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Simulation of the normal concentric needle electromyogram by using a muscle model

E. Stålberg*, L. Karlsson

Department of Clinical Neurophysiology, University Hospital, SE-751 85Uppsala, Sweden

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Abstract

Objectives: To study the correlation between anatomical parameters and EMG signals by means of simulations.

Methods: A mathematical model of the electrical activity from muscle fibres and motor units has been developed. The electrical fields around the muscle fibres are simulated using a line source model. The model permits the simulation of single muscle fibre action potentials obtained by SFEMG, concentric and Macro EMG electrodes. By using appropriate anatomical parameters EMG recordings with these electrodes can be simulated. The model is flexible and permits a number of anatomical parameters to be changed such as; number of muscle fibres in a motor unit, fibre diameter distribution, and motor end-plate geometry. Some physiological parameters can be optionally varied; firing rate, threshold for recruitment, jitter.

Results: In this study, simulations of CNEMG are performed and the influence of a number of parameters on the CNEMG signal is studied. It is shown that the model produces motor unit potentials reasonably well resembling those from live recordings. More important is however the relative change in MUP parameters when certain conditions are changed; number of muscle fibres in a motor unit, recording position, muscle fibre diameters and some special effects of the recording conditions.

Conclusions: The simulated muscle and corresponding EMG recording can be used both as a research tool and for teaching.

Keywords: Simulation; Muscle model; Electromyography; Motor unit; Concentric needle electromyogram

1. Introduction

A number of features regarding electromyogram (EMG) cannot easily be studied in the living muscle. It is not possible to keep a number of variables constant while changing one or a few others. Furthermore, biopsy data from the same motor unit as that explored by EMG is not easy to obtain. It would therefore be very useful to simulate various situations in the muscle and to study the generation of corresponding EMG patterns. It is now possible to obtain a relatively realistic model of the muscle as a generator of muscle fibre signals by integrating existing knowledge from anatomy, physiology and signal theory.

The aim of the present work is to study the relationship between various anatomical parameters and the generated EMG signal by using a model of a muscle, which has been developed by us.

2. Methods

A muscle model is developed with a number of parameters that can be set optionally. The mathematical basis for the model is described in some detail elsewhere but will presented in brief. The single muscle fibre action potentials (SFEMG) are simulated with a line source model described earlier (Nandedkar and Stålberg, 1983) and further developed for this study. Parameters regarding volume characteristics and electrode effects have been obtained from earlier studies (Nandedkar et al., 1988). The obtained EMG signals are generated by the summation of single fibre action potentials with respect to the recording electrode that has been chosen for the simulation. In the model, SFEMG, concentric needle EMG (CNEMG) and Macro EMG electrodes can be simulated. In this particular study only CNEMG is studied. The following main parameters have been taken into consideration in the model: Some of these can be changed optionally, indicated in Table 1.

* Corresponding author. Fax: +46-18-55-61-06.
E-mail address: erik.stalberg@nc.uas.lul.se (E. Stålberg).

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Table 1
Parameters that may be changed in the model; range and default values are shown

Menu	Parameter	Range	Default value
Motorunit	# Fibres	Indefinite	100
Motorunit	Territory radius	Size of muscle	2.5 mm
Motorunit	Minimal firing frequency	0–10	5
Motorunit	Maximal firing frequency	10–100	40
Motorunit	Frequency distribution	± 5	± 2
Motorunit	Force threshold	0–100%	30%
Fibre	Diameter	20–90 μm	50 μm
Fibre	Diameter distribution	± 30 μm	± 5 μm
Fibre	End-plate position (from centre)	−20–20 mm	0 mm
Fibre	End-plate position distribution	± 20 mm	2 mm
Fibre	Delay	0–1000 μs	500 μs
Fibre	Jitter	0–250 μs	20 μs

2.1. Electrode parameters

The simulation of the EMG signal takes into account the geometrical extension of the electrode as well as the cannula of the electrode, being the reference electrode in the live recordings in SFEMG and CNEMG (Nandedkar et al., 1988).

2.2. Muscle fibre parameters

The following parameters can be optionally changed; fibre diameter (mean and distribution), end-plate position (mean and distribution), delay and jitter (mean values). The propagation velocity of the SF action potentials is defined by a given relationship to the muscle fibre diameter.

