Analysis of electrical activity of normal muscle in man at different degrees of voluntary effort

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SYNOPSIS Electrical activity during voluntary effort was analysed in 33 normal subjects. Parameters of activity measured were number of peaks, mean amplitude, distribution of time intervals and of amplitudes between peaks. Recording from 10 sites evenly distributed over a muscle gave adequate representation of activity; force should be a fixed proportion of maximum rather than constant.

When a force of 2 kg was exerted at the wrist by the brachial biceps or triceps muscles the electrical activity showed a greater number of peaks ('turns'), a lower amplitude ('amplitude between peaks'), and a relatively higher incidence of short time intervals between peaks in patients with progressive muscular dystrophy than in controls (Willison, 1964; Rose and Willison, 1967; Dowling *et al.*, 1968). When the same force is exerted by the weak muscle of a patient as by a control, it remains undecided whether the increase in 'turns' is due to activation of more motor units (or increase in their firing rate) to exert a given force or to changes in shape and duration of the individual motor unit potentials associated with disease. Moreover, most actions of the human body are carried out by several muscles often involved differently under pathological conditions. Even the relative contribution of different portions (heads) of a single muscle differs from subject to subject.

The purpose of the study presented in this report was then (1) to analyse how turns and mean amplitude vary with maximum force, (2) how variations in balance of the force of different muscles and different heads of a given muscle contribute to this variability, and (3) to obtain a group of controls in whom maximum force and systematic differences between different sites were taken into account.

METHOD

The pattern of electrical activity was characterized (Willison, 1964; Dowling *et al.*, 1968) by: (1) the incidence of voltage reversals, denoted as 'turns' (a turn was counted if it originated from two successive voltage shifts, 100 μ V or more in amplitude and of opposite sign); (2) the amplitude of voltage changes, counted whenever the voltage of the signal changed in the same direction by 100 μ V; (3) the mean amplitude, obtained from the number of counts of amplitude divided by that of turns; (4) the distribution of time intervals between turns; (5) the distribution of amplitudes between turns.

RECORDING The electrical activity was led-off from one or two muscles by concentric needle electrodes with a leading-off area of 0.07 mm² (DISA 13 K 32) and amplified with a lower limiting frequency of 20 Hz and an upper limiting frequency of 10 000 Hz (3 dB down, DISA 14 C, 10). To diminish overload (of importance when recording on tape) and to ensure a suitable signal-to-noise ratio (40 dB) the gain of the amplifier was 4 000 times (500 μ V/div). The pattern of activity was analysed both on-line and off-line to obtain simultaneous data from two muscles and histograms of intervals and of amplitudes between turns. For off-line analysis the potentials were recorded on tape (frequency modulation). The tape recorder (Lyrec TR 81) had a frequency range from DC to 10 000 Hz. The upper limiting frequency required for analysis did not exceed 5 000 Hz as seen from a comparison of the same pattern analysed from tape with 5 000 and 10 000 Hz as upper limiting frequency (Table 1).

TABLE 1

URNS AND AMPLITUDE RECORDED IN BRACHIAL BICEPS (FORCE 2 KG, RECORDING FROM 15 SITES) AS FUNCTION OF UPPER LIMITING FREQUENCY

	Upper limiting frequency		
	10 kHz ₂	5 kHz ₂	3 kHz ₂
Turns/5 s	1 946	1 930	1 880
Ampl./5 s	761	763	738
$\Delta t \leq 0.75$ ms	5 720	5 720	5 110

Nevertheless, an upper limiting frequency of 10 000 Hz was used throughout. Data obtained off-line and on-line were the same within $\pm 3\%$ for turns and $\pm 1\%$ for amplitudes. For analysis, five seconds of the pattern of electrical activity were converted to two pulse trains, one as a gauge of turns, the other as a gauge of amplitude (Fitch, 1967; Medelec APA 6). An amplifier connected to the input of the analyser ascertained that one count occurred per 100 μ V change on the input (the overall amplification gave 100 μ V/count). Histograms of time intervals between turns were sampled by a small digital computer (Fabri-tek, type 1062, plug-in units SH 1 and SH 2) with intervals of 10 μ s, and of amplitudes between turns in steps of 100 μ V.

