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Functional Significance of Force Fluctuation During Voluntary Muscle Contraction

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1. Introduction

Human movement is the result of the joint torque or muscle force generated by the contraction of multiple muscles. The force generated during voluntary muscle contraction is not constant, but fluctuates as observed through the variability in movement. The normalised force fluctuation (measured according to the standard deviation (SD) of force) during isometric contractions is referred to as 'steadiness', which influences functional human movement (Carville et al., 2007; Kornatz et al., 2005; Marmon et al., 2011; Salonikidis et al., 2009). For example, Salonikidis et al. (2009) and Kornatz et al. (2005) report that greater fluctuation during voluntary muscle contraction can influence functional human movement in the upper limbs. With regard to the lower limbs, Carville et al. (2007) report that the elderly who tend to fall exhibit less steady knee extension than do both the young and the elderly who do not tend to fall. However, the relationship between force fluctuations in lower limb muscles and human movements for daily activities remains unclear. The ability to control posture during quiet standing is one of the fundamental activities of daily living. Furthermore, the muscle activities of lower limb muscles are important for postural stability during quiet standing. Therefore, this chapter focuses on the relationship between force steadiness in lower limb muscles and postural stability during quiet standing.

1.1 Asymmetry of muscle function in leg muscles

Some studies demonstrate that the asymmetry of muscle function between the 2 legs may influence human movement. For example, Skelton et al. (2002) report that although 'fallers' (20 women living at home, aged >65 years with a history of falls in the past year) and 'non-fallers' (15 age-matched women with no history of falls) have asymmetric lower limb power, the fallers exhibit significantly greater asymmetry. Furthermore, the relationship between the asymmetry of leg strength and walking speed in 1,205 healthy women aged 30–89 years old has been reported (Oshita et al., 2009). Walking speed is fastest when the asymmetries of knee extension and flexion strength are below 5%, as shown in Fig. 1. However, if the asymmetry of one of the parameters (i.e. knee extension or flexion) is more than 10%, walking speed is still reduced. Furthermore, the walking speed is slowest when the asymmetries of knee extension and flexion strength are more than 10% (Fig. 1). Moreover, the asymmetry of leg strength does not affect the walking speed of subjects with higher leg

strength (Fig. 2). However, in subjects with low leg strength, walking speed decreases with increasing asymmetry of leg strength.

