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# SOME BASIC STUDIES ON RECORDING AND PROCESSING TECHNIQUES IN EMG DATA ASSESSMENT

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## Introduction

The motor system, which performs the volitional movements of the body, consists of the nervous system and the skeletal muscles which are composed of many muscle fibers. A motor neuron and the muscle fibers innervated by this motor neuron are called a "neuro-muscular unit (hereafter NMU)" with this being the smallest kinetic unit. Figure 1 shows the relationship between the motoneuron and the muscle fibers.

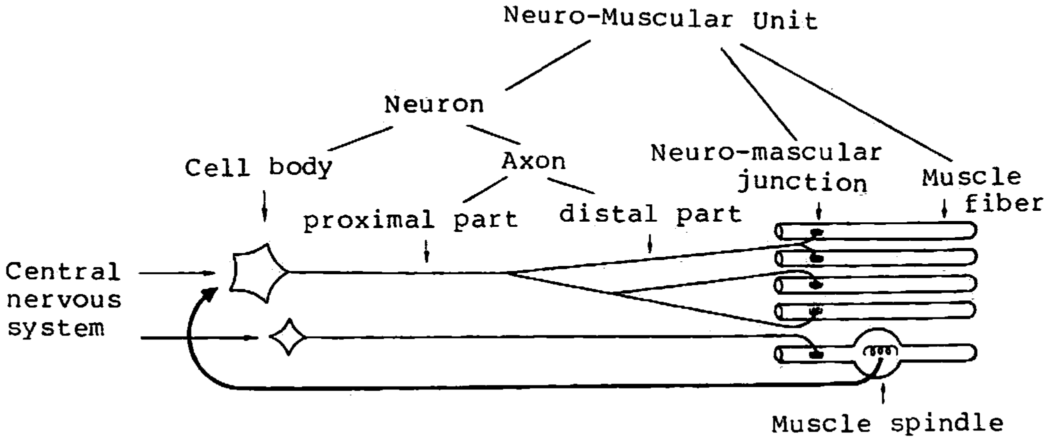


Fig. 1: Schema of the Neuro-Muscular Unit

In the schema, the gamma system which is responsible for the feedback system of the muscle contraction is also shown. The number of muscle fibers which belong to the same NMU is known as innervation ratio.

The innervation ratio is different for different muscles and generally greater for muscles which perform rough movements and smaller for muscles which perform finer movements.

Figure 2 (a) shows schematically the conduction of the excited part on a muscle fiber. The excited portion of the muscle fiber is charged by the negative potential caused by the change in the permeability of the muscle membrane. This electrically negative portion spreads along the muscle fiber and results in the contraction of the muscle fiber.

The velocity of the spreading of the excitation has been reported to be between 2 m/sec to 5 m/sec. Figure 2 (b) shows the change in the potential recorded from an electrode on the surface of a muscle fiber. Figure 2(c) shows the electrical activity which is recorded from an electrode located at some distance from the active muscle fiber. Electromyography (EMG) can be considered to be the sum of the potentials from the various muscle

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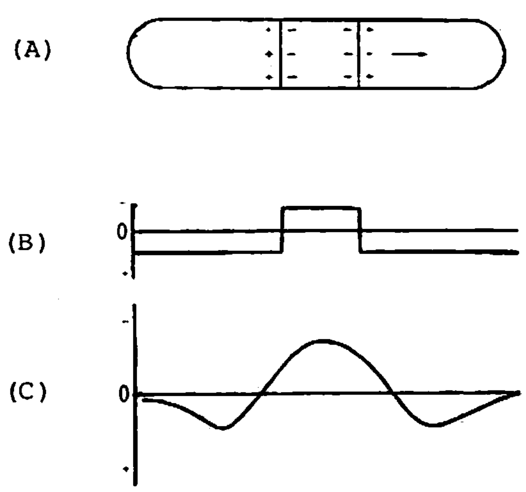


Fig. 2: Electrode impedance and frequency characteristics

fibers. Thus, the EMG pattern should reflect the spatial distribution of the muscle fibers of a given and other NMU's, the firing pattern of the muscle fibers and the other physiological properties of the NMUs. Beside these factors, for evaluation of the EMG signals, we should take into account the electrophysiological properties of the electrodes and the spatial relationship between the electrode and the muscle fibers.

Recently, as EMG studies in experimental phonetics have begun doing more quantitative evaluations of muscle activities, several problems in recording and processing techniques of the EMG data assessment should be re-considered.

1. Electrodes

Two major groups of EMG electrodes have been generally used. One group are the surface electrodes and the other are the intra-muscular electrodes. A surface electrode is suitable if the target muscle is located just below the skin and isolated from other muscles. As regards the articulatory system, the target muscles are usually located rather deeply and are surrounded by various other muscles so that intra-muscular electrodes are preferable. Since the articulatory muscles move vigorously during speech production, a fine wire electrode has been recommended because of the thinness of the wire and it its flexibility.[1] The electrode affords minimum interference with the articulatory movements. At RILP, we are using a plutinum-irisium alloy wire 50μ in diameter. The electrode assembly is a double wire type - bipolar electrode. One of the problems of the hooked-wire electrode is the inconsistency of the distance between the two wires. Recently, the correlation between the movement of the articulator and the EMG from some particular muscles have been studied quantitatively to some extent.[2, 3, 4] For this purpose, a consistent EMG pattern for some particular gesture was not found even in repeated trials. Thus, it would seem that we need to re-consider the electrode itself.

