J. Human Ergol., **29**: 7-14, 2000

EFFECTS OF AGING ON EMG VARIABLES DURING FATIGUING ISOMETRIC CONTRACTIONS

Hiroshi Yamada [1], Morihiko Okada [2], Toshiaki Oda [3], Satoko Nemoto [4], Tomomi Shiozaki [2], Tomohiro Kizuka [5], Shinya Kuno [2], and Tadashi Masuda [1]

[1] *Institute for Human Science and Biomedical Engineering, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, 305-8566, Japan*
[2] *Center for Tsukuba Advanced Research Alliance, University of Tsukuba, Tsukuba, Ibaraki, 305-8577, Japan*
[3] *Graduate School of Arts & Sciences, The University of Tokyo, Meguro-ku, Tokyo, 153-8902, Japan*
[4] *Department of Occupational Therapy, School of Health Sciences, Ibaraki Prefectural University of Health Sciences, Ami, Ibaraki, 300-0394, Japan*
[5] *Institute of Health and Sport Sciences, University of Tsukuba, Tsukuba, Ibaraki, 305-8574, Japan*

The purpose of this study was to evaluate the neuromuscular adaptation that occurred with aging, by comparing young and aged subjects with respect to changes in surface EMG from the tibialis anterior muscle during fatiguing contractions. EMG variables such as the averaged rectified value (ARV), median frequency (MDF), and muscle fiber conduction velocity (MFCV) were calculated during maximal (MVC, 3 sec) and submaximal (60% MVC, 60 sec) isometric contractions. Muscular force, ARV, MDF, and MFCV during MVC were significantly greater in the young than in the elderly ($p<0.05$). EMG amplitude increased and the waveform slowed in all subjects during submaximal contractions, indicating the development of local muscle fatigue. As fatigue progressed, the ARV increased and the MDF and MFCV decreased significantly ($p<0.01$). The fatigue-induced changes in the MDF and MFCV were significantly smaller in aged than in young subjects ($p<0.05$), a trend also seen in the ARV change, which means that the elderly cannot be fatigued as much as the young with contractions of the same relative intensity. These results as a whole suggest that the aged subjects hold an adaptive motor strategy to cope with age-related neuromuscular deteriorations, due to the decline of motor unit activation and selective atrophy of fast twitch muscle fibers.

INTRODUCTION

Studies on muscle fatigue are one of the issues of prime importance in human ergology. Since population structure is rapidly changing in developed countries including Japan to have higher proportion of the elderly, clarification of the features of fatigue in the elderly should have socioeconomic significances. This applies particularly to lower limb muscles related with the locomotor capacity, which is essential for the activity of daily life in the elderly.

It is conventional in evaluation of muscle fatigue under ergological situations to use surface EMG, which is real-time and non-invasive in nature. It has been shown with surface EMG, for example, that its magnitude increases and the power spectrum shifts toward lower frequencies as fatigue progresses (Kogi and Hakamada, 1962; Okada, 1971). Recent years, in addition to the EMG magnitude and spectral parameters, muscle fiber conduction velocity (MFCV) reflecting the metabolic state of muscle tissues (Sadoyama et al., 1988) is increasingly utilized in the fatigue evaluation on the ground that MFCV is less vulnerable to the recording conditions than the other EMG variables. In terms of the behavior of these variables in fatiguing contractions, relative contribution of the central/neural versus peripheral/metabolic factors in muscle has been discussed (Bigland-Ritchie et

Received for publication March 17, 2000

al., 1981; Fuglevand et al., 1993).

However, characteristics of muscle fatigue in the elderly as compared with the young have not been investigated by using the above variables, except in a few studies in which the variables measured are limited in number, and focuses are simply laid on the comparison between “before” and “after” fatigue (Schwendner et al., 1997; Hara et al., 1998). A reason for the paucity of such studies appears to be the difficulties in acquiring reliable measurements of MFCV in the field situations.

In this study, we compared aged and young subjects regarding the changes in surface EMG variables during fatiguing contractions of the tibialis anterior muscle that plays critical roles in walking (Kameyama et al., 1990), and discussed the age-related alteration of motor control strategy.