2.3. Motor unit parameters (MUP)

A number of motor unit parameters can be optionally varied; number of muscle fibres, territory radius, firing frequency (minimum, maximum, distribution) and recruitment threshold of the motor unit. The number of muscle fibres for a given motor unit varies randomly and they are distributed randomly in the territory of the motor unit. Both these parameters could also be individualised for single motor units, used when some of the pathological features should be tested. The firing threshold is given in relationship to the size of the motor unit (number of fibres), not to violate the so called 'size principle' in normal muscle. Default values of motor unit characteristics are based on the findings in our own earlier studies (Stålberg and Dioszeghy, 1991) and on information from muscle anatomy literature (Coërs and Woolf, 1959).

2.4. Muscle parameters

The number of motor units can be varied. In some instances only one motor unit should be studied, in others, a complete muscle is required. The diameter of the muscle is fixed and therefore the total number of muscle fibres of a given size has an upper limit. For the complete muscle each motor unit was given as default value of 175 muscle fibres, with a given variation from this mean. The fibres were randomly distributed within their given territory. In some instances, the entire muscle area was filled with motor units, amounting to 489 motor units (Table 2).

The aim of the present study is firstly to assess whether the parameters of the simulated motor unit potentials (MUPs) are in reasonable agreement with the findings in live recordings. The second aim is to study the effect on the CNEMG MUP of a number of combinations of parameters that may occur in the live EMG investigation.

In this study the following main tests were made: (1) reproducibility in random recordings in a muscle, simulating a routine EMG investigation. (2) Effect of the extension of the motor unit territory on the MUP. (3) Effect of the motor unit density of fibres on the MUP. (4) Effect of recording position in relation to the end-plate zone. (5) Effect of the muscle fibre diameters on the MUP.

3. Analysis

The obtained simulated MUPs were exported to the commercial EMG equipment (Keypoint, Medtronic, Copenhagen) that is normally used in our live recordings. The analysis was made with the standard analysis algorithms, which allows the comparison to live recordings (Stålberg et al., 1995). Amplitude (peak-peak), duration (slope and amplitude criteria), area (within the duration), turns, phases

Table 2
Characteristics of standard muscle in the model

Number of motor units in muscle	489
Number of fibres in motor unit	175 ± 125
Density of fibres (fibres/mm^2)	5 ± 1
Fibre diameter (μm)	50 ± 5
End-plate position (mm from muscle centre)	0 ± 1
Jitter (μs)	20 ± 10

Table 3
Obtained results from the simulation in comparison with reference values from different muscles for a group of healthy subjects, aged 40 years[a]

Muscle	Amplitude (μV)	Duration (ms)	Area (ms*μV)	SI	Phases	Thickness (ms)
Simulated	779	7.2	695	0.63	3.10	0.93
Biceps	437	10.1	630	0.62	2.62	1.45
Tib ant	562	11.4	1801	1.53	2.87	1.86
Edc	525	10.0	833	0.84	3.21	1.41
Frontalis	288	4.7	279	−0.28	2.75	0.77
APB	631	9.4	895	0.95	3.18	1.40

[a] Each parameter in the simulation is given as the average of the mean values obtained for each muscle ($n = 5$), the same principle as is used for live recordings.

and size index (area/ampl normalized for amplitude, (Sonoo and Stålberg, 1993)) were measured.

4. Results

In some of these recordings, the changes in the shape of a MUP generated by a given motor unit have been studied when different parameters are changed. In others the pooled result from many motor units for different conditions have been analysed, a situation which is most close to the live situation.

4.1. Individual MUPs

Default values of the motor unit characteristics were used (Table 2). MUPs from five complete studies were collected. For each study, four different sites in the muscle were obtained resulting in 20–25 MUPs from each study, i.e. a total of about 100 MUPs. The MUPs had grossly the same