(1) Unfavorable damage to the insulation of the wire:

Unfavorable damage to the insulation is apt to occur at the hooked edge during handling of the electrode and also during insertion. In order to avoid damage, the cut end edge of the hypodermic needle should be blunt. Gentle handling of the needle is also necessary.

Stability of the electrode in the muscle tissue:

Ordinal electrodes that we have been using have had approximately 0.5 mm distance between the two ends of the wires. Since the two wires are not connected but are rather free, we are not sure whether this 0.5 mm distance can be kept in the muscle after insertion. We are now trying to adhere the two wires to each other to keep the distance consistent even in the muscle and during the experimental session. We hope the adhered wires will improve the consistency of the EMG signals for the same gesture.

(3) Impedance of the electrode:

It is obvious that electrode impedance has some effect on the EMG signals. First of all, the exposed end of the electrode should be controlled and should be used as much in the same way as possible. The cutting method [5] of the wire is responsible for some differences. Our cutting method is to use an NS cutter on a piece of paper placed on a piece of glass. The range of impedance of our electrode is from 30 Kohm (10KHz) to 100 Kohm (1KHz). It is known that the electrode impedance also influences the frequency response of the EMG recording system (Figure 3) Since our electrode impedance is in the range from 30Kohm to 100Kohm, there is practically no problem.

Another problem of electrode impedance is thermal noise. Thermal noise is considered as linear to the square root of the impedance [6]. With our electrode, thermal noise can be calculated as 15μV (1-5KHz). On the other hand, EMG potentials are somewhere in the range from 200μV to 500μV, thus, thermal noise would be negligible.

2. Factors of the NMU affecting the EMG.

Since the EMG signals are derived from the electrical potentials from limited area around the tip of the electrode, it is essential to know the morphological and physiological characteristics of the NMU. In particular information about the innervation ratio and the spatial distribution of the muscle fibers seems to be important.

(1) Innervation ratio:

The number of muscle fibers divided by the number of alpha-moto neurons represents the innervation ratio [7-8]. Generally, muscles for fine movement have smaller innervation ratios (for example, the innervation ratio of the extrinsic ocular muscle has been reported as 13), whereas, the muscles for rough movement or for anti-gravity show a greater innervation ratio (for example 610 for the tibialis anterior muscle, 1720 for the gastrocunemius muscle). There have been few reports on the innervation ratios of the speech organs. The innervation ratio has been reported differently by different researchers; for example, the innervation ratio of the cricothyroid muscle has ranged from 22.5 to 116 [9, 10].

(2) Spatial distribution of the muscle fibers belonging to the same NMU:

It is very difficult to know the spatial distribution of the NMU (or territory of the NMU) because an alpha-motoneuron makes various branchings to make connections with many muscle fibers. There are several methods to determine the territory of the NMU. In an animal experiment, a histochemical method is available. The aim of the method is to determine histochemically the glycogen content of the muscle fiber [11]. A single motor neuron is stimulated repeatedly to make the muscle fibers contract tetanically, after which, glycogen depletion is measured by a glycogen stain method. Bradstater et al. reported the territory of the NMU of the rat tibialis anterior to be $6.6mm^2$ and the innervation ratio to be about 118.

The territory can also be determined electromyographically [12, 13].

