


# Characteristics of Lower Limb Muscle Activity in Elderly Persons After Ergometric Exercise

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## Abstract

This study examined the characteristics of lower limb muscle activity in elderly persons after ergometric pedaling exercise for 1 month. To determine the effect of the exercise, surface electromyography (SEMG) of lower limb muscles was subjected to Daubechies-4 wavelet transformation, and mean wavelet coefficients were compared with the pre-exercise coefficients and the post-exercise coefficients in each wavelet level. The characteristics of muscle activity after pedaling exercise were also compared between the elderly subjects and young subjects. For the elderly subjects, the mean wavelet coefficients were significantly decreased in the tibialis anterior and the gastrocnemius medialis at wavelet levels of 3, 4, and 5 (125–62.5, 62.5–31.25, and 31.25–15.625 Hz, respectively), by pedaling exercise. However, the mean power of wavelet levels of 2 and 3 (250–125 and 125–62.5 Hz) within the rectus femoris and the biceps femoris were significantly increased in the young subjects. The effect of pedaling exercise is different from the effects of heavy-resistance training. It was suggested that the muscle coordination, motor unit (MU) firing frequency, and firing fiber type of lower limb muscles are changed with the different characteristics between elderly and young persons by pedaling exercise for 1 month.

## Keywords

elderly person, lower limb muscles, pedaling exercise, surface electromyography, wavelet analysis

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## Introduction

Japan has the highest proportion of elderly citizens in the world. It is called a “super-aging society” (Muramatsu & Akiyama, 2011). Falls and bone fracture are some of the main causes for requiring care (Panel on Prevention of Falls in Older Persons American Geriatrics Society and British Geriatrics Society, 2011; Tinetti & Williams, 1997). Numerous studies have examined how prevention of falls and bone fractures (Neyens et al., 2011; Stubbs et al., 2015 and references therein), multifactorial fall prevention intervention (e.g., Tinetti, 2003) and resistance training (Buchner et al., 1997; Dyer et al., 2004; Schnelle et al., 2003; Webber & Porter, 2010) are effective in reducing the risk of falling among elderly persons. Lower limb muscle strength played a key role in preventing falls, and muscle exercises had a beneficial effect on muscle strength in elderly persons (Pijnappels et al., 2008; Suzuki et al., 2004). In the last two decades, a large number of studies have been conducted on the effect of resistance training on muscle

strength, power, and selected functional abilities in elderly subjects (e.g., Macaluso & De Vito, 2004 and references therein). These studies have reported that heavy-resistance training for muscles has been shown to increase muscle strength and size even in elderly persons. However, few studies have been conducted thus far on ergometric pedaling exercise in elderly persons from the viewpoint of an isokinetic exercise. Ergometric pedaling exercise is a functional, safe, and accessible mode of exercise for patients with a wide range of ambulatory capability (Fujiwara et al., 2003).

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In this study, we have investigated the characteristics of lower limb muscle activity in elderly persons after ergometric pedaling exercise. To determine the effect of the exercise, the electromyographic activity (electromyography; EMG) of the lower limb muscles while pedaling has been compared with the pre-exercise and the post-exercise activity. Hug and Dorel (2009) have shown in full detail the method of electromyographic analysis while pedaling. They have remarked that the extraction of information from the electrical signal generated by the activated muscles has been regarded as an easy way to gain access to the less accessible activity of motor control centers. In our study, the surface EMG (SEMG) waveforms for the lower limb muscular activations while pedaling were evaluated by using of Wavelet Transform (WT).

The WT is interesting for the analysis of non-stationary signals, because it provides an alternative to the classical Short-Time Fourier Transform or Gabor transform. The transform produces time series of coefficients at different scales, each corresponding to a different range of frequencies (Issartel et al., 2006; Rioul & Vetterli, 1991; Torrence & Compo, 1998). Wavelet analysis using the WT is becoming a common tool for analyzing localized EMG data variations of power within a time series and a frequency. The wavelet analysis has been used to study muscle fatigue (Beck et al., 2005a; Bilgin et al., 2015; Chowdhury & Nimbarte, 2015; Graham et al., 2015; Sparto et al., 1999), neuromuscular disorders (Doulah et al., 2014; Prosser et al., 2010; Sacco et al., 2014; Tomczykiewicz et al., 2012), and single MUs (Fang et al., 1999; Flanders, 2002; Gazzoni et al., 2004; Pham et al., 2014; Ren et al., 2006). The WT of SEMG is informative in understanding the characteristics of muscle activity, which include the MU firing frequency, number of recruited MUs, and fiber type. The purpose of this study was to assess the effect of pedaling exercise on elderly persons from the viewpoint of mechanisms of muscle activity and kinesiological motor skills.