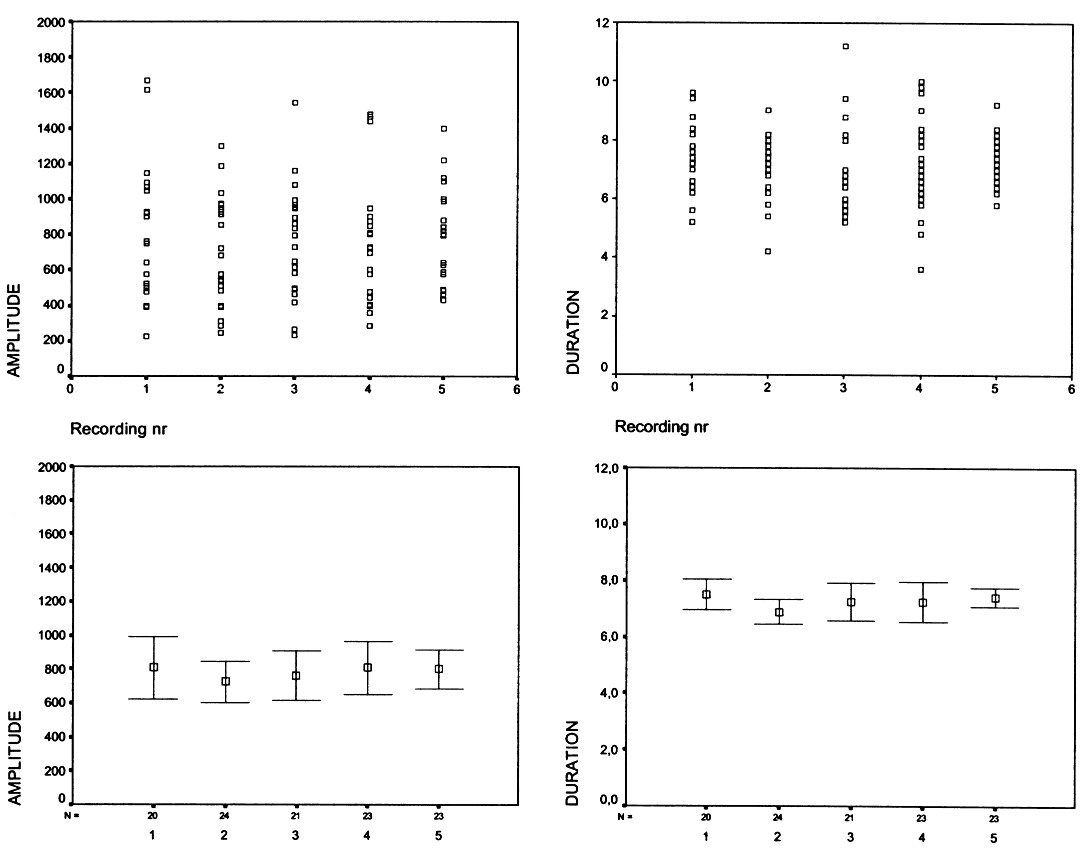

Fig. 1. Individual MUP values for amplitude and duration in five repeated recordings from the same model muscle (upper panels) and the mean values with 95% confidence interval for duration and amplitude in the same five recordings (lower two panels). Mean values show a high reproducibility.

Table 4
Mean, SD and coefficient of variance for individual MUPs in five repeated studies in a simulated normal muscle

	Amplitude	Rise	Duration	Area	Thickness	SI	Phases	Turns
Mean	778	0.7	7.2	694	0.93	0.63	3.10	3.18
1SD	323	0.4	1.3	258	0.17	0.34	0.47	1.23
CoeffVar	41.5	57.1	18.0	37.2	18.3	54.0	15.2	38.7

shape and parameter statistics as those obtained in live recordings (Table 3). In live recordings, the reference values from healthy controls differ between muscles and therefore no exact comparison can be done to the simulated situation. The amplitude was within the same range as we have found in most limb muscles. The duration was somewhat shorter. The main result was however similar enough to live recordings to be acceptable, particularly since most of the studies will concern changes in shape when anatomical parameters are changed.

4.2. Reproducibility at multiple recordings

The standard muscle was used. Recordings were performed from four random insertions 10–30 mm from the end-plate zone, a situation similar to the live recording. In this way 20–25 MUPs were obtained. The procedure was repeated five times for the study of reproducibility.

The mean values for the five repeats for the different parameters did not differ from each other significantly ($P < 0.05$) but for individual data there is a large scatter (Fig. 1; Table 4).

4.3. Effect of the extension of the MU territory

Nineteen motor units were simulated containing 50, 75, 100, …, 500 muscle fibres with the same number of muscle fibres per square mm. Three random recordings were obtained form each motor unit with a concentric needle at variable positions in the muscle 10–30 mm from the EP zone.

