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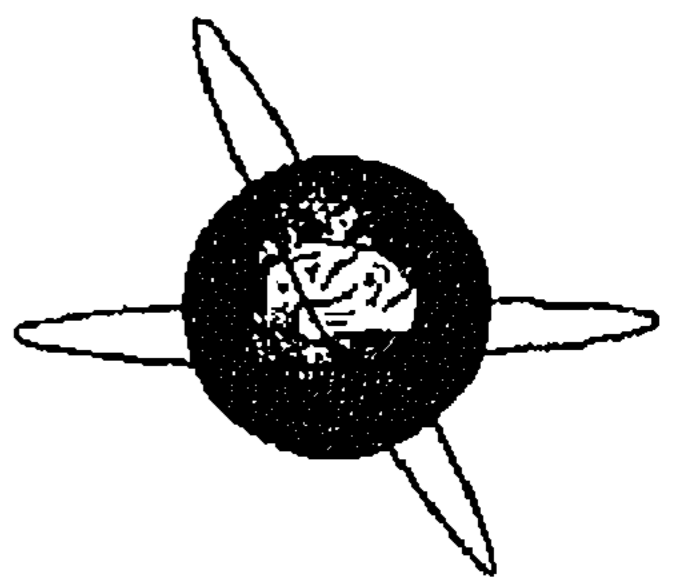
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# Motor unit size estimation: confrontation of surface EMG with macro EMG

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## Abstract

Surface EMG (SEMG) is little used for diagnostic purposes in clinical neurophysiology, mainly because it provides little direct information on individual motor units (MUs). One of the techniques to estimate the MU size is intra-muscular Macro EMG. The present study compares SEMG with Macro EMG. Fifty-eight channel SEMG was recorded simultaneously with Macro EMG. Individual MUPs were obtained by single fiber triggered averaging. All recordings were made from the biceps brachii of healthy subjects during voluntary contraction at low force. High positive correlations were found between all Macro and Surface motor unit potential (MUP) parameters: area, peak-to-peak amplitude, negative peak amplitude and positive peak amplitude. The MUPs recorded with SEMG were dependent on the distance between the MU and the skin surface. Normalizing the SEMG parameters for MU location did not improve the correlation coefficient between the parameters of both techniques. The two measurement techniques had almost the same relative range in MUP parameters in any individual subject compared to the others, especially after normalizing the surface MUP parameters for MU location. MUPs recorded with this type of SEMG provide useful information about the MU size. © 1997 Elsevier Science Ireland Ltd.

**Keywords:** Motor unit; Size; EMG; Surface; Macro

## 1. Introduction

A motor unit (MU) comprises the motor neuron, its axon, the motor end-plates and the muscle fibers innervated by the axon. MUs and their activity can be characterized by the number of muscle fibers, cross-sectional area of the motor unit territory, fiber density, fiber type, recruitment threshold, mean firing rate, contractile characteristics, fatigability, fiber length, fiber diameter and position of the motor end plates. Many neuro-muscular diseases cause changes in the MUs. Many of these changes of the motor unit characteristics can be detected with electromyographic (EMG) techniques.

Needle electrodes with different recording areas provide information about different aspects of the MU (Stålberg, 1986). With its large recording area, Macro EMG provides information of the entire cross-sectional area of the MU inside the muscle and is often used to estimate the MU size, while other needle EMG methods only record from a

portion of the MU (Stålberg, 1980). A technique using surface recordings and spike triggering (intra-muscular needle electrode) for estimation of the number of MUs has been developed by Doherty et al. (1995). Otherwise, there is little experience of using surface EMG (SEMG) to study individual motor units and their details. The non-invasive character of SEMG has advantages compared to needle EMG: it is less painful for patients, giving the opportunity of studying more muscles and it is easily applicable in children. Disadvantages for clinical diagnostic routines may be a low resolution to detect details of the motor unit. There is lack of knowledge regarding the relationship between the signal generator, the motor unit, and the signal parameters.

The problem in studying individual MUs with SEMG is twofold. Firstly, the isolation of individual MUs from the interference pattern, and secondly the dependence of the action potential shape and amplitude on the MU position relative to the skin-surface. Averaging is necessary to study individual MU activity in Macro and SEMG. Like in standard Macro EMG, a Single Fiber electrode can be used for triggering purposes. In the long run it is, of course, desirable to avoid needles in combination with SEMG. A trigger sig-

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nal from SEMG can be obtained by applying a spatial filtering technique to a two dimensional array of surface electrodes with small leading off surfaces (Reucher et al., 1987a,b).

The aim of this study was the representation of the MU in SEMG. This was realized by comparing Macro MUPs with surface MUPs using a single fiber electrode for triggering.

## 2. Materials and methods

### 2.1. Subjects

Six healthy volunteers without signs of neuromuscular disorders were investigated. Relevant subject data are given in Table 1. The m. biceps brachii was investigated, because of its well defined structure with fibers parallel to each other and to the skin surface. The upper arm circumference (AC) was determined around the middle of the upper arm. Also the thickness of the fat layer was determined at that position as the distance between the muscle tissue and the skin surface derived from the most superficial position of the needle where it was possible to record single fiber EMG (SFEMG). The electrode holder to skin distance and the electrode holder to single fiber electrode distance were subtracted. All subjects gave their informed consent. The Committee on Experiments in Humans of the Faculty of Medicine at the University of Uppsala approved the experimental protocol.

### 2.2. Macro EMG and SFEMG

Macro EMG was recorded with a standard Macro EMG electrode (Stålberg, 1980; Stålberg, 1990). The electrode has a single fiber recording surface on the side of the cannula, 7.5 mm from the tip and 35 mm from the electrode holder. A two-channel recording was made. On one channel the SF signal was recorded (using the cannula as reference). On the other channel, the signal between the cannula and a remote reference was recorded. The same reference electrode was used for the SEMG.