## Methods

### Subjects

The study was carried out on seven healthy elderly subjects and eight healthy young subjects. The elderly subjects consisted entirely of females, the eldest of which was 90 years old (age:  $77.3 \pm 13.0$  years; body mass:  $52.0 \pm 7.3$  kg; height:  $150.8 \pm 6.5$  cm).

The college students engaged in the study voluntary as the young subjects (age:  $23.6 \pm 3.3$  years; weight:  $60.9 \pm 6.7$  kg; height:  $159.4 \pm 2.9$  cm). None of the subjects were daily bicycle users and none were in any specific training program at the time of the study. They had no history of neuromuscular disorders. All participants provided written informed consent before participating in the study as approved by the University Institutional Review Board.

### Procedures and Exercise Regimen

All subjects participated in an ergometric pedaling for a month. Firstly, subjects sat on an ergometer (M3 INDOOR CYCLE, KEISER, USA) in a sitting position. A height of saddle was determined by a knee flexion angle. The knee flexion angle was measured by using of joint angle sensor (MLTS700 Goniometer, ADInstruments, New Zealand). The knee flexion angle was fixed 40 degrees at a bottom dead center. Their toenails were clipped down using clippers to exercise lower limb muscles during a knee flexion phase. The ergometer was set in constant power mode, and the subjects maintained a cadence of approximately 75 rpm. Repetition cadence was set by an electrical metronome. After a standardized warm-up, subjects were asked to perform a pedaling exercise at a constant power output equal to 60% of the maximal power. The maximal power was detected as the pedaling load which was no longer pedaled by each subject. Pedaling exercise was carried out two times a week. The exercise was performed for 15 minutes of each pedaling exercise under the monitoring and guidance of the experimenter.

### Data Collection

SEMG signals were recorded simultaneously from four right leg muscles: rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius medialis (GM) by using a wireless EMG system (Trigno Wireless System, DELSYS, USA) during the pedaling movement. The reason why these four muscles were selected is that they are the main lower limb muscles that generate the pedaling movement (Hug & Dorel, 2009). Hug et al. (2010) identified three muscle synergies during pedaling in trained cyclists from the view point of muscle synergy vectors and synergy activation coefficient. They suggested that the synergy 1 consisted of gluteus maximus, soleus, and three muscles of the quadriceps group (i.e., RF); the synergy 2 consisted of activity in the hamstrings group (i.e., BF) and the plantar flexors (i.e., GM); the synergy 3 mainly consists of the activity in the RF and TA. Before the wireless EMG electrodes were attached to these muscles, the skin was shaved and cleaned with rubbing alcohol. The wireless EMG electrodes were placed longitudinally with respect to the underlying muscle fiber arrangement and were located according to the recommendations of SENIAM (Hermens et al., 2000). Since comparing SEMG amplitude between different muscles does not provide any information about the degree of activation, normalization of EMG amplitude is recommended (Rainoldi et al., 2016). However, there is no agreement for the best normalization procedure. It is well known that the SEMG signal is influenced by the relative location between the electrode and the innervation zone. In this study, a pattern of neuromuscular activation was monitored before putting electrodes on the muscles to avoid the innervation zone.

These electrodes were well secured with adhesive tape and surgical tape to avoid movement-induced artifacts. The frequency range and the gain of amplifier were set from 20 to 450 Hz and 80 dB, respectively. In order to remove motion artifacts, the low cut frequency was set at 20 Hz (De Luca et al., 2010). The EMG signals were stored on a personal computer through an A/D converter (PowerLab, ADInstruments, New Zealand) with a sampling frequency of 1000 Hz.

