

Quantitative EMG Changes During 12-Week DeLorme's Axiom Strength Training

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Strength training is one of the most common exercises practiced in the field of physical therapy or sports training. However, limited methodology is available to evaluate its effect on the target muscle. This study aimed to test the hypothesis that surface electromyographic (EMG) data from both isometric and isotonic exercise can express changes within the muscle during a 12-week strength training program. Ten healthy male volunteer students (5 for training, 5 for controls) from Yonsei University were recruited for evaluation in this study. DeLorme's axiom was practiced for 12 weeks in the dominant elbow flexors and knee extensors of the training group. Tension for 1 repetition maximum and maximal voluntary isometric contraction, and surface EMG information such as the integrated EMG and three variables from the regression line of median frequency (MDF) data were measured at weeks 0, 3, 6, 9, and 12. The limb circumference was measured at weeks 0 and 12. During the strength training, which was enough for the increment of muscle strength and limb circumference, the rectified-integrated EMG and initial MDF increased with a significant linear pattern in both types of contraction. The two surface EMG variables were able to monitor the physiologic muscle changes during the training. Based on these results, we propose that these two surface EMG variables can be used for monitoring electrophysiological changes in the specific muscle that is undergoing the training program, under conditions where the contraction mode for EMG data collection is either static or dynamic.

Key Words: Surface EMG, fast Fourier transformation, integrated EMG, median frequency, strength training

Received May 20, 2004

Accepted September 27, 2005

*Both authors contributed equally to this work.

This work was supported by grants from RRC Program of MOST and KOSEF.

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INTRODUCTION

Muscle contractions can produce many metabolic, mechanical, and myoelectrical changes. The maximum mechanical force that a muscle group can generate is defined as the muscular strength.^{1,2} Many principles are involved in strength training, and many methods are available for measuring its effect.^{1,3} The increase in muscle strength during the earlier period of training comes from a neural training mechanism or an improved motor unit recruitment ability, either of which is related to a noticeable increase in electromyographic (EMG) activity.⁴⁻⁷ The increase during the later training period originates from muscle fiber hypertrophy, which occurs selectively in the fast twitch fibers.^{8,9} In addition, biopsy studies have shown that long-term strength training has a selective hypertrophic effect on the fast twitch fibers.^{2,9,10} Based on their contractile characteristics, muscle fibers are typically classified into slow twitch (type I) and fast twitch (type II) fibers, even though other subtypes have been described.^{2,11} Therefore, fast twitch fibers can be regarded as the key factor for the functional changes arising from strength training.¹²

Since Henneman et al. first proposed the 'size principle', many quantitative EMG studies on time domain, and/or frequency domain analysis of muscle contraction have been practiced.^{13,14} Time domain analysis uses either root mean square (RMS) or integrated EMG to represent the amplitude of an EMG signal, and frequency domain analysis uses the frequency spectrum

analysis.^{14,15} The RMS and integrated EMG depend on the number of recruited motor units in addition to their firing rate.¹⁶ A large amount of evidence exists showing that the changes in the frequency spectrum analysis of local muscle fatigue can provide information on the type of muscle fiber recruited.¹⁷⁻²⁰ When the frequency spectrum is represented by the median frequency (MDF), its change is dependent on both the number of recruited fast twitch fibers and the muscle fiber conduction velocity.^{14,20,21} As local muscle fatigue (LMF) develops, the muscle fiber conduction velocity decreases, less fast twitch fibers are recruited, and the MDF shifts toward a lower frequency area.²²⁻²⁴ Although the LMF is a mechanical property by definition, researchers have demonstrated that the time-trend of the MDF reliably represented an LMF in isotonic muscle contractions as well as in static contractions.²⁴⁻²⁶ Therefore, the MDF can be regarded as a valid indicator of the level of LMF, which is particularly sensitive to the changes in the fast twitch fibers.¹⁹ In addition, previous studies have suggested that the MDF can be used as a non-invasive electrophysiological muscle biopsy because it can represent the activity of the fast twitch fibers in a given muscle.²⁷⁻²⁹