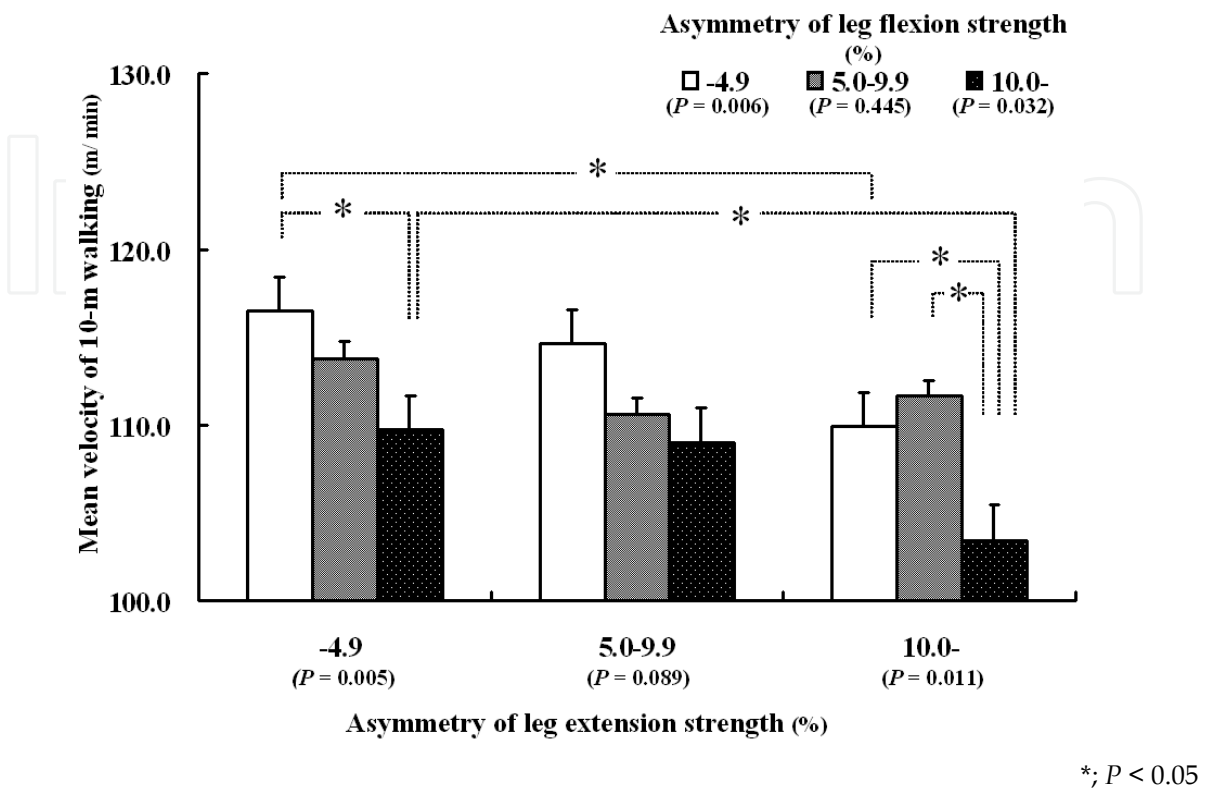


Fig. 1. Relationship between walking speed and asymmetry of leg strength

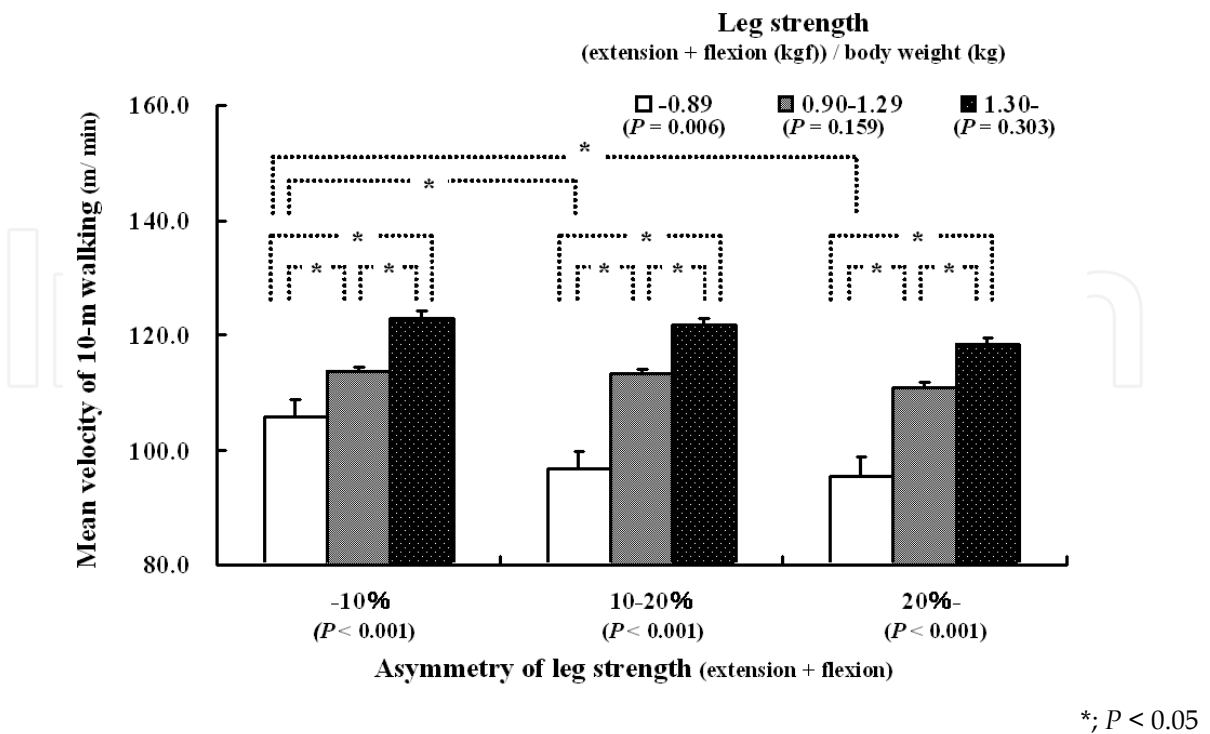


Fig. 2. Relationship between walking speed and leg strength and asymmetry of leg strength

Although these previous studies suggest that the asymmetry of leg strength might affect the human movement regarding postural stability, the intensity of most daily activities is not maximal, but is thought to be less than approximately 20% of maximum voluntary contraction (MVC) (Sawai et al., 2004). These studies lead us to hypothesise that asymmetry in muscle function at less than 20% MVC is an important factor for postural stability. Thus, in section 3, we introduce the asymmetry of force fluctuations during isometric contraction in lower limb muscles during low-intensity muscle contraction.

1.2 Plantar flexor muscles during quiet standing

Based on the dynamics of human quiet standing, numerous studies (i.e. analyses using electromyograms or the model of a single-joint inverted pendulum rotating around the ankle joint) show that the plantar flexor muscles play a significant role in stabilising the body during quiet standing. For example, the activities of the plantar flexors during bipedal quiet stance are coherent with both spontaneous body swaying (Gatev et al., 1999; Masani et al., 2003) and mechanically induced body swaying (Fitzpatrick et al., 1996). Although many factors (e.g. proprioception, control of upper body motion, etc.) are related to postural stability during quiet standing, the plantar flexors (i.e. the soleus muscle) are the most activated muscles in the entire body during quiet standing (Ohnishi et al., 2005; Sawai et al., 2004). These studies lead us to hypothesise that quiet standing is associated with force fluctuation in the plantar flexors. If force fluctuation in the plantar flexors is one of the most important factors for postural stability during quiet standing, the amplitude of force fluctuation will indicate a relationship between ability and posture stability. In section 4, we discuss the relationship between force steadiness of the plantar flexors and the postural sway during quiet standing.

1.3 Practice reduces force fluctuation and improves human movement

In order to increase muscle strength in healthy adults, the American College of Sports Medicine (1998) recommends strength training at least 2–3 times per week. Further, 1 day of exercise per week may not develop into habitual exercise; for example, the definition of habitual exercise according to a national health and nutrition survey is least 2 sessions of exercise per week (Ministry of Health, Labour, and Welfare of Japan, 2011). Although this training frequency is generally recommended for strength training, it might be not necessarily realistic for people aiming to maintain their health or who are unable to devote a considerable amount of time to strength training alone (Ohmori et al., 2010). However, previous studies involving relatively low-frequency strength or functional training (1 session per week or per 2 weeks) demonstrate increases in muscle strength in both normal young adults (Hayashi and Miyamoto, 2009; Ohmori et al., 2010) as well as in normal and functionally limited older adults (Oshita et al., 2008; Sato et al., 2007). The improvement in strength brought about by such low-frequency training is attributed to several neural factors such as motor learning, adjustment of motor function, acquisition of skills, excitability of alpha-motor neurons, increased motor neuron firing rate, and motor unit synchronisation (Ohmori et al., 2010).