### Signal Processing

As a wavelet analysis, a discrete wavelet transform (DWT) (Rioul & Vetterli, 1991) was applied to the SEMG data. DWT is becoming a common tool for analyzing SEMG data (Beck et al., 2005b; Chowdhury & Nimbarte, 2015; Kaneko et al., 2007; Kumaran et al., 2000). In brief, the DWT is defined as the convolution between the signal  $x(t)$ , which has its wavelet transform coefficients  $C_{j,k}$  and the wavelet functions  $\Psi_{j,k}(t)$

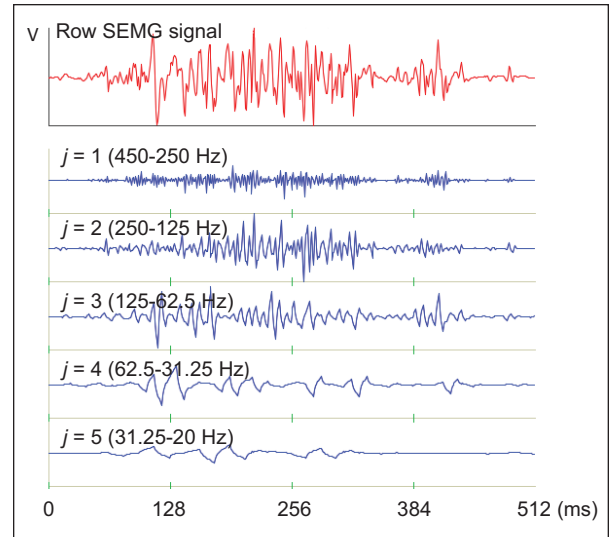
$$C_{j,k} = \int_{-\infty}^{\infty} x(t) \psi_{j,k}(t) dt, \quad (1)$$

where  $\Psi_{j,k}(t) = 2^{j/2} \Psi(2^j t - k)$  is controlled by a scale integer index  $j$  and a translation integer index  $k$ . Under some assumptions, these coefficients uniquely represent  $x(t)$ , which can be reconstructed by the following wavelet series:

$$x(t) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} C_{j,k} \psi_{j,k}(t). \quad (2)$$

In this study,  $C_{j,k}$  were estimated by using the Daubechies-4 (Daubechies, 1990) wavelet algorithm and SEMG data of 512 points in relation to the pedaling movement. EMG onset and offset thresholds were defined as 20 % of the visually determined maximum activity. EMG data analysis was conducted using software (LabChart Pro ADInstruments, New Zealand). The SEMG data were decomposed into five separate scales (i.e.,  $j=1$ : 450–250 Hz,  $j=2$ : 250–125 Hz,  $j=3$ : 125–62.5 Hz,  $j=4$ : 62.5–31.25 Hz, and  $j=5$ : 31.25–20 Hz, respectively), by analysis software (MATLAB MathWorks, USA; see Figure 1). According to Nyquist's theory, the maximum frequency of a signal is half of its sampling frequency. However, the detected signals were filtered (band-pass filter, 20–450 Hz). The maximum frequency in this study was 450 Hz.

It is debatable how to select a mother wavelet. Fang et al. (1999) focused on waveform similarity of single motor unit (SMU) potentials in the wavelet domain when using the Daubechies mother wavelet. Additionally, Flanders (2002) has also found the Daubechies mother wavelet to be useful in recognizing multiunit EMG burst. Therefore, the Daubechies mother wavelet can be employed for this signal processing. Finally, to examine



**Figure 1.** Schematic diagrams illustrating discrete wavelet transform with Daubechies-4 wavelet algorithm. A row SEMG signal was decomposed into five frequency bands ( $j=1$ : 450–250 Hz,  $j=2$ : 250–125 Hz,  $j=3$ : 125–62.5 Hz,  $j=4$ : 62.5–31.25 Hz, and  $j=5$ : 31.25–20 Hz, respectively). An amplitude of decomposed waveform showed a value of  $C_{j,k}$  at wavelet decomposed level  $j$  and time domain  $k$ .