METHODS

Subjects and procedures

Subjects were 13 healthy aged females (70.8±3.1 years old) and 12 healthy young females (21.4±1.7 years old) informed of the aim and procedure of experiments (Figure 1). Sitting in a chair with the hip, knee, and ankle joints flexed at 90 degrees, the subjects conducted isometric dorsiflexion of the ankle using a maximal voluntary effort for 5 seconds while the dorsiflexion forces exerted were measured. After a 5-minute rest, subjects carried out isometric ankle dorsiflexion of 60% MVC for 60 sec, monitoring their own force output shown on a display (Figure 1). Experiments were conducted using the right lower limb in all subjects.

(A) (B)

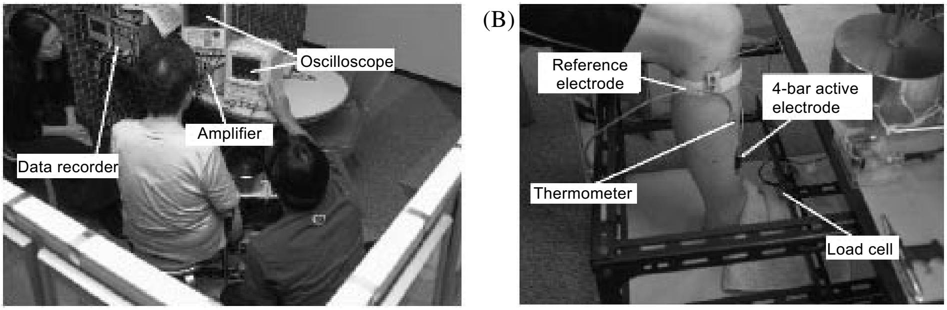

Fig. 1. Experimental setup for recording muscular force and EMG (A) and arrangement of pick-up electrodes over the muscle (B).

The dorsiflexion forces were measured with a load cell placed in contact with the mid-dorsum of the foot. Surface EMGs were recorded from the tibialis anterior muscle both during the MVC task and 60% MVC task, to obtain EMG variables including MFCV. Simultaneously, skin temperature was monitored using a thermometer (Coretemp, CTM-205, Termo Inc.) attached to the muscle belly of the tibialis anterior. The EMG signals were picked up with a surface electrode array consisting of 4 stainless steel contacts spaced at 10 mm intervals (DEM, Torino, Italy), and amplified at a time constant of 0.03 sec with a high cut-off frequency of 1,000 Hz. Signals were led bipolarly in 3 channels from neighboring contacts and monitored using a digital oscilloscope (DL154OC, Yokogawa).

Before the MVC task, preliminary experiments were repeated to precisely measure the MFCV by placing the electrode in parallel to muscle fibers (Sadoyama et al, 1985; Masuda, 1985); the subjects exerted moderate contractions, and the site where EMG waveforms of each channel most closely resembled each other was adopted as the recording location (Figure 2), with attentions paid to the site of neuromuscular junctions.

EMG signal processing and statistical analysis

The EMG signals and dorsiflexion force were recorded on magnetic tapes using a data recorder (RTP-670A, Kyowa). After the experiment, the recorded signals were digitized at a sampling frequency of 5 kHz with a resolution of 12 bits (DAS Mini, SDS). Digitized signals were transferred to a personal computer to calculate EMG variables for those signals corresponding to the exerted force above the target level. Following the method of Masuda et al. (1999), the frame size to calculate EMG variables was 819.2 msec, corresponding to 4,096 samples. Shift lengths were 500 msec, corresponding to 2,500 samples.

As EMG variables to evaluate the development of muscle fatigue, we adopted the average rectified value (ARV), median frequency of the power spectrum (MDF) and MFCV. The ARV and MDG were calculated from the myoelectric signals of the middle channel. The correlation coefficient (CC) was calculated between the signals from the neighboring channels, and the pair yielding the highest CC with an appropriate time shift was selected. Following the method of Masuda (1985), the MFCV was computed from the inter-contact distance (10 mm) and the time shift of signals giving the maximal CC.

Student's paired t-test was used to compare Mean±SD between the groups with $p<0.05$ regarded as statistically significant.