### 2.3. Surface EMG

Fifty-eight gold coated screws, with a diameter of 1.2 mm

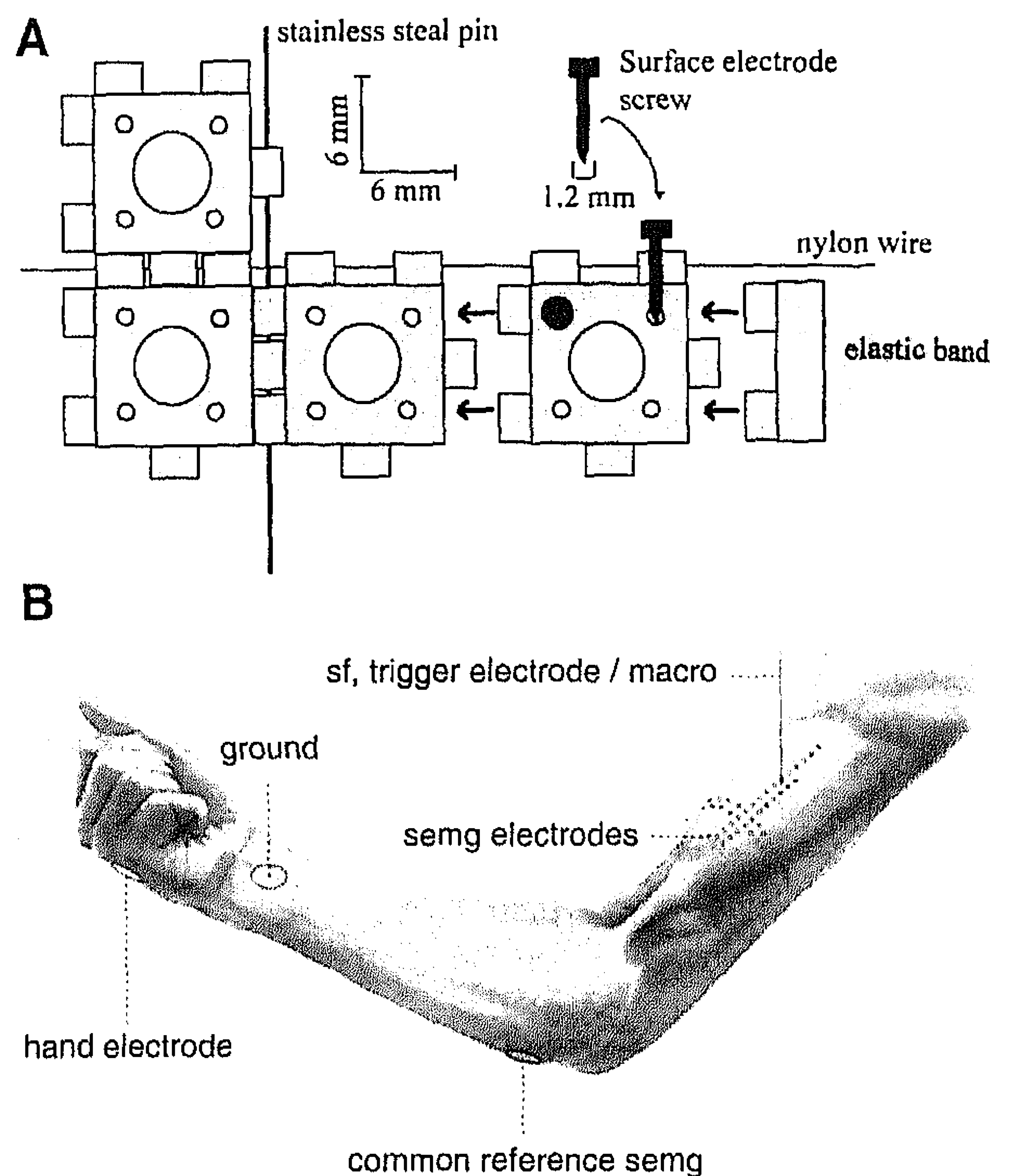


Fig. 1. Experimental set-up with a few elements of the electrode holder (A) and an impression of the position of all electrodes over the biceps brachii in this study (B).

and a length of 6 mm, were mounted into an electrode holder and used as surface electrodes (see Fig. 1A). The electrode holder was constructed from identical elements. Each element was made of a perspex body in which four recording electrodes could be placed with an inter-electrode distance of 6 mm. In the center of each element a circular hole was made to provide simultaneous access to the muscle with the Macro EMG electrode. The elements were bound together in a cross-form (see Fig. 1B and Fig. 2). In the muscle fiber direction (proximal-distal) eight elements holding two electrode columns with 15 and 11 electrodes were bound together by stainless steel pins. In the other direction (medial-lateral) nine elements holding two rows of 18 electrodes were bound together by nylon wires, to fit limb geometry. The outer sites of the medial and lateral part of the electrode holder were connected with elastic bands. By connecting the elastic bands, the electrodes could easily be placed on a fixed position on the muscle with a constant inter-electrode distance. Double electrode rows were used to check signal profiles for consistency. The electrodes perpendicular to the muscle fiber direction were placed approximately halfway between the motor endplate region and the distal muscle fiber-tendon transition.

Additionally, two gold coated electrodes with a diameter of 1 cm were attached to the skin with electrode paste on the elbow (common reference) and the hand (to validate the elbow as a silent reference electrode). A metal plate around the wrist was used as ground electrode.

Table 1

#### Selected anthropometric data

Subject	Gender	Age (years)	AC (cm)	Fat layer (mm)
1	Female	24	21.5	2
2	Male	25	28.0	2
3	Female	55	23.0	10
4	Male	30	28.0	3
5	Male	30	29.0	3
6	Male	29	26.3	3

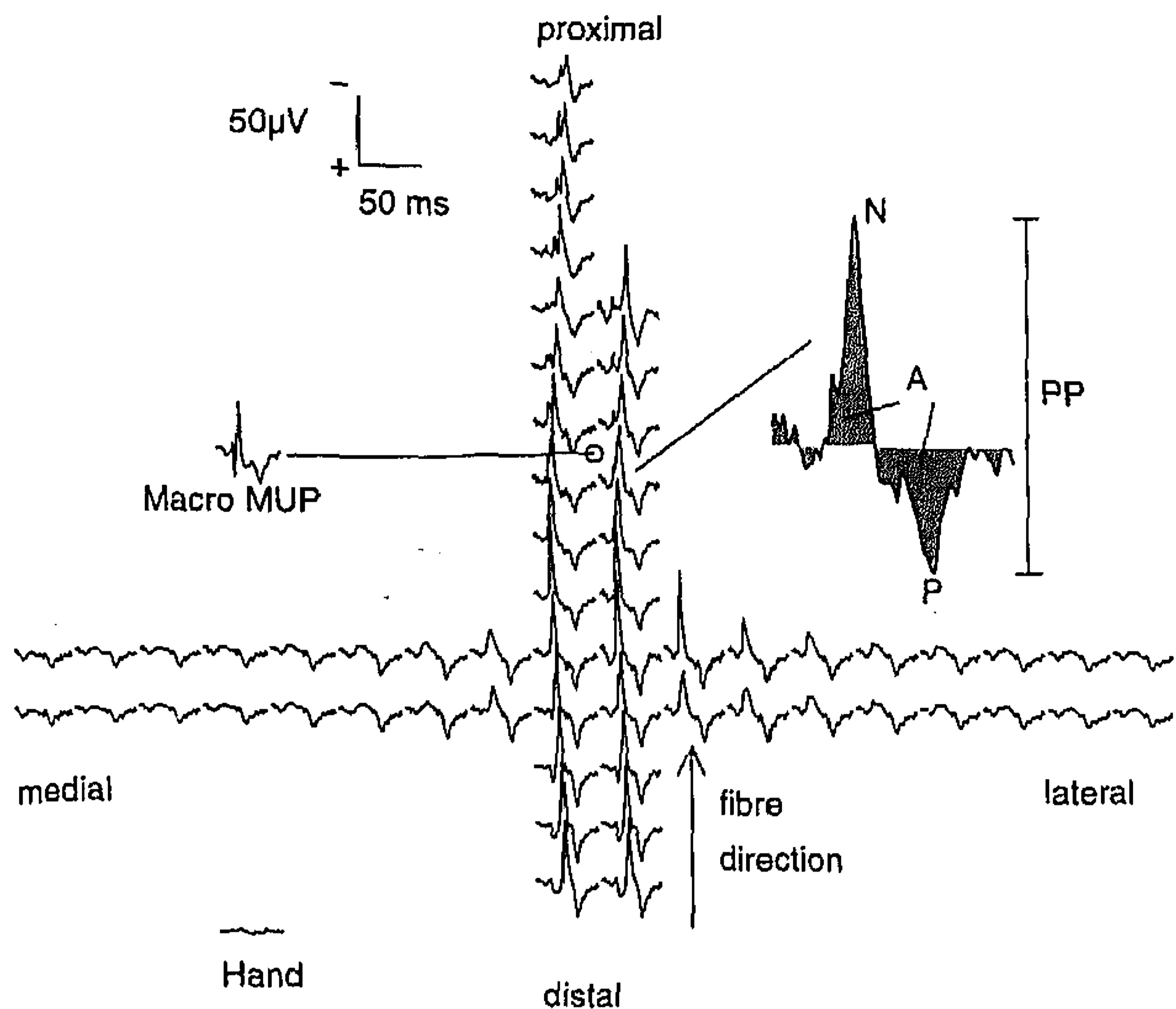


Fig. 2. Typical example of the unipolarly recorded MUP distribution over the skin surface from a superficial MU simultaneously with the Macro MUP. The parameterization of the MUPs is shown in the insert.