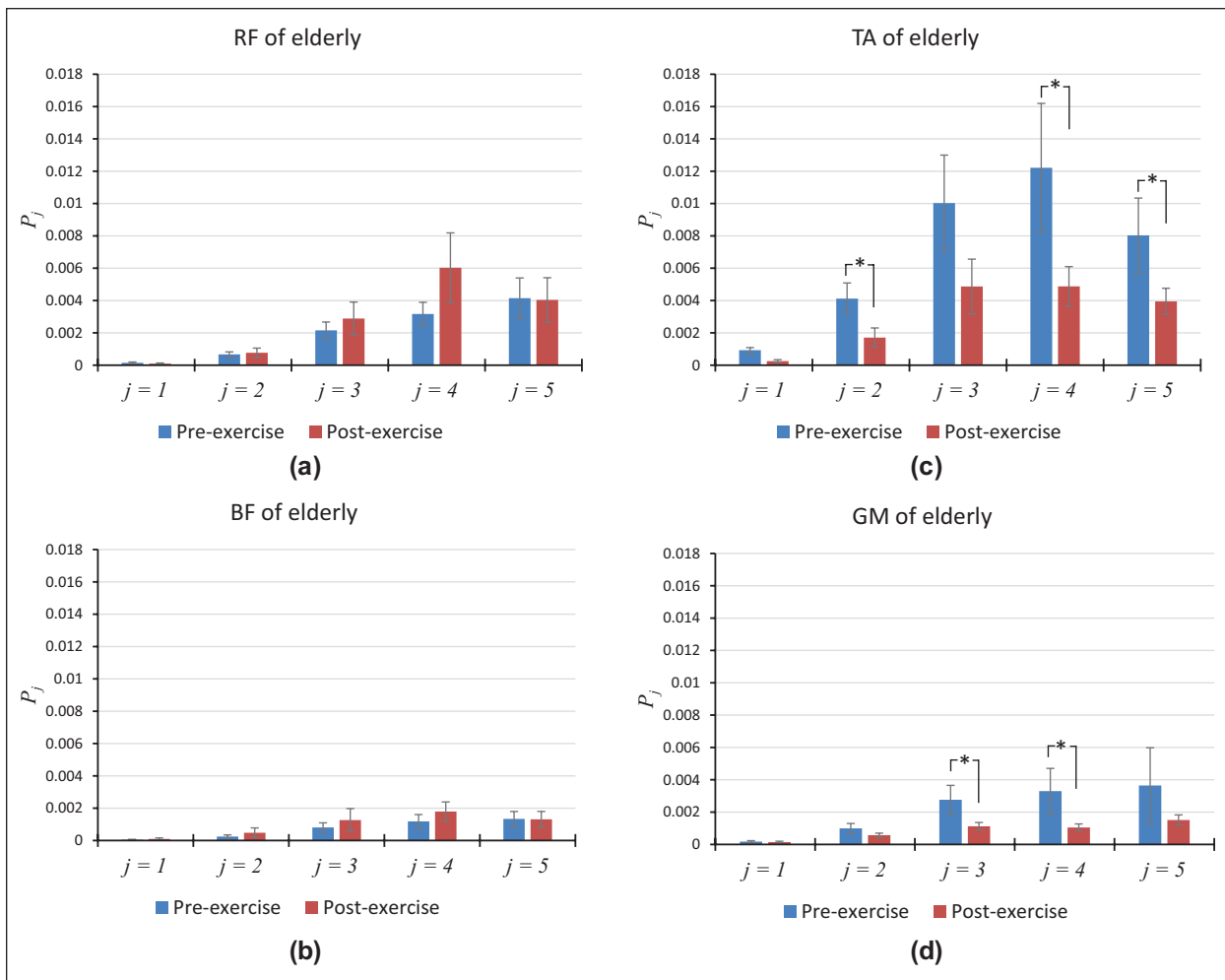
the mean power of each frequency band,  $P_j$  was quantified as

$$P_j = \frac{\sum_k^N (|C_{j,k}|^2 / \Delta t_j)}{N} \quad (3)$$

( $\Delta t_j$  was sampling time). It was considered to reduce an influence of the period of analyzing time (Kaneko et al., 2012, 2015). The value of  $P_j$  as a function of force generated, a gradual MU recruitment and MU firing rate modulation between pre-exercise and post-exercise periods was compared in each muscle.