The results show a great variation in the parameters for each motor unit, exceeding that corresponding to the relative the difference in motor unit size. There is no systematic relationship between any of the parameters and territory size, except for the duration parameter, that increased when the motor unit size was increased from 50 up to 200 fibres, e.g. for motor unit diameter less than 7 mm (Fig. 2).

4.4. Effect of # fibres/mm^2 on CNEMG

In the normal muscle it is likely that motor units may be more or less dense, i.e. different number of muscle fibres/ mm^2. The normal motor unit is assumed to have its muscle fibres randomly distributed within the territory, as opposed to the situation in reinnervation with clustering of the fibres called grouping. The effect of number of muscle fibres in a normal motor unit was simulated (Fig. 3). Motor units with a territory of 6-mm diameter containing 50,75,100,125, …500 muscle fibres were simulated. The MUPs were recorded randomly in each of these motor units 10–-30 mm from the end-plate zone. The test was repeated three times.

When the number of fibres increased, the following parameters increased namely; amplitude (linearly), duration (between 50 and 250 fibres/ mm^2), area (linearly), size index (fastest in the range 50–150 fibres/ mm^2). The other

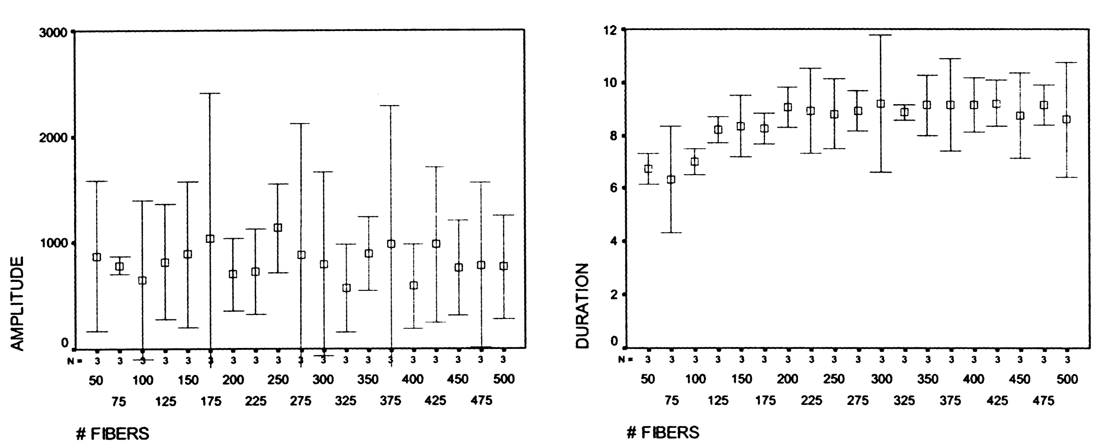

Fig. 2. Mean values ($n = 3$) with 95% confidence interval for amplitude and duration with different MU territory, i.e. different total number of muscle fibres distributed with constant number of muscle fibres/mm^2. Duration increases up to 200 fibres/mm^2 corresponding to a MU territory diameter of 7 mm. Amplitude is not affected by territory size.