The error of the analysis of counts of turns and amplitude pulses was tested by introducing a sinusoidal voltage corresponding to an input signal of

FIG. 1 Estimation of error on counts of turns and amplitude. A: amplitude of a sinusoidal signal just sufficient to generate a turn-pulse for each peak in the signal. Ordinate: percentage change in input amplitude relative to input amplitude at 500 Hz. B: variation in number of amplitude pulses. A sinusoidal signal with an amplitude which gave 10 amplitude pulses between two peaks at a frequency of 500 Hz was analysed. Ordinate: percentage change in number of amplitude pulses between two peaks. Abscissa: frequency of the sinusoidal signal.

100 μ V and 1 000 μ V. Below 50 Hz and above 5 000 Hz the analyser required a 25% higher input voltage to generate a turn pulse than in the mean frequency range (Fig. 1). The error on the count of amplitude pulses was lower, the count being independent of frequency from 20 to 5 000 Hz. Above 5 000 Hz an amplitude pulse to be generated needed a 20% higher input signal (120 μ V).

MEASUREMENT OF FORCE The isometric force at the wrist exerted by an attempt at flexion or extension at the elbow was recorded via a strain gauge (Darcus, 1953) on an inkwriter. In most experiments, the electrical activity during flexion at the elbow was analysed when the force exerted at wrist was 2 kg (Willison, 1964) and 30% of maximum force. The electrical activity during an attempt to extend the arm at the elbow was analysed in the brachial triceps muscle when the force at the wrist was 10% and 20% of maximum force and 2 kg. The ratio between the lever from the wrist to the axis of the elbow joint and from the insertion of the brachial biceps to the axis of the elbow joint is nearly constant (4.9, SD = 0.3; Ikai and Fukunaga, 1968). The force measured at the wrist was therefore one fifth of the force referred to the insertion of the brachial biceps.

SUBJECTS The experiments were performed on 33 volunteers without history, signs, or symptoms of neuromuscular disease. Elbow flexion was examined in 19 adults 18–63 years old—nine men with a mean maximum force measured at the wrist of 31.9 kg (SD 5.1), and 10 women with a mean maximum force of 19.9 kg (SD 2.2)—and two boys and three girls 7–14 years old. Elbow extension was studied in 12 adults 22–54 years old—six men with a mean maximum force measured at the wrist of 18.1 kg (SD 4.3 kg) and six women with a mean maximum force of 11.3 kg (SD 3.1 kg).

PROCEDURE The subjects were in a supine position with the elbow flexed at 90°, the forearm supinated and fixed on a splint. The force during maximum effort was recorded before insertion of the electrodes and again after the electrodes had been withdrawn. To ascertain constant force, the subjects were instructed to keep the pointer of a galvanometer at a given deflection. In this way, variation in force during analysis did not exceed 5%. The subjects were allowed a one minute rest between pulls. In each muscle 10–15 sites were examined, obtained by three insertions in proximal, medial, and distal parts of the muscle and by changing the depth of insertion in steps of at least 5 mm. At each site, the electrode was adjusted at 10% of maximum force until activity was recorded which originated near the electrode as

evidenced from the steep deflection of the action potentials. Then the subject was instructed to exert a given force. When the force had reached the correct level, the electrical activity was analysed over a period of five seconds.

RESULTS

FINDINGS IN A GIVEN SITE *Reproducibility of the electrical activity* Reproducibility was studied in the brachial triceps of six subjects who innervated 30 times at intervals of a minute, the force alternating between 2 kg and 10% and 20% of maximum force of extension. The number of turns recorded from a given site was reproducible

to within $\pm 10\%$ and the mean amplitude to within $\pm 10\text{--}25\%$. The 30 stretches performed within about half an hour were accompanied by an overall decline in turns of 4–8% and a decline in mean amplitude of 20%. These changes are opposite to those to be expected from fatigue. Maximum force was unchanged.

Electrical activity at different loads The next question was to what extent the changes in turns and amplitude reflect the increase in number of active motor units and the increase in their discharge frequency associated with an increase in effort. This was studied in the brachial biceps, the brachial triceps, and the brachioradialis muscles of five subjects. The number of turns and mean amplitude recorded in a given site increased linearly with effort up to 30–50% of maximum force (Fig. 2). With greater effort the number of turns remained unaltered or decreased while the mean amplitude continued to rise.