### Statistical Analysis

All values of  $P_j$  were given as mean  $\pm$  standard error (SE) for seven elderly subjects and eight young subjects, respectively. For a multiple comparison procedure, homogeneity of variance was assessed by Levene's test. The analysis of variance (ANOVA) of two-way repeated layout was used to test the effect of the pedaling exercise (i.e., pre-exercise vs. post-exercise; after 1 month) and the effect of the frequency band (i.e.,  $j=1$ : 450–250 Hz,  $j=2$ : 250–125 Hz,  $j=3$ : 125–62.5 Hz,  $j=4$ : 62.5–31.25 Hz, and  $j=5$ : 31.25–20 Hz, respectively) for the  $P_j$  from four recording locations (i.e., the RF, the BF, the TA, and the GM), respectively. Significances of individual differences were evaluated by using the post-hoc comparisons if ANOVA was significant. Tukey's honestly significant difference (Tukey's HSD) was applied for post-hoc comparisons with significance levels of .01 and .05. For comparisons of proportion of  $P_j$  ( $\%P_j$ ),



**Figure 2.** Mean values of  $P_j$  ( $\pm SE$ ) related to pedaling movement were compared between the pre-exercise and post-exercise in elderly group. The mark \* indicate a significantly different level of 5% of post-hoc test.

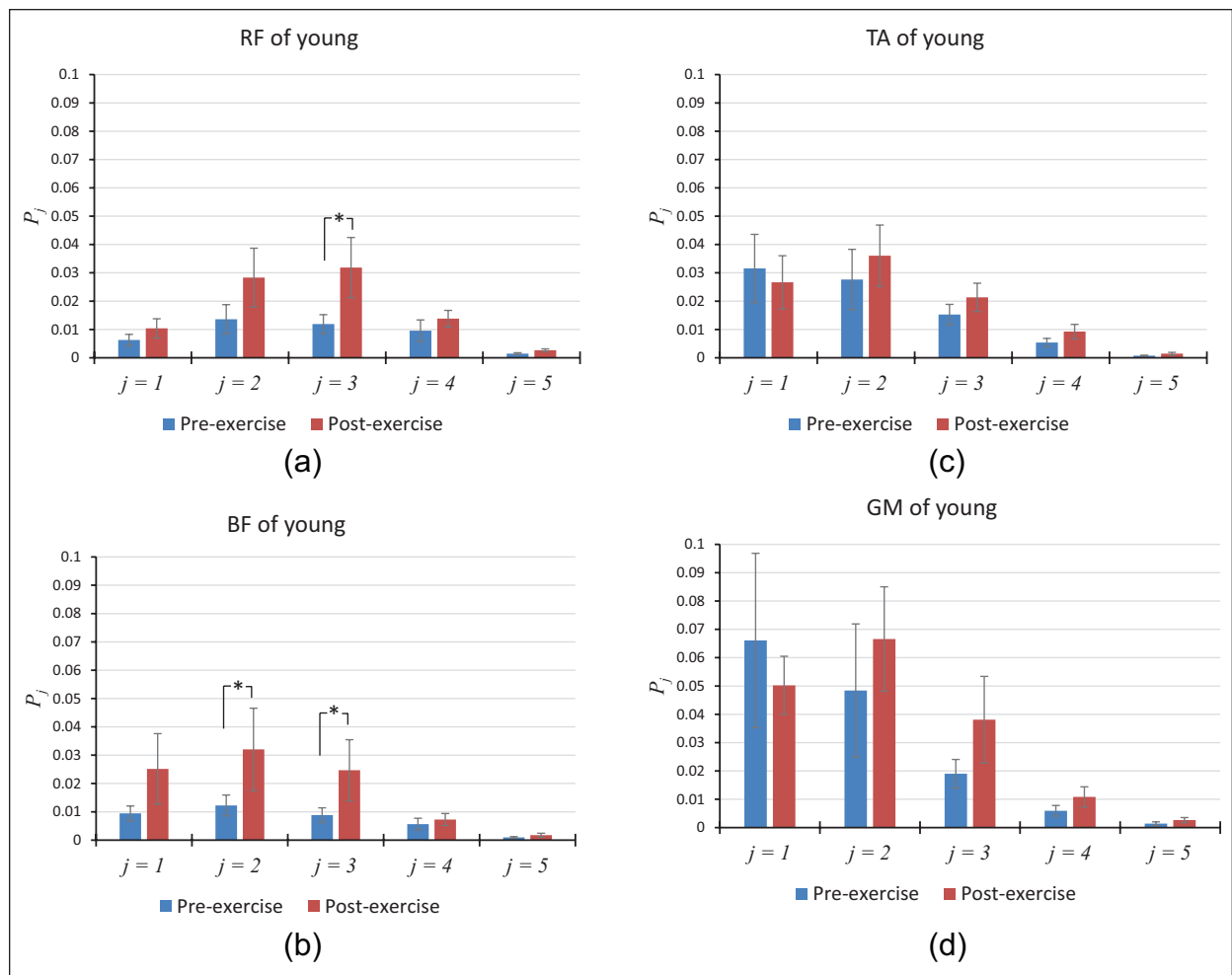
chi-square test for independence was performed to investigate how independence changes with significance levels of .01 and .05. All statistical analysis was completed using IBM SPSS Statistics for Windows, Version 20.0.

