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Evaluating Indices of age-related Muscle Performance by Using Surface Electromyography

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Abstract— **Recently, there has been an increasing focus on the rapid reduction of muscles that are required for the bending of the hip joint during walking (flexor muscles around the hip joint) with age. The flexor muscles around the hip joint include femoral rectus and abdominal muscles. These muscles have been implicated in falling in the elderly. In this study, we examined the smoothed surface electromyography (sEMG) of femoral rectus muscles during biofeedback training (BFT) of the dominant leg. To this end, we developed parameters for the measurement of shapes in the smoothed sEMG, and evaluated the changes in these parameters in the muscles with age. Statistical analysis indicated that it was necessary to include the time constant of the exponential decay curve fit to maximal points during prolonged muscular contraction, to evaluate the changes with age by using the smoothed sEMG during BFT. Reduction of the muscular regulation capacity due to aging can be detected by performing sEMG during BFT by using the time constant.**

I. Introduction

Currently, several electromyographic methods are used, and needle electromyography (nEMG) and surface electromyography (sEMG) are most often applied. To physiologically evaluate electromyographic wave patterns for the detection of abnormalities, wave patterns obtained by nEMG or sEMG are macroscopically examined, and subjectively judged by physicians.

A) In nEMG, findings are used for the evaluation of whether a disorder is neurogenic or myogenic, and if it is both neurogenic and myogenic, they provide important information about whether it is acute, subacute, or chronic [1]. However, the probe is a needle electrode, which is percutaneously inserted into muscular tissues.
B) In sEMG, findings are used for various evaluations, such as classification of trembling for the diagnosis of involuntary motion, the diagnosis or differential diagnosis of dystonia and spasm, and identification of involuntary constrictor muscles [2].
C) sEMG is further used for the determination of electric potential by nerve conduction examination (evoked EMG). In evoked EMG, electrostimulation of peripheral nerves is percutaneously performed [1].

The examination methods, except for method B), are invasive, and cause severe pain in patients. Generally, “Smoothing” and “integration” refer to two ways of quantifying EMG energy over time; Smoothing refers to continuously averaging out the peaks and valleys of a changing electrical signal. On the other hand, integration refers to measuring the area under a curve over a time period. These are used for the examination of the relative degree of muscular contraction, and also employed as a parameter for the evaluation of muscular training conditions [3]. However, their results were affected by the location of the measuring electrodes, and the shape and size of the probes. That is, EMG findings are macroscopically and subjectively evaluated, as described above, and no algorithm for the quantification of the degree of muscular abnormalities or recovery has been established.

A biofeedback instrument has three tasks [4]: i) To monitor (in some way) a physiological process of interest, ii) To measure (objectify) what is monitored, iii) To present what is monitored or measured as meaningful information. The contributions of many earlier researchers and practitioners can be cited as forerunners of biofeedback: Edmund Jacobsen commenced research at Harvard in 1908, and throughout the 1920's and 1930's worked to develop progressive muscle relaxation as an effective behavioral technique for the alleviation of neurotic tensions and many functional medical disorders [5]. He used crude electromyographic equipment to monitor the levels of muscle tension in his patients during the course of treatment. Classification and historical perspectives on biofeedback applications can be found in Gaarder and Montogomery [6], Gatchel and Price [7], and Basmajian [8].

Recently, the rapid reduction of muscles for the bending of the hip joint during walking (flexor muscles around the hip joint) with age has drawn attention. The flexor muscles around the hip joint consist of femoral rectus and abdominal muscles. It has been indicated that these muscles are involved in falling of the elderly. In this study, we examined the smoothed sEMG of femoral rectus muscles performed during BFT of the dominant leg, using the above measurement parameters, and evaluated their changes with age.

II. Materials and Methods

A. Biofeedback training

Temporal data are obtained by sEMG, and here, they are expressed as $\{x(t)\}$. Generally, sEMG data are recorded in a

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computer at 1 kHz. Here, integral calculation is performed every 0.1 sec using the following equation:

$$y(t) = \sum_{k=0}^{99} \left| x(t + 0.001k) \right| , \quad (1)$$

and smoothed sEMG $\{y(t)\}$ are calculated in real time, and outputted. The subject observes the outputted wave patterns and rectangular waves $f(t)$ of a 10-sec cycle superimposed on the same display (Fig.1), and performs intermittent continuous contraction of femoral rectus muscles corresponding to the patterns (BFT).