FINDINGS IN MULTIPLE SITES *How many sites are sufficient?* Turns and mean amplitude differ in different sites of the muscle. The number of sites to be studied is a compromise between that giving the least discomfort to the patient and that necessary to describe the pattern throughout the muscle with sufficient accuracy. The number of sites to be tested should be such that the standard error of the average values in the individual muscle be small compared with the variation from subject to subject. To determine this number of sites, mean values and scatter within each subject and between subjects were compared for various numbers of sites: five, 10, and 15 sites were tested in the brachial biceps and five and 10 sites in the brachial triceps. Measurements were made in 10 adult subjects to evaluate the variation from subject to subject. The findings are summarized in Table 2.

The mean values of turns and mean amplitude for all subjects were independent of the number of sites studied. With a force of 2 kg, the number of turns was on the average 20% greater and the mean amplitude 45% greater in the brachial triceps than in the biceps. The differences are related to the different strength of the two muscles (p. 684). In both muscles, for turns as well as for mean amplitude, the variation between subjects and the variation in a given sub-

FIG. 2. Turns per 5 s (left) and mean amplitude (right) as a function of force in percentage of maximum. Top: *m. brachial biceps* (five subjects, one site each). Middle: *m. brachioradialis* (five subjects, one site each). Bottom: *m. brachial triceps* (two subjects, five sites each). The dashed line is the average of five subjects.

TABLE 2

MEAN VALUES AND SCATTER OF TURNS PER 5 s AND MEAN AMPLITUDE IN mV WITH FIVE, 10, AND 15 SITES OF RECORDING AT DIFFERENT DEGREES OF EFFORT

Load	<i>M. biceps brachii</i>								<i>M. triceps brachii</i>					
	2 kg		10%		20%		30%		10%		2 kg		20%	
Turns	Turns	SD*	Turns	SD*	Turns	SD*	Turns	SD*	Turns	SD*	Turns	SD*	Turns	SD*
Five sites:														
Mean, 10 subjects†	1 607	456	—	—	—	—	2 664	482	1 562	501	1 915	605	2 120	623
SD†	511	273	—	—	—	—	278	183	317	117	289	298	338	201
Ten sites:														
Mean, 10 subjects†	1 595	485	1 693	703	2 477	738	2 713	501	1 582	495	1 917	576	2 148	538
SD†	473	170	234	219	352	238	212	119	231	132	215	218	308	134
Fifteen sites:														
Mean, 10 subjects†	1 509	480	—	—	—	—	2 718	498	—	—	—	—	—	—
SD†	476	151	—	—	—	—	252	118	—	—	—	—	—	—
Mean amplitude	Ampl.	SD*	Ampl.	SD*	Ampl.	SD*	Ampl.	SD*	Ampl.	SD*	Ampl.	SD*	Ampl.	SD*
Five sites:														
Mean, 10 subjects†	0.289	0.091	—	—	—	—	0.519	0.126	0.352	0.092	0.414	0.124	0.441	0.141
SD†	0.084	0.032	—	—	—	—	0.090	0.040	0.086	0.040	0.090	0.044	0.118	0.065
Ten sites:														
Mean, 10 subjects†	0.283	0.079	0.332	0.097	0.468	0.145	0.538	0.117	0.358	0.112	0.407	0.134	0.446	0.138
SD†	0.076	0.023	0.022	0.021	0.074	0.030	0.099	0.031	0.082	0.040	0.072	0.018	0.114	0.040
Fifteen sites:														
Mean, 10 subjects†	0.271	0.079	—	—	—	—	0.524	0.117	—	—	—	—	—	—
SD†	0.064	0.022	—	—	—	—	0.077	0.036	—	—	—	—	—	—

* Scatter within the individual muscle.

† Scatter from subject to subject.

‡ Five subjects for 10% and 20% of maximum force in *m. biceps brachii*.

