the amplitude or the variability of the synaptic noise liable to affect specifically the FF and SF motor unit pairs. It is also possible that the preferential use of one arm may be associated with the enhancement of inhibitory inputs possibly common to the FF and SF pairs but not involving the SS pairs. No experimental data have been available up to now, however, to support speculations of this kind. A simpler and much more plausible hypothesis is that the broader and larger peaks observed among the SF and FF pairs in the preferred arm may reflect an enhancement of the presynaptic synchronization of the motoneurons' common inputs.

Among the narrow peaks (<7.5 ms), which were assumed to be the least affected by the input synchronization, the SP/T and SIF of the SF and FF pairs were significantly larger in the preferred than in the non-preferred arm, which suggests, as in the case of the category SS, that the efficiency of the common excitatory inputs was enhanced owing to the preferential use of the arm. Such an enhancement might be expected to act not only at the motoneuronal but also at the pre-motoneuronal level. This might consequently produce a general increase in the synchronization of the motoneuronal inputs, which would be particularly effective in the case of the high-threshold motor units, which require a stronger drive to be recruited.

### **Synchronization gradient depending on the motor units' biomechanical properties**

No differences were reported in the rate of synchronization observed among motor units distinguished either on the basis of their recruitment thresholds (Datta & Stephens, 1990) or on the basis of their contractile properties (Schmied *et al.* 1993). In the present report, however, in both the preferred and non-preferred arms, significant peaks were observed more frequently in the categories SF, and particularly FF, than in the category SS. This difference was particularly marked in the preferred arm. Differences in the rates of synchronization would suggest that the synchronizing inputs were more effective in the category FF. This might be in keeping with the fact that the motor units recruited at higher thresholds require a

stronger drive, which is liable to involve more common and presynaptically synchronized inputs than in the case of the motor units recruited at lower thresholds.

In the non-preferred arm, the synchronization peaks were found to be rather narrow and both the SP/T and SIF were found to be correlated with the motor units' biomechanical properties in a way that suggested that low-threshold, slow-contracting motor units might receive stronger synchronizing common inputs than motor units with higher recruitment thresholds and faster contraction times. In the preferred arm, however, no correlation was found to exist between the peak amplitude assessed from either the SP/T or the SIF and the motor units' biomechanical properties. Likewise, in the first digitorum interosseus muscle, the synchronization peaks of pairs consisting of two high-threshold motor units (presumably tested in the preferred arm, given the peak durations) were found to have a similar mean SP/T to that of the pairs consisting of two low-threshold motor units (Datta & Stephens, 1990). As discussed above, the broader and larger peaks observed both in this previous study as well as in the present one, particularly in the preferred arm, are likely to have involved inputs synchronized at a pre-motoneuronal level, which may have obscured the primary effects of common inputs on the motor unit discharges.

We attempted here to overcome this limitation by analysing separately the peaks lasting less than 7.5 ms, which were assumed to be less strongly affected by input synchronization than the broader peaks. Under these conditions, in both the preferred and the non-preferred arm, the SP/T and the SIF were negatively correlated with the mean recruitment threshold of the motor unit pairs and positively correlated with their mean contraction times. Accordingly, in both arms, the SS pairs yielded narrow peaks, which were significantly larger than the peaks generated by the FF pairs or by the mixed pairs, SF. Assuming the main origin of these narrow peaks to be short-term synchronization, these results might indicate that during a voluntary isometric contraction, regardless of whether or not the subjects are using their preferred arm, low-threshold, slow-contracting motor units share common inputs which are apparently stronger than those shared by either the high-threshold, fast-contracting motor units or by the mixed pairs consisting of low-threshold, slow-contracting motor units and high-threshold, fast-contracting motor units. This suggests that, regardless of arm preference, at least some of the common inputs that control motoneurone activity during a voluntary contraction might act in a similar way to what occurs in the case of the primary muscle spindle afferents, which produce larger EPSPs in cat's motoneurons corresponding to low-threshold, slow-contracting motor units (Burke *et al.* 1976).

## Possible origin of the handedness-related asymmetry in the control of motoneurone activity

The presence of some asymmetry has also been suggested at the spinal level in humans by the fact that higher H reflex recovery curves were obtained in the right wrist flexor muscles of right-handed subjects and vice versa in left-handed subjects (Tan, 1989).

In the present experiments, however, which involved voluntary isometric muscle contractions, the differences observed in the motoneurone command between the preferred and non-preferred arms might involve supraspinal and, particularly, corticospinal afferents. In agreement with this hypothesis, it has been reported that in animals the synchronization peaks were not affected by dorsal root section (Kirkwood *et al.* 1982; Powers & Rymer, 1988). Furthermore, no changes in the synchronization patterns were observed in deafferented human patients (Baker, Bremner, Cole & Stephens, 1988) and, in the respiratory muscles, the synchronization has been found to be stronger during voluntary breathing than during reflexly induced breathing (Adams *et al.* 1989).

The possibility that spinal asymmetry might be correlated with cortical lateralization was suggested by Goode, Glenn, Manning & Middleton (1980). In favour of this hypothesis, an asymmetry has been demonstrated in the corticospinal innervation of the right and left sides in the spinal cord of human fetuses and neonates (Yakovlev & Rakic, 1966). Another argument favouring the hypothesis that an asymmetry depending on hand preference may exist in the corticospinal tract is provided by the findings that more numerous and larger zones representing the distal forelimb movements in the motor cortex were observed on the side opposite the preferred arm compared with the side controlling the non-preferred hand, in adult squirrel monkeys (Nudo, Jenkins, Merzenich, Prejean & Grenda, 1992).

In conclusion, handedness appears to be expressed at the spinal level by a lateralization of the motoneurones' synaptic connectivity, since the short-term synchronization of motor unit discharges, particularly in the case of the low-threshold, slow-contracting motor units, seemed to have been stronger when the subjects were using their preferred arm and since the presynaptic input synchronization seemed also to have been stronger on the preferred side, particularly in the case of the high-threshold, fast-contracting motor units, which require a stronger drive. These two phenomena might reflect a general enhancement of the synaptic efficiency affecting pathways which might be preferentially activated depending on the subject's handedness.

It now needs to be determined which pathways are involved and whether the asymmetrical motoneurone

control results from synaptic plasticity, with changes due to the more intensive use of the muscles, or whether it is the ontogenetic outcome of the cortical lateralization of the motor control.

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