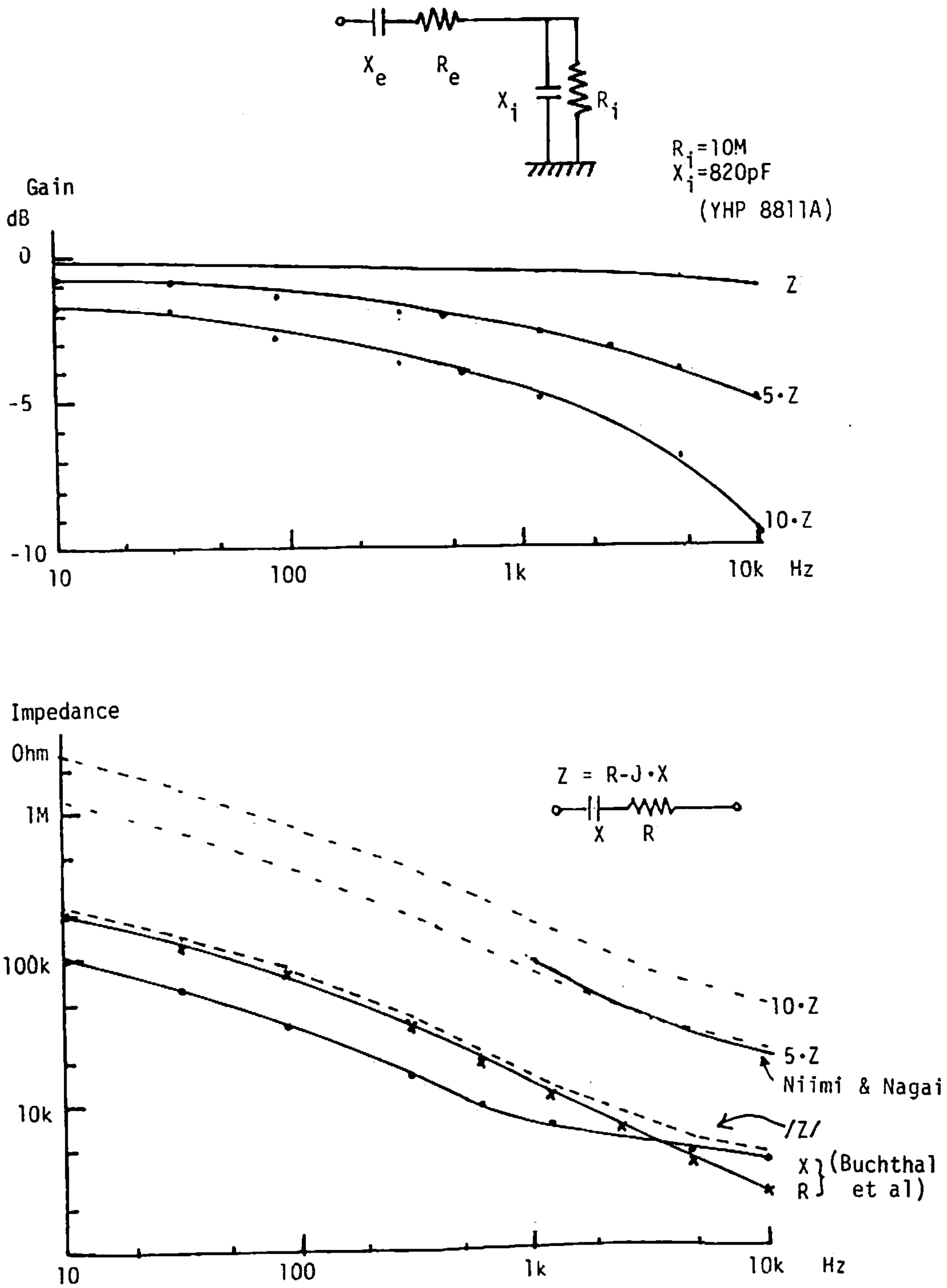


Fig. 3: Electrode impedance and frequency characteristics

There has been no report on the territory of the articulatory muscles, but Buchthal reported that the NMU territory of the superior ocular muscle was about 10mm in diameter. This has been the only report on the NMU territory for the head and neck region.

(3) Firing pattern (physiological property) of the NMU:

Muscle force is a function of the contraction force of a single muscle fiber, the number of active NMU, the innervation ratio and the firing frequency of the NMU. The frequency of the pulse train along the single neuron, seems to parallel the muscle force. The maximum frequency of the impulses from the CNS to an NMU is different for different muscles. It has been reported that the maximum frequency is 20/sec. for the tonic NMU and 50/sec. for the phasic NMU. It is well known that the average interval between the two consecutive pulses and the standard deviation of the interval show a positive correlation. There can be some discrepancy between the number of the neural commands and the pulses of the EMG, because a synchronous firing of the different muscle fibers can occur. It has long been known that the NMU generates a smaller potential for a smaller contraction force (size principle [15)]). In order to interpret the EMG signal as a muscle force, we should take into account these facts.

## Theoretical considerations

In order to obtain some basic insight into the characteristics of the different measures of the EMG signal, a few fundamental theoretical formula on the relationship between the activity level of the muscle and the values of the power, the rectified integral and the level cross count of the interference EMG signal will be derived in the following, under the simplifying assumption that the interference EMG signal is stationary Gaussian noise.

It can be shown easily that, under the assumption that the interference EMG signal y(t) is the wideband Gaussian process wi th a mean of zero and the variance $\sigma^2$, the values of the power p and the rectified integral r of the EMG signal are given as follows.

$$p=E[y^2(t)]=\sigma^2 \qquad \text{-------} \quad (1)$$

$$r=E[|y(t)|]=\sqrt{2/\pi}\cdot\sigma \qquad \text{-------} \quad (2)$$

In addition to the above formula, elementary theory on the random noise signal given the following expression for the mean value of the level cross count:

$$n=c\cdot e^{-\theta^2/2\sigma^2} \qquad \text{-------} \quad (3)$$

$$c=\sqrt{\frac{\int_0^\infty f^2\cdot w(f)\cdot df}{\int_0^\infty w(f)\cdot df}} \qquad \text{-------} \quad (4)$$

Here, $\theta$ is the threshold value for the level cross count and w(f) is the power spectrum of the EMG signal. The above equations show that all three measures under consideration are given as functions of the variance $\sigma^2$ (and the threshold level $\theta$ for the level cross count) under the wideband Gaussian noise assumption of the EMG signal. It is generally known that the inteference EMG signal has smooth wiseband spectrum. Therefore, it is considered that the above equ ations are valid when the degree of the interference in the EMG signal is large.