#### 2.4. Data acquisition

For displaying the needle electrode signals, a Medelec MS-20 (Mystro®) was used. The SFEMG was amplified over a frequency range of 500 Hz to 16 kHz and the Macro EMG over 8 Hz to 8 kHz. On line, the Macro MUP was extracted by averaging the cannula signal using the SFEMG recording for triggering. This Macro MUP was printed on paper and the trigger generated by the SFEMG was turned into an analogue trigger pulse by the trigger option (Aswip) of the Mystro. The continuous Macro EMG signal together with the trigger pulse signal and the 58 SEMG signals was also amplified (500 times, input impedance 100 MΩ) over a frequency range of 2–800 Hz, A/D converted (16 bits) and stored on the hard-disk of a computer with a sample frequency of 4 kHz/channel (Vision Research, Amsterdam®). Just before and after the recording, the SEMG signals were displayed on a computer screen. During the recording, it was not possible to display the SEMG signals.

#### 2.5. Experimental protocol

Recordings were performed from the biceps brachii muscle during voluntary, low force (up to 10% MVC), isometric contraction. During the experiment, the subject was sitting in a chair, the upper arm slightly abducted besides the trunk, the forearm supinated and the elbow angle at around 100 degrees. Prior to electrode placement body lotion was applied to the skin surface, because conventional electrode paste short-circuits the electrodes, but dry skin gives a too high electrode-to-skin impedance. After placing the surface electrodes and visually inspecting the signals, the Macro needle electrode was placed 2 cm proximal to the surface electrode row perpendicular to the muscle fiber direction.

Once a stable firing individual muscle fiber action potential was found, an amplitude threshold was set to the SF-signal to generate a trigger signal. The signals were recorded for 30–40 s until at least 150 trigger pulses were detected. After each recording, the depth of the single fiber recording site was determined by measuring the length of the remaining part of the Macro electrode above the skin. On average, recordings from 10 MUs per subject were obtained, at different sites.

#### 2.6. Parameterization

Surface and Macro MUPs were obtained off-line by averaging the recordings around the trigger signals with a window of 128 ms (50 ms pre- and 78 ms post-trigger time) so that the MUPs having a constant temporal relation with the activity of the triggering signal were extracted from the background EMG. This digitized Macro MUP was visually compared to the printout of the on-line obtained Macro MUP using software written in Matlab®.

The inactivity of the reference electrode was checked by inspection of the hand to elbow montage before further signal processing. Fig. 2 shows a typical example of the potential distribution over the skin-surface of a superficial MU. In the present study, the parameters from the electrodes placed parallel to the muscle fibers (top to bottom in Fig. 2) were used to estimate the position of the electrode grid with respect to the motor endplate and to check the quality of the measurement. From the 36 surface MUPs obtained from the electrodes perpendicular to the muscle fibers (left to right in Fig. 2) and the Macro MUPs, the peak value and the area of the propagating negative wave (*N* and *AN*) and the final positive wave (*P* and *AP*), the peak-to-peak amplitude (*PP*) and total area under the signal during the epoch of 45 ms around the MUP (*A*) were calculated (see inset Fig. 2). The parameters of the surface MUPs recorded from the two rows perpendicular to the muscle fiber direction were averaged in pairs, leaving 18 parameters representing the

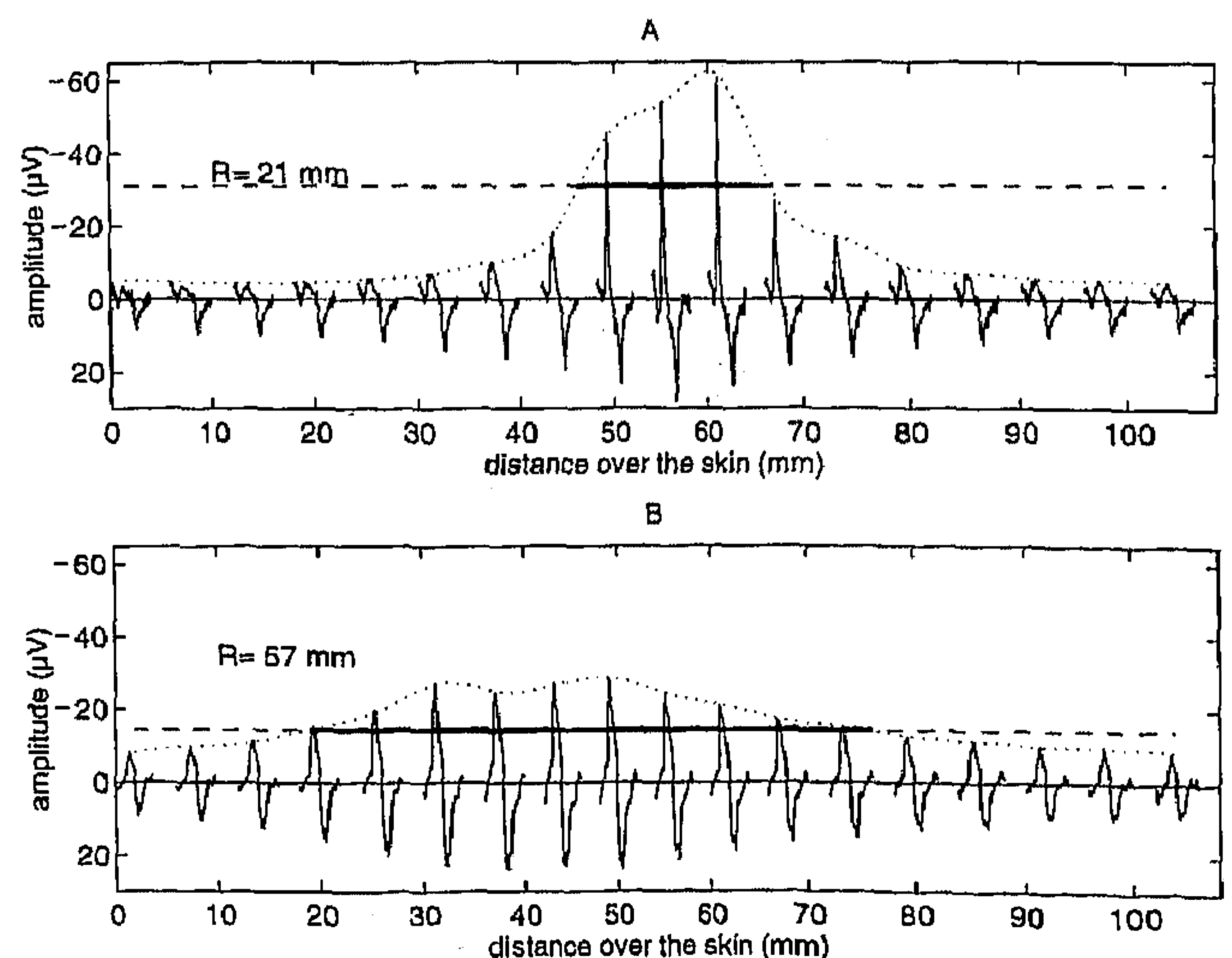


Fig. 3. The determination of *R* for a superficial (a) and a deep (b) MU.