B. Subjects

The subjects were 31 healthy adults aged 20-73 years (mean, 44.3±19.9 years); all of them were Japanese and lived in Nagoya and its environs. The following were the exclusion criteria for subjects: subjects working in a night shift, subjects with dependence on alcohol, subjects who consumed alcohol and caffeine-containing beverages after waking up and meals within two hours, subjects who may have had any previous histories in the bone, the joint, and the nerve, and special strength training exercises were not usually done. The subjects were not prescribed drugs for any disease by doctors.

They performed BFT for 2 min. We ensured that the body sway was not affected by environmental conditions; using an air conditioner, we adjusted the temperature to 25 °C in the exercise room, which was large, quiet, and bright. All subjects were tested from 10 am to 5 pm in an exercise room. All subjects gave consent in writing after sufficient explanation of this study.

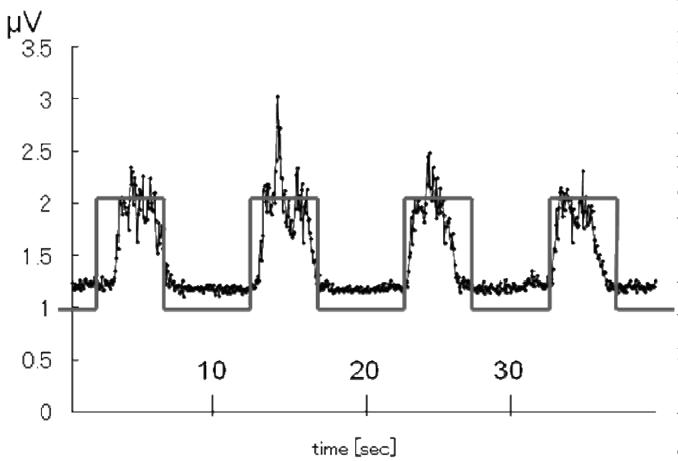

Fig.1 Biofeedback training instruction signal. BFT instruction signal produced by superimposing smoothed sEMG on the target instruction signal

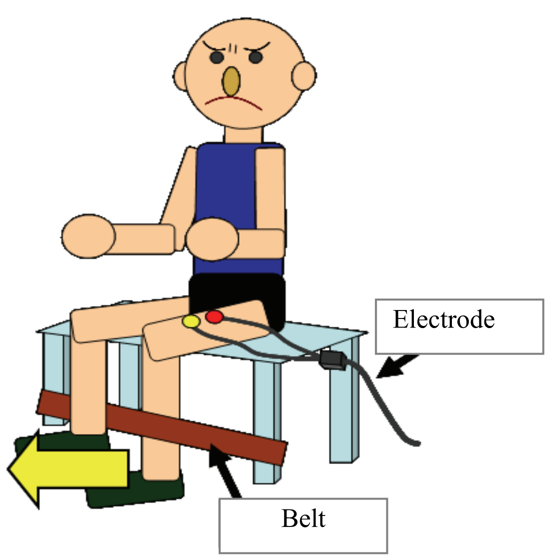

Fig.2 Biofeedback training of femoral rectus muscles [9].

C. Examination Procedure

The subject sat back on a four-legged stool, and electromyographic electrodes were applied at an interval of several centimeters to the venter of femoral rectus muscles in the dominant left or right leg (Fig.2). The subjects were instructed to kick a fixed belt with the bottom of the lower leg forward (kicking motion). A special electromyographic transformation box (AP-U027, TEAC Co.) was connected to a commercially available portable and versatile amplifier and recorder (Polymate AP1532, TEAC Co.), and electromyographic electrodes (bipolar) with a preamplifier were used.