Next, we will consider the interference EMG signal as a linear summation of the independent pulse trains originating from different motor units. Assuming that there are N motor units, and the i-th motor unit has a mean inter-spike interval $\mu_i$ and a spike waveform at the electrode position $h_i(t)$, it can be shown that the variance of the interference EMG signal is given by the equation (5):

$$\sigma^2=\sum_{i=1}^{N}\frac{1}{\mu_i}\int_0^{\infty}h_i(t)\cdot dt \quad \text{-------} \quad (5)$$

(In the derivation of the above equation, it is assumed that the spike interval has a Guassian type fluctuation, the standard deviation of which is smaller than the mean spike interval.) If we assume further that all the motor units have the same mean spike interval $\mu$ the equation (5) can be reduced to the following simpler forms.:

$$\sigma^2=\alpha\cdot\frac{N}{\mu} \quad \text{-------} \quad (6)$$

$$\alpha=\frac{1}{N}\sum_{i=1}^{N}\int_0^{\infty}h_i^2(t)\cdot dt \quad \text{-------} \quad (7)$$

It can be seen in the above equations that the variance of the interference EMG signal is proportional to the density of the motor unit spikes in the whole muscle, $N/\mu$. By substituting the equations (6) and (7) into the equations (1) (2) and (3), we can get the following expressions for the relationship between the total firing rate $N/\mu$ of the muscle and three measures of the EMG signal p, r and n.

$$p=\alpha\cdot\frac{N}{\mu} \quad \text{-------} \quad (8)$$

$$r=\frac{1}{\pi}\sqrt{\frac{2\alpha N}{\mu}} \quad \text{-------} \quad (9)$$

$$n=c\cdot e^{-\frac{\mu e^2}{2N}} \quad \text{-------} \quad (10)$$

Simulation procedure

Simulated interference EMG signals were computed by summing the spike waves originating from the spatially distributed motor units. In order to perform the simulation computation, the data on the waveform of the motor unit spike and the characteristics of its spatial transmission are necessary. In the absence of pertinent data on the human speech muscles, the following simulation conditions were determined based on the reference data cited in a review paper by Rosenfalck.

1) Spike waveform:

The waveform of the motor unit spike used in the present simulation is shown in Figure 4. This was determined by referencing the single muscle fiber spike given by Rosenfalck. Compared to the original curve, the waveform is simplified as bi-phasic, neglecting the terminal inflection of the smaller amplitude and, considering the spatio-temporal distribution of the muscle fiber spikes within the motor unit, the time axis was expanded by a factor of approximately two.

2) Spatial attenuation of the spike amplitude.

The amplitude of the spike is assumed to be nearly constant within the territory of the motor unit and is assumed to attenuate in proportion to $1/d^{1.8}$ outside the motor unit, where d is the distance from the center of the motor unit.

The exact formula used to determine the spike amplitude at a distance d from the motor unit center is as follows.

$$\text{Amplitude Ratio} = \begin{cases} 1.0 & 0 \leq d \leq 0.2D \\ \{1.0 + (0.3D)^{1.8}/d^{1.8}\}/2 & 0.3D \leq d \leq 0.5D \\ (0.3D)^{1.8}/d^{1.8} & d \geq 0.5D \end{cases}$$

where D is the diameter of the motor unit territory.

3) Spatial broaden of the spike width.

The temporal width of the spike waveform is assumed to broaden with the distance form the motor unit. The broadening factor is determined as a function of the distance d according to the following formula.

$$\text{Duration Ratio} = \begin{cases} 1.0 & 0 \leq d \leq 0.375D \\ (6.66 + 29.3d)/18.0 & d \geq 0.375D \end{cases}$$

4) Pattern of the motor units firing.

In the present simulation, the cricothyroid muscle is assumed to be the object muscle and the values of the physio-anatomical parameters are selected as follows. The cross-sectional area of the muscle is taken as 4mm x 16mm and the muscle fibers are assumed to be running perpendicular to the cross section. The value of D, the diameter of the motor unit territory, is assumed to be 1mm. The total number of the motor units in the muscle is assumed to be 637, these are located uniformly in the cross section of the muscle in a grid pattern of 13 x 49. The level of the unit firing was varied as follows: the ratio of the firing NMUs to the total NMUs in the muscle--13%, 47%, 100%, and the firing rate of the NMU -- 10, 20, 30, 40 and 50 Hz. A combination of the changes in the number of firing NMUs and the firing rate results in 15 different levels of muscle activity. The pair of electrodes are assumed to be located parallel to the muscle fibers, with a distance between them of 1.5mm. Conduction velocity of the spike along the muscle fiber is taken as 3m/sec, which means

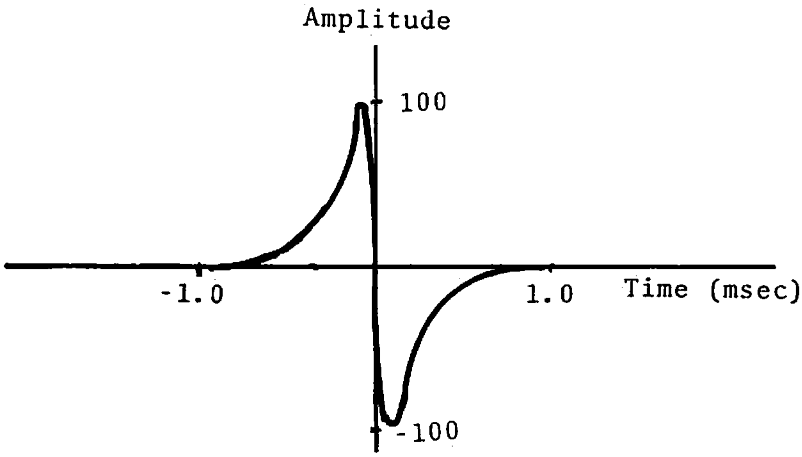


Figure 4 : The waveform of the motor unit spike used in the simulation.

that the recorded signal is the summation of the two spikes of the same waveform, having opposite polarities and a time difference of 0.5msec between them.