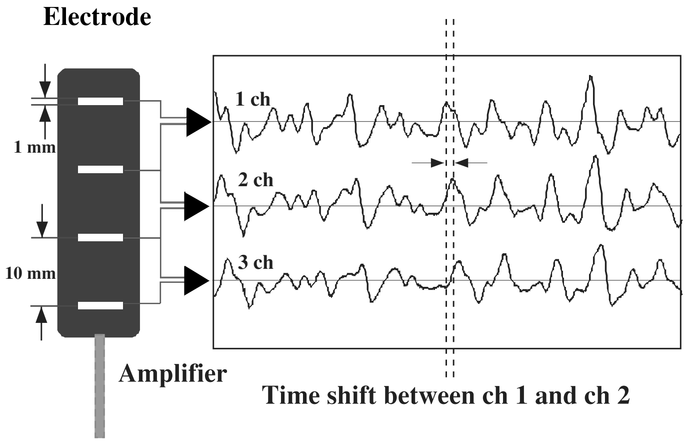

Fig. 2. EMG signals detected by using a 4-contact active electrode. The time shift between channels is shown in an extended time scale. MFCV was calculated from the inter-contact distance (10 mm) and the time shift of signals between channel 1 and 2.

RESULTS

MVC task

Table 1 shows the force exerted and absolute values of EMG variables during the MVC task. The ARV, MDF, and MFCV as well as the force were significantly smaller in the aged than in the young subjects. The CC between each channel was as high as around 0.9 in both age groups, indicating that EMG propagation patterns were picked up appropriately.

Fatigue task

The surface EMG amplitude increased while the waveform slowed in all subjects during fatiguing contraction at 60% MVC for 60 sec, indicating the development of muscle fatigue (Figure 3). When we plotted the ARV, MDF, and MFCV against the time endured, the temporal change of these variables were steady and continuous, with the least variability found in MFCV (Figure 4). To com-

Table 1. Muscular force and EMG variables during maximum voluntary contraction. Asterisks show significant differences between the young and elderly subjects.

	Young	Elderly		All subjects
Force (kg)	22.78 ± 2.72	17.05 ± 4.68	**	19.91 ± 4.75
ARV (μV)	413.76 ± 147.22	274.06 ± 109.39	*	343.91 ± 145.53
MDF (Hz)	63.68 ± 7.15	52.29 ± 7.52	**	57.98 ± 9.24
MFCV (m/s)	4.73 ± 0.99	3.85 ± 0.56	*	4.29 ± 0.90
CC	0.87 ± 0.05	0.92 ± 0.02	**	0.90 ± 0.04

Valus are Mean±S.D. *$p<0.05$, **$p<0.01$

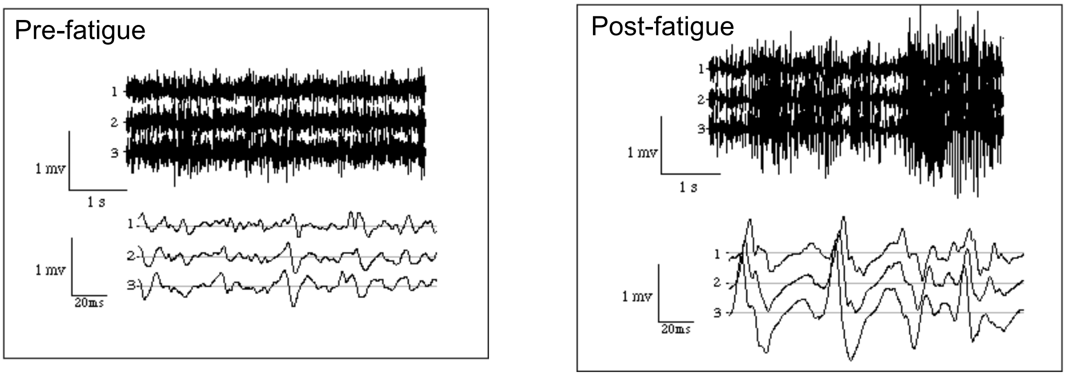

Fig. 3. Changes in EMG waveforms during 60% MVC fatiguing contractions. The surface EMG amplitude increases while the waveform slows as fatigue progresses.