TABLE 3

AVERAGE VALUES OF TURNS, MEAN AMPLITUDE, AND DISTRIBUTION CURVES

Load	<i>Muscle</i>								
	<i>M. biceps brachii</i>			<i>M. brachioradialis</i>			<i>M. triceps brachii</i>		
	2 kg	30%		2 kg	30%		2 kg	10%	20%
Subjects (no.)	15	15		15	15		12	12	12
Sites (no.)	10–15	10–15		10–15	10–15		10	10	10
Maximum force (kg)	17–38	17–38		17–38	17–38		8–24	8–24	8–24
Turns and amplitude:									
Turns/5 s	1 531	2 680		950	2 984		1 852	1 567	2 113
SD turns	403	246		594	495		249	212	291
Mean amplitude (mV)	0.303	0.529		0.237	0.497		0.410	0.366	0.450
SD mean amplitude	0.061	0.075		0.062	0.082		0.068	0.076	0.103
Histograms									
% time interval ≤ 0.75 ms	21.6	25.4		—	—		22.7	24.0	—
SD time interval ≤ 0.75 ms	6.5	6.3		—	—		6.3	6.3	—
% amplitude ≤ 0.4 mV*	70.5	64.3		—	—		68.5	73.7	—
SD amplitude ≤ 0.4 mV*	10.2	7.6		—	—		6.6	8.7	—

* *M. biceps brachii* 2 kg 0.3 mV, 30% 0.5 mV.

ject were independent of the number of sites tested.

In the brachial biceps muscle, the standard deviation of turns measured from different sites of the individual muscle averaged 484; in the brachial triceps 556. Therefore, the standard error on the average number of turns in the brachial biceps of the individual subjects was 216 ($=484/\sqrt{5}$) when five sites were tested, 153 when 10, and 125 when 15 sites were tested. In the brachial triceps the standard error was 248 ($=556/\sqrt{5}$) for five sites and 176 for 10 sites. A comparison of these values with the data of Table 2 shows that the variation between subjects exceeded the standard error of the mean value in the individual muscle whether five, 10, or 15 sites were tested, the difference being more pronounced in the brachial biceps than in the brachial triceps muscle. Similarly, the variation of mean amplitude in the individual muscle averaged 83 μV (2 kg) and 120 μV (30%) in the brachial biceps, 102 μV (10%), 129 μV (2 kg), and 139 μV (20%) in the triceps. Hence, the standard error with which the average of mean amplitude was determined in the individual subject was 37–62 μV when five sites were studied, 26–44 μV when 10, and 21–31 μV when 15 sites were tested. Compared with the values of Table 2, this shows that the standard error of the average values for different subjects was smaller than the variation from subject to subject.

From these findings, it follows that, if 10 sites are scanned, average values of turns and mean amplitude are obtained which are representative of the muscle. When 10 sites are tested, the variation in turns and mean amplitude within the individual subject is obtained with a standard error of 24% ($=100/\sqrt{2(10-1)}$).

ELECTRICAL ACTIVITY IN DIFFERENT PARTS OF THE MUSCLE AND IN SYNERGISTIC MUSCLES In four of five subjects the number of turns was 20%–90% greater in the medial head than in the long and lateral heads of the brachial triceps, the difference tending to be greatest at small forces. Similarly, with a force of 2 kg the number of turns was two to three times greater in three of five subjects when the electrode was placed in the brachialis muscle than when it was placed in the brachial biceps. At 30% of maximum force, only one subject showed a greater number of turns in the

brachialis muscle than in the biceps (50%, Fig. 3).

FIXED LOAD COMPARED WITH LOAD ADJUSTED TO MUSCLE STRENGTH A force of 2 kg resulted in a lower number of turns when the maximum force of the subject was high than when it was low. This applied to the brachial biceps, the brachial triceps, and the brachioradial muscles (Fig. 4).

FIG. 3 Turns in distal and proximal sites of the muscle as a function of force. Ordinate: ratio between turns in distal and proximal sites (five subjects, three to seven sites in each region of the muscle). $\circ$ — $\circ$ *m. biceps brachii* (proximal) and *m. brachialis* (distal), (2 kg and 30%). $\bullet$ — $\bullet$ *m. triceps brachii caput laterale and longum* (proximal) and *caput mediale* (distal) (2 kg, 10% and 20%). The difference between turns in proximal and distal sites was significant except at a force of 30% in the brachial biceps muscle.

