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Motor Unit Properties in the Biceps Brachii of Chronic Stroke Patients Assessed with High-Density Surface EMG

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Abstract—**Motor unit (MU) properties of the biceps brachii and Fugl-Meyer score were assessed in stroke patients and healthy controls during passive and active elbow flexion and extension contractions. The level of motor recovery as assessed with the Fugl-Meyer score was correlated with the ratio of the size of the motor unit action potentials (MUAPs) at the affected side and the unaffected side. This ratio may reflect the extent to which reinnervation has occurred on the affected side. The RMS value of the MUAPs recruited during the stretch phase of the passive contractions was lower than the RMS value of MUAPs recruited during active contractions. This may indicate that only smaller MUs are affected by increased sensitivity to muscle stretch while a larger part of the MU pool can be recruited voluntarily.**

Keywords-motor unit properties; stroke;high-density surface EMG; biceps brachii; elbow flexion and extension

I. Introduction

As a consequence of a stroke, motor control and motor unit (MU) characteristics may change. Spasticity may occur, control of MUs of the affected muscles may be lost (paresis), and voluntary motor control of remaining MUs may change. Many researchers have investigated muscle activation and coordination patterns after stroke. Weakness, abnormal co-contraction of antagonistic muscles, abnormal co-activation patterns, muscle fatigue and delays in initiation and termination of muscle activity have been reported [1-7]. However, knowledge about underlying changes in properties and control of motor units (MUs) after a stroke is still limited.

In dynamic contractions, the often reported hyper-excitability of the stretch reflex (for review see [8]) plays an important role. The increased response to muscle stretch may amongst others be related to hyperexcitability of the α motor neuron pool or to an increased sensitivity of the muscle spindles (Ia and II afferents). However, it is unknown whether the complete MU pool or only part of it is affected.

So far, MU characteristics after a stroke have been investigated using intramuscular EMG recordings. With a grid of small, closely spaced electrodes placed on the skin above the muscle of interest (Fig. 1), a 3-dimensional (2D-spatial and in time) picture of muscle activity can be obtained non-invasively: high-density surface EMG (HD-sEMG).

Figure 1. 2D-electrode array that was used for the recordings (Helmholtz Institute, Aachen, Germany). The array was placed on the biceps brachii with the columns parallel to the line from the acromion to the cubital fossa.

Because of the high spatial selectivity that can be obtained in this way, motor unit action potentials (MUAPs) can be distinguished and extracted, and their propagation along the muscle fibers can be tracked [9-12].

The aim of this study was to investigate MU characteristics of the biceps brachii in post-stroke subjects with HD- sEMG.

II. Methods

A. Subjects

Twenty healthy volunteers without known neuromuscular disorders were included in the study. Hemiparetic stroke patients with a first unilateral ischemic stroke and sufficient cognitive abilities to understand spoken instructions were recruited from rehabilitation center 'Het Roessingh'. Subjects had to be at least six months post-stroke and had to be able to move their arm against gravity (Medical Research Council score for biceps brachii ≥ 3). Passive shoulder abduction to at least 70 degrees had to be possible without pain. Exclusion criteria were presence of additional orthopedic diseases of the upper extremities, psychiatric comorbidity, hypersensibility, shoulder-hand syndrome, and use of antispastic medication. Eighteen stroke patients participated in the study. All subjects signed an informed consent. The study was approved by the local medical ethics committee and experiments were performed in accordance with the Helsinki Declaration of 1975. Demographic characteristics of the population are reported in Table 1.

TABLE I. DEMOGRAPHIC CHARACTERISTICS

	Control group	*Patient group*
Sex	5 men, 15 women	12 men, 6 women
Age (years)	59 (46-71)	64 (39-78)
Weight (kg)	72 (60-93)	80 (55-155)
Height (cm)	171 (159-193)	176 (158-184)
Body mass index (kg/m^2)	24.4 (21.2-30.7)	25.7 (21.6-34.8)
Time since stroke (years)	n.a.	2 (0.5-10)
Affected side	n.a.	11 left, 7 right
Fugl-Meyer score	n.a.	35.5 (9-62)
Ashworth score	n.a.	2 (0-4)

Median values and ranges (jn brackets) are reported. N.a.: not applicable

B. General procedures

In the stroke patients, the Fugl-Meyer score for the upper extremity, a clinical scale for motor recovery, was assessed. Subsequently, the maximal voluntary contraction (MVC) of elbow flexion was determined at both sides. Static isometric step contractions (10 force levels from 5% to 50% MVC were performed with unaffected side followed by the same series of contractions for the affected side. Next, cyclic passive and active elbow flexion and extension movements were performed with the dominant side (healthy subjects) or the affected side (stroke patients). During passive movement, the experimenter supported the elbow and moved the arm throughout the range of motion at a fast speed (approximately 1.25 s per cycle). During active movement, subjects moved their arm at a self-selected comfortable speed (approximately 2 s per cycle) throughout the full range of motion. When a stroke patient was not able to move the arm the experimenter helped by supporting the elbow joint. Both active and passive movements were repeated ten times per trial, and three trials were performed.