In order to reduce force fluctuations in healthy adults, strength training and/or steadiness practice can be used during voluntary contraction of the distal muscles of the upper and lower limbs. Keen et al. (1994) report that in young adults, 4 weeks of strength training of the first dorsal interosseous muscle using a heavy load (80% of maximum) reduces the force fluctuations measured during isometric contraction at 50% MVC. Similarly, steady

contractions or force-tracking tasks also reduce force fluctuations. For example, 2 weeks of practicing a steadiness task with a light load (10% of maximum) on the index finger reduces force fluctuations and the discharge rate variability of single motor units in the hand muscles of older adults (Kornatz et al., 2005); similar effects are observed in young adults. Patten and Kamen (2000) report that the ability to match force trajectory in the dorsiflexor muscles improves after 2 weeks of isometric force modulation training. However, the effect of low-frequency steadiness practice (1 day of practice per week) on force fluctuations during isometric contraction is currently unknown. Furthermore, if the force fluctuations in the plantar flexor muscles are associated with postural stability, force steadiness practice should improve postural stability during quiet standing. Thus, in section 5, we discuss the effects of low-frequency steadiness practice in the plantar flexor muscles on force fluctuations during isometric contraction and postural stability during quiet standing.

2. Method

2.1 Experimental setup

Here, we describe the design used for the plantar flexion exercise. Each participant performed a static unilateral plantar flexion exercise (Fig. 3). Participants were instructed to remove all footwear and sit on an insulated straight-backed chair. An additional strap was used to secure the thigh of the leg to the chair. Force was measured with a load cell (LPR-A-S10, Kyowa, Tokyo, Japan) positioned between a metal base plate and the foot. The foot was secured with a strap at the foot lever plate. The strain gauge transducer was aligned between the 2 plates near the distal part of the foot. The exact position of the entire device was carefully adjusted such that the knee was fully extended with the ankle joint angle at 90° . The amount of force produced and the target were displayed on a computer screen (14.1 inches) positioned 1 m away at the level of the participant's eyes to provide visual feedback.

The following paragraph outlines the design used for the knee extension exercise (Fig. 3).

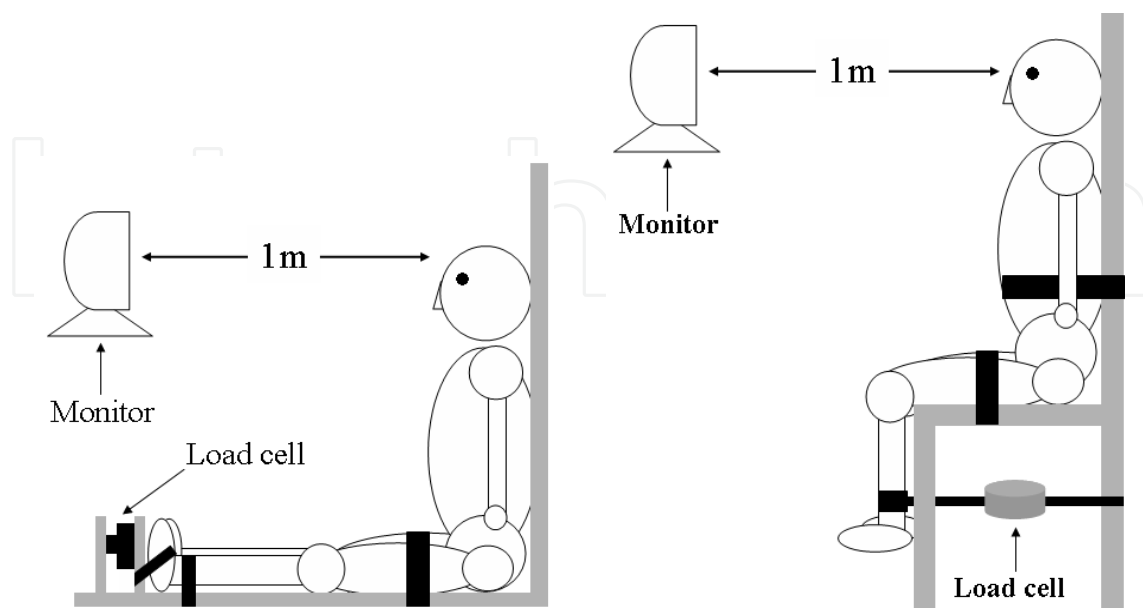


Fig. 3. Schematic drawing of the setup used for the isometric plantar flexion (left) and knee extension (right)

Each participant performed an isometric unilateral knee extension exercise with each leg while in a seated position, with the hip and knee joints both flexed at 90° (full extension = 0°). Throughout the experiment, the participant's upper body was firmly fixed to a chair with a seat belt. The force of the isometric contraction of the knee extensor muscles was measured by a load cell (LTZ-100KA, Kyowa, Tokyo, Japan) attached to the ankle just above the malleolus by a strap. The amount of force produced and the target were displayed on a computer screen (14.1 inches) positioned 1 m away at the level of the participant's eyes to provide visual feedback.

2.2 Muscle strength test (MVC measurement)

Each participant performed MVC for a period of 5 s with encouragement from the investigators. Participants performed 3 trials with subsequent trials performed if the difference in the peak force of 2 MVCs was $>5\%$. Participants were allowed to reject any effort that they did not consider 'maximal'. The trial with the highest peak force was chosen for analysis.

2.3 Force-matching (steady isometric contraction) task

On the basis of the MVC measurements, the participants performed a steady isometric contraction task for 15-20 s at levels corresponding to 10%, 20%, or 30% of the MVC; there was an approximately 30-min rest period between MVC measurement and these tasks. The force signals were obtained by a sensor interface with a 12-bit analogue-to-digital converter at a sampling frequency of 1 kHz (PCD-300A, Kyowa, Tokyo, Japan) and stored on the hard disk of a computer for future analysis. Data were collected for 1 trial with each target, and the order of the target forces was randomised for each participant. There was a rest period of >1 min between trials, and between-trial rest periods of up to 5 min were also allowed at subject's request.