Conversely, if different subjects exerted the same relative force the number of turns was independent of maximum force (Fig. 4). The regression lines relating turns and maximum force were the same when attempts were made to flex and extend the arm at the elbow with a force of 2 kg. The regression lines must, however, be used with caution to predict the number of turns in subjects with reduced muscular strength. Thus, when extrapolating the curve for the biceps brachii to the maximum force of 6.7 kg where 2 kg is 30% of maximum force, the expected number of turns was 2120 ± 324 (SD). In fact, the number of turns found at a force of 30% was 2680 ± 246 (SD) independent of maximum

FIG. 4 Turns as a function of maximum force at 2 kg and at 10, 20, and 30% of maximum force. Left above: *m. biceps brachii* (15 normal adults and five children with maximum force of 6–15 kg). $\circ$ 2 kg ($y = 2\,699 - 45.1x$, $SD = 309$, $P < 0.001$; adults alone $y = 2\,340 - 32.3x$, $SD = 324$, $P < 0.05$). $\bullet$ 30% of maximum force. Right: *m. triceps brachii* (12 subjects). Above: $\circ$ 2 kg ($y = 2\,382 - 36.1x$, $SD = 165$, $P < 0.01$). Below: $\triangle$ 20% and $\square$ 10% of maximum force. Left below: *m. brachioradialis* (15 subjects). $\circ$ 2 kg ($y = 2\,464 - 60.4x$, $SD = 406$, $P < 0.05$). $\bullet$ 30% of maximum force. The thick lines give the regression lines, the thin lines are displaced ± 1 times SD . The dashed lines (left above) in the brachial biceps give the regression line including five children.

FIG. 5 To illustrate that recording of turns at 2 kg with disregard of maximum force gives rise to error. Regression line (thick line) and 95% confidence limits (thin lines) for turns at 2 kg as a function of maximum force. The dashed lines give the 95% confidence limits disregarding the influence of maximum force. Subjects 1 and 2 would have been considered abnormal and patients 3 and 4 normal when maximum force is disregarded (hatched areas). *M. biceps brachii*, 15 normal subjects, recording from 10 to 15 sites in each muscle.

force in the range 16.8–37.6 kg. The significance of maximum force was further emphasized by findings in the brachial biceps of five children (maximum force during an attempt at flexion of 6.2–15 kg). Turns and mean amplitude at a force of 2 kg were only slightly higher than expected from the finding in adults (Figs 4 and 6). Hence, regression lines that included findings in children were only slightly different from those of adults.

If the relation between turns and maximum force at a force of 2 kg is disregarded, findings in muscles with low force may be misinterpreted. When 2 kg was exerted, certain subjects appeared to have more turns than normal (Fig. 5, subjects 1 and 2, brachial biceps). In fact, when the variation with maximum force was taken into account, the number of turns was within the 95% confidence limit. Conversely, other subjects exerting 2 kg appeared to give a normal number of turns, whereas turns fell above or below the normal range when the variation with maximum force was considered (Fig. 5, subjects 3 and 4).

Mean amplitude varied differently with force

and with maximum force in the brachial triceps and in the biceps. With a force of 10% or 20%, mean amplitude in the brachial triceps increased with increasing maximum force. With a force of 2 kg or of 30% of maximum, mean amplitude in the brachial biceps muscle was independent of maximum force (Fig. 6). In the brachial biceps the mean amplitude amounted to 0.30 ± 0.06 (SD) mV at a force of 2 kg and to 0.53 ± 0.08 (SD) mV at 30%. In the brachial triceps the mean amplitude at a force of 2 kg was 0.41 ± 0.07 (SD) mV.

Influence of age and sex At a force of 30% of maximum applied to the brachial biceps muscle,

the number of turns was independent of age and sex. Conversely, at a force of 2 kg the number of turns varied with age, in the same way in both sexes (Table 4). Before 25 years the number of turns decreased with age, after 25 years there was a smaller but significant increase. The change in turns at a force of 2 kg reflects the increase in maximum force up to 25 years of age and the decrease above 25 years of age (Table 4).

Correction of turns in m. biceps brachii for differences between subjects in contribution of m. brachioradialis to force When turns in the brachial biceps muscle are related to the isometric force exerted at wrist, it must be considered that muscles of the forearm, especially m. brachioradialis, contribute to the force. The ratio of the forces contributed by m. biceps brachii and m. brachioradialis varies with the force and presumably also between subjects and may account for some of the scatter in turns. Within a certain range of force the number of turns and their mean amplitude increased with increasing force also in the brachioradialis muscle (Fig. 2). It was then assumed that the ratio between turns in the brachial biceps and in the brachioradialis muscle reflects the ratio between forces exerted by the muscles of the upper arm and of the forearm.