C. High-density sEMG measurements

HD-sEMG of the biceps brachii was recorded with a two dimensional 16-channel electrode array placed on the skin above the muscle (Fig. 1). The array consisted of four columns of gold-coated pin-electrodes with a diameter of 1.5 mm, the first and fourth containing three electrodes and the middle two containing five electrodes. The inter-electrode distance was 10 mm in both directions.

Electrode placement was done in accordance with the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) recommendations for surface EMG recordings [13]. The electrode array was placed on the biceps brachii with the columns parallel to the line from the acromion to the cubital fossa, with the center of the array placed one third of the distance from the cubital fossa.

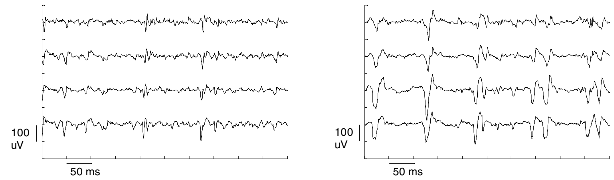

Figure 2. Example of high-density sEMG signals from the biceps brachii muscles of a stroke subject. Left: unaffected side, right: affected side. The contraction level was 20% of the maximum voluntary contraction force. Bipolar signals from one column of a 16-channel electrode array are shown.

Signals were visually inspected online. Propagation of signals, absence of innervation zones and minimal shape differences between subsequent signals were used as criteria for correct placement and alignment of the electrode columns in parallel to the muscle fibres. If necessary, the electrode array was repositioned. In most subjects, a small amount of conducting gel was applied to the electrodes to improve the signal-to-noise ratio.

D. Data analysis

Bipolar signals with an inter-electrode distance of 10 mm were constructed from the two middle columns of monopolarly recorded signals. This resulted in two sets of four unidirectionally propagating bipolar signals. The set with the best signal quality was manually selected for further processing. Motor unit action potentials (MUAPs) were extracted from the sEMG signals using an algorithm based on the Continuous Wavelet Transform. Variables describing the MUAPs were calculated for all detected MUAPs without classifying them to their corresponding MU. The RMS value (RMS_{MUAP}) and the median frequency of the power spectrum ($FMED_{MUAP}$) of each detected MUAP were calculated. Histograms of these variables were used to examine properties of the MU population. RMS_{MUAP}, related to the size of the MU, was calculated by taking the square root of the sum of all squared data samples of the MUAP, divided by the number of samples. $FMED_{MUAP}$ reflects the frequency content of the MUAP, which is related to the MUAP duration [14] and muscle fiber conduction velocity [15-17] which in turn is related to the recruitment threshold of the MU [18]. $FMED_{MUAP}$ was calculated as the median value of the power spectrum, obtained using the fast Fourier-transform with a Hanning window. Ratios of $FMED_{MUAP}$ and RMS_{MUAP} at the affected side divided by the unaffected side were assessed to quantify within-subject differences between the sides.

For the static contractions, median values of the MUAP properties were calculated for each step. For the dynamic contractions, median values of the MUAP properties across the three trials were calculated for each subject.

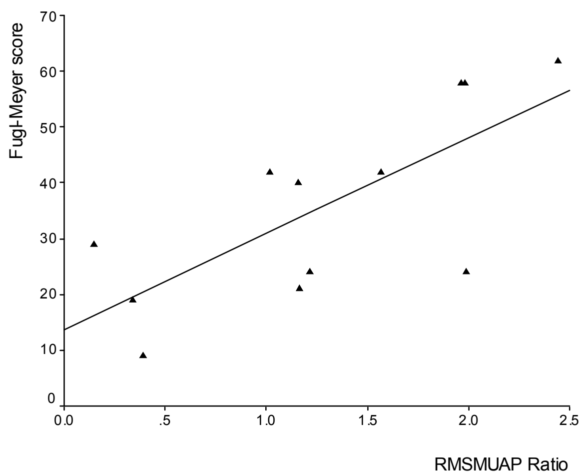

Figure 3. Scatter plot of the ratio of RMS_{MUAP} on the affected side divided by RMS_{MUAP} on the unaffected side against Fugl-Meyer score. Data from step 7 (35% MVC). The explained variance is 50% ($p<0.011$).

E. Statistics

To investigate differences in EMG variables between sides, groups and movement type (active or passive), mixed linear models were applied. For the static contractions, the model included step (contraction level), side (affected or non-affected) and the interaction of step with side as fixed factors. The interaction between step and side was included to examine differences between the sides in response to an increasing force level. For the dynamic contractions, the model included movement type (passive or active movement), group, and the interaction of movement with group as fixed factors. The interaction between movement and group was included to examine whether differences between the active and passive movements depended on the group.