2.4 Postural sway during quiet standing

Each participant was instructed to remove all footwear and maintain quiet standing for 30-40 s on a platform (Fig. 4). The subjects had their arms alongside their body and their feet were kept parallel with the centres of the heels 15 cm apart. To assess the trajectory of the centre of mass displacement (CoMdis) during quiet standing the horizontal position of a lumbar point at L3 was measured by a laser displacement sensor (ANR 1251, SUNX, Japan). The present study focused on anteroposterior CoMdis, because the force produced by the plantar flexor muscles mainly contributes to the body sway in this particular axis (Masani et al., 2003). The signals were acquired at a sampling frequency of 100 Hz with a 16-bit analogue-to-digital converter (AI-1608AY, CONTEC, Japan) and stored on the hard disk of a computer for future analysis.

2.5 Data analysis

The data were processed with SPCANA waveform analysis software (version 4.71, Japan) and Microsoft Excel. For the stored force signals, the data for an 8-s period in the middle portion of the collected data (15-20 s) were selected for analysing individual trials because there was no systematic change in fluctuations within trials. After low-pass filtering (<100 Hz), the SD of the force was calculated to evaluate the amplitude of force fluctuation.

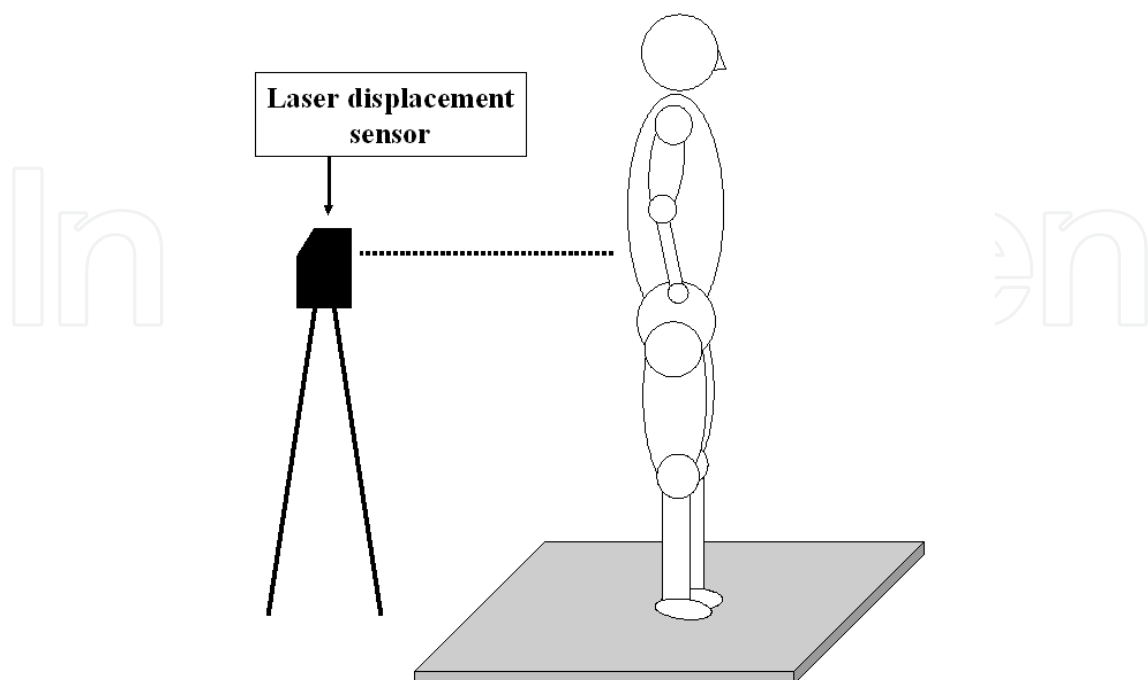


Fig. 4. Schematic drawing of the setup used for the measurement of postural sway

For the CoMdis signals, the data for a 20-s period in the middle portion of the collected data (30-40 s) were selected for analysing individual trials. The velocity of CoMdis (CoMvel) was calculated by numerically differentiating CoMdis as a function of time. This is because the velocity of body sway (i.e. the centre of pressure displacement or CoMdis) in the anteroposterior axis is the most sensitive parameter capable of distinguishing not only children and young adults from seniors, but also middle-aged subjects from seniors (Abrahamova and Hlavacka, 2008; Prieto et al. 1996; Masani et al., 2007). Furthermore, the SD of CoMvel was calculated to assess postural sway during quiet standing.

3. Asymmetry of force fluctuation in leg muscles

3.1 Proximal part (Knee extension)

In this section, we discuss the asymmetry of force fluctuations during isometric knee extension (Oshita and Yano, 2010a). Data were obtained from 12 healthy men (age, 21 ± 1 years). Each participant performed the steady isometric knee extension task for 15 s at levels corresponding to 10% or 20% MVC. Force fluctuations were compared between the stronger and weaker MVC limbs. In all subjects, the right limb was stronger. The MVCs of the stronger and weaker limbs were 688.0 ± 49.6 and 625.8 ± 43.1 N, respectively. Figure 5 shows the force fluctuations during the steady isometric knee extension task. Force fluctuation was significantly greater in the 20% MVC task than in the 10% MVC task in both limbs. However, no significant differences in force fluctuations during the 10% and 20% MVC tasks were observed between the stronger and weaker limbs. Thus, although force fluctuation increased with contraction intensity, no asymmetry of force fluctuation was observed during low-intensity steady isometric knee extension.