These facts suggest that EMG analysis can represent the changes in the muscle during long-term strength training. Strength training is one of the most common exercises practiced in the field of physical therapy or sports training. However, its effect on the target muscle has only been evaluated using limited methods. The muscle circumference increases only at a slow rate, and mechanical devices that measure the contraction power still require cooperation from the subject. Furthermore, those measurements are not performed on specific muscles, but on a group of agonists. Several studies have examined the possibility that EMG data can measure the effect of strength training using integrated EMG and RMS, but few studies have been conducted using frequency spectrum analysis.^{5,15} Because all of the aforementioned studies used the EMG data collected from isometric exercises, the isotonic exercises that are related to activities associated with daily living and sports require further study.³⁰ The difficulty in studying the frequency charac-

teristics of EMG from isotonic contraction lies in the instability of the signal due to the continuous changes in the muscle length and tension, distance between the electrode and the muscle, and the position of the electrodes.^{26,31} In addition, relatively fluctuating blood circulation within the muscle undergoing isotonic contraction causes fewer chemical changes inside, and causes fewer changes in the MDF.^{32,33}

Recent studies have shown that the shift in the frequency power spectrum during isotonic contractions can be better expressed by median frequency (MDF) than by mean frequency (MNF).^{15,20,34} Therefore, the MDF was adopted for both the isometric and isotonic contractions in this study. However, the MDF data from isotonic exercises has a great deal of noise involved with each joint motion. This made it difficult to identify any definite decline trend during the development of local muscle fatigue. In order to compensate for these difficulties, this study adopted the following conditions from the results of our preliminary studies: 1) consecutive overlapping fast Fourier transformation, which is resistant to the instability of the EMG signal, and 2) variables from the linear regression line (initial MDF, fatigue index, slope), which represent the shift pattern of the MDF through time.³⁵⁻³⁷

This study examined the hypothesis that the quantitative analysis of the surface EMG from both isometric and isotonic contractions can express the changes within the muscle during 12 weeks of strength training. The aim was to determine if the surface EMG could be used to monitor the electrophysiological changes in the specific muscle throughout a training program, and whether the contraction mode for collecting the EMG data is static or dynamic.

MATERIALS AND METHODS

Subjects

Ten healthy male volunteer students (5 for training, 5 as controls) from Yonsei University were enrolled in this study. The exclusion criteria were regular strength training or a history of musculoskeletal or neurological disorders. This

research protocol was reviewed and approved by the research ethical committee of Yonsei University, and informed consent was obtained from each subject. The average age of training group was 22.90 ± 2.10 years, height was 165 ± 4 cm and weight was 63.60 ± 5.00 kg. The average age of the control group was 26.30 ± 3.60 years, height was 166 ± 5 cm and weight was 65.80 ± 6.30 . The age, height, and body weight of the control and training groups were similar ($p > 0.05$).

Experimental design

A 12-week strength training period was initiated after measuring the initial maximum strength and EMG signal, and the measurements were repeated every three weeks (weeks 3, 6, 9, 12). In order to avoid the effect of muscle fatigue on the EMG characteristics, the maximum strength measurement was performed approximately 48 hours before measuring the EMG signals. The circumferences of the upper arm and thigh were measured at the marked position on a central metal bar of the active EMG electrode on weeks 0 and 12. These measurements were repeated for the control subjects only on weeks 0 and 12.

Maximal strength

The tension for the maximal voluntary isometric contraction (MVIC), which is the static strength, was recorded in kilograms using a digital tensiometer TSD121C (BIOPAC System Inc. CA, USA, Fig. 1. A), in which a fixed rope was connected to either the wrist or ankle cuff. Analog signals from the device were converted to digital data using the MP100 system (BIOPAC System Inc. CA, USA). The sampling rate for the TSD121C was 125 Hz, and the cut-off frequency for the low pass filter was 5 Hz.

For the MVIC test of the elbow flexor, the subject stood erect with both his back and posterior surface of the upper arm in contact with the wall behind, the shoulder joint in the anatomical position, the elbow joint flexed to 90° , and the forearm supinated. This avoided the supinating effect of the biceps brachii. For the MVIC of the knee extensor, the subject sat on the N-K table (Preston, NJ, USA) and the knee joint was fixed

at 70° flexion using Velcro and an outrigger on an N-K table. The subjects were instructed to maintain the MVIC for at least 3 seconds, and the average tension for 1 second before and after the maximum peak was determined as the tension for the MVIC trial. After three trials, with 10-minute rests in between, the maximum of three trials was determined to be the MVIC for each subject.