Furthermore, if we assume that deviations from the regression line describing the decrease in turns with increasing maximum force for the brachioradialis muscle were due mainly to deviations from the average ratio between contributions to force from muscles of the upper arm and forearm, an increased number of turns in the brachioradialis muscle should be associated with a decreased number of turns in the

FIG. 6 Mean amplitude as a function of maximum force. Top: m. biceps brachii (15 normal adults and five children). ○ at 2 kg ($y=0.434-0.005x$, $SD=0.049$, $P<0.001$). ● at 30% of maximum force. Middle and below: m. triceps brachii (12 subjects). ○ at 2 kg. □ at 10% ($y=0.201+0.011x$, $SD=0.051$, $P<0.01$), and △ at 20% of maximum force ($y=0.233+0.015x$, $SD=0.068$, $P<0.01$). The thick lines give the regression lines, the thin lines are displaced ± 1 times SD. The dashed lines in the brachial biceps give the regression lines including five children. In each muscle 10 to 15 sites were examined.

TABLE 4
INFLUENCE OF AGE

	Turns 2 kg		Turns 30% of maximum		Maximum force kg	
	< 25 yr	> 25 yr	< 25 yr	> 25 yr	< 25 yr	> 25 yr
Subjects (no.)	10	11	10	11	10	11
Mean	1 939	1 428	2 732	2 668	19.1	24.2
Intersept*	3 144	524	2 798	2 593	5.0	37.6
Slope*	-73.4	23.4	-4.0	1.9	1.47	-0.35
P	< 0.01	< 0.01	NS	NS	< 0.001	< 0.05

* Of regression line.

brachial biceps muscle. Experimental support was obtained for this assumption. In 15 subjects examined at a force of 2 kg, the per cent deviation of turns from the regression line was inversely related to the corresponding deviation in the brachioradialis muscle (percentage deviation in brachial biceps muscle = $-0.21 \times \% \text{ deviation in brachioradialis muscle} + 0.6$; $P < 0.05$).

The number of turns recorded in the brachial biceps was corrected in the following way. If turns recorded in the brachioradialis muscle were a per cent above the regression line, the force exerted by the muscles of the forearm was a per cent above the average of normal. If the brachial biceps muscle in the average subject exerted 80% of the total force, then the contribution was $80 - (20a/100)$.

To obtain the number of turns to be expected in this muscle if its contribution had been 80%, the number of turns recorded in the brachial biceps was multiplied by $80/(80 - 0.2a)$. The full correction reduced the variation around the

regression line for the brachial biceps from 324 to 282 turns—that is, a change of 15% (Fig. 7). Different force ratios between biceps brachii and brachioradialis muscle were tested in the correction. The highest correlation coefficient was found with a ratio of about 80 to 20. At a force of 30% it was not possible to obtain a smaller scatter by correction, no matter which ratio was used. The correction above is likely to be too great, since the number of turns in the brachioradialis muscle increased somewhat less than proportional with force. Thus, in 15 subjects, turns at a force of 2 kg increased linearly with the relative force. Using this relation, the correction was about half that obtained with proportionality.

Time interval histograms Turns grouped according to their time intervals had a peak at about 1 ms, but the shape of the histogram varied widely (Fig. 8). Therefore we characterized the distribution of time intervals by the percentage

FIG. 7 Turns in the brachial biceps muscle as a function of maximum force at 2 kg corrected for the contribution of *m. brachioradialis* to the force in 10 different subjects. The arrows give the correction calculated as described on page 690.

FIG. 8 Histograms of time intervals (shorter than 5 ms) between turns in the brachial biceps muscle. Ordinate: number of intervals in per cent of the number of intervals within 5 ms. A: single motor unit, time intervals shorter than 1.5 ms. B: two motor units firing at different frequency. The time intervals within each motor unit potential are < 1.5 ms, whereas the time intervals between motor unit potentials extend over the time intervals studied (5 ms). C and D: distribution of time intervals in two normal subjects (10 sites) at 2 kg (left) and 30% of maximum force (right). The smooth lines give the cumulated histograms.

of intervals shorter than 0.75 ms; intervals longer than 5 ms were disregarded. This area of the histogram gave the most significant differences between normal and diseased muscle. In the brachial biceps muscle (five sites, in each of three subjects) the percentage of turns with short time intervals increased with increasing force (Fig. 9). Nevertheless, the percentage of short intervals was independent of the maximum force, both at 30% and 2 kg (m. biceps brachii) and at 10% and 2 kg (m. triceps brachii), the variation in the histogram to be expected being within the scatter (Table 2).