Table 2

Mean and standard deviation (mean  $\pm$  SD) of all parameters obtained from the Macro MUPs and the Surface MUPs with the 95% confidence interval of the slope between the parameters obtained with the two measurement techniques

	$A$ ( $\mu\text{V ms}$ )	$PP$ ( $\mu\text{V}$ )	$AN$ ( $\mu\text{V ms}$ )	$AP$ ( $\mu\text{V ms}$ )	$N$ ( $\mu\text{V}$ )	$P$ ( $\mu\text{V}$ )
Macro	456 $\pm$ 278	105 $\pm$ 80	181 $\pm$ 130	164 $\pm$ 110	82 $\pm$ 71	23 $\pm$ 14
Surface	301 $\pm$ 209	33 $\pm$ 26	99 $\pm$ 92	90 $\pm$ 72	18 $\pm$ 18	15 $\pm$ 9
Slope	0.59–0.71	0.23–0.31	0.51–0.62	0.50–0.60	0.14–0.22	0.55–0.66

change in MUP magnitude with increasing distance over the skin. The maxima of these sets of unipolar surface MUP parameters were used as MU size indicators ( $Nu$ ,  $Pu$ ,  $PPu$ ,  $ANu$ ,  $APu$ ,  $Au$ ) to be compared with the Macro MUP parameters ( $Nm$ ,  $Pm$ ,  $PPm$ ,  $ANm$ ,  $APm$ ,  $Am$ ).

### 2.7. Depth normalization of the Surface MUPS to a depth of 1 mm

The course over the skin of  $Nu$  in the direction perpendicular to the muscle fiber direction was used for motor unit depth ( $d$ ) estimation. Firstly, a cubic spline fit (Matlab® was made through  $Nu$  as a function of electrode position on the skin (Fig. 3). Thereafter, the maximal value was obtained. The distance over the skin where higher  $Nu$ 's were measured than 50% of this maximum was denoted as  $R$ . This last parameter is directly related to  $d$ . Assuming that  $Nu$  and distance are inversely related (Gydikov et al., 1972; Gydikov and Kosarov, 1974; Monster and Chan, 1980) and that the upper arm can be described by a cylinder,  $d$  was estimated (see Appendix A). Considering the 18 surface electrodes with 6 mm inter-electrode distances, the largest possible  $R$  is 10.8 cm. With an arm circumference of 29 cm, the  $d$  estimation is limited to parts not deeper than 22 mm.

The  $d$  estimates were used to normalize the surface MUP parameters with depth. The area parameters and the positive peak are known to have a different relationship with dis-

tance (Gydikov et al., 1972; Gydikov and Kosarov, 1974; Monster and Chan, 1980). The actual magnitude - distance relationship for  $Au$  and  $Pu$  are  $1/r^{0.7}$  and  $1/r^{0.9}$  ( $r$  = radial distance; Fig. 3; Roeleveld et al., 1997). The following normalization (to 1 mm) equations arise:

$$nNu = Nu \left( \frac{d}{1} \right)^1 \quad nPu = Pu \left( \frac{d}{1} \right)^{0.9}$$

$$nAu = Au \left( \frac{d}{1} \right)^{0.7} \quad nPPu = PPu \left( \frac{d}{1} \right)^1$$

### 2.8. Statistical methods

The data are presented as mean  $\pm$  SD. Using SPSS® statistical software, the Pearson's correlation coefficient on the logarithmic data was used to study the interrelationship between parameters. Ninety-five percent confidence intervals of the slopes estimates were obtained by linear regression through the origin. The results were considered as significant when  $P < 0.05$ .

## 3. Results

In total, 63 different MUs in 6 subjects were studied. No visual differences in shape and amplitude of the printed

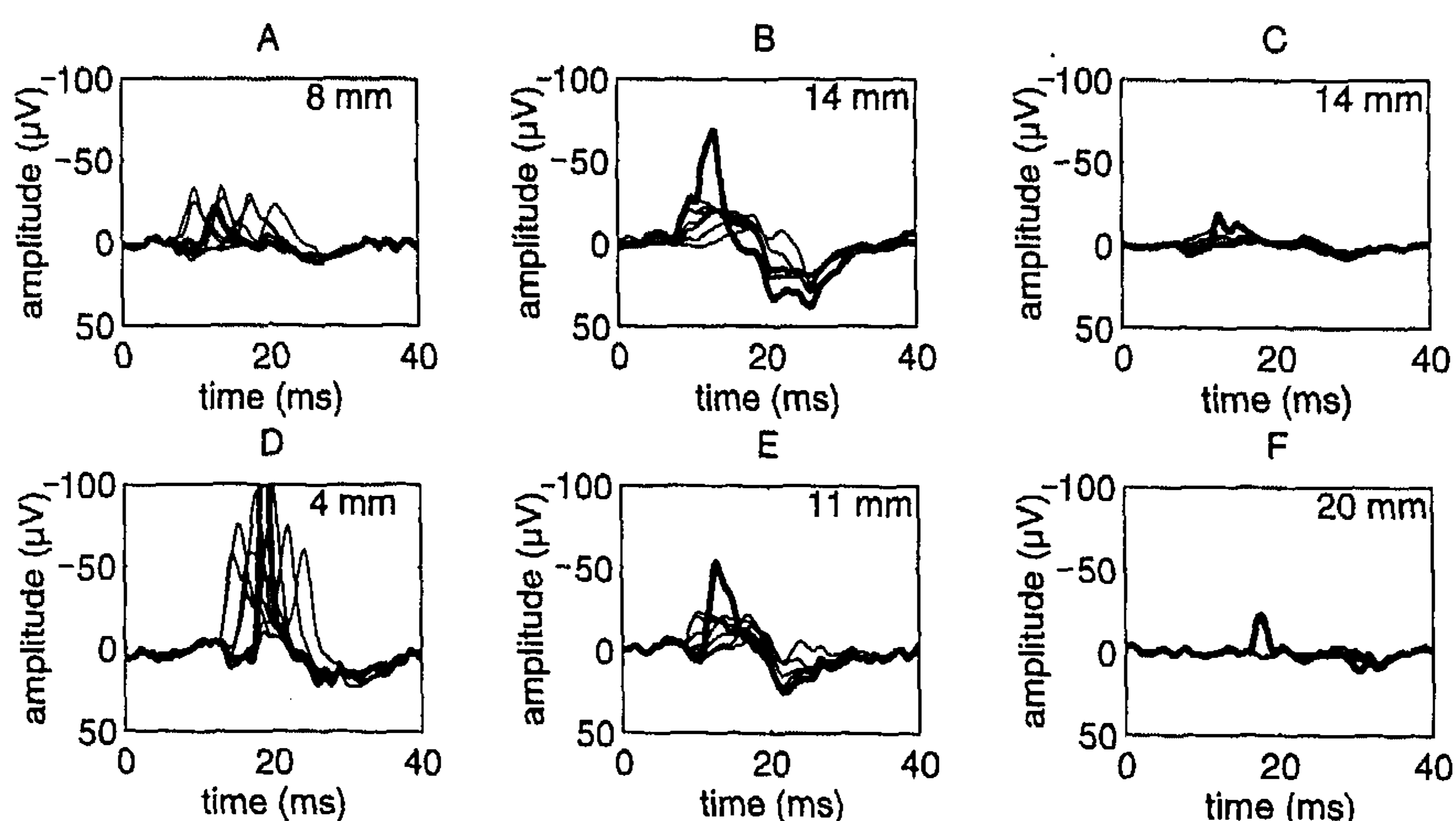


Fig. 4. Six typical examples of MUPs of different MUs at different depths. In each graph 7 MUPs recorded with surface electrodes (thin lines) placed parallel to the fiber direction (top bottom) are shown with the Macro MUP (thick line) of the same MU. The depth of the single fiber recordings are indicated in mm.