Firstly, electromyographic wave patterns obtained during the kicking motion at the maximum effort (maximum voluntary contraction (MVC) [10]) for several sec were integrated in real time using a computer, and the smoothed sEMG on the display were shown to the subject. Secondly, the threshold line at 75% of the mean smoothed sEMG (mV) during the muscular contraction period was shown to the subject, who was requested to perform muscular training aiming at the threshold line for 1 min 20 sec. In other words, BFT was performed at 75% of the MVC. During BFT, data were recorded in a notebook computer (AP Monitor, NoruPro) at a sampling rate of 2 kHz. The high- and low-frequency cut-off filters were used at 100 Hz and 16 Hz, respectively, and an alternating current-eliminating filter was also used.

D. Calculation Procedure

Of the sEMG data recorded over 1 min 20 sec, the initial 20-sec data were excluded, because the subjects may not have adjusted to the training. sEMG data of the following 6-cycle rectangular waves (target value) $f(t)$ and the smoothed sEMG were analyzed in accordance with our mathematical algorithm of the sensor output signal evaluation system [11], [12] (Fig.3). Taking a mean smoothed sEMG as a threshold H to determine continuous muscular contractions, time sequences above the threshold H were regarded as continuous muscular contractions. Maximal series during the continuous muscular contractions were extracted as shown in Fig.4.

(a) The mean value of the smoothed sEMG during the muscular relaxation period (x^a) and the following measurement parameters [13]-[15], indicating the shape of the smoothed sEMG, were determined every cycle, and the smoothed sEMG obtained from the femoral rectus muscles were evaluated.

(b) Maximum amplitude (x^b): The maximum value was examined, and recorded.

(c) Duration of continuous muscular contraction (x^c): The duration between the first and last maximal values exceeding the mean smoothed sEMG in a cycle was measured (Fig.4).