## Results

The values of  $P_j$  were calculated as a power of muscle activity related to the pedaling movement. The mean of the  $P_j$  values with each frequency band from the RF, BF, TA, and GM were compared between the pre-exercise aspects and the post-exercise aspects for the elderly group and the young group, respectively (see Figures 2 and 3). A proportion of frequency component for the  $P_j$  value was evaluated as a % $P_j$ . The values of % $P_j$  were compared between the elderly group and the young group in Figure 4.

Firstly, for the elderly group, the mean values of  $P_j$  of the RF and the BF showed an increasing tendency in the post-exercise aspect at the frequency bands of  $j=2$  (250–125 Hz), 3 (125–62.5 Hz), and 4 (62.5–31.25 Hz).

However, there were no significant effects of pedaling exercise (RF:  $F_{(1,60)}=0.088$ , n.s.,  $\eta^2=.01$ ; BF:  $F_{(1,60)}=1.664$ , n.s.,  $\eta^2=.02$ ). The largest values of  $P_j$  during five frequency bands were obtained at the  $j=5$  (31.25–20 Hz) in the pre-exercise aspect for the both RF and BF. After pedaling exercise for 1 month, the largest values of  $P_j$  were shifted into the higher frequency of  $j=4$  (62.5–31.25 Hz) as shown in Figure 2a and b. On the other hand, for the TA and the GM of the elderly group, the mean values of  $P_j$  were decreased after 1 month of pedaling exercise. The ANOVA revealed significant effects of pedaling exercise (TA:  $F_{(1,60)}=11.955$ ,  $p < .01$ ,  $\eta^2=.12$ ; GM:  $F_{(1,60)}=5.655$ ,  $p < .05$ ,  $\eta^2=.08$ ). According to Tukey's HSD, the significant differences between the pre-exercise and the post-exercise aspects at  $j=2$  (250–125 Hz), 3 (125–62.5 Hz), and 5 (31.25–20 Hz) of the TA; at  $j=3$  (125–62.5 Hz) and 4 (62.5–31.25 Hz) of the GM were noted, respectively. After pedaling exercise, the proportion of  $P_j$  at  $j=3$  (125–62.5 Hz) of the TA and at  $j=2$  (250–125 Hz) of the GM increased relatively as shown in Figure 2c and d.



**Figure 3.** Mean values of  $P_j$  ( $\pm$ SE) related to pedaling movement were compared between the pre-exercise and post-exercise in young group. The mark \* indicate a significantly different level of 5% of post-hoc test.

Secondly, as for the value of  $P_j$  in the young group, the post-exercise mean values increased as compared with the pre-exercise value. There were significant effects for pedaling exercise (RF:  $F_{(1,70)}=8.417$ ,  $p < .01$ ,  $\eta^2=.11$ ; BF:  $F_{(1,70)}=6.850$ ,  $p < .05$ ,  $\eta^2=.08$ ; TA:  $F_{(1,70)}=4.715$ ,  $p < .05$ ,  $\eta^2=.13$ ) (see Figure 3a to c). However, no significant change was observed for the GM ( $F_{(1,63)}=.328$ , n.s.,  $\eta^2=.07$ ) (see Figure 3d). Using Tukey's HSD with the paired data, the values of  $P_j$  in the post-exercise aspects significantly increased by 5% as compared with the pre-exercise aspects at  $j=3$  (125–62.5 Hz) of the RF;  $j=2$  (250–125 Hz) and 3 (125–62.5 Hz) of the BF, respectively.