Amplitude histograms The amplitude histograms were cumulated and the percentage of amplitudes between turns below the mean amplitude at the force under study was chosen to characterize the distribution. In the brachial

FIG. 9 Distribution of time intervals (above) and of amplitudes (below) as a function of force in percentage of maximum. Above: number of turns with time intervals of 0.75 ms or less in percentage of time intervals within 5 ms. Below: number of turns with amplitudes of 0.4 mV or less in percentage of total number of turns. M. biceps brachii, five sites in each of three normal subjects (Δ $\square$ $\circ$).

FIG. 10 Percentage of small amplitudes as function of maximum force: Left: *m. biceps brachii*. Above: force 2 kg ($y = 46.6 + 1.0x$, $SD = 7.5$, $P < 0.01$). Below: 30% of maximum force, 15 normal subjects. Right: *m. triceps brachii*. Above: force 2 kg. Below: 10% of maximum force, 12 normal subjects ($y = 94.1 - 1.38x$, $SD = 4.4$, $P < 0.01$). Ordinate: number of turns with amplitudes < 0.3 mV 2 kg < 0.5 mV 30% (*m. biceps brachii*) and < 0.4 mV (*m. triceps brachii*) in per cent of the total number of turns. Abscissa: maximum force in kg.

biceps muscle (five sites in each of three subjects) the percentage of small amplitudes (< 0.4 mV) decreased with increasing force (Fig. 9). The percentage of small amplitudes varied differently with the maximum force in the brachial triceps and the brachial biceps muscles. Thus, in the brachial triceps muscle, the percentage of small amplitudes decreased with increasing maximum force at 10% and 20% of maximum and was unaltered at 2 kg. In the brachial biceps muscle at 30% of maximum force the percentage of small amplitudes was unaltered with increasing maximum force, while it decreased at a force of 2 kg (Fig. 10). This decrease was unexpected since mean amplitude was not related to maximum force.

DISCUSSION

Our analysis of the method of Willison and his colleagues (1964) to quantify the electromyogram during voluntary effort aimed to clarify the following points: (1) how are sites of recording to be selected? (2) how many sites have to be tested? (3) should a standard force

(2 kg) be used or should the force be adjusted to the strength of the muscle? (4) what is the significance of the contribution from muscles other than the one under study which participate in exerting the force?

1. SELECTION OF SITES At a given site turns varied in the brachial triceps with a standard deviation of 10% and mean amplitude with 10–25%. There were systematic variations in different parts of the muscle, much greater than in the single point. The number of turns in the medial head was on the average 50% greater than in the long and lateral head. Willison (1964) recorded from the lateral head assuming that the long head contributed little to extension with a force of 2 kg. In the flexor muscles, the number of turns in the brachialis was often twice that in the brachial biceps. However, since the contribution of these muscles varied in different subjects, it is necessary to distribute evenly the 10 sites to be tested. The systematic difference between heads of a muscle or different muscles of a synergy, as well as its variation from subject to subject, were less at high (30%) than at low force (10% of

maximum force). Therefore, 30% of maximum force gave better reproducibility than 10%.

2. NUMBER OF SITES Fourteen (Hayward and Willison, 1973) and 10 different sites (Colston and Fearnley, 1967) were considered representative, though no systematic experiments were reported. To obtain representative average values of the parameters which characterize the pattern of electrical activity, we have determined the number of sites which gave a mean error in the individual muscle which was small compared with the variation from subject to subject. The variation in turns and amplitude from site to site was about 30% in the brachial triceps and biceps muscles (2 kg).

With 10 different sites the variation in turns and mean amplitude from subject to subject was two to three times greater than the standard error of the mean in the individual muscle.