Macro MUPs (amplified over 8 Hz–8 kHz) and the digitized Macro MUPs (amplified over 2 Hz–800 Hz) were observed. Most surface MUPs had lower amplitudes than the Macro MUPs (Table 2). The area parameters  $A$ ,  $AP$  and  $AN$  showed less difference between the Macro and surface MUPs than the peak parameters  $PP$ ,  $P$  and  $N$ . The positive peak  $P$  also showed less difference between the two recording techniques than the negative peak  $N$ .

Generally, both the MUPs from the SEMG and the Macro EMG recordings consisted of a large negative wave followed by a positive wave. This negative component was recorded earlier around the central part of the muscle than at the proximal and distal sites, while the positive peak was detected everywhere simultaneously (see Figs. 2 and 4). As shown in examples in Fig. 4, the shape and the amplitude of the Surface MUPs and the Macro MUPs could be very similar, but could also have substantial differences. Especially, the surface MUPs recorded on the skin surface caused by deep MUs obviously differed from the Macro MUPs and hardly showed a propagating peak along the muscle fiber direction (Fig. 4C, Fig. 4F).

The MUPs recorded on the skin surface were dependent on the depth of the MU. From the deeper MUs lower amplitudes were recorded. Despite the  $d$  dependency of the surface MUPs, all Macro MUP parameters correlated significantly ( $P < 0.001$ ) with the MUP parameters recorded with the surface electrodes (Fig. 5, Table 3). The correlation coefficient was substantially higher for the area ( $r = 0.84$ ) and the positive peak ( $r = 0.85$ ) than for the negative peak amplitude ( $r = 0.63$ ). The data were divided into three different groups, recordings from the most superficial 33%, the deepest 33% and the intermediate 33% MUs as determined by the amplitude distribution of  $Nu$  (Fig. 5). The slope of the relationship decreased with increasing  $d$ . There was a significant difference in slope between the superficial 33% and the deep 33%. Normalizing the surface MUP parameters by  $d$  (see Section 2) eliminated the depth dependent differences between Macro and surface MUP parameters (slopes became the same for the three different data groups), but hardly improved the correlation between the Macro MUPs and surface MUPs (Table 3).

An important practical finding is that the relative range of the MUP parameter values of Macro EMG and SEMG in

Table 3

Correlation coefficients between the logarithmic Surface MUP parameters and the logarithmic Macro MUP parameters

	Macro MUP					
	$A$	$PP$	$AN$	$AP$	$N$	$P$
Surface MUP	0.84	0.75	0.74	0.84	0.62	0.85
Depth normalized Surface MUP	0.85	0.77	0.75	0.83	0.64	0.81

All correlations were significant ( $P < 0.001$ ).

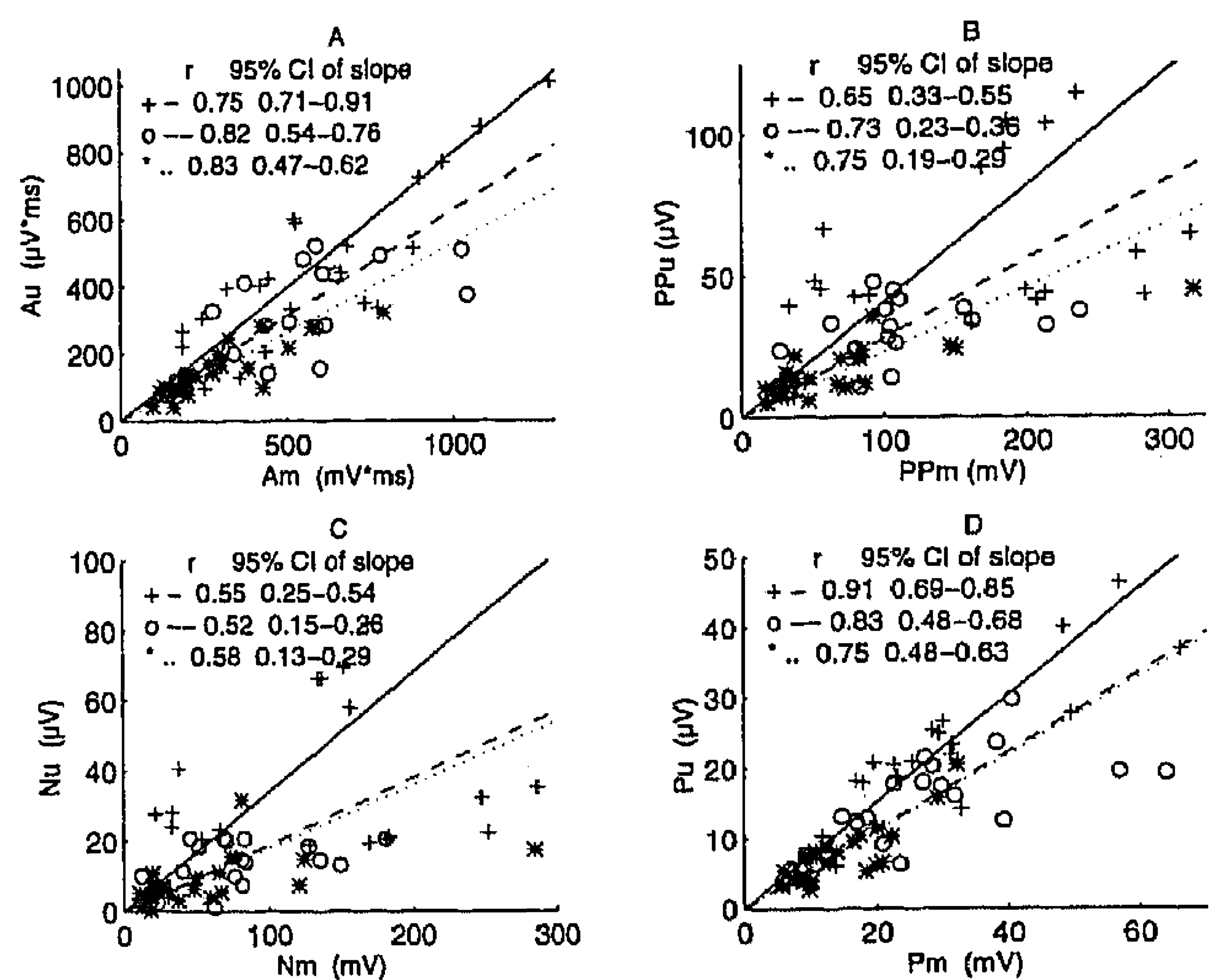


Fig. 5. Relationship between the same parameters extracted from the Macro MUP and surface MUP. These relationships, including their correlation coefficients ( $r$ ) and the 95% confidence interval of the slope, are shown for three  $d$  levels; recordings from the most superficial 33% (+), the deepest 33% (\*...) and the intermediate 33% (o) MUs.

each subject compared to the other subjects hardly differ from each other (Fig. 6). Before normalization some surface MUP parameters in a few subjects still could show slight differences from the Macro MUP parameters, after  $d$  normalization a nice match with the Macro MUP parameters was obtained.