The isotonic strength, which is the dynamic strength, is presented as kilogram per 1 repetition maximum (RM). A chest pulley weight (Preston, MI, USA) was used for the elbow flexor, and an N-K table was used for the knee extensor. The required range of motion was $0-135^\circ$, and $0-110^\circ$, respectively. 1 RM was calculated using equation (1), where W_0 is the weight capable of 7-8 repetitions for the subject, and R is the maximal number of repetitions practiced. The 1 RM value was rounded up to the first decimal.³⁸ Eighty percent of the 1 RM was used as 10 RM.

$$1 \text{ RM} = W_0 + W_1, \quad W_1 = W_0 \times 0.025 \times R \quad (1)$$

Strength training

DeLorme's axiom was practiced on the dominant elbow flexors and knee extensors in the training group for 12 weeks. Exercise was performed on Monday, Wednesday, and Friday of each week. The exercise program for each day was to repeat each set of exercises three times with 2-minute rest intervals in between. Each set was composed of a series of progressive load: 10 repetitions at 50% of the 10 RM, 10 repetitions at 75% of the 10 RM, and 10 repetitions at 100% of the 10 RM. A 5-minute warm-up exercise was practiced prior to every training exercise. The 10 RM, which was used to determine the load for the DeLorme's axiom was measured at week 0 and every three weeks thereafter. For the 12 weeks of training, both the control and training groups were allowed to participate in various recreational low-intensity physical activities such as walking, jogging, or bicycle riding.

Surface EMG acquisition

The surface active EMG electrodes, Bagnoli DE3-1 (DeSys Inc. MA, USA), contained a double differential pre-amplifier (gain: $\times 10$), which was

resistant to motion artifact and crosstalk. The skin contact sites of the electrode contained three silver bars, each 1 mm wide and 10 mm long, fixed 10 mm apart and placed in parallel on a plastic housing. The biceps brachii and the rectus femoris, which were the locations for the EMG record, acted as primer movers of the elbow joint flexion and knee joint extension, respectively.³⁹⁻⁴¹ Those features can be regarded as being suitable for inducing changes through strength training which are recognizable with the surface EMG. The middle bar acts both as an active and reference electrode, and the other two bars are composed two separate differential amplifiers in parallel. The output signals from the two amplifiers were passed through a third differential amplifier to obtain the differences as the final output of the active electrode. The middle bar of the active electrode was placed on the lower 1/3 of the biceps brachii's muscle belly that was palpable at 90° of elbow flexion, and the midpoint was placed on the rectus femoris between the anterior superior iliac spine and the patella. The dominant arm and

leg, which were the right arm and leg in every subject, were used for measurements. The locations for placing the electrode were marked with dermatographic ink in order to maintain the same place during the 12-week training program. Prior to electrode placement, the skin was scrubbed with fine sand paper and alcohol-soaked cotton. The ground electrode was placed on the ipsilateral dorsum of the hand or patella.

The EMG signal went through a Bagnoli DE3-1 EMG amplifier, and was sent to a MP100 A/D converter, and then to "Acknowledge" software (BIOPAC System Inc. CA, USA) on a PC for processing and saving. The sampling rate was 1,024 Hz, the bandwidth was 20-450 Hz, and a 60 Hz notch filter was used (Fig. 1).

Fatiguing isometric and isotonic exercise was practiced in order to obtain a valid fast Fourier transformation (FFT) from the surface EMG data. For the isometric exercise, the subjects were encouraged to maintain $80 \pm 5\%$ of the MVIC for the elbow flexor or the knee extensor for 12 seconds while the EMG was recorded.¹⁵ In order