In addition to the noise free signal, two types of noise-added signals are generated; the r. m. s. amplitude of the added white noise is either 2% or 4% of the maximum peak amplitude of the motor unit spike. Thus, a total of 45 different types of EMG signals are generated. The length of each sample signal is 500msec. The signal is lowpass filtered with a cut-off frequency of 1kHz. The values of the power, rectified integral and the level cross count were calculat ed for every 100 msec interval. The average and the standard deviations of these values are shown in Figures 5, 6 and 7.

Simulation results

Figures 5(a), (b) and (c) show the relationship between the muscle activity level and the level cross count for the three different conditions of the amplitude of the added noise. The abscissa is the total firing rate of the muscle which is defined as the number of firing motor units x firing

The ordinate is the value of the level cross count. The data points for the same threshold level are connected by lines. It can be seen that, for the lower threshold level, there are saturation characteristics in the relationship between the total firing rate and the level cross count. as is predicted in the equation(1). As the threshold value increases, the relationship becomes linear. It can also be observed that for a fixed threshold level, the saturation characteristics become more apparent with the increase in the amplitude of the added noise.
These results can be interpreted as follows. When the threshold value is higher, only the large amplitude spikes from the motor units close to the recoding electrodes are counted. For these spikes, the interference pattern is not as strong and the saturation characteristics given by the equation (10) do not come into play. With the lowering of the threshold, the aggregate of the small amplitude spikes from the remote motor units and the added noise come into the counting region. Then, the effect of the interference pattern becomes greater, resulting in greater saturation characteristics. Thus, in the practical application of the level cross count, it is necessary to select the appropriate value of the thr
so that the level cross count does not show saturation characteristics with in the range of the muscle activity under investigation. Naturally, with the higher level of the threshold, the number of effectively counted motor unit spikes decreases, resulting in a loss of information in the measurement of the activity level of the muscle. In Figure 7, it can be seen that the value of the power increases linearly with the increase in the total firing rate, as in predicted in equation (7).

Figures 6 and 7 show the relationship between the total firing rate and the rectified integral and the power, respectively. In the case of the rectified integral, the relationship appears to be nonlinear. However, the degree of nonlinearity is less than is indicated by the equation (9). This result is also considered to be due to the fact that the EMG signal is the composite of the large spike component and the small spike interference pattern. For the large spike component, the relationship between the