(d) Time constant of the exponential decay curve fit to

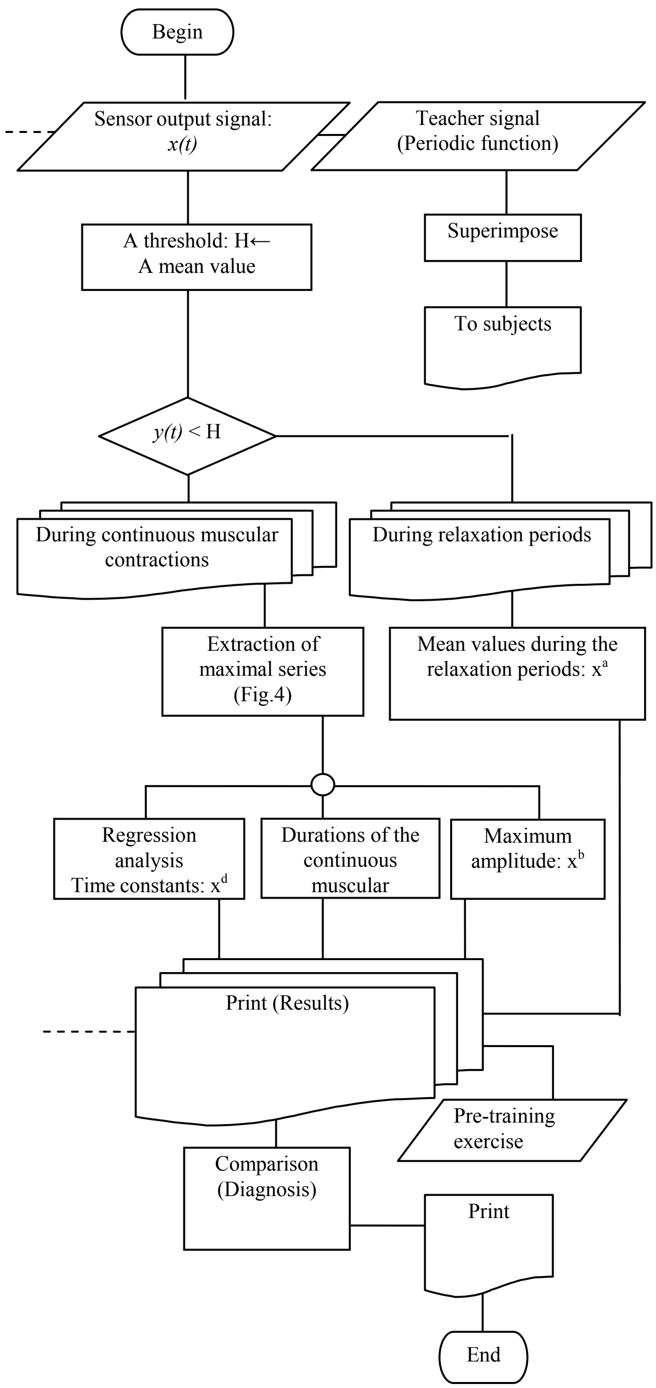

Fig.3 A part of the flow chart of Our mathematical algorithm of the sensor output signal evaluation system [3].

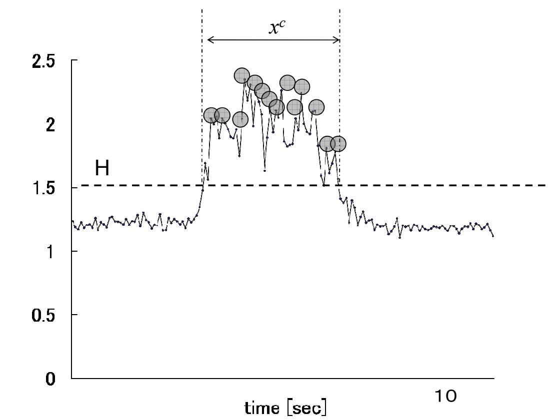

Fig.4 Maximal series during the continuous muscular contractions were extracted by our mathematical algorithm of the sensor output signal evaluation system [11], [12].

maximal points during the continuous muscular contraction period (x^d): All maximal values between the first and last maximal values over the mean smoothed sEMG in a cycle were extracted.

Numerical sequences of the 4 measurement parameters were determined at a repetition number of 6.

1) The relationship between the age (z) of the subjects who had undergone sEMG and the value $x^i(z)$ (i=a, b, c, d) estimated in 5th cycle was statistically examined to evaluate correlations between each measurement parameter and age (Appendix).

2) Since there were differences in not only the unit but also numerical order between the parameters, they were normalized using the intermediate values $\overline{x}^i$ for each cycle, and the reproducibility (stability) of measurements was evaluated using the standard deviation $\sigma[x^i/\overline{x}^i]$. The normalized value is 1 when the measurement is equal to the intermediate value. When the reproducibility (stability) of measurements is high by repeated measurement, there are only small variations around this value, and the standard deviation is close to 0.

III. Results

1) *Relationships between the measurement parameters and age*

Numerical sequences of each of the measurement parameters at a repetition number of 6 were obtained by sEMG performed during BFT. The relationship between theage (z) of the subjects who had undergone sEMG and the value $x^i(z)$ (i=a, b, c, d) was examined in 5th cycle. Fig.5 shows the $x^i(z)$ in all 50 subjects. The linear regression analysis by the least-square method demonstrated that the coefficient by which age (z) was multiplied was 0.071, -0.268, -0.006, and -0.010 for (a), (b), (c), and (d), respectively, and the parameters, except for (a), decreased with age. Since the linear regression coefficients varied with measurement parameters, correlations between the parameters and age could not be judged only using the coefficients by which age

(z) was multiplied. In the t-test for the evaluation of the null hypothesis ($\hat{b} = 0$) for the regression coefficient ($\hat{b}$), the test value (A.3) was 1.105, 0.238, 1.621, and 3.245 for (a), (b), (c), and (d), respectively, and the only parameter exceeding $t_{48}(0.975)$ was the time constant of the exponential decay curve fit to the maximal points during the continuous muscular contraction period (x^d).