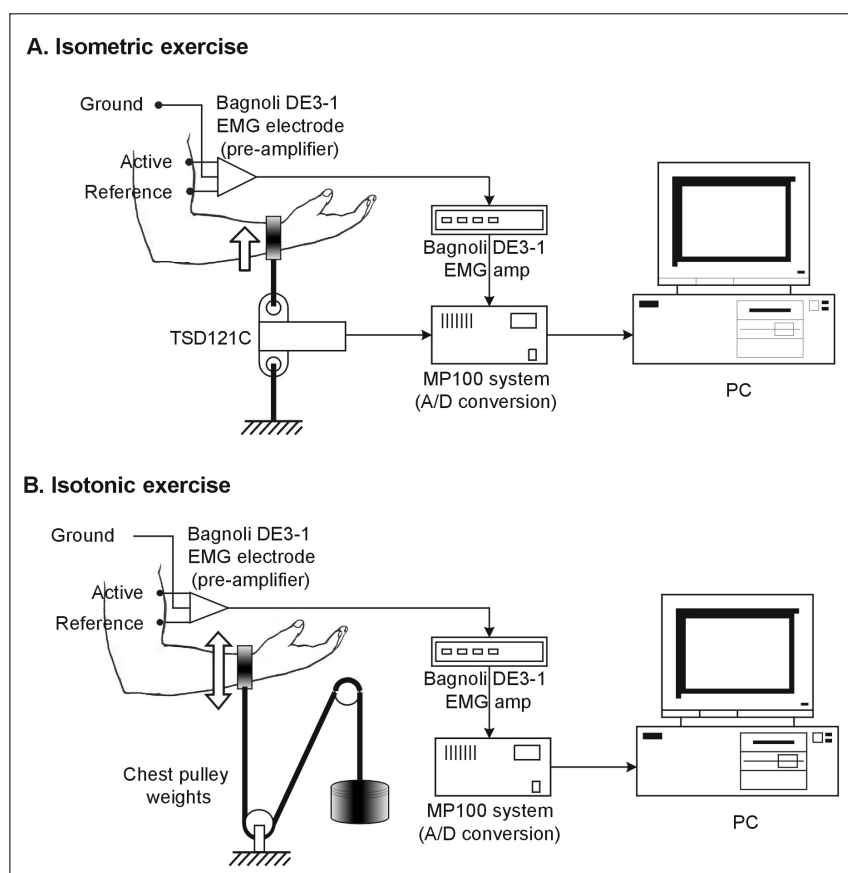


Fig. 1. Experimental setup.

to help maintain tension, the visual feedback of the tension data from the TSD121C together with the target tension were provided. The EMG data for the middle 8 seconds of the isometric exercise, excluding the rather unstable first and last two seconds of the 12-second long data collection period, were accepted as being valid and were subsequently analyzed. For the isotonic exercise, 10 repetitions of flexion and extension with a 10 RM load were practiced while the EMG was recorded. The EMG data for the middle 8 repetitions, which excluded the rather unstable first and last two repetitions, were accepted as being valid for analysis.

EMG signal processing and statistics

The level of EMG activity is presented with the rectified-integrated EMG for the whole valid period of each contraction session. In an isometric contraction, the value for the middle 8 seconds at week 0 (prior to strength training) was used to normalize the integrated EMG for the following 12 weeks. In the isotonic contraction, the value for the middle 8 contractions at week 0 was used for the same purpose.

Fig. 2 shows the process for FFT analysis using the LabView application. 42 all the epochs for the FFT had 512 data points that were 0.5 seconds long. Each epoch was overlapped with the next epoch by 75% (128 points) of the epoch length, and a total of 8 FFTs per second were performed.

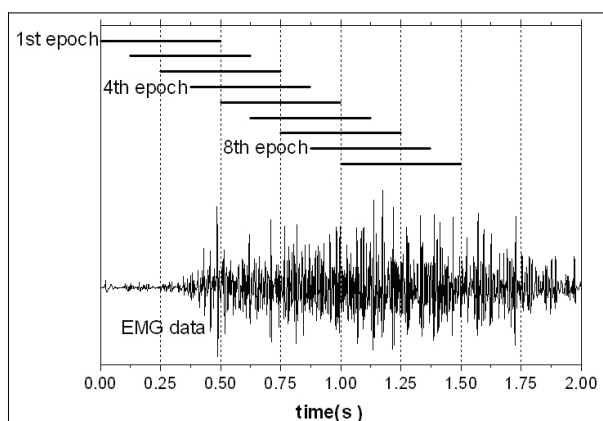


Fig. 2. Concept of consecutive overlapping FFT (fast Fourier transformation). Sampling rate = 1,024 per second, epoch length = 512, data = 0.5 second. If sliding gap is 128, data = 8 FFTs per second.

A series of MDF data was derived from the successive FFT for the whole length of the valid EMG data.

Three MDF regression line variables were employed using the linear regression analysis of MDF data against time 't' to express the characteristics of the decline trend: the slope of the line, the y intercept (initial MDF), and the fatigue index of equation (2).^{43,44} The initial MDF can express the composition of the fast twitch fibers in a given muscle.^{22,37} The slope means the rate of the development of local muscle fatigue and the fatigue index expresses the level of fatigue that occurs in a given muscle, which is sensitive to the fatiguing of the fast twitch fibers. In addition, the last MDF was calculated using the regression equation by substituting time t at the end of the valid data. All values from the MDF regression line, the 1 RM, and the MVIC at week 0 were used as the normalization standard for the following 12 weeks.

$$\text{Fatigue Index} = \frac{\text{initial MDF} - \text{last MDF}}{\text{initial MDF}} \quad (2)$$

Two-way ANOVA for repeated measure was practiced to test the effect of strength training on the dependant variables during the 12 weeks. Before and after the 12 weeks of training, comparison within the training subject was performed with a paired t-test. The comparison between the control and training groups at week 12 was done with independent t-tests. SPSS for Windows (version 10.0, SPSS Inc. Chicago, IL, USA) was used for all of the statistical analysis with the significance level of 0.05.