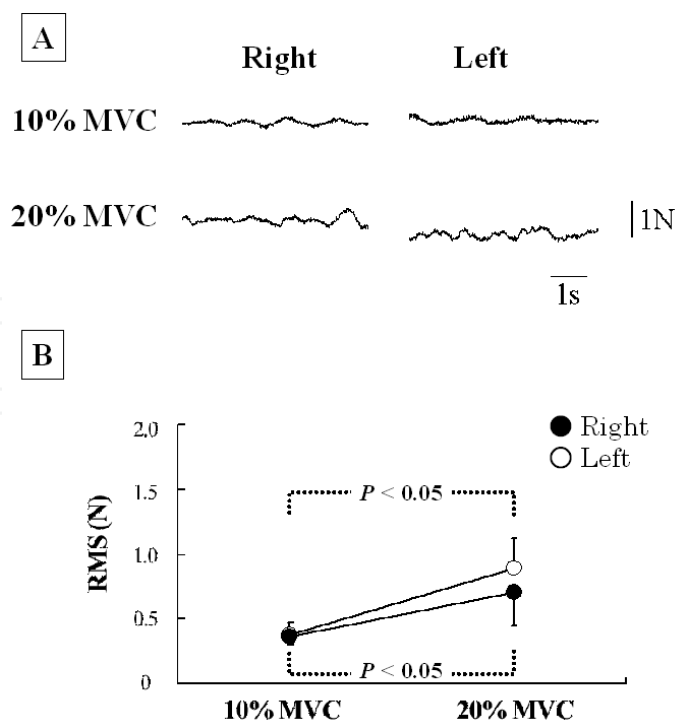


Fig. 5. Representative force fluctuations during isometric knee extension (A) and means and standard errors of the means (B) (Oshita and Yano, 2010a)

Adam et al. (1998) report significantly greater fluctuation in the non-preferred hand than in the preferred hand during a 30% MVC isometric abduction task in the index finger; furthermore, the discharge rate variability during task is greater in the non-preferred hand than in the preferred hand. One of the important factors in the asymmetry differences in the upper limb is their daily preferential use. However, our results indicate that no asymmetry in force fluctuation was observed during steady isometric knee extension at 10 or 20% MVC.

Furthermore, figure 5 and 6 show mechanomyogram signals in vastus lateralis during the steady isometric knee extension task. These results indicate that no asymmetry differences in the mechanical characteristics in the active muscle were observed. In contrast to the upper limb, the role of limb preference in lower limbs is not clear. For example, if a person kicks a ball with their preferred limb, the other limb is often required to support the entire body weight. Therefore, it is unclear which limb is stronger: the limb preferred for daily use or the other limb regularly supporting the body weight over many years. However, our results are consistent with those of Semmler and Nordstrom (1995) who report that no asymmetry of force fluctuation or discharge variability is observed during isometric index finger abduction. The difference in the results of Adam et al. (1998) and Semmler and Nordstrom (1995) is thought to be due to differences in contraction intensity. Although the asymmetry of force fluctuation is observed during 30% MVC (Adam et al., 1998), it is not observed during <10% (Semmler and Nordstrom, 1995), 10%, or 20% MVC (Fig. 5). The force fluctuations observed during isometric contraction are correlated with the discharge rate variability, which is thought to be a major determinant of force fluctuations (Mottram et al., 2005; Tracy et al., 2005). Thus, no asymmetry of force fluctuations might be observed during low-intensity contraction because the variability in the discharge rate is too small. Furthermore, the present results indicate asymmetry of mechanomyogram signals in the

active muscle. These results suggest that no asymmetry of force fluctuations during low-intensity isometric knee extension is observed, because there are no differences regarding mechanical characteristics in the active muscle between stronger and weaker legs.

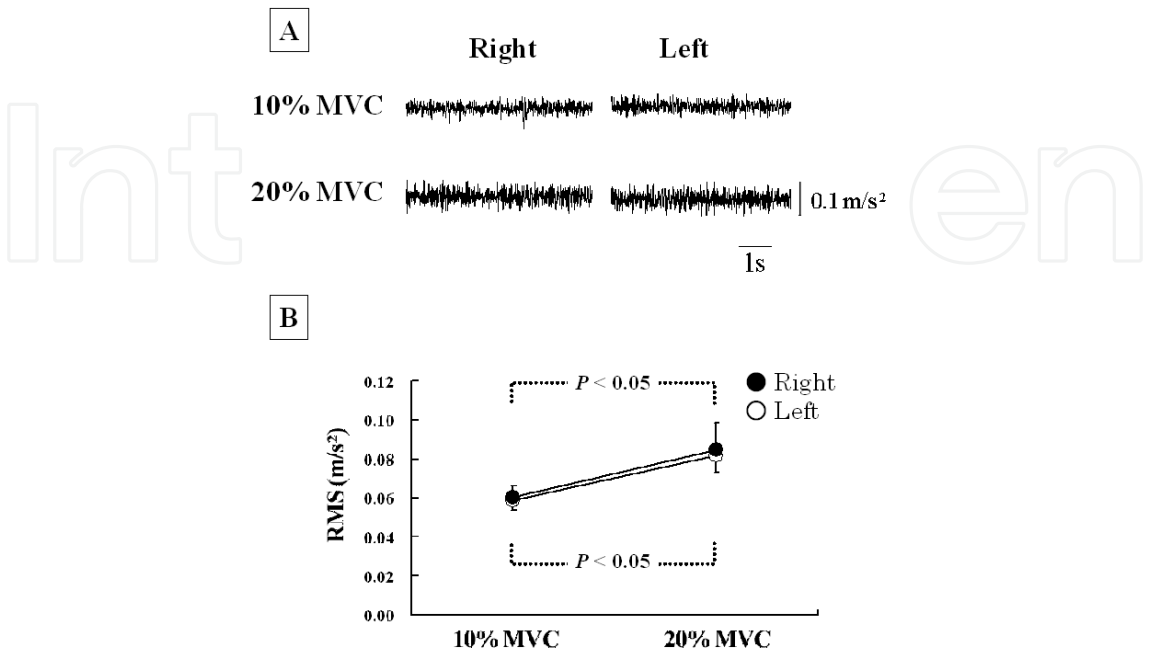


Fig. 6. Representative amplitude of mechanomyogram signal during isometric knee extension (A) and means and standard errors of the means (B) (Oshita and Yano, 2010a)