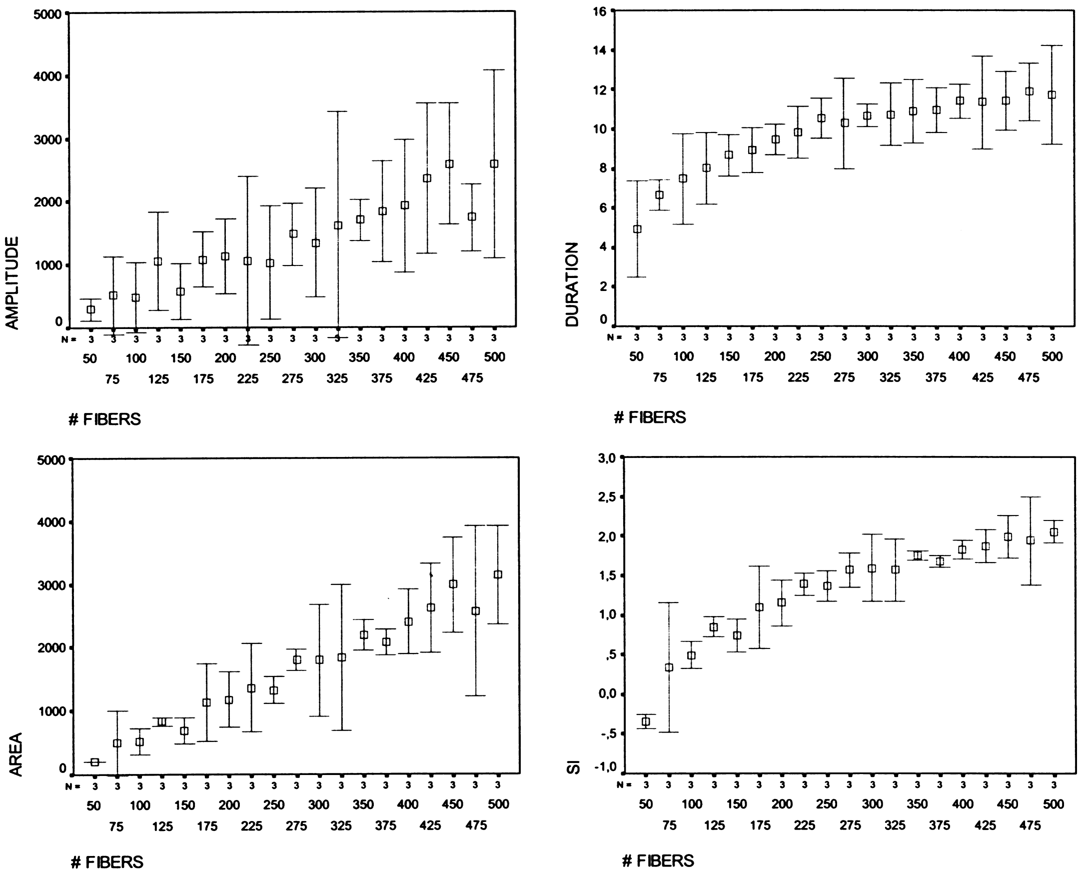

Fig. 3. Mean values with 95% confidence interval for amplitude, duration, area and size index for motor units with different density of muscle fibres i.e. number of muscle fibres within a given territory (6 mm diameter in this case).

parameters did not show any direct relationship to fibre density.

4.5. Effect of recording distance from end-plate

The standard muscle was used. The electrode was placed randomly in the muscle. Twelve MUP recordings were obtained at each distance from the end-plate zone, namely at 0, 10, 20, 30, 40 and 50 mm. The tendon is at 60 mm. The same six motor units were followed for each of these distances. The recording was made twice at each distance to receive twelve MUPs. The shape changed according to expectations with a distinct initial negative going phase close to the end-plate and then a growing positive phase at the tendon (60 mm) (Fig. 4). Due to the abrupt changes at the first 10 mm from the end-plate, the conclusions are drawn from recordings at the intervals 10–50 mm (Table 5 also includes data from position 0 mm). Here the amplitude, area and size index decreased while the mean number of turns and phases showed a tendency to increase (Fig. 5) and to increase in scatter. The other parameters were unchanged.

4.6. Effect of ploughing

When the concentric needle electrode is inserted into the muscle, there is a certain chance of cutting muscle fibres or, with another rotation, a ploughing of muscle fibres. This may not have a dramatic effect in the normal condition, and the ploughing may not be extreme since the recording surface is close to the bevelled tip of the electrode. In some occasions of pathology on the other hand, the intrusion of the electrode into the centre of a group of muscle fibres in a motor unit may play a role for the recording. The effect of ploughing in the normal muscle was tested in discrete experiments. It was seen that the MUP shape could be

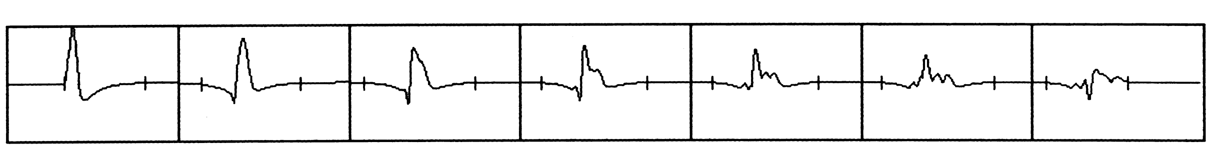

Fig. 4. MUPs for the same motorunit at 0, 10, 20, 30, 40, 50 and 60 mm from end-plate zone. At 0 mm (end-plate) the signal has a sharp negative take off and at 60 mm (tendon) the signal is mainly positive going.