RESULTS

Limb circumference

The limb circumference of both upper arm and thigh in subjects from the training group increased significantly after the 12-week training period ($p < 0.05$). The control group did not show such changes (Table 1).

Muscle strength and integrated EMG (IEMG)

The changes in muscle strength and the inte-

Table 1. Changes of Limb Circumference

Group	Limb	Pre-training circumference (cm)		Post-training circumference (cm)		Mean difference (cm)
		Mean	SD	Mean	SD	
Training (n = 5)	Upper arm	28.9	2.26	29.82	2.17	0.92*
	Thigh	46.24	2.14	48.3	1.31	2.06*
Control (n = 5)	Upper arm	28.44	1.57	28.54	1.47	0.10
	Thigh	46.5	2.41	45.76	2.34	0.16

*paired student's *t*-test.*p* < 0.05.**Table 2.** Two-way Repeated ANOVA for Relative Strength and Relative IEMG

Exercise	Pattern of influence	Strength (MVIC or 1RM)			IEMG		
		M	W	M*W	M	W	M*W
IM	Linear	0.34	88.106*	0.59	2.54	47.53*	2.70
	Quadratic		12.326*	0.44		4.99	0.67
	Cubic		0.62	0.00		0.14	0.90
IT	Linear	10.25	55.04*	18.03*	1.35	18.63*	1.29
	Quadratic		72.76*	0.21		3.61	2.45
	Cubic		0.79	0.00		2.70	2.09

Number in the cell is F values of ANOVA test.

MVIC, maximal voluntary isometric contraction; 1RM, 1 repetition maximum; M, muscles repeat effect; W, weeks repeat effect; M*W, cross repeat effect of muscles and weeks; IM, isometric exercise; IT, isotonic exercise.

**p* < 0.05.

grated EMG were monitored using the relative values that normalized to values from week zero. In both isometric and isotonic exercise, the relative IEMG showed a significant linear increase during the 12-week training period (*p* < 0.05, Table 2, Fig. 3). The relative MVIC for the isometric contraction or the relative 1 RM for the isotonic contraction increased significantly in a linear-quadratic pattern (*p* < 0.05), which meant that the increase was rapid in the earlier period and slower in the later period.

The muscle difference had no significant influence on the patterns of change (Table 2). When the training was complete, both the muscle strength and IEMG of the training group were significantly higher than those of the control group (*p* < 0.05).

MDF variables

The relative initial MDF increased with a significant linear pattern in both types of exercise (*p* < 0.05, Table 3, Fig. 4). In subjects undergoing isometric exercise, the relative initial MDF also showed a significant cubic pattern of change, which indicated an increase-decrease-increase pattern (*p* < 0.05). When the training was complete, the relative initial MDF of the training group was found to be significantly higher than that of the control group (*p* < 0.05).

Both the relative fatigue index and the relative slope change during the training period were not significant due to the large amount of variation (Table 3, Fig. 5, 6). Comparison of the training vs. the control group at the end of training showed