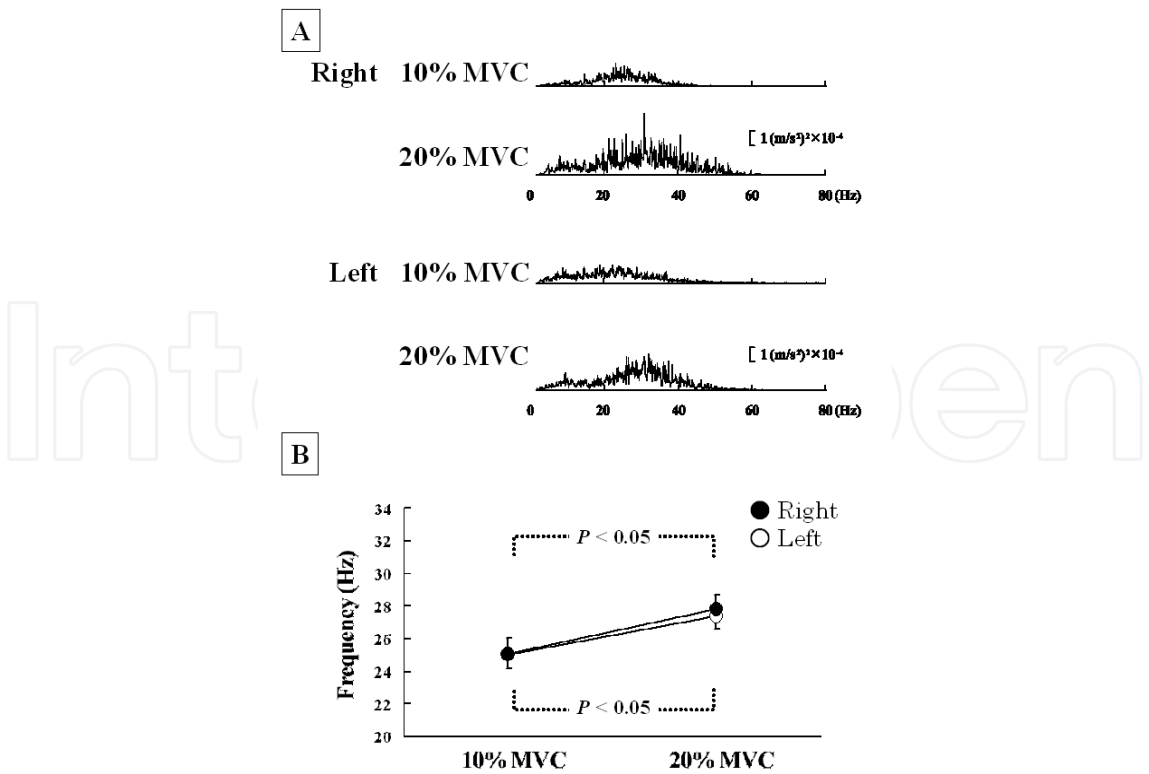


Fig. 7. Representative mean power frequency of mechanomyogram signals during isometric knee extension (A) and means and standard errors of the means (B) (Oshita and Yano, 2010a)

3.2 Effect of contraction intensity

In section 3.1, we found that force fluctuations during isometric knee extension at 10% and 20% MVC were not significantly different between the 2 legs. However, Adam et al. (1998) reported a significantly greater fluctuation for the non-preferred than the preferred hand during a 30% MVC isometric abduction task with the index finger. The different results obtained by Adam, et al. (1998) and Semmler and Nordstrom (1995) are thought to reflect the difference in intensity of contraction. If the asymmetry of force fluctuations is influenced by intensity of contraction, asymmetry of force fluctuation in the lower limbs which was not observed below 20% MVC might be observed above 30% MVC. Furthermore, although the intensity of most daily activities is below 20% MVC, some activities of high intensity are required in daily life (e.g., climbing stairs or walking up or down a slope) or sports activities. Apparently, although Oshita and Yano (2010a) reported the asymmetry of force fluctuation in leg muscle at low intensity, the asymmetry of force fluctuation in the leg muscles at moderate intensity remains unclear. In this section, we discuss the asymmetry of force fluctuation during isometric knee extension at low and moderate intensities (Oshita and Yano, 2011a).

Data were obtained from 11 healthy men (age, 21 ± 1 years). Each participant performed the steady isometric knee extension task for 15 s at levels corresponding to 20% or 30% MVC. Figure 10 shows the force fluctuations during the steady isometric knee extension task. Although force fluctuation was not statistically significantly different between the 2 legs during the 20% MVC task, it was statistically significantly higher in the left leg than in the right leg during the 30% MVC task (Fig. 8). These results indicate asymmetry of force fluctuation during isometric knee extension was observed in the moderate intensity task (30% MVC) but not in the low intensity task (20% MVC). In the section 3.1, we reported the force fluctuations during isometric knee extension at low intensities (10% and 20% MVC) were not significantly different between the 2 legs (Oshita and Yano; 2010a). In the upper limbs, Semmler and Nordstrom (1995) also reported the force fluctuation during isometric abduction of the index finger at below 10% MVC was not statistically significantly different between the 2 hands. These previous data are consistent with the present result; force fluctuation during isometric knee extension at low intensity (20% MVC) was not statistically significantly different between the 2 legs. However, Adam et al. (1998) reported a statistically significantly greater fluctuation for the non-preferred than for the preferred hand during a task with 30% MVC isometric abduction of the index finger. They suggested the different results of Adam et al. (1998) and Semmler and Nordstrom (1995) were influenced by the difference in the intensity of contraction. In the current study, force fluctuation during knee extension which was not different between the 2 legs at low intensity (20% MVC) was statistically significantly different between the legs at moderate intensity (30% MVC). Therefore, the present results were consistent with the suggestion of Adam et al. (1998) that the asymmetry of force fluctuation in lower limbs was also influenced by the contraction intensity.