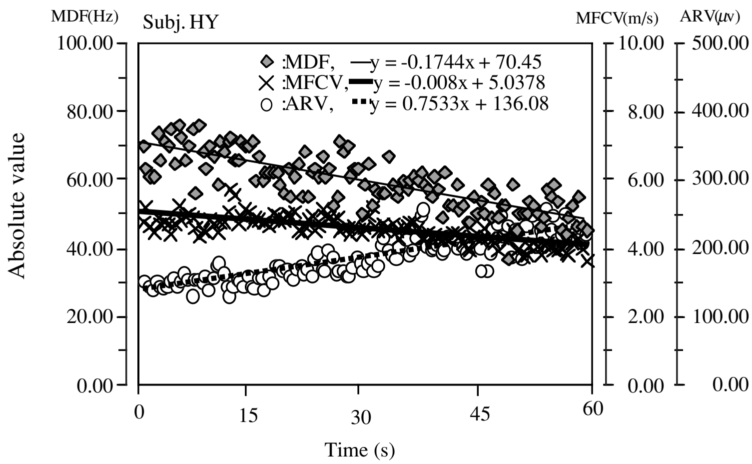

Fig. 4. Typical changes in median frequency (MDF), muscle fiber conduction velocity (MFCV), and averaged rectified value (ARV) as fatigue progresses. The values were obtained from one subject. Percent changes of these values were calculated from the regression lines applied to the plots of EMG variables.

pare the magnitude of each variable between the initial and final phase of contraction, we applied a regression line to each EMG variable following the method of Mannion and Dolan (1996), and the intercepts at 0 sec and 60 sec were calculated to represent the initial and final values, respectively. As a result, while the force exerted and CC remained unchanged, the ARV increased, and MDF and MFCV decreased significantly as muscle fatigue developed (Figure 5). Skin temperature did not change significantly (32.2±0.8 ˚C vs. 32.4±0.8 ˚C) during the 60 sec contraction.

Comparison between aged and young subjects

To compare the relative change in EMG variables during the contraction between aged and young subjects, the percentage of the increment or decrement against the initial value was calculated. As illustrated in Figure. 6, the decreasing rate in the MDF and MFCV was significantly smaller in the aged than in the young subjects. The increasing rate in the ARV was also smaller in the aged than in the young subjects, although without statistical significance.

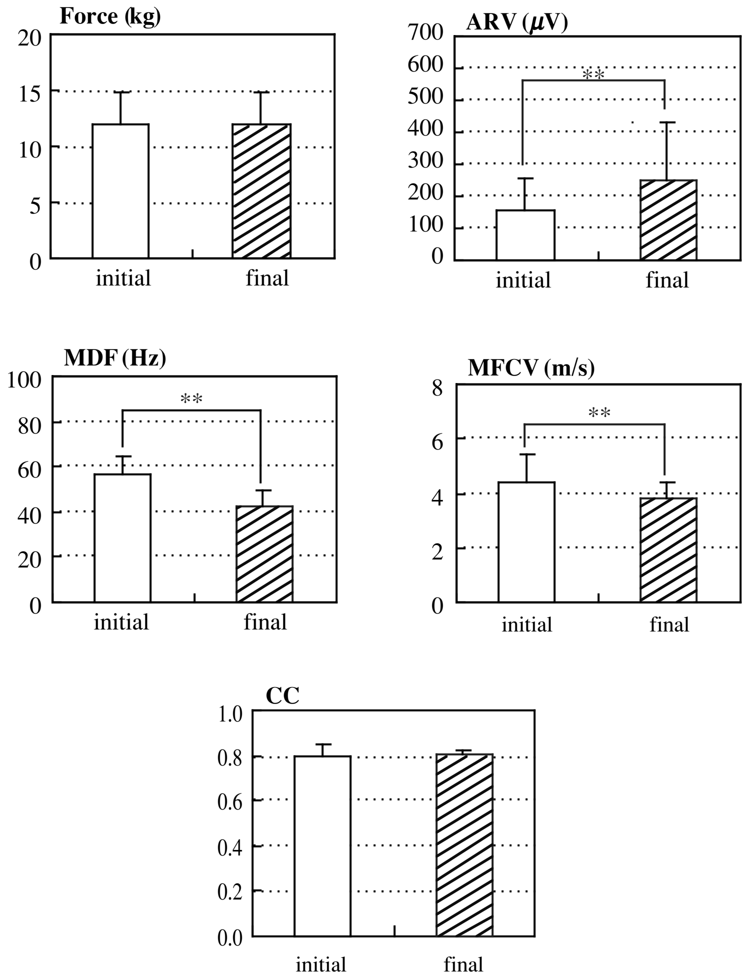

Fig. 5. Fatigue-induced changes in the force and EMG variables. Comparison was made between the initial and final value calculated from the regression line. Asterisks show significant differences (p<0.01) between the initial and final value.