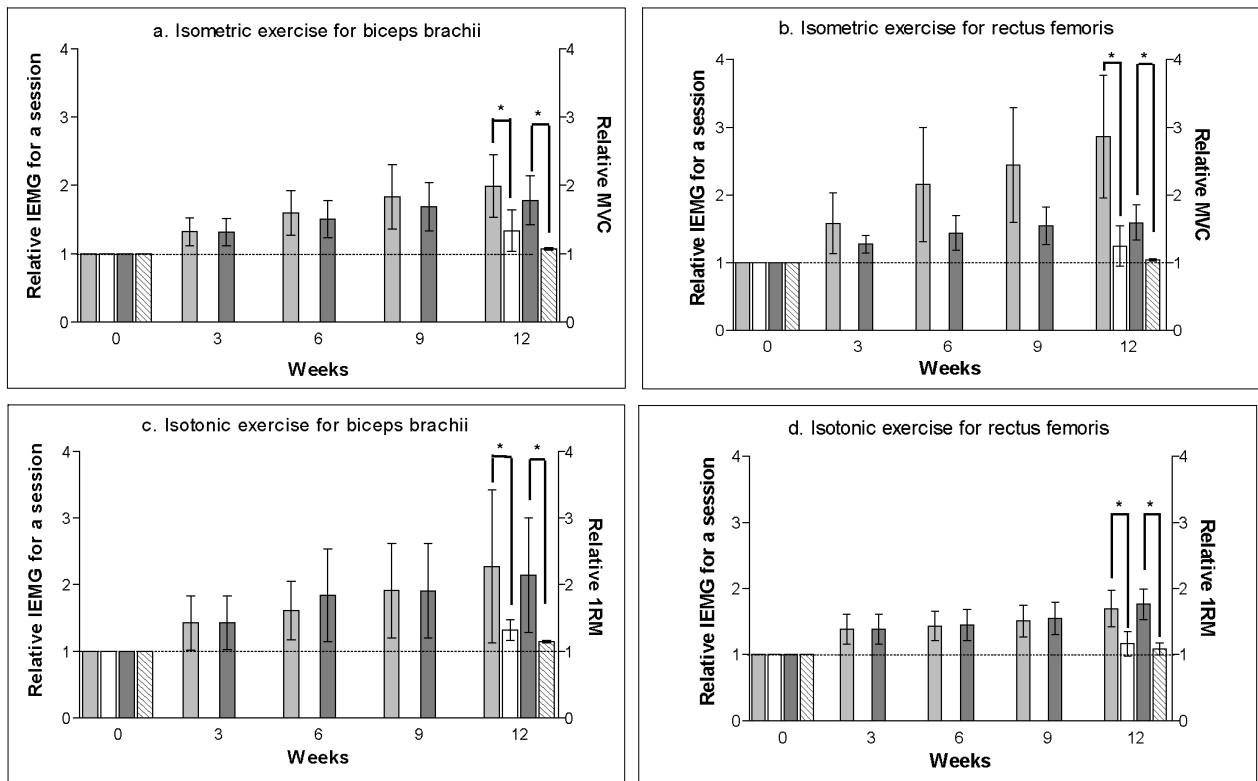


Fig. 3. Comparison of changes in IEMG and MVC. ■ IEMG of the training group (n = 5), □ IEMG of the control group (n = 5), ■ isometric MVC or isotonic 1RM of the training group (n = 5), □ isometric MVC or isotonic 1RM of the control group (n = 5). IEMG: integrated EMG. 1RM: one repetition maximal. MVC: maximal voluntary contraction. *: significant differences ($p < 0.05$) by independent t-test. All the values were normalized and presented as "relative" values. Dotted horizontal line indicates the standard for normalization.

Table 3. Two-way Repeated ANOVA for Relative MDF Variables

Exercise	Pattern of influence	IMDF			Fatigue index			Slope		
		M	W	M*W	M	W	M*W	M	W	M*W
IM	Linear	1.17	25.94*	0.87	2.35	0.5	4.64	2.47	1.24	0.66
	Quadratic		0.13	0.27		0.73	0.10		2.73	0.00
	Cubic		10.79*	0.25		1.7	0.34		0.03	0.26
IT	Linear	0.36	28.56*	0.62	0.29	0.14	0.00	0.56	0.13	0.84
	Quadratic		1.92	0.26		0.72	0.74		0.23	0.04
	Cubic		2.32	0.32		0.15	1.01		0.96	0.27

Number in the cell is F values of ANOVA test.

IMDF, initial median frequency; M, muscles repeat effect; W, weeks repeat effect; M*W, cross repeat effect of muscles and weeks; IM, isometric exercise; IT, isotonic exercise.

* $p < 0.05$.

a significant difference in only two variables: the relative fatigue index of isometric exercise in the biceps brachii, and the relative slope of isotonic

exercise in the rectus femoris (Fig. 5, 6). These differences are potentially indicative of an increased resistance to the development of local muscle