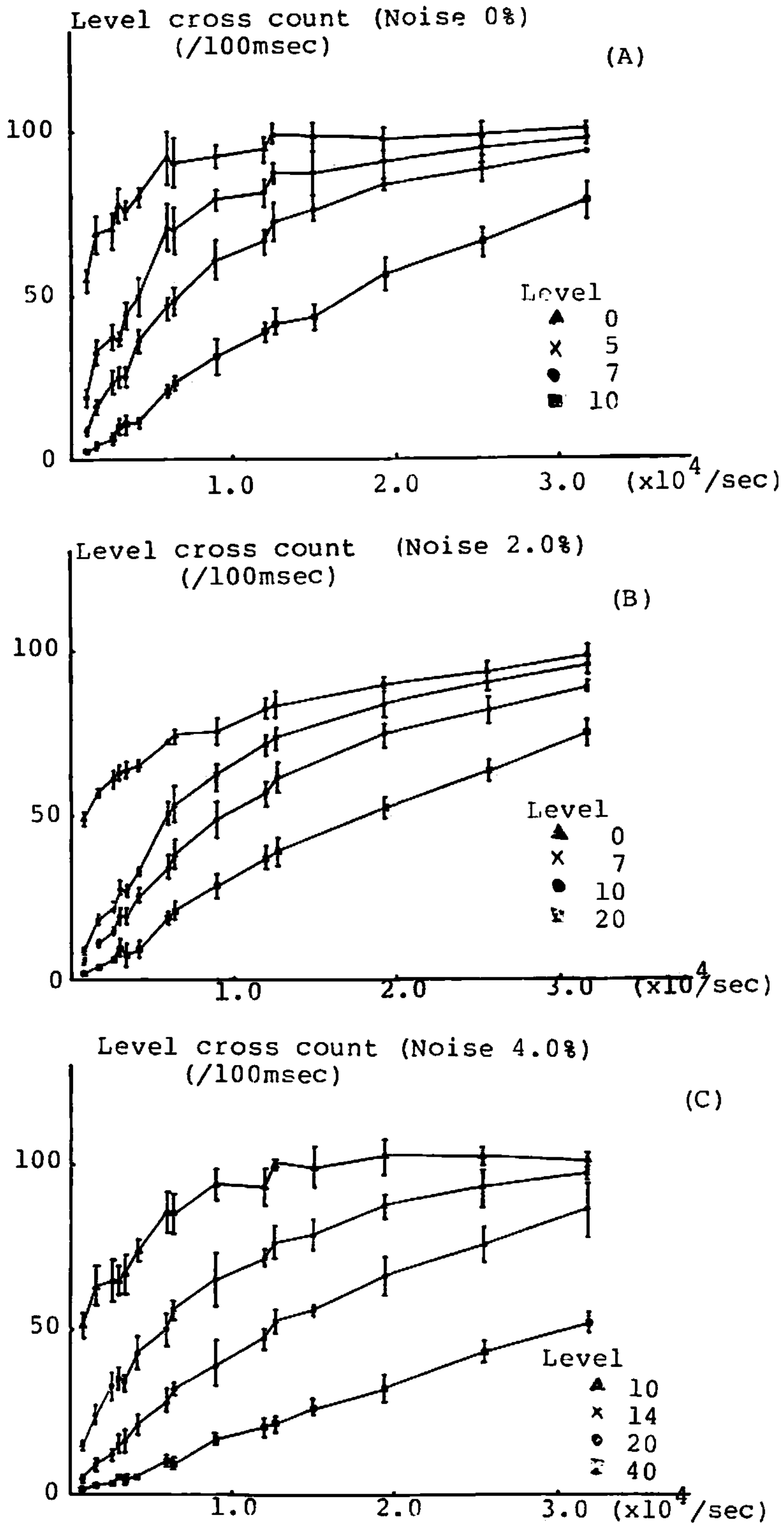


Figure 5: Relationship between the level cross count and the total firing rate (x-axis) with three different noise-levels.

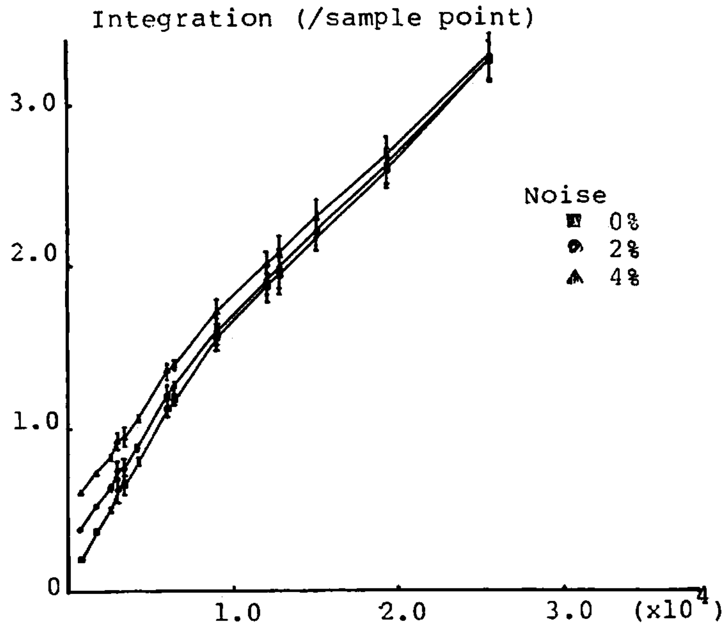


Figure 6: Relationship between the value of the rectified integral and the total firing rate.

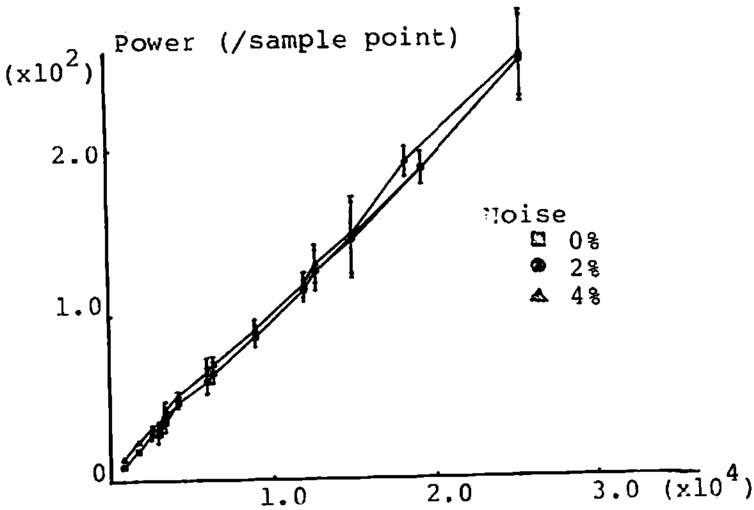


Figure 7: Relationship between the power and the total firing rate.

rectified integral and the total firing rate is expected to be linear, because the interference between these spikes is small. Because of this, the relationship as a whole is closer to linear than is indicated by equation (9).

3. Considerations of the actual EMG patterns

For the level cross count method, the proper threshold should be set up by the contraction condition--the firing rate of each muscle fiber, and noise level. In this section, the actual EMG data will be discussed.

Figure 8 shows the EMG patterns from the levator veli palatini muscle during the preduction of the test word /beN'pee/. The bottom curve is the EMG pattern processed by the integration method and the other four graphs are by the level cross count method with different threshold