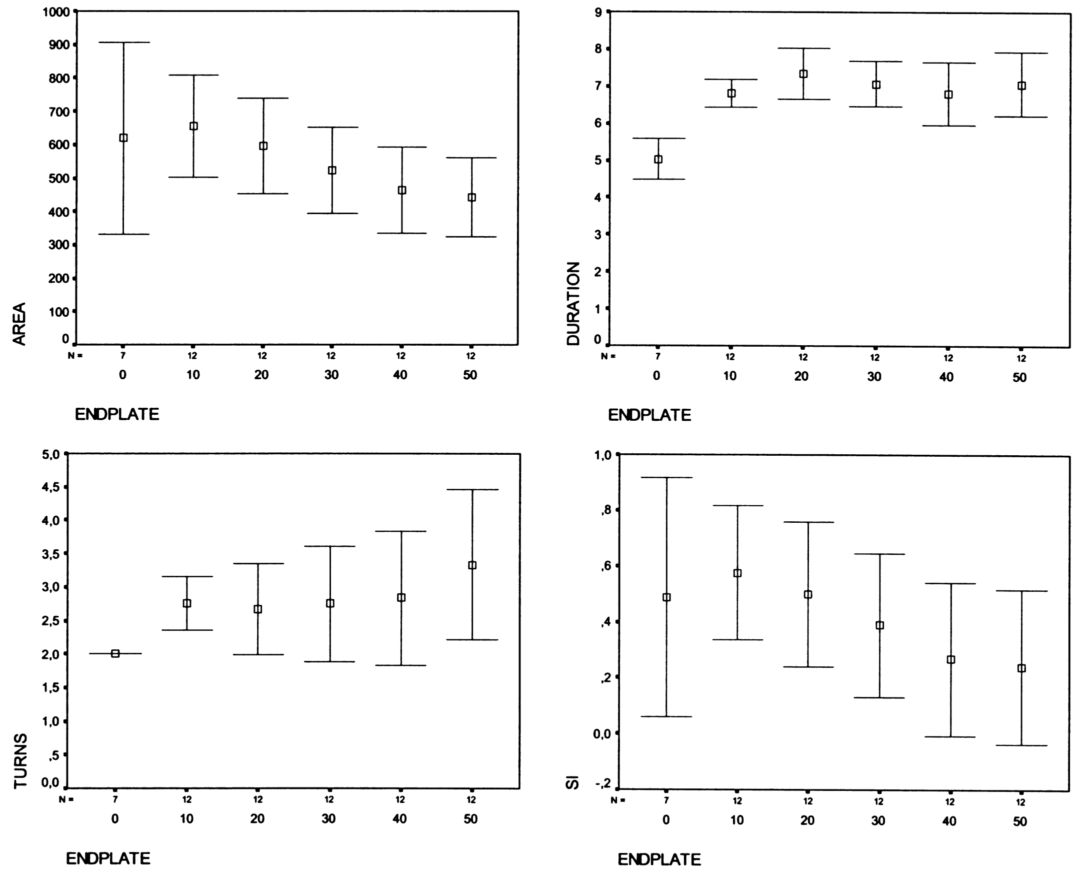

Fig. 5. Effect on MUP parameters of recording distance from the end-plate. Mean values with 95% confidence interval for area, duration, turns and size index (SI) with different distance to end-plate zone. Area and SI decrease due to phase cancellation. Duration does not change outside the end-plate zone itself.

quite different in a motor unit if it was pierced in such a way that many of its fibres were routed to the recording side or to the backside of the electrode. A parallel repositioning of the electrode may only differ by a few hundred μm to give these changes. In such a case the MUP parameters may show distinct change (Fig. 6)

4.7. Effect of normal variation of fibre diameters, Fig. 7

The study was performed at two distances from the end-plate zone; at 0–20 and at 20–50 mm. Three different muscles were used with standard properties except for muscle fibre diameters. The mean fibre diameters of the muscles were 40 ± 4, 50 ± 5 and 60 ± 6 μm. Five recording sites were explored for each muscle, which resulted in 20–25 MUPs. As seen in Tables 4 and 5, the amplitude, area and size index increased while risetime decreased with increasing fibre diameter. The duration was unchanged. It should be noted that amplitude and area were higher for the short recording distances (Tables 6 and 7).