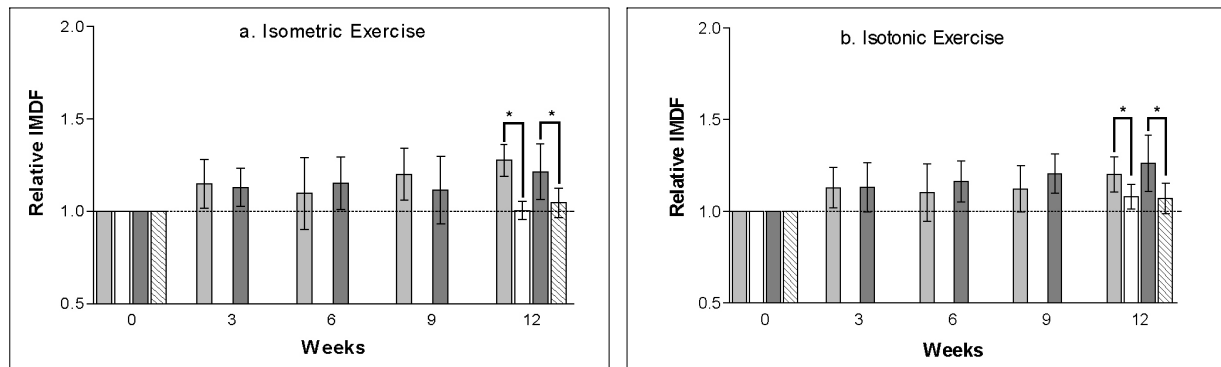


Fig. 4. Changes of initial median frequency. ■ biceps brachii of the training group (n = 5), □ biceps brachii of the control group (n = 5), ■ rectus femoris of the training group (n = 5), ▨ rectus femoris of the control group (n = 5). IMDF: initial median frequency. *: significant differences ($p < 0.05$) by independent t-test. All the values were normalized and presented as "relative" values. Dotted horizontal line indicates the standard for normalization.

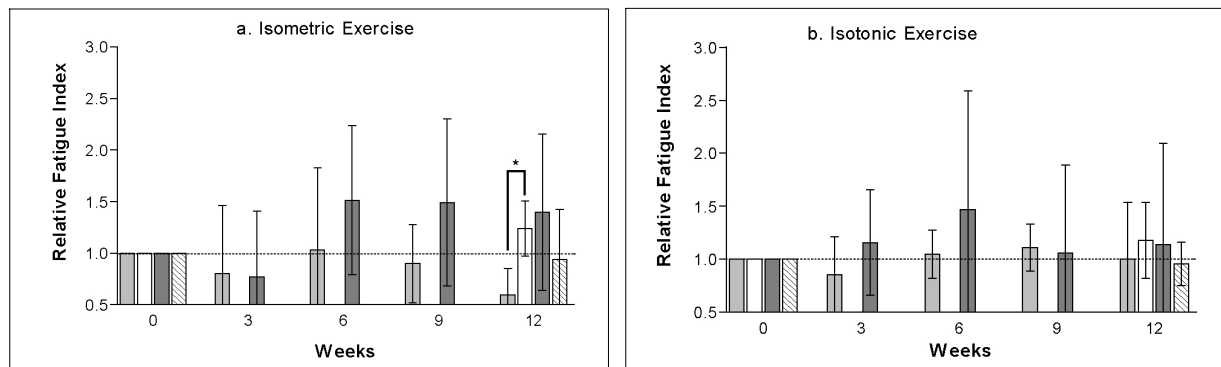


Fig. 5. Changes of fatigue index. ■ biceps brachii of the training group (n = 5), □ biceps brachii of the control group (n = 5), ■ rectus femoris of the training group (n = 5), ▨ rectus femoris of the control group (n = 5). *: significant differences ($p < 0.05$) by independent t-test. All the values were normalized and presented as "relative" values. Dotted horizontal line indicates the standard for normalization.

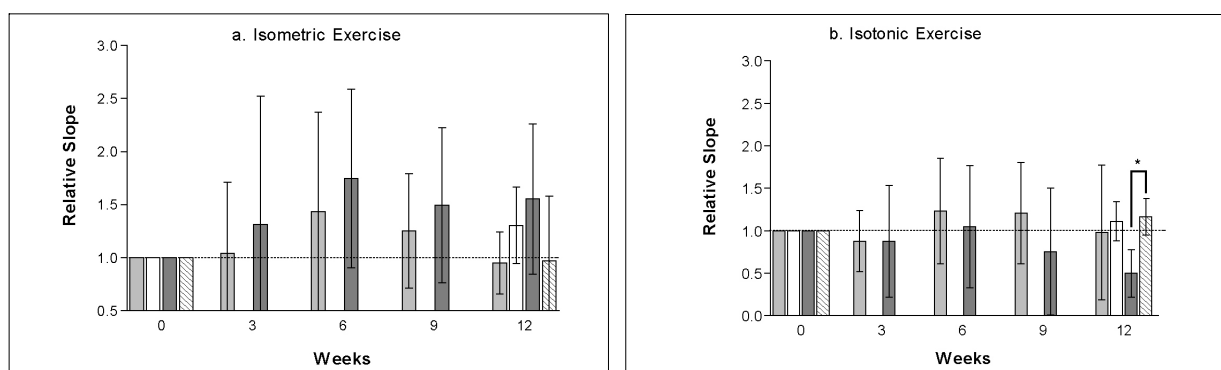


Fig. 6. Changes of regression slope. ■ biceps brachii of the training group (n = 5), □ biceps brachii of the control group (n = 5), ■ rectus femoris of the training group (n = 5), ▨ rectus femoris of the control group (n = 5). *: significant differences ($p < 0.05$) by independent t-test. All the values were normalized and presented as "relative" values. Dotted horizontal line indicates the standard for normalization.

fatigue.