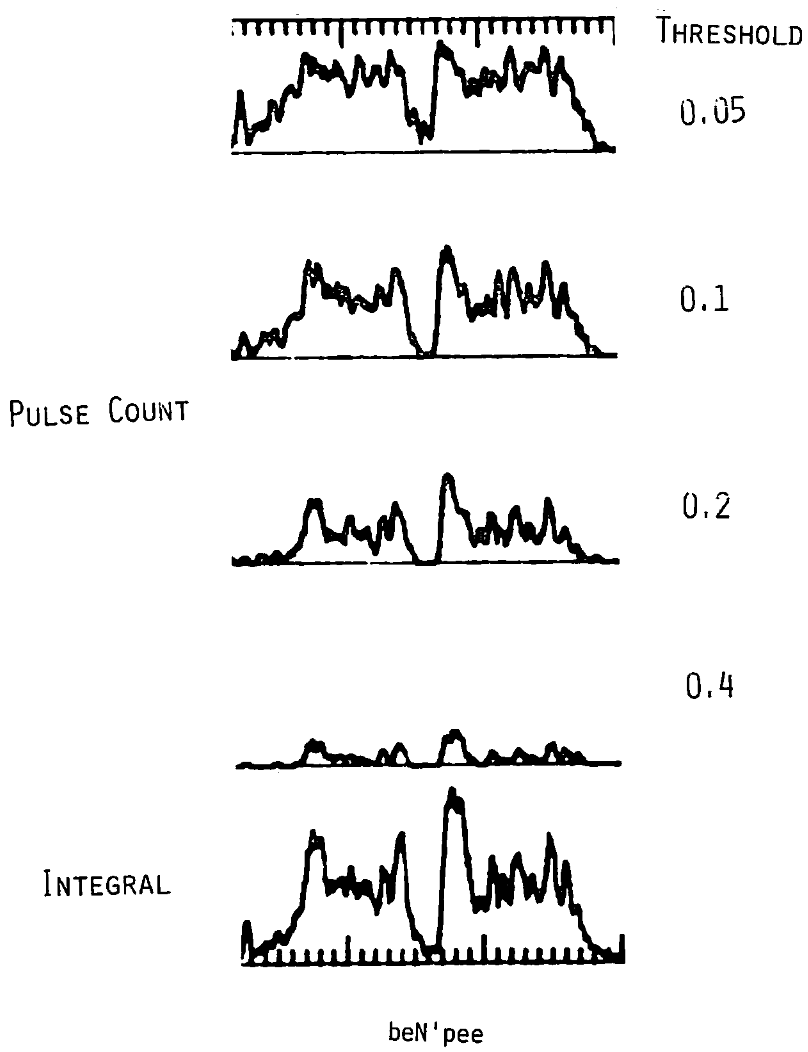


Figure 8: EMG patterns from the levator veli palatini muscle processed by the level cross count m thod and the integration method. The test word is /beN'pee /.

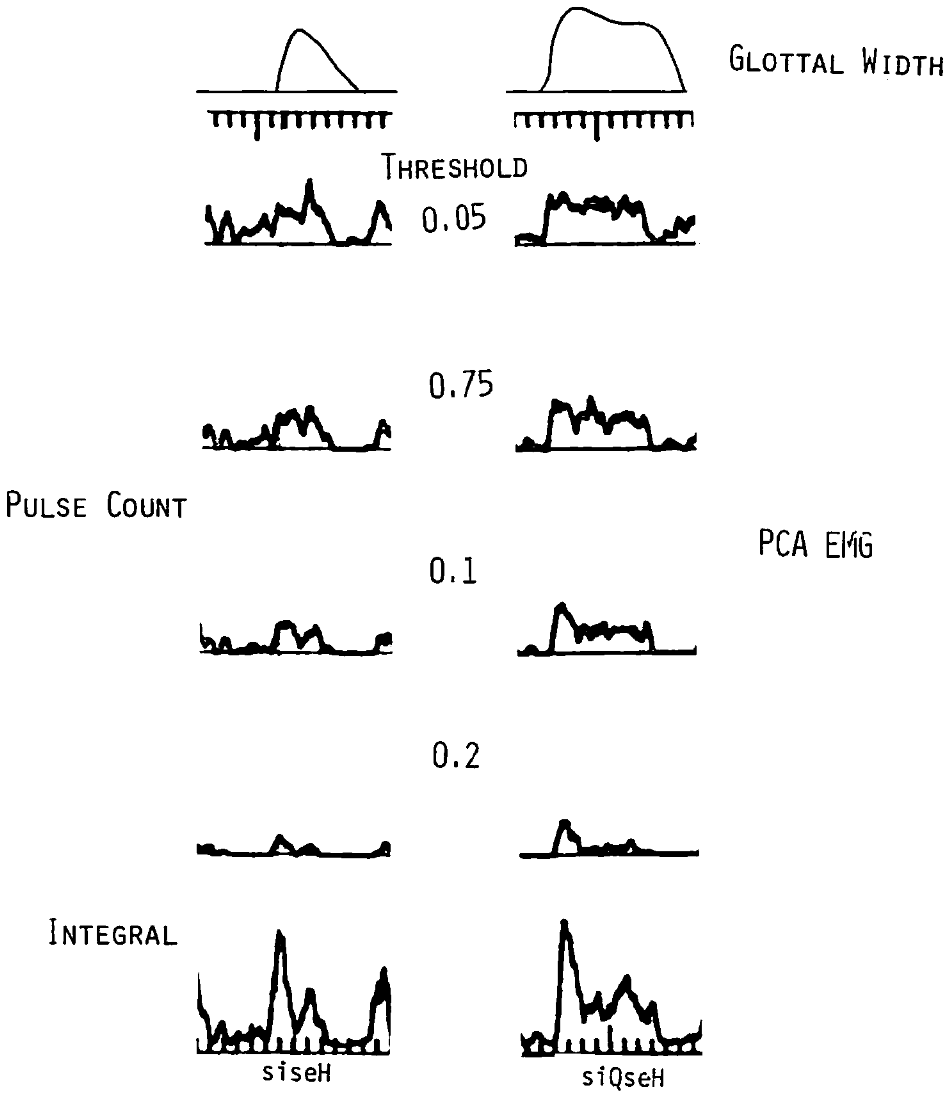


Figure 9: EMG patterns from the posterior cricoarytenoid muscle and the glottal width.
The test words are /siseH/ (left) and /siQseH/ (right)