The parameter values of the normalized surface MUPs were higher than the Macro MUP values. To scale the normalized surface MUP values to Macro MUP values,  $Au$ ,  $PPu$ ,  $Nu$  and  $Pu$  had to be divided by 4.0, 4.0, 2.7 and 6.6, respectively (Fig. 6).

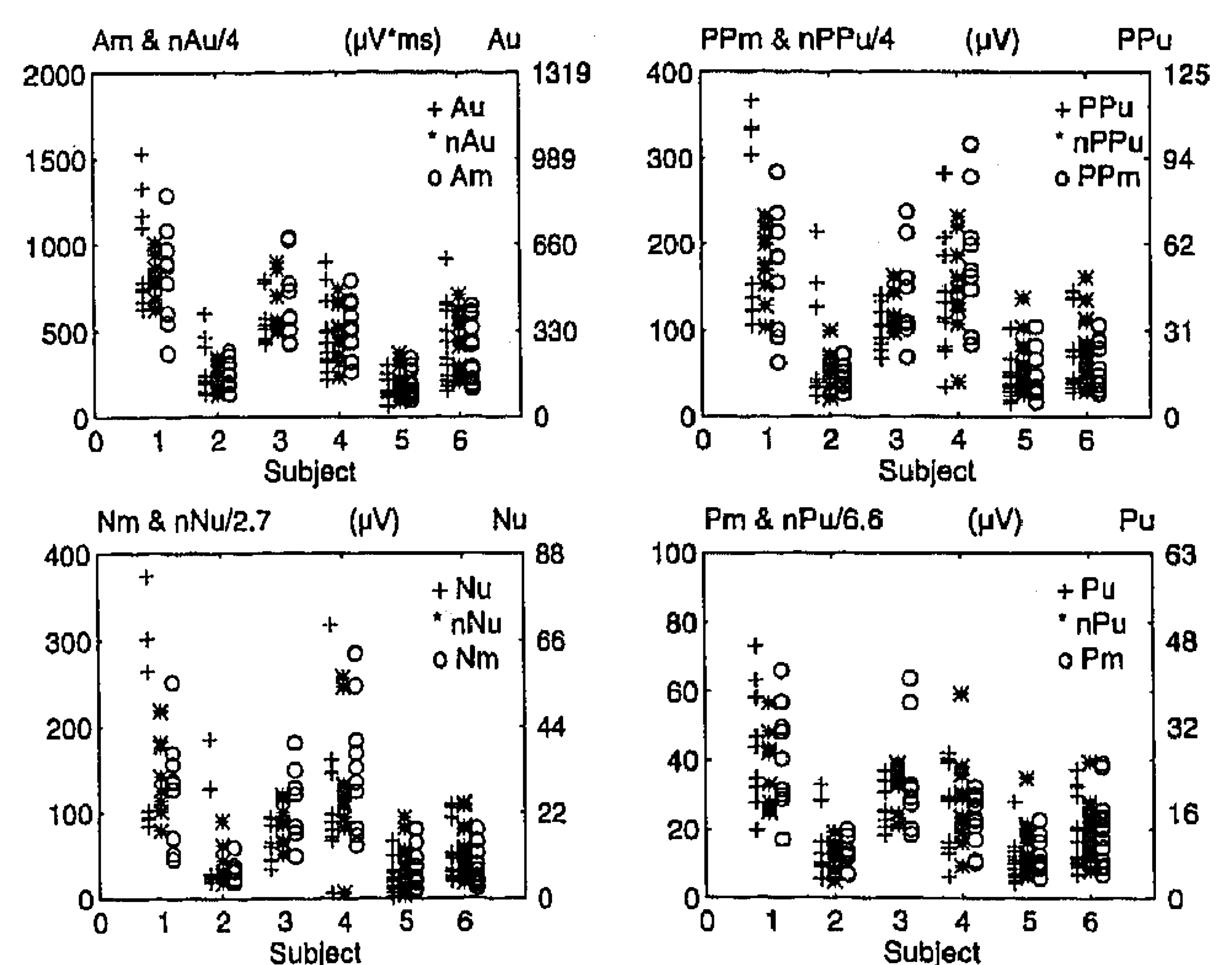


Fig. 6. Individual MUP parameters  $A$ ,  $PP$ ,  $N$  and  $P$  obtained from Macro EMG, SEMG and the  $d$  normalized SEMG. The not normalized SEMG parameter values are scaled to the Macro EMG values, so that the mean value of each parameter recorded with the two techniques is equal.