The difference in muscle type had no significant

influence on the patterns of change in all the MDF variables (Table 3).

DISCUSSION

In previous studies, the FFT has been applied to the consecutive epochs of the EMG data to obtain a series of MDF values. However, this method does not appear to be appropriate when applied to non-stationary EMG data from isotonic exercise. A recently introduced method of overlapping consecutive epochs has the ability to increase the number of FFT epochs, provide more representative MDF values, and increase the processing speed on personal computers without the need for additional hardware.⁴⁵⁻⁴⁸ Until now, the number of consecutive overlapping FFT epochs per second was < 4 . Recently, a software algorithm was devised for eight consecutive overlapping FFTs per second.³⁵ Its reliability and reproducibility expressed with the intraclass correlation coefficient (ICC) was 0.92 for isometric contractions and 0.81 for the isotonic contractions, which indicated good-to-excellent reliability for both types of contractions.⁴⁹

A definite enlargement of the limb circumference occurred as a result of the strength training. This could be seen as muscle hypertrophy; however, an MRI or biopsy study will be needed to confirm these findings. During the 12-week training, the maximum muscle strength increased rapidly in the earlier period and less rapidly in the later periods, irrespective of the muscle types tested. This finding agrees with previous reports showing that sufficient strength training for an untrained subject has a larger effect in the earlier stage of training.⁵⁰ Our DeLorme's axiom for the 12 weeks can be regarded as being sufficient to produce observable and significant changes to the target muscles.

Moritani and Devries reported that muscle strength improvement in untrained normal adults depends on the level of neural adaptation in the earlier stage and muscle hypertrophy in the later stage.⁶ According to Hakkinen and Komi, the earlier period of strength training during the 12-week program showed a large increase in the maximum IEMG and minor muscle hypertrophy.⁵ During the later period of their study, the maximum IEMG increased at a diminishing rate while the level of muscle hypertrophy was greater, thereby contributing to

the improvement in the maximal muscle strength.⁵

In this study, the muscle strength of the subjects improved at a greater rate in the earlier period, and the pattern of the serial change fit into both the linear and quadratic pattern significantly ($p < 0.05$). It is possible that this is due to the strength response for neural adaptation in the earlier period being larger than that for muscle hypertrophy.^{7,8} The rectified IEMG represents the amount of the EMG signals that is proportional to the firing rate, synchronization, and the number of motor units.^{7,8,14} The serial pattern of IEMG changes fitted significantly into a linear model ($p < 0.05$), which might be due to the rather slow shift in the mechanism for the muscle response from neural adaptation to muscle hypertrophy.

The initial MDF can represent the recruitment and/or composition of the fast twitch fibers in a given muscle.^{20,21} Its increase during strength training can be due to the increase in the recruitment of the fast twitch fibers in the earlier period, and the increase in their composition in the later period.^{51,52} Therefore, the change in the initial MDF during training can be interpreted in a similar way as the change in the IEMG. The significantly higher IEMG and initial MDF at week 12 in the training group indicate significant expression of the training-induced physiological muscle changes.

Both the fatigue index and slope showed a great deal of variation between subjects, obscuring any definite pattern during the training period. Some of the comparisons with the control group at week 12 were significant, indicating that training made the muscle more resistant to muscle fatigue. In the earlier period, the initial MDF increased as a result of the increase in the recruitment of fast twitch fibers, while the fatigue index and slope tended to increase over the same period due to the characteristics of fatigability. In the later period, the initial MDF tended to increase continuously while the fatigue index and slope decreased. This suggests an increase in fatigue resistance due to the increase in the recruitment and composition of the fast twitch fibers, as a result of the remodeling of the type IIB fibers to type IIA fibers.^{9,53} However, the change in muscle fiber composition still needs to be verified using

a muscle biopsy study, which was lacking in this study. These findings can be applied to any major limb muscle for strength training because none of the variables mentioned above showed significant differences between the different muscle types examined. However, it is possible that the small number of subjects was a major limitation in the statistical analysis.

During the strength-training program, which was sufficient to increase the muscle power and limb circumference, the IEMG and initial MDF increased linearly in both the static and dynamic exercise used in this study. Therefore, the two surface EMG variables can be used to monitor physiological muscle changes during training. These results suggest that the EMG data (whether the contraction mode for collection is static or dynamic) can be used monitor the electrophysiological changes in a specific muscle undergoing training.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Kwang-Suk Cha for his advice about the strength-training program. Our experiments complied with the current laws of Republic of Korea in which the experiments were performed.

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