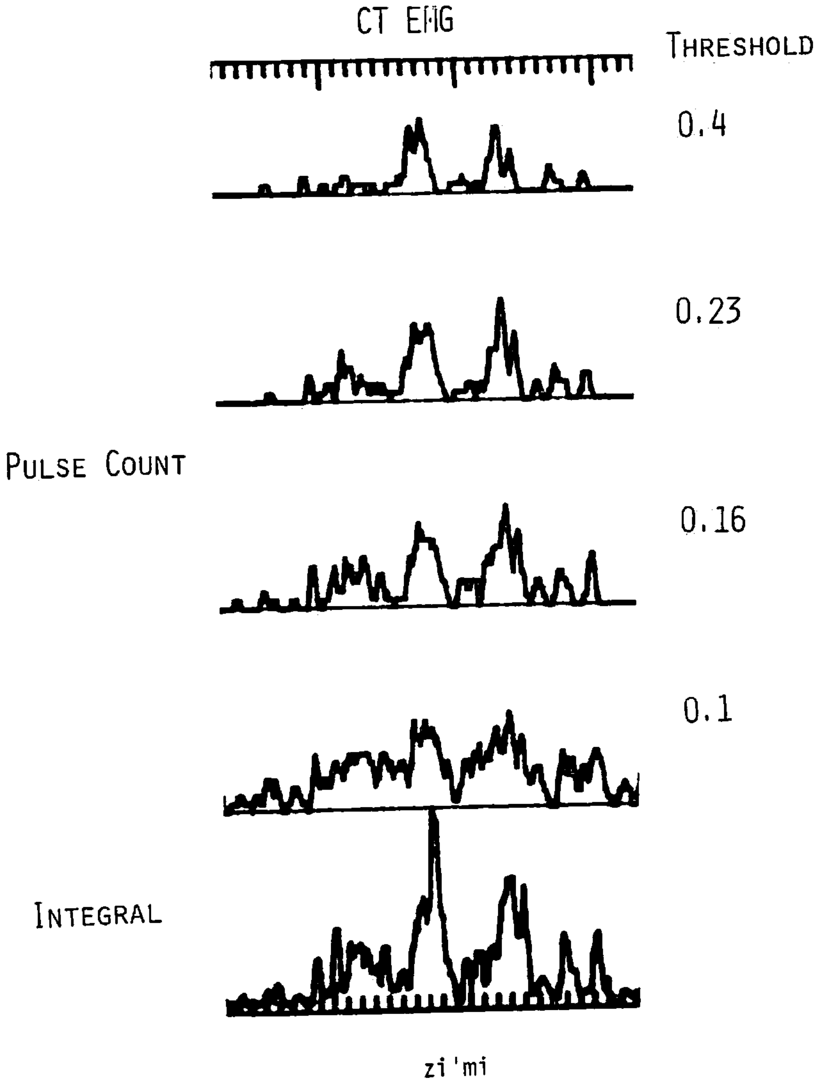


Figure 10: EMG patterns from the cricothyroid muscle. The test word is /zi'mi/.

levels. Of course, the original EMG data is the same for all five graphs with this being picked up by the use of an ordinary hooked wire electrode. The values of the threshold in the figure are relative to the original EMG amplitude; in this case, the original EMG amplitude was set at 2. During the nasal /N/ of the test word, the levator veli patatini muscle is supposed to be suppressed. In the level cross count (pulse count in the graph) method with a low threshold, low potential activity can be observed. This low activity is probably the result of low voltage potentials delivered from muscle fibers located relatively far away from the electrode. A part of this activity might be noise. This low level potential is also seen in the integral curve (bottom graph of Figure 8).

On the contrary, in the graphs with higher threshold, the suppression of the activity for the /N/ segment is remarkable. Next, let us consider the EMG peak for /p/ after /N/. For stop /p/, the elevation of the velum to close the velopharyngeal port is necessary and this movement is known to be achieved by the contraction of the levator veli palatini muscle. The EMG peak would be expected for this period. Among the five graphs we can see the prominent peak in the integral EMG pattern and also in the pulse count graphs with relatively higher thresholds. This tendency indicates the possibility of saturation which we discussed in the simulation part of this paper.

Figure 9 shows the EMG patterns of the posterior cricoarytenoid muscle (PCA) which is the opener of the glottis. The test words are /siseH/ and /siQseH/. For both test words, two EMG peaks are expected. The first peak would be to open the glottis and the second one is to keep the glottis open. For these samples, the saturation tendency we have discussed on the levetor veli palatini muscle data can be also seen.

Figure 10 shows the EMG patterns from the cricothyroid muscle for the utterance /zi'mi/. Though the integral curve shows a spiky peak for the syllable with stress accent, in the pulse count patterns, the spikey peak is not clearly seen. This spike might have been caused by the synchronous firing of the different NMUs.

The data mentioned above suggest that in order to interpret the EMG data, we must consider the processing techniques and the physiological properties of the NMU and muscle as a complex organization of multiple NMUs.


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