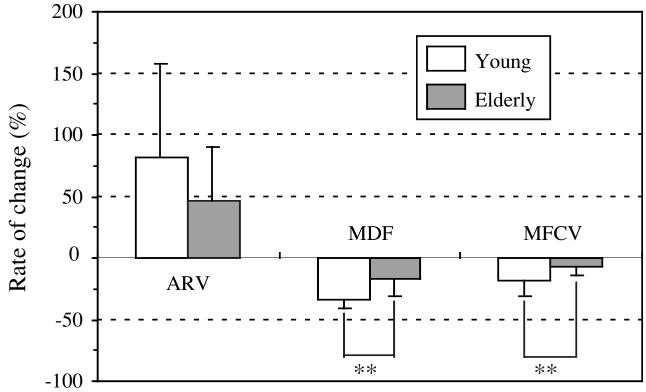

Fig. 6. Percent ratio of the fatigue-induced changes against the initial value in the EMG variables, as compared between the young and elderly. Asterisks show significant differences ($p<0.01$) between the age groups.

DISCUSSION

In the maximum voluntary contractions, the force exerted and surface EMG variables were significantly smaller in aged than in young subjects. The smaller MFCV in the aged confirms our results previously reported (Okada et al., 2000). Smaller MFCV and MDF suggest that the proportion of slow twitch (ST) fibers is higher in the tibialis anterior muscle of the aged subjects, owing to selective atrophy of fast twitch (FT) fibers as demonstrated by histochemical studies (Porter et al., 1995; Kimura, 1996). A lower ARV in the aged suggests a reduced capacity for recruiting motor units, which, combined with the aforementioned atrophy of FT fibers, causes smaller forces exerted.

With sustained submaximal contractions, the EMG waveforms slowed consistently in all subjects, accompanied by a constant decrease in the MDF, indicating a gradual development of local muscle fatigue (Figures 4 and 5). Numbers of previous studies reported consistent slowing of surface EMG as fatigue progresses (Okada, 1971; De Luca, 1984; Kiryu et al., 1998). These changes are claimed to be brought about by two factors; first, a decrease in pH caused by lactic acid accumulation due to sustained contraction and ischemia may lower the MFCV during fatiguing contractions (Lindström, 1970; Sadoyama et al., 1983; Brody et al., 1991); second, changes in motor unit firing statistics with decreased MFCV concurrently may affect EMG waveforms (Naeije and Zorn, 1982; Kranz et al., 1983). Frequency variables such as the MDF are especially susceptible to the first factor (Stulen and De Luca, 1982; Kiryu et al., 1998).

This first factor appears to strongly influence our results because a consistent decrease in the MFCV was seen in all subjects. The MFCV is reported to increase with muscle temperature (Bigland-Ritchie et al., 1981; Masuda et al., 1999), which may affect the MDF. Since, however, skin temperature did not change significantly during the contraction in our study, we consider the influence of muscle temperature on EMG variables to be negligible. Further, an increase in the muscle temperature, if any, should have weakened, not enhanced, our results.

An increase in the ARV with fatigue has been widely documented (Maton, 1981; Hagberg, 1981; Fuglevand et al., 1993). Unlike the MDF and MFCV, which depend on metabolic conditions of muscle tissue, the increase in the ARV has been claimed to be affected by central factors, i.e., recruitment of the motor unit and increase in its firing rate. (Moritani et al., 1985; Maton, 1981; Viitasalo and Komi, 1977). These factors are useful to compensate for reduced metabolic functions reflected in the decreased MDF and MFCV (Maton, 1981; Yamada et al., 2000). Given the observation in our study that ARV increased in all subjects, without difference in the force level between the initial and final stages of contraction, the central compensatory mechanisms as above appear to function in the tibialis anterior.

When we compared these EMG changes during contractions between aged and young subjects, we found that changes both in the MDF and MFCV were consistently smaller in aged than in young subjects. These results suggest that neuromuscular responses during fatiguing contractions differ between these two groups. The degree of the spectral shift in surface EMG with fatigue depends on the proportion with which a muscle has different types of fibers, i.e., muscles having a higher proportion of FT fibers demonstrate a greater shift to lower frequencies, due to the accumulation of by-products such as lactic acid (Komi and Tesch, 1979). The observation that relative increase in ARV tended to be smaller in the aged subjects appears to match with these peripheral fatigue mechanisms specific to the aged.