5. Discussion

A number of parameters determine the MUP, some of which are relatively well known, based on empirical and

Table 5
Mean values/1SD for MUPs, recording from different distance to end-plate zone

Distance to EP mm	Amplitude	Rise	Duration	Area	Thickness	SI	Phases	Turns
0	833/480	0.5/0.2	5.0/0.6	619/311	0.77/0.08	0.49/0.46	2.00/0.00	2.00/0.00
10	715/368	0.8/0.4	6.8/0.6	655/240	0.97/0.15	0.57/0.38	3.00/0.00	2.75/0.62
20	651/373	0.9/0.5	7.3/1.1	595/224	0.99/0.24	0.5/0.41	3.08/0.67	2.67/1.07
30	590/386	0.8/0.7	7.1/1.0	522/202	0.98/0.25	0.39/0.41	3.00/0.74	2.75/1.36
40	543/384	0.8/0.6	6.8/1.3	464/204	0.95/0.25	0.27/0.43	3.25/1.14	3.25/1.59
50	497/357	1.0/0.9	7.1/1.4	442/188	1.00/0.28	0.24/0.43	3.58/1.16	3.33/1.78

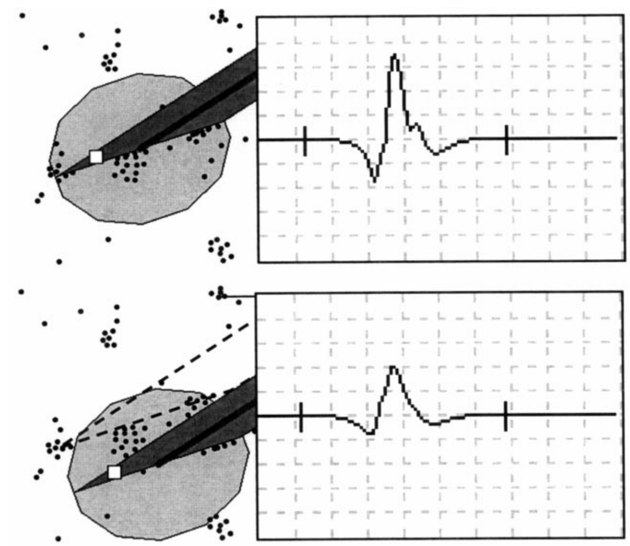

Fig. 6. Effect on MUP of the ploughing by the tip of the concentric needle electrode. Parallel repositioning of the needle about 300 μm in the same motor unit showing grouping. Note the change in amplitude, whereas the duration is the same.

theoretical knowledge (Buchthal et al., 1954a,b; Falck et al., 1995; Stålberg et al., 1996). When the electrode is inserted randomly in a motor unit, the recording condition is completely different for each insertion, even if the recording is made from one motor unit. This is due the small uptake radius of the CN electrode of up to 2 mm (Nandedkar et al., 1988). This variation for a given motor unit has been shown in live recordings by means of so called scanning EMG (Stålberg and Dioszeghy, 1991). In this simulation, the variation of MUP within a given motor unit is well demonstrated. The test of reproducibility showed a certain variability at repeated tests in the same muscle. One reason is the fact just discussed reflecting variation even within the same motor unit. The other reason is the real variation among motor units. Duration and thickness parameters showed least variation, probably reflecting the fact that they are less dependent on the exact localisation of the recording electrode in relation to individual muscle fibres.

The simulation also shows a small dependence of the MUP on the extension of the motor unit territory using a constant number of fibres/mm^2. This is due to the relatively small recording area of the electrode. The findings support the earlier suggestion that the CN EMG is a poor indicator of the total size of a given motor unit (Ertas et al., 1995). For motor units with a diameter less than 7 mm the territory size seems to affect the duration parameter. For other parameters the diameter is of no importance at least for territory diameters down to 3.5 mm which is probably smaller than normal motor units in limb muscles.