Finally, for the comparison between the elderly group and the young group, the mean values of the  $P_j$  within four muscles were smaller for the elderly group than for the young group. A proportion of frequency component for the total value of the  $P_j$  was evaluated as a  $\%P_j$  in each subject group. The  $\%P_j$ s were compared between the elderly group and the young group in Figure 4a to d. The value of  $\%P_j$ s for the elderly group were lower than those for the young group in all muscles. The chi-square

test for independence showed statistical differences of 1% for all four muscles.

## Discussion

In the present study, the characteristics of lower limb muscle activity after ergometric pedaling exercise for elderly subjects and young subjects were examined by the WT of SEMG signals. The mean values of  $P_j$  of the TA and the GM were significantly smaller post-exercise than pre-exercise for the elderly subjects (see Figure 2c and d). These results suggested that the muscle activity of cruris were reduced by ergometric pedaling exercise in the elderly persons. The reduced values of the  $P_j$  of cruris indicated that the motor skills coordination for the pedaling movement improved in the elderly persons after 1 month of ergometric pedaling exercise. Namely, the elderly persons have been able to perform the pedaling movement with smaller muscle activations as compared with before ergometric pedaling exercise. It was seen as a learning effect for the pedaling movement. Macaluso and De Vito (2004) suggested that a rapid





**Figure 4.** Values of proportion of  $P_j$  ( $\%P_j$ ) were compared between the elderly group and the young group for four muscles (a, b, c, and d). According to the chi-square test for independence, there were significant differences of 1% within all four muscles.

improvement in the ability to perform a training exercise is mainly the result of a learning effect in the first phase of training for heavy-resistance training, such as lifting weights. The learning effect is mediated by changes in motor skill coordination. Ergometric pedaling exercise is not a type of heavy-resistance training; however, it is inferred that the pedaling movement is made smoother by improving motor skill coordination. The improving of motor skill coordination in relation to the pedaling movement will bring about the reduction of muscle activity of cruris.

On the other hand, the mean values of  $P_j$  of the RF and the BF were not changed significantly in the elderly subjects (see Figure 2a and b). However, the mean values of  $P_j$  at  $j=3$  (125–62.5 Hz) and 4 (62.5–31.25 Hz) were slightly increased post-exercise, and the value of  $\%P_j$  shifted into the higher frequency bands (see Figure 4a and b). It was considered by these results that ergometric pedaling exercise in the elderly persons caused the change of muscle activity patterns in relation to knee extensors (RF) and knee flexors (BF) during the pedaling movement. The relationship between the SEMG frequency power spectral data, the MU recruitment, and the MU firing frequency is a well-understood subject. The increase in EMG amplitude might represent MU recruitment and/or MU firing frequency modulation, whereas the increase of mean frequency (MPF) of the power spectrum might represent the additional recruitment of superficial high threshold MUs that most likely possess large and sharp spikes affecting high frequency bands of the SEMG power spectrum (Moritani et al., 2004). Takaishi et al. (1998) reported that the cyclists have a certain pedaling skill regarding the positive utilization of knee flexors up to the higher cadences, which would alleviate muscle activity for the knee extensors. Our results suggested that the aspect of the MU firing frequency and the number of recruited MUs within the muscles of the femoral region during the pedaling movement increased after pedaling exercise in the elderly persons.

In addition, we shall discuss the effects of ergometric pedaling exercise in the young subjects. The mean values of  $P_j$  within the RF and the BF were significantly increased post-exercise as compared with pre-exercise. Furthermore, the values of  $\%P_j$  increased at  $j=3$  (125–62.5 Hz) and decreased at  $j=4$  (62.5–31.25 Hz) within both the RF and BF (see Figure 4a and b). The frequency of SEMG activity within the femoral region shifted into the higher frequency band pre-exercise. These results suggested that the isokinetic adaptations of the knee extensors (RF) and knee flexors (BF) during the pedaling movement were improved by ergometric pedaling exercise in the young persons. Sale (1988) stated that the resistance training causes adaptive changes within the nervous system that allow a trainee to more fully activate prime movers in specific movements and to better coordinate the activation of all relevant muscles. The

adaptive changes of the nervous system are called neural adaptations. Neural adaptations include many elements such as an increased activation of prime mover muscles (number of recruited MUs or firing rate and synchronization of the individual MUs), a better coordination of synergistic and antagonist muscles, and an increased neural drive from the highest levels of the central nervous system (Macaluso & De Vito, 2004).