3. STANDARD OR ADJUSTED FORCE At a standard force of 2 kg the number of turns decreased by 30–40% with increasing maximum force of different adult subjects (from 8–24 kg with extension at the elbow and from 17–38 kg with flexion at the elbow). When the force was adjusted relative to maximum force the number of turns was the same in different subjects. This suggests that the number of motor units required to exert a given force is determined by the relative force, the total number of motor units being about the same regardless of muscle strength. Differences in maximum force would then be due mainly to difference in diameter of muscle fibres. This view is supported by the finding of a 20% smaller mean fibre diameter in women than in men (Moore *et al.*, 1971; Vilppula, 1972), resulting in the 35% lower maximum force (p. 684).

Therefore, to compensate for difference in muscle strength in different subjects, we prefer to use a fixed *relative* force rather than a fixed *absolute* force. Although the variation from subject to subject was the same whether the force was 10, 20, or 30% of maximum, we recommend 30%, since reproducibility was best.

4. CONTRIBUTIONS FROM OTHER MUSCLES The scatter in turns in the brachioradialis muscle was 45% when corrected for maximum force. Nevertheless, in normal subjects, this muscle

contributes 20% to flexion; this variability could account for no more than about one-sixth of the variability in turns for the brachial biceps. On the other hand, in patients with proximal weakness when the brachioradialis muscle contributes more to flexion, correction for its contribution is probably necessary.

The change in maximum force with age explains the variation in turns when a force of 2 kg was exerted by the brachial biceps. Turns decreased up to 25 years of age as maximum force increased, and turns increased above 25 years as maximum force decreased. These findings reflect the changes in fibre diameter with age, the diameter being largest between 20 and 30 years of age (Moore *et al.*, 1971). With a force of 30% of maximum the number of turns was independent of age. These findings differ from those of Colston and Fearnley (1967) who found a decrease in turns with increasing age when a load of 2 kg was applied to the deltoid muscle, implying that their older subjects were systematically stronger than the younger ones. This could have been the case if all their old subjects had been men and the younger subjects women. However, the range of age is given as being similar in both sexes. Unfortunately, they give no information about the maximum force of their subjects.

INTERVAL BETWEEN SPIKES WITHIN INDIVIDUAL MOTOR UNIT POTENTIALS AND BETWEEN SPIKES ORIGINATING FROM DIFFERENT MOTOR UNITS Since intra-spike intervals from individual motor units are independent of the force exerted and those originating from different motor units vary with force, there is no basis for selecting any relative force for measurement. Finally, since the percentage of small amplitudes was closely related with mean amplitude ($P < 0.001$), the latter describes adequately the amplitude of the pattern of activity in normal subjects.

SUMMARY

Using the criteria suggested by Willison (1964) and Dowling *et al.* (1968), the electrical activity during different degrees of voluntary effort was analysed in flexors and extensors of the arm at elbow.

During repeated contractions the number of

spikes (turns) and the mean amplitude of the pattern of electrical activity were reproducible within 10–25%, suggesting that the same motor units are activated during repeated contractions.

The minimum number of recording sites representative for a muscle was found by comparing averages obtained from five, 10, and 15 sites. Ten sites were sufficiently representative, since the standard error of the average value of turns and of mean amplitude in the individual muscle was small compared with the variation from subject to subject.

The number of turns was often greater in the medial than in the long and lateral head of the brachial triceps and in the m. brachialis than in the brachial biceps. Hence, it is necessary to distribute the 10 sites of recording evenly over the muscle.

With a tension adjusted relative to maximum force, the number of turns was the same in different subjects, whereas turns decreased markedly with increasing maximum force when a standard force of 2 kg was exerted. Hence, a fixed relative force is less apt to give false positive data or to obscure abnormalities than a fixed absolute force.

The number of turns was independent of age with a fixed relative force and varied as did maximum force with a force of 2 kg.

Turns as a function of force recorded in the brachial biceps muscle were affected by the contribution to flexion at the elbow of the brachioradialis muscle. Correction for this contribution reduced the scatter by only 10–15% around the regression line of turns as a function of maximum force. The correction must be expected to increase under abnormal conditions when the contribution of the brachioradialis muscle to flexion is greater.

The shape of the histograms of time intervals and of amplitudes between turns varied con-

siderably. The percentage of short time intervals (<0.75 ms) and of small amplitudes (<0.4 mV) was best suited to compare with findings in patients. The percentage of turns with short time intervals increased with force and the percentage of small amplitudes decreased. Both were independent of maximum force at 30% of maximum.

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