It appears therefore that aged subjects whose spectral shift is less pronounced do not reach fatigue of the same level as in young subjects, because the elderly have muscles with a higher proportion of ST fibers as described above. Moreover, the sustained load of 60% MVC is adjusted against the individual's maximum effort, which is suppressed to be smaller in aged than in young subjects (Yue et al., 2000). Both of these effects may moderate the accumulation of metabolites, thus leading to smaller EMG changes during fatiguing contractions in aged than in young subjects. These assumptions would be validated by our observation that the aged subjects could not maintain the force of 60%MVC for 60 sec, if the relative intensity of contraction was equalized for the both age groups by using electrical stimulations (Yamada et al., 2000).

The present study, using submaximal exercises and surface EMG variables, has revealed that the aged subjects cannot be fatigued as much as the young, which means that the elderly holds adaptive motor strategy to cope with age-related neuromuscular deteriorations. In the tibialis anterior muscle, however, these neuromuscular deteriorations potentially cause inadequacy in the clearance and placement of the foot during walking, which in turn may lead to stumbling and falling in the elderly. Further studies are needed to clarify the age-related change in neuromuscular control of these swift motions.

The present authors are grateful to Mr. Masao Ishizu, Governor of Taiyou Village, Ibaraki Prefecture, for giving us conveniences in collecting aged volunteers. This study was conducted as a TARA Project (Senior Researcher: Morihiko Okada) of the Center for Tsukuba Advanced Research Alliance, University of Tsukuba, financially supported in part by Special Coordination Funds of the Ministry of Education, Culture, Sports, Science and Technology, the Japanese Government.

REFERENCES

Bigland-Ritchie, B, Donovan, EF, and Roussos, CS (1981) Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *J. Appl. Physiol.*, **51**: 1300-1305.

Brody, LR, Pollock, SH, Roy, SH, De Luca, CJ, and Bartolome, C (1991) pH-induced effects on median frequency and conduction velocity of the myoelectric signal. *J. Appl. Physiol.*, **71**: 1878-1885.

De Luca, CJ (1984) Myoelectrical manifestations of localized muscular fatigue in man. *CRC Crit. Rev. Biomed. Eng.*, **11**: 251-279.

Fuglevand, AJ, Zackowski, K, Huey, K, and Enoka, RM (1993) Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. *J. Physiol.*, **460**: 549-572.

Hagberg, M (1981) Muscular endurance and surface electromyogram in isometric and dynamic exercise. *J. Appl. Physiol.*, **51**: 1-7.

Häkkinen, K (1995) Neuromuscular fatigue and recovery in women at different ages during heavy resistance loading. *Electromyogr. clin. Neurophysiol.*, **35**: 403-413.

Hara, Y, Findley, TW, Sugimoto, A, and Hamanaka, K (1998) Muscle fiber conduction velocity (MFCV) after fatigue in elderly subjects. *Electromyogr. Clin. Neurophysiol.*, **38**: 427-435.

Kameyama, O, Ogawa, R, Okamoto, T, and Kumamoto, M (1990) Electric discharge patterns of ankle muscles during the normal gait cycle. *Arch. Ohys. Med. Rehabil.*, **71**: 969-974.

Kimura, T (1996) Age-related morpho-functional changes of skeletal muscle. Cross sectional area of tibialis anterior muscle. *J. Therap.*, **78**: 155-158 (*in Japanese*).

Kiryu, T, Morishita, M, Yamada, H, and Okada, M (1998) A muscular fatigue index based on the relationships between superimposed M wave and preceding background activity. *IEEE. Trans. Biomed. Eng.*, **45**: 1194-1204.

Kogi, K and Hakamada, T (1962) Slowing of surface electromyogram and muscle strength in muscle fatigue. *Rep. Inst. Sci. Lab.*, **60**: 27-41.

Komi, PV and Tesch, P (1979) EMG frequency spectrum, muscle structure, and fatigue during dynamic contractions in man. *Eur. J. Appl. Physiol.*, **42**: 41-50.

Kranz, H, Williams, AM, Cassell, J, Caddy, DJ, and Silberstein, RB (1983) Factors determining the frequency content of the electromyogram. *J. Appl. Physiol.*, **55** : 392-399.