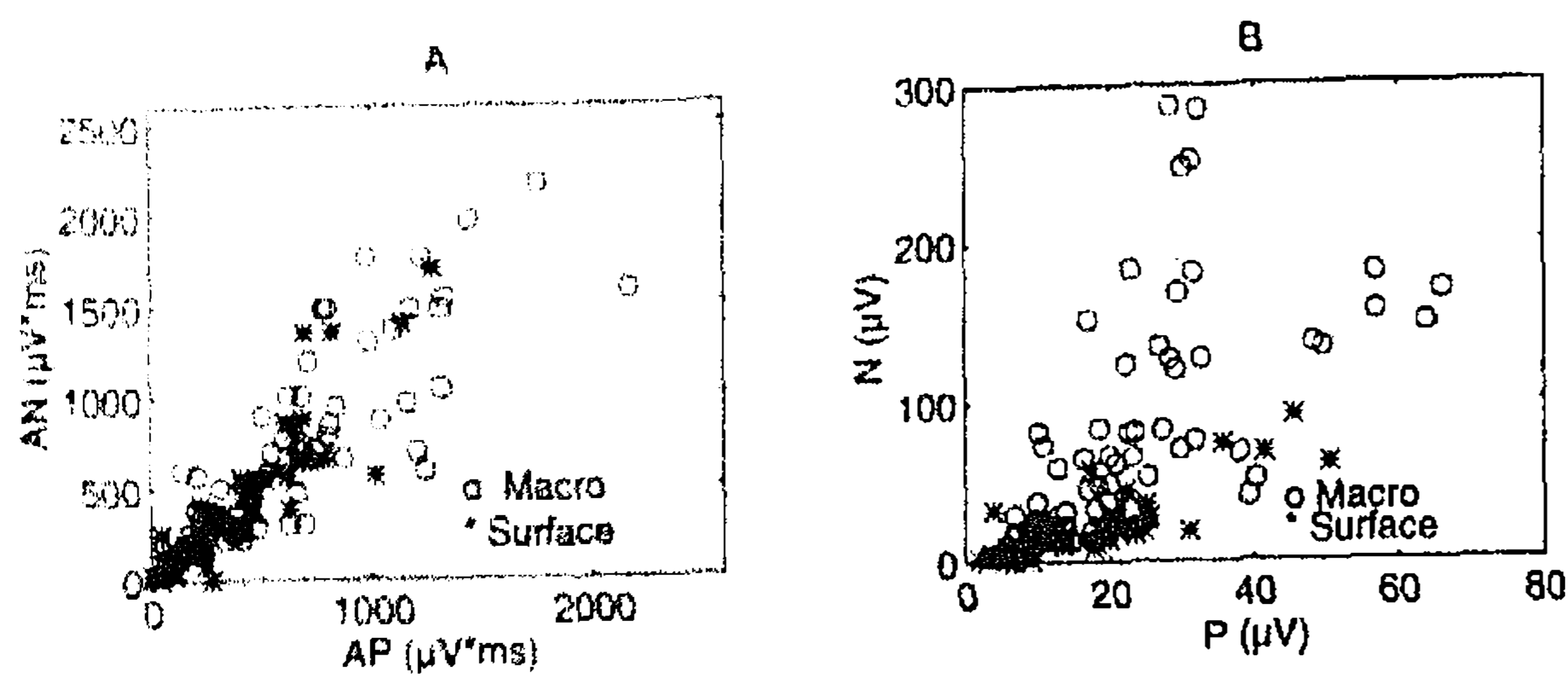


Fig. 7. Relationship between the negative and the positive wave expressed in  $AN$  and  $AP$  (A) and  $N$  and  $P$  (B) of the surface and the Macro MUP.

From the SEMG results it is clear that MUPs consist of a propagating negative and a non-propagating positive part (Fig. 2). These two components have different volume conducting properties and represent essentially different aspects of the MU (Gydikov et al., 1972; Gootzen et al., 1991; Dumitru and King, 1991). The relationships between  $AN$  and  $AP$  and  $N$  and  $P$  are shown in Fig. 7. The correlation coefficients between  $ANm$  and  $APm$  and  $Nm$  and  $Pm$  were 0.83 and 0.61. For the Surface MUP parameters, the correlation between  $ANu$  and  $APu$  and  $Nu$  and  $Pu$  were 0.90 and 0.83.

#### 4. Discussion

Although the shape of Surface MUPs are dependent on the distance between the MU and the skin surface, the presented results indicate that the Surface MUPs and the Macro MUPs are comparable with respect to MU characteristics. Firstly, because all Macro MUP parameters ( $A$ ,  $PP$ ,  $AN$ ,  $AP$ ,  $N$ ,  $P$ ) correlate significantly with the same parameters obtained from surface MUPs (Fig. 5; Table 3). Secondly, because the two measurement techniques have almost the same relative range in the MUP parameters in any individual subject compared to the other subjects (Fig. 6).

Usually, Macro EMG is used to estimate the size of the MU (Nandedkar and Stålberg, 1983; Stålberg, 1980, 1990). The large recording surface of the Macro needle electrode avoids the MUPs being dominated by the closest individual muscle fibers. Therefore, the Macro MUP is thought to represent activity from the whole cross-sectional area of the MU. Surface MUPs are not dependent on a few close muscle fibers either, because they are always relatively far away from the active fibers. Therefore, both the Surface and Macro EMG recordings could theoretically produce good measures for MU size.

In addition to the dependency on MU size, the fixed position of the electrodes makes a Surface MUP also dependent on the position of the MU relative to the skin surface. Because of the volume conduction properties of the tissues surrounding MUs, the amplitude of the MUP decreases with increasing distance between the active MU and the recording electrode (Fig. 5; Buchthal et al., 1957; Plonsey, 1974). Therefore, the amplitude of a Macro MUP is larger than the

surface MUP amplitude. Moreover, a surface MUP of a deep MU is smaller than of the MU of an equally large superficial one. This  $d$  dependency can be defined (see Appendix A) and has been used to normalize the surface MUP parameters to MU depth. The used method to estimate the MU depth is limited to a depth of 22 mm, while Macro EMG is limited to a depth of 35 mm (position of SF electrode). Therefore only Surface potentials from MUs not deeper than 22 mm could be normalized to depth properly. The size of MUs deeper than 22 mm were underestimated. In this study most subjects did not have a large fat layer and most of the MUs studied were more superficial than 2 cm.

Both techniques detected some variation in MU size parameters between subjects (Fig. 6). After depth normalization of the surface MUPs, the two measurement techniques have almost the same relative range in the MUP parameters in any individual subject compared to the other subjects.

Above the results are discussed comparing surface MUPs with Macro MUPs. The results also provide new information about the representation of the different MUP parameters. Both the MUPs from SEMG and Macro EMG recordings consisted of a negative wave followed by a positive wave. The negative component was recorded earlier around the muscle center than at the proximal and distal sites, while the positive peak was detected everywhere simultaneously. The bio-electric source of the propagating action potential can be approximated by an electric current tripole starting at the motor endplate region, propagating towards both tendons (Rosenfalck, 1969; Griep et al., 1982). When this propagating tripole reaches the muscle fiber-tendon junction, its leading part is suppressed. This suppression causes the generation of the terminal positive wave complex caused by a dipolar source component (Gootzen et al., 1991; Dumitru and King, 1991; Stegeman et al., 1987). This positive wave can only be detected when the reference electrode is relatively far from the recording electrode (unipolar recording; Gootzen et al., 1991), as was the case in both Macro and SEMG recordings. Then, changing the recording position in the muscle fiber direction will not alter the MUP amplitudes substantially, except when the electrode is located close to the motor endplate region or to the muscle-fiber tendon transition. Therefore, it is advisable to position the recording electrode just in the middle between the motor endplate region and the tendon.

Because the different parts of the MUP have different sources, the different MUP parameters have different volume conducting properties.  $N$  is more affected by distance than the other parameters (Fig. 5). Therefore, the ratio between  $Nu$  and  $Nm$  is, on average, substantially larger than between the other MUP parameters (Table 2). Probably due to prominent influence of the closest muscle fibers,  $N$  has also a larger variation. In line with this, the areas and the positive peak amplitudes between both techniques showed higher correlations than the negative peak amplitudes. Furthermore, looking at the correlations between the parameters obtained from one technique, except for  $Nm$  and  $Pm$