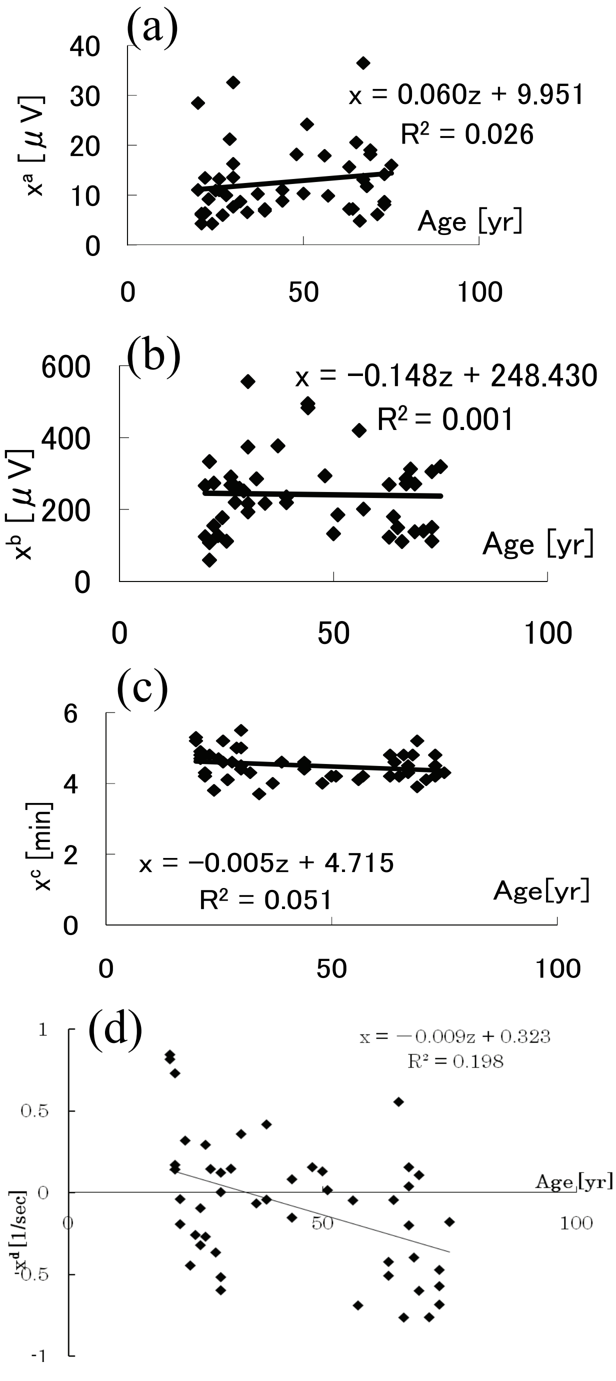

Fig.5 Relationships between the measurement parameters of smoothed sEMG and age, and its linear regression. R^2 shows the coefficient of determination. (a) Mean smoothed sEMG during the muscular relaxation period x^a. (b) Maximum amplitude x^b. (c) Duration of continuous muscular contraction x^c. (d) Time constant of the exponential curve fit to maximal points during the continuous muscular contraction period x^d.

TABLE 1

STANDARD DEVIATIONS OF NORMALIZED INDICES $x/\bar{x}$ [8]

Age group	N	Mean during relaxation	Maximul amplitude	Duration of continuous muscular contraction	Time constant
≤25	8	0.24	0.13	0.06	1.51
≤45	9	0.21	0.14	0.08	0.55
≤65	6	0.33	0.14	0.08	1.84
60 <	8	0.07	0.06	0.06	0.89

N expresses the number of subjects in each age group.

2) *Reproducibility (stability) of measurements of the parameters*

The intermediate values of parameters and standard deviations (σ) of normalized measurements were determined in each subject, and medians of σ in the age groups were compared in Table 1. The duration of continuous muscular contraction (x^c) alone showed $\sigma<0.1$ for any age group.

IV. DISCUSSION

We examined correlations between parameters of smoothed sEMG and age. Regression equations (2) of each parameter (i=a, b, c, d) were determined, and the null hypothesis ($\hat{b}=0$) for the regression coefficient ($\hat{b}$) was examined by the t-test. Since the test value (3) was larger than the two-sided 5% point t_{48} (0.975) in the t distribution with a latitude of 48, the null hypothesis was rejected in the case of i = d. Therefore, the time constant of the exponential decay curve fit to the maximal points during the continuous muscular contraction period (x^d) significantly depend on age ($p<0.05$).