Laxell, J, Taylor, CC, and Sjöström, M (1988) What is the cause of the aging atrophy? Total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15-to 83-years old men. *J. Neurol. Sci.*, **84**: 275-294.

Lindström, L, Magnusson, R, and Petersén, I (1970) Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. *Electromyography*, **10**: 341-356.

Mannion, AF and Dolan, P (1996) Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. *Eur. J. Appl. Physiol.*, **74**: 411-419.

Masuda, K, Masuda, T, Sadoyama, T, Inaki, M, and Katsuta, S (1999) Changes in surface EMG parameters during static and dynamic fatiguing contractions. *J. Electromyogr. Kinesiol.*, **9**: 39-46.

Masuda, T (1985) Interface device which displays the propagation of motor unit action potentials on a television screen. *Med. & Biol. Eng. & Comput.*, **23**: 493-495.

Maton, B (1981) Frequency analysis of surface electromyogram during sustained isometric contractions. *Eur. J. Appl. Physiol.*, **43**: 173-182.

Moritani, T, Muro, M, Kijima, A, Gaffney, FA, and Persons, D (1985) Electromechanical changes during electrically induced and maximal voluntary contractions: surface and intramuscular EMG responses during sustained maximal voluntary contraction. *Exp. Neurol.*, **88**: 484-499.

Naeije, M and Zorn, H (1982) Relation between EMG power spectrum shifts and muscle fibre action potential conduction velocity changes during local muscular fatigue in man. *Eur. J. Appl. Physiol.*, **50**: 23-33.

Okada, M (1971) Some properties of the 'global' electromyogram in man as revealed by frequency analysis. *J. Fac. Sci. Univ. Tokyo*, **4**: 61-80.

Okada, M, Yamada, H, Oda, T, Kizuka, T, Shiozaki, T, Kuno, S, and Masuda, T (2000) Age-related changes in the conduction velocity and spectral variables of myoelectric signals detected from the tibialis anterior with surface electrode array. *In* Proc. 13th Congress Int. Society of Electrophysiology and Kinesiology, Sapporo, pp. 225-229.

Porter, MM, Vandervoort, AA, and Laxell, J (1995) Aging of human muscle: structure, function and adaptability. Scand. *J. Med. Sci. Sports*, **5**: 129-142.

Roos, MR, Rice, CL, Connelly, DM, and Vandervoort, AA (1999) Quadriceps muscle strength, contractile properties, and motor unit firing rates in young and old men. *Muscle Nerve*, **22**: 1094-1103.

Sadoyama, T, Masuda, T, and Miyano, H (1983) Relationships between muscle fibre conduction velocity and frequency parameters of surface EMG during sustained contraction. *Eur. J. Appl. Physiol.*, **51**: 247-256.

Sadoyama, T, Masuda, T, and Miyano, H (1985) Optimal conditions for measurement of muscle fiber conduction velocity using surface electrode arrays. *Med. Biol. Eng. Comput.*, **23**: 339-342.

Sadoyama, T, Masuda, T, Miyata, H, and Katsuta, S (1988) Fibre conduction velocity and fibre composition in human vastus lateralis. *Eur. J. Appl. Physiol.*, **57**: 767-771.

Schwendner, KI, Mikesky, AE, Holt, WSJr., Peacock, M, and Burr, DB (1997) Differences in muscle endurance and recovery between fallers and nonfallers, and between young and older women. *J. Gerontol. A Biol. Sci. Med. Sci.*, **52**: 155-160.

Skinner, JS and McLelan, TH (1980) The transition from aerobic to anaerobic metabolism. *Res. Quart. Exerc. Sports.*, **51**: 234-248.

Stulen, FB and De Luca, CJ (1982) Muscle fatigue monitor : A noninvasive device for observing localized muscular fatigue. *IEEE. Trans. Biomed. Eng.*, **29**: 760-768.

Viitasalo, JHT and Komi, PV (1977) Signal characteristics of EMG during fatigue. *Eur. J. Appl. Physiol.*, **37**: 111-121.

Yamada, H, Kizuka, T, Masuda, T, Kiryu, T, Shiozaki, T, and Okada, M (2000) Voluntary muscle activation estimated with twitch interpolation and endurance capacity in fatiguing isometric contractions. *In* Proc. 13th Congress Int. Society of Electrophysiology and Kinesiology, Sappro, pp. 551-557.