Several researchers have suggested that a major determinant of the force fluctuation is the variability in motor-unit discharge rate (Mottram et al., 2005; Tracy et al., 2005), viz., the positive association of force fluctuation with variability of the discharge rate during isometric contraction (Mottram, et al., 2005; Tracy, et al., 2005). Although the present study did not measure the activities of motor units directly, the firing rate of the motor unit in active muscle (i.e. vastus lateralis) was evaluated using an mechanomyogram. Further, there was a statistically significant association between the 2 legs' mean power frequency of

mechanomyogram signal during the 20% MVC task but not during the 30% MVC task (Fig. 9), so individuals who had higher (or lower) mean power frequency of mechanomyogram signal in the right leg’s active muscle also tended to have higher (or lower) mean power frequency in the left leg during isometric knee extension at low intensity (20% MVC). In contrast, mean power frequency of mechanomyogram signal during the moderate intensity (30% MVC) task was uneven between the 2 legs. Thus, the asymmetry of the firing rates of the motor units in active muscle during isometric knee extension is associated with intensity of the contraction.

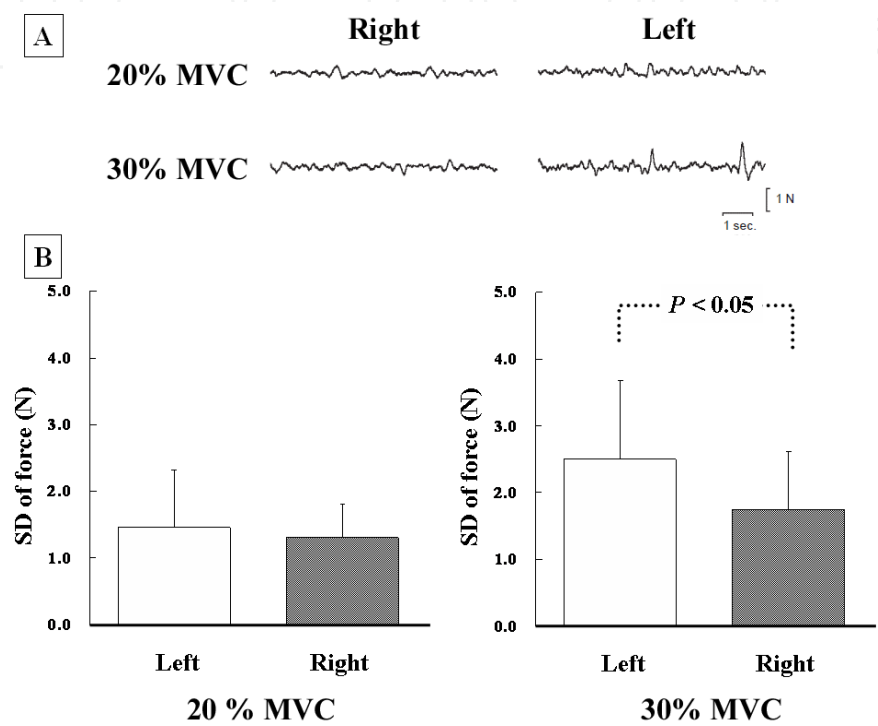


Fig. 8. Representative force fluctuations during isometric knee extension (A) and means and standard errors of the means (B) (Oshita and Yano, 2011a)

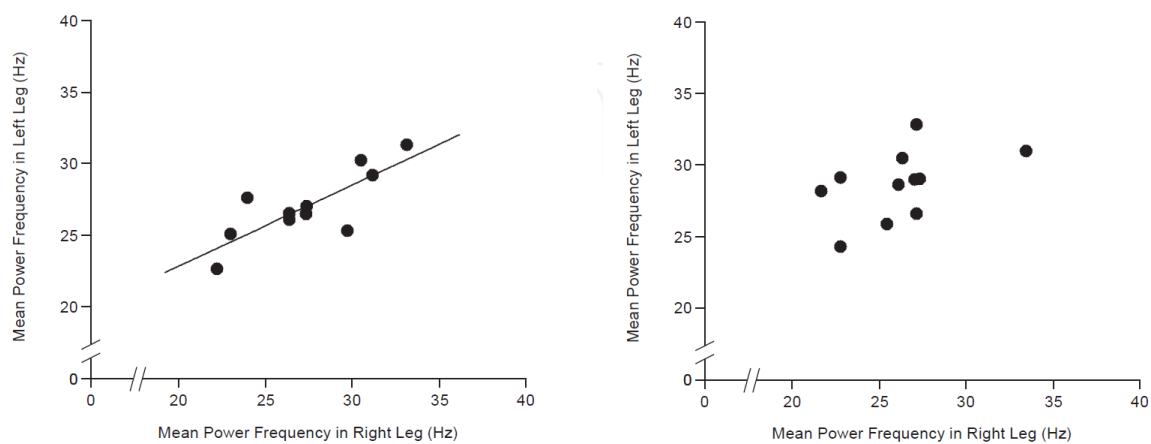


Fig. 9. Relationships regarding mean power frequency of mechanomyogram signal during isometric knee extension at 20% (left) and 30% (right) MVC between the right and left legs (Oshita and Yano, 2011a)

Force fluctuation may influence functional performance of controlling finger or limb movements in daily life. Although the intensity of most daily activities is below 20% MVC, some activities of high intensity are required in daily life or sports activities. Asymmetry of force fluctuation might be important in these motions. Most importantly, although the intensity of most daily activities is below 20% MVC for individuals with normal or high muscle strength, it would be of higher intensity for those with lower muscle strength. Asymmetry of force fluctuation during voluntary contractions of high intensity might affect normal daily activities of individuals with low muscle strength.