If the number of muscle fibres increase within a constant territory (increased fibres/mm^2), the MUP parameters change significantly. This latter is the situation in pathological situations with grouping, where the scatter of data is expected to be larger than shown in this simulation with some extreme values, outliers.

When the electrode is moved along the muscle, temporal dispersion will come into play and some of the parameters therefore change particularly the shape of the central spike (amplitude, turns). This is of importance when it comes to

Table 6
Mean values/1SD for MUPs, recording 0–20 mm from end-plate zone from motor units with different muscle fibre diameters

Mean	Amplitude	Rise	Duration	Area	Thickness	SI	Phases	Turns
40	503/179	0.9/0.4	6.5/1.3	476/170	0.96/0.18	0.31/0.35	2.88/0.34	2.75/1.22
50	819/330	0.7/0.3	6.8/0.9	767/240	0.98/0.15	0.73/0.29	3.09/0.29	2.95/0.65
60	1161/498	0.6/0.3	6.8/0.8	958/332	0.88/0.20	0.92/0.33	3.09/0.42	3.04/0.71

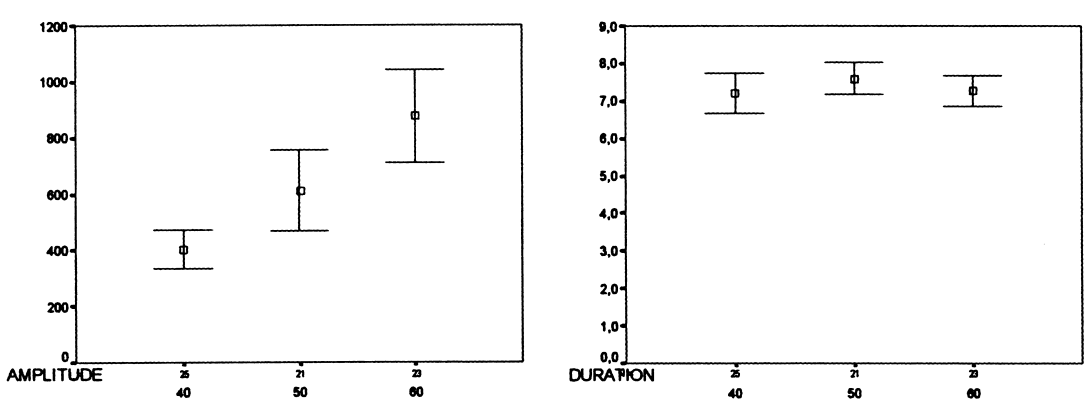

Fig. 7. Relationship between fibre diameter (μm) and MUP amplitude and duration. Data represent recordings performed at 20–50 mm from the end-plate zone.

Table 7
Mean values/1SD for MUPs, recording 20–50 mm from end-plate zone from motor units with different muscle fibre diameters

Mean	Amplitude	Rise	Duration	Area	Thickness	SI	Phases	Turns
40	403/168	1.2/0.6	7.2/1.3	422/152	1.11/0.27	0.24/0.31	3.36/1.22	3.44/1.26
50	612/311	0.8/0.4	7.6/0.9	591/201	1.08/0.30	0.53/0.30	3.52/0.91	3.81/1.53
60	877/381	0.8/0.5	7.3/0.9	768/225	0.97/0.27	0.76/0.29	3.65/1.11	4.35/1.56

pathological situations. In contrast, the duration is relatively constant. This is of principle interest, supporting the concept that duration reflects number of muscle fibres more than temporal dispersion (Stålberg et al., 1996). In one study in biceps muscle, it was shown (Falck et al., 1995) that the duration and amplitude increased somewhat towards the tendon. The discrepancy to the simulation studies may be narrowing of the muscle, not taken into consideration in the model, but other explanations are also possible.

Obviously fibre size is influential, a parameter that may come into play in pathological situations. The amplitude and area are most sensitive to the size factor.

The study of these few parameters already indicates that the MUP is influenced by technical and biological factors. Some of these may be reduced by more standardised methods, e.g. recording distance from the end-plate zone, if this is known. However, many of these factors are unknown in most situations, and their induced influence has to be part of the variation in the reference material. The knowledge of these factors may however help to avoid mistakes in the detailed interpretation of the MUP parameters in relation to the signal generator, the motor unit.

Acknowledgements

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