III. RESULTS

Data of three subjects were of insufficient quality and were not used in the analysis.

An example of a recording of EMG signals of the affected and unaffected side is shown in Figure 2. In this subject, the MUAPs were generally larger on the affected than on the unaffected side.

In the static contractions, 7 out of 15 subjects showed larger RMS_{MUAP} values at the affected side than at the unaffected side, 5 subjects showed smaller values and 3 subjects did not show differences. Interestingly, the median Fugl-Meyer score was considerably higher in the group with larger RMS_{MUAP} values at the affected side (Fugl-Meyer score 42 versus 20 out of 66). The ratio of RMS_{MUAP} of the affected side divided by that of the unaffected side correlated with the Fugl-Meyer score for the force levels from 15% to 45% (Spearman's rho between 0.6 and 0.74, $p<0.039$), see Fig. 3.

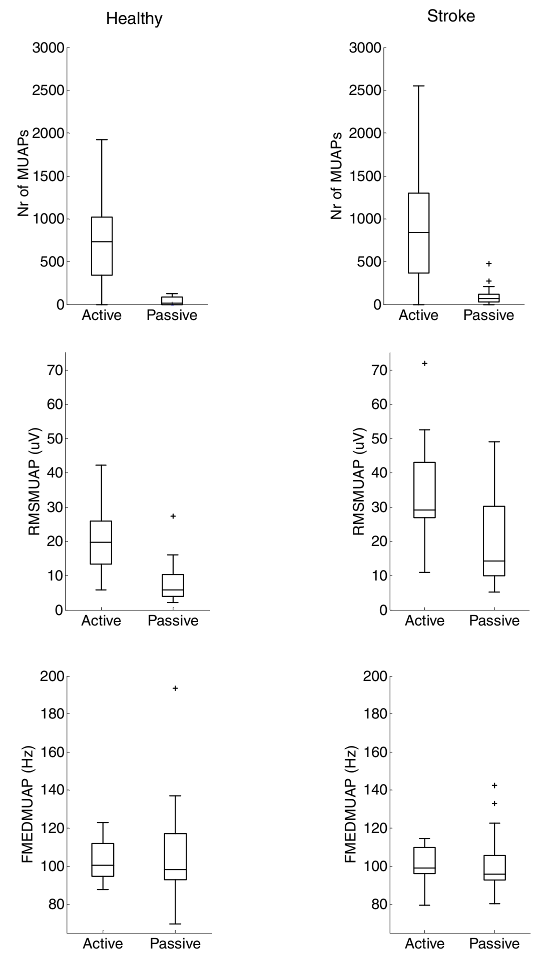

Figure 4. MUAP properties during active and passive contractions in both groups. + indicates outliers (values between 1.5 and 3 bar lengths from the upper edge of the bar).

The results of the cyclic contractions are presented in Fig. 4. The number of detected MUAPs was significantly larger during active than during passive movements ($p<0.001$), and there was a trend for a higher number of MUAPs in the stroke group than in the control group ($p<0.07$). RMS_{MUAP} was higher in the stroke group ($p<0.001$) and in both groups it was higher during active movements than during passive movements ($p<0.001$). $FMED_{MUAP}$ was not different in both groups nor in both movement conditions.

IV. DISCUSSION

The aim of the study was to investigate MU characteristics in post-stroke subjects.

For the dynamic contractions larger MUAPs, as reflected in higher RMS_{MUAP} values, were found in the stroke group compared to the control group. In the static contractions a correlation between a clinical scale, the Fugl-Meyer score, and the ratio of RMS_{MUAP} at the affected divided by the unaffected side was found. Since RMS_{MUAP} is related to MU size,

RMS_{MUAP} and RMS_{MUAP} ratio might reflect the extent to which re-innervation, resulting in larger MUs, has occurred. Re-innervation is a compensation strategy for paresis and is therefore likely to be related to the functional capacity of the muscle, which may explain the correlation between RMS_{MUAP} ratio and Fugl-Meyer score.

For the dynamic contractions, the MUAPs during the stretch phase of the cycle were considerably smaller than the MUAPs recruited during the active movements. Several studies in cats [19-20] and in humans [21-23] have shown that recruitment of MUs during the stretch reflex follows the Henneman size principle. Apparently, the recruitment during the stretch reflex is limited to the smaller low-threshold MUs while a much larger part of the MU pool can be recruited voluntarily. This might mean that the hyperexcitability of the stretch reflex could be reduced when the activity of small MUs with small diameter motor neurons could selectively be suppressed by medication. Future research should aim at investigating if such an approach is feasible and clinically effective.

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