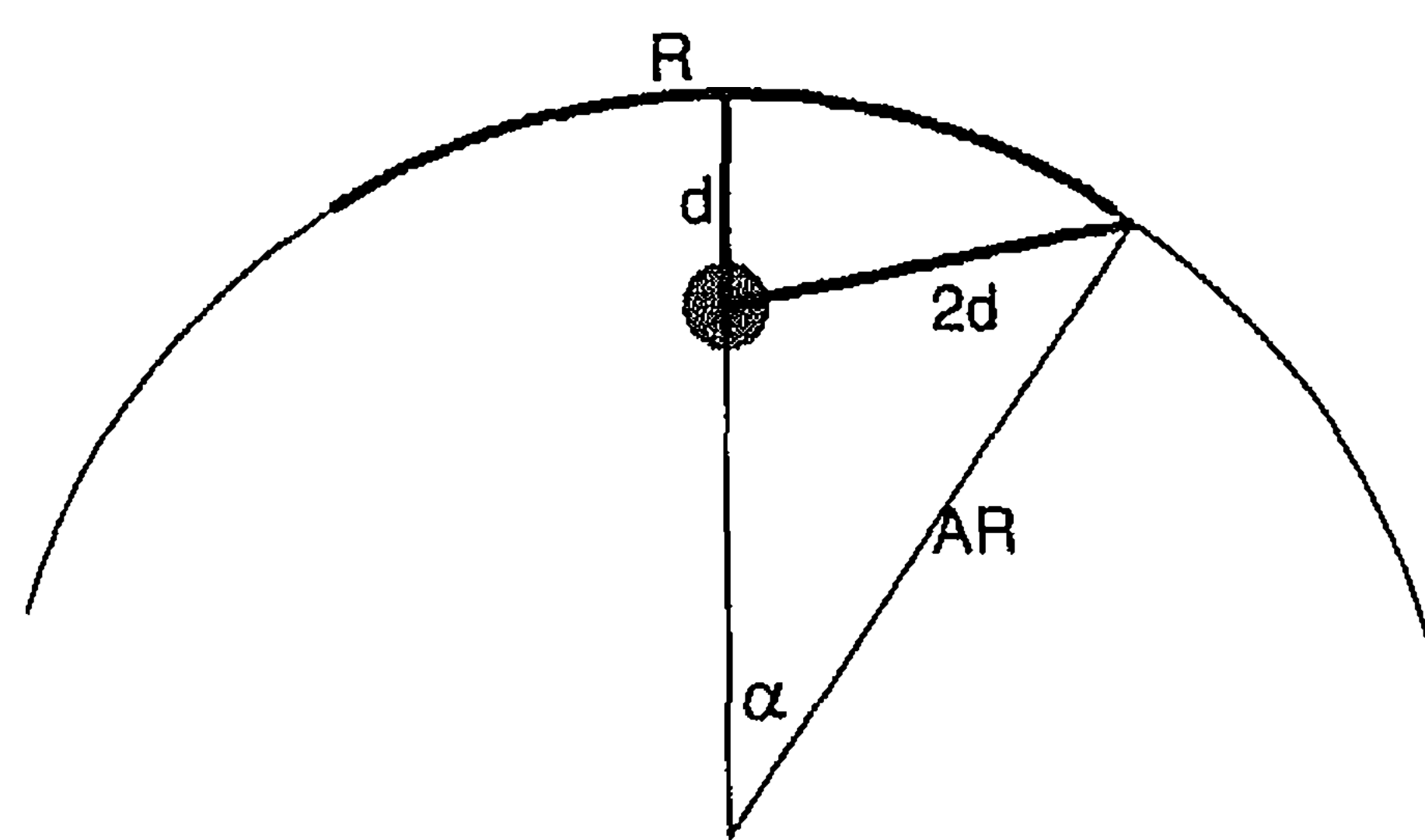


Fig. 8. Schematic relation between  $R$ , arm radius ( $AR$ ) and  $d$ .

all parameters show good correlations with each other. This indicates that the  $Nm$  represents something different from any of the other parameters.  $Nm$  is most dependent on local activity, and of the parameters studied least suitable to represent MU size. Although no information is available about the real MU size, with respect to Macro EMG  $Am$  and  $Pm$  and all surface MUP parameters seem to be more robust indicators of MU size than  $Nm$ .

The parameter values of the normalized surface MUPs were higher than the Macro MUP values. This could be expected, because the surface MUP values were normalized to an average muscle fiber depth of 1 mm, while the average distance of the contributing muscle fibers to the Macro MUP is larger (Nandedkar and Stålberg, 1983). In fact, the different scaling factors for the different surface MUP parameters result from a different field of view for the different Macro MUP parameters. Therefore, our results indicate that the average distance ( $Dm$ ) of the contributing muscle fibers to the Macro MUP parameters  $Am$ ,  $PPm$ ,  $Nm$  and  $Pm$  are around 7.3 mm ( $4.0 = Dm^{0.7}$ ), 4.0 mm ( $4.0 = Dm^1$ ), 2.7 mm ( $2.7 = Dm^1$ ) and 8.2 mm ( $6.6 = Dm^{0.9}$ ), respectively. The  $Dm$  values corresponding to  $PPm$  and  $Am$  are in approximate agreement with extrapolated results from the model study of Nandedkar and Stålberg (1983).

Macro EMG has the advantage over SEMG used in this study that it utilizes only two recording channels. Therefore, relative simple EMG equipment is needed and on-line averaging can be used to obtain Macro MUPs. However, when proper equipment is available, multi-channel SEMG recordings are easily applicable as well. With simultaneous recording of the same MU at several places, the motor endplate region, the propagation velocity and the position of the muscle fiber tendon transition and their effect on the shape of the MUP can be detected and corrected for. It is possible to normalize the amplitude for MU to electrode distance, although that increases the demands of equipment and processing time. Using a tungsten needle electrode for triggering purposes, surface MUPs can be obtained during high contraction levels, which is not possible with Macro EMG. However, a proper 'needle-less' trigger signal is preferable and we are currently searching for the optimal solution.

For Macro EMG filter settings of 8 Hz to 8 kHz are recommended (Stålberg, 1980), while SEMG never contains power at frequencies over 800 Hz. In the present

study with healthy subjects, this was proven not to be important, because the 8 Hz to 8 kHz and the 2 Hz to 800 Hz filtered Macro MUPs did not show visible differences. However, in patients with myopathy this may give rise to loss of information, especially when one is interested in other aspects of the MU than its size.

In conclusion, SEMG provides useful information on MU characteristics in healthy subjects. With the multi-electrode SEMG recording it is also possible to obtain information about the motor endplate site and average propagation velocity of muscle fibers. On the other hand, it does not give information about local fiber density or jitter, that are obtained with Macro EMG. Furthermore, it was shown that a MUP recorded with an inactive reference electrode consists of a propagating and a non-propagating part which have different volume conducting properties and represent essentially different aspects of the MU. Of all Macro- and Surface- EMG parameters studied, the negative peak recorded with Macro EMG reflects least the global MU characteristics. Finding needle-less triggering techniques is a challenge to make SEMG even more attractive in the neurophysiological laboratory for further evaluation of the usefulness of this technique in the studies of normal and diseased muscle.

### Acknowledgements

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### Appendix A

The decline in MUP amplitude with increasing radial distance between the recording electrode and the MU can be described by a power function (Buchthal et al., 1957; Gydkov et al., 1972; Monster and Chan, 1980). The negative peak of the MUP decreases the fastest. Therefore,  $N$  is changing steepest with  $d$  and is the most suitable parameter to obtain information on  $d$  from.  $N$  approximately has a linear relationship with distance (Gydkov et al., 1972; Monster and Chan, 1980). In other words, for double distance between the motor unit and the recording electrode, the amplitude is halved. Because  $R$  was defined as the distance over the skin surface with a  $N$  value of more than 50% of its maximum, the distance from the MU to the highest point in  $R$  is half the distance from the MU to the lowest point in  $R$ . In Fig. 8, these two distances are shown as  $d$  and  $2d$ , respectively. Using the arm radius ( $AR$ , obtained from the arm circumference  $AC$ ) and the angle between the two lines from the arm center to the two places on the arm surface ( $\alpha$ ), the cosines rule provides  $d$ .



In equations (see also Figs. 3 and 8)

$$\alpha = \frac{2\pi * \frac{1}{2}R}{AC}$$

$$d = \frac{1}{6}(-2AR(1 - \cos \alpha))$$

$$+ \sqrt{(2AR(1 - \cos \alpha))^2 + 24AR^2(1 - \cos \alpha)}$$

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