The analysis of sEMG data is generally performed by fast Fourier transformation (FFT), which is a linear analytic method. Since muscular conditions always vary, signals should be regarded as non-steady [16]. Since spectral estimation by Fourier analysis is based on the assumption that the signals to be analyzed are steady and linear, this linear analysis of sEMG data is inappropriate.

Myopotentials are induced by changes in the firing pattern of nerve impulses. Several muscle fibers controlled by a motor nerve are collectively called a motor unit (MU), and several MUs are excited by nerve impulses, causing an MU action potential. The MU action potential measured on the skin surface is a superficial myopotential, and it is observed at a site spatially distant from the local region where MU action potential waves are generated. In sEMG, a very large number of MU action potential waves are superimposed, and the state of activity of whole muscles is observed by this method [17]. Therefore, it should be considered that sEMG signals are nonlinear, or more generally, sEMG shows a time series produced by stochastic processes. Recently, sEMG data have been recognized to be examined by nonlinear analytic methods, such as the recurrence plot and Wayland algorithm

[17], [18]. The measurement parameters used in the present study, such as time constant of the exponential decay curve fit to the maximal points during the continuous muscular contraction period (x^d), are used as a nonlinear analytic method of sEMG, and this method is useful.

The only parameter rejecting the null hypothesis for the regression coefficient ($\hat{b}$ =0) was herein the time constant of the exponential decay curve fit to the maximal points during the continuous muscular contraction period (x^d) ($p<0.05$). Statistically, the only parameter showing a correlation with age was the time constant (x^d), which decreased with age, and became negative over 40 years of age (Fig.5 (d)). This strongly suggested that the smoothed sEMG, which should be maintained as constant during muscular contraction in the BFT, was not flat at an age of more than 40 years, indicating that the smoothed sEMG, which should be flat, gradually increased, because of poor muscular regulation function.

The reproducibility of the duration of continuous muscular contraction, which slightly decreased with age, was highest, and this parameter was not correlated with age. Although changes in the σ value caused by aging were small in the remaining parameters, it was slightly lower in the group over 60 years than in the remaining age groups (Table 1). The σ value may have been decreased by mechanical output due to the reduction of muscular regulation function.

We showed that the time constant (x^d) was necessary for the evaluation of changes with age using the smoothed EMG during BFT. In other words, reduction of the muscular regulation capacity by aging can be detected via sEMG during BFT using the time constant (x^d). However, even the coefficient of determination involved in the time constants was lower than 0.2 (Fig.5 (d)). Using this parameter alone, an evaluation of age-related changes in muscle control might be difficult. A meaningful combination of this parameter with other parameters should be proposed in the next step.

APPENDIX

The relationship between each of the above measurement parameters and age was examined. $x_j^i(z_j)$ of subject j ($j = 1,2,\cdots,50$) was plotted, and linear regression analysis of these 50 points was performed by the least-square method [19]. The regression equation of each measurement parameter was determined.

$$x^i = \hat{a} + \hat{b}\,z \tag{A.1}$$

$$\text{s.t.}\quad \hat{a} = \frac{1}{50}\left(\sum_{j=1}^{50} x_j^i - \hat{b}\sum_{j=1}^{50} z_j\right), \tag{A.2}$$

$$\hat{b} = \frac{1}{S_{zz}}\sum_{j=1}^{50} x_j^i\left(z_j - \frac{1}{50}\sum_{j=1}^{50} z_j\right). \quad (i = \text{a, b, c, d})$$

Here, S_{zz} denotes a variance of age. The dependence of each measurement parameter on age was statistically evaluated by the two-sided t-test with the null hypothesis that the regression coefficient $\hat{b} = 0$.

$$\left|\hat{b} - 0\right| \Big/ \sqrt{S_E / 48 S_{zz}} \tag{A.3}$$

If the above value is larger than $t_{48}(1-\alpha/2)$, the null hypothesis is rejected, and the measurement parameter is considered to be correlated with age [20]. Here, S_E denotes the residual sum of squares by the least-square method, and $t_{48}(1-\alpha/2)$ the t distribution at a probability of $1-\alpha/2$ and a latitude of 48. In this study, since the significance level (α) was defined as 0.05, $t_{48}(1-\alpha/2)$ was about 2.010.

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