The values of  $P_j$  within the TA and the GM did not change significantly; however, there is a tendency to increase the values of  $P_j$  at  $j=2$  (250–125 Hz), 3 (125–62.5 Hz), and 4 (62.5–31.25 Hz) after ergometric pedaling exercise. There were large differences among individuals for the muscle activity of cruris as compared with that of the femoral region (see Figure 3c and d). The values of  $\%P_j$  of the TA and the GM decreased at  $j=1$  (450–250 Hz), and increased at  $j=3$  (125–62.5 Hz) and 4 (62.5–31.25 Hz) post-exercise. Namely, the frequency of SEMG activities of cruris shifted into relatively lower frequency bands. Human muscles have different fiber types such as fast- and slow-twitch or type I and II fibers. A study of Wakeling et al. (2002) on fish showed that the fast twitch fibers generally have a higher frequency band than that of slow twitch fibers. Von Tscherner and Nigg (2008) pointed out that the power spectra of EMG signals depend primarily on the task and are subsequently modulated by factors such as length change, lactate accumulation, and volume conduction. They analyzed the EMG activities of TA and GM before/after heel contact while running from the viewpoint of the time-frequency domain. The frequency of EMG activities within the TA showed EMG activities before heel contact with relatively high frequencies, a result of activities of high frequency-generating groups (HFG) of MUs. After heel contact, the frequency of EMG activities became low by the task of heel strike. The heel strike could be performed with activity from low-frequency groups (LFG) of MUs. For the GM, it was reported that the MUs of both LFG and HFG activated simultaneously, resulting in low and high frequencies during initial ground contact (Von Tscherner & Nigg, 2008). In our study, the frequency of SEMG activities of cruris (BF and TA) shifted into a relatively lower frequency band after ergometric pedaling exercise. It was considered that the ratio of activity of LFG increased within the TA and the GM as the effect of ergometric pedaling exercise in young persons.

Finally, let us look closely at the effect of ergometric pedaling exercise from the comparison between the elderly subjects and the young subjects. The values of  $P_j$  of elderly subjects were smaller than those of young subjects within all four lower limb muscles (see Figures 2 and 3). The values of  $\%P_j$  of elderly subjects were significantly lower than those of young subjects within all four lower limb muscles (see Figure 4). Macaluso and De Vito (2004) reviewed the studies of causes of muscle strength loss in elderly persons. Muscle size is reduced

with ageing and this quantitative loss of muscle affects the generation of force. The loss of muscle tissue in elderly people has been attributed to reduced numbers of both slow-twitch fibers and fast-twitch fibers, plus a reduction in the cross-sectional area (CSA) of single fibers, especially of type II. Furthermore, the older muscle is not only atrophied, but is also slower and tetanizes at lower fusion frequencies (Macaluso & De Vito, 2004). In this study, the SEMG activities of lower limb muscles during pedaling movement will show the aspect of muscle strength loss in elderly subjects. The values of  $P_j$  and  $\%P_j$  were a useful index to evaluate the effect of ergometric pedaling exercise on elderly persons to reduce of sarcopenia population. In the future, the studies on longer-term and/or heavier-load pedaling exercise, H reflexes, muscle synergies, and advanced glycation end products (AGEs) are needed to assess directly the mechanisms of muscle strength loss (i.e., sarcopenia) in elderly persons.

## Conclusion

The characteristics of lower limb muscle activity after ergometric pedaling exercise for one month were estimated by the WT of SEMG signals within the femoral region and cruris. There were different effects of ergometric pedaling exercise between the femoral region and cruris. The learning effect was shown in the cruris of elderly persons. The muscle activity pattern and an isokinetic adaptation were changed by ergometric pedaling exercise in the femoral region of both groups. The effects of pedaling exercise for the lower limb muscles were different between the elderly persons and the young persons. This study should be useful as an assessment for the effect of pedaling exercise on elderly persons from the viewpoint of treatment of sarcopenia.

## Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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