3.3 Distal part (Plantar flexion)

Although the force fluctuations were not significantly different between the 2 legs during low-intensity isometric knee extension, the asymmetry of force fluctuations in the plantar flexor muscles is currently unknown. The apparent biomechanical differences between limb segments are reflected in the distinct control of proximal versus distal joints. There are different control loops for distal and proximal muscles in the cerebellum and reflex pathways (Kurata and Tanji, 1986; Nisky et al., 2010). According to previous studies (Lemon and Griffiths, 2005; Davidson and Buford, 2006; Nisky et al., 2010), humans are more accurate in control and perception of the position of endpoint of the limb. Opposite gradients in maximum controllable force and resolution of force control were reported; that is, proximal joints are more successful than distal joints in the control of force (Hamilton et al., 2004; Nisky et al., 2010). Thus, a significant difference in the force fluctuations between the 2 legs might be observed in the plantar flexor muscles. In this section, we discuss the asymmetry of force fluctuations during isometric plantar flexion (Oshita and Yano, 2010b).

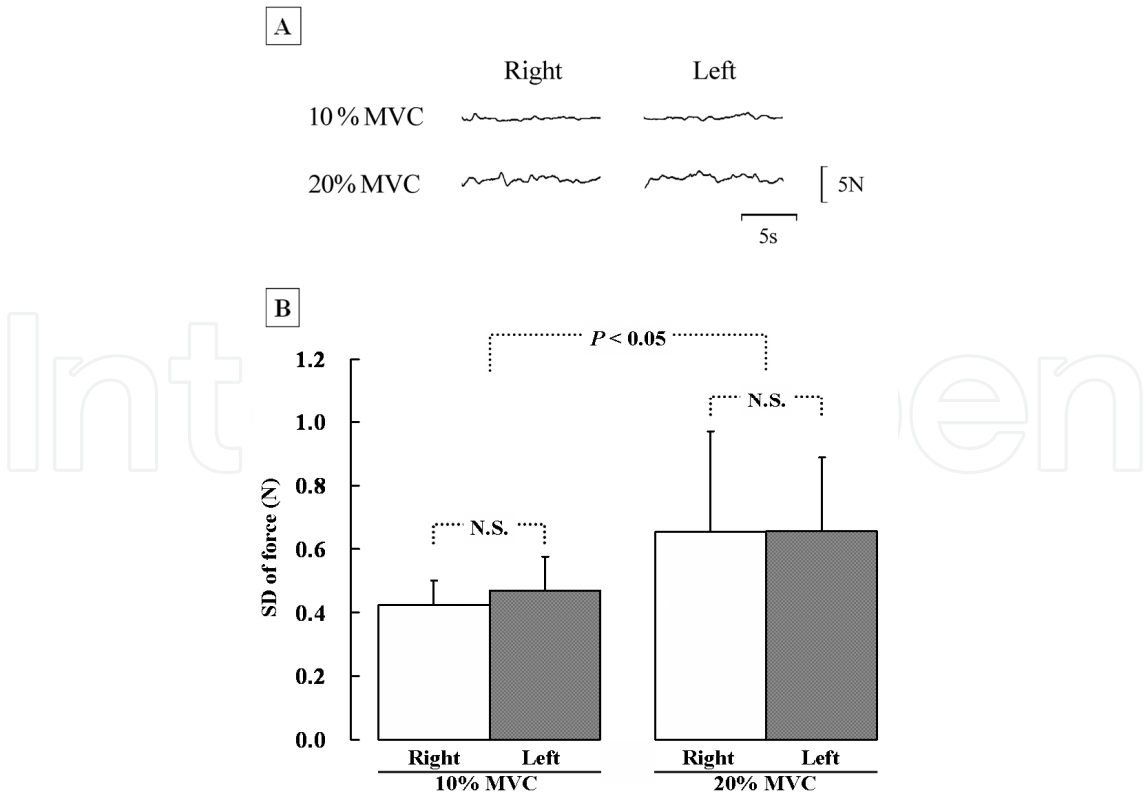


Fig. 10. Representative force fluctuations during isometric plantar flexion (A) and means and standard errors of the mean (B) (Oshita and Yano, 2010b)

Data were obtained from 12 healthy men (age, 21 ± 1 years). Each participant performed the steady isometric plantar flexion task for 20 s at levels corresponding to 10% and 20% MVC. Force fluctuations in the plantar flexors were compared between the stronger (right) and weaker (left) MVC limbs. In all subjects, the right limb was the stronger limb. Figure 10 shows force fluctuations during the steady isometric plantar flexion task. Force fluctuation was significantly greater in the 20% MVC task than in the 10% MVC task in both limbs. However, no significant differences in force fluctuations in both the 10% and 20% MVC tasks were observed between the right and left limbs. Furthermore, the force fluctuation was significantly associated between the 2 legs (Fig. 11). In addition, the participants who had greater (or smaller) force fluctuations in the right limb also had greater (or smaller) fluctuations in the left limb. Although force fluctuation increased with contraction intensity, no asymmetry of force fluctuation was observed during low-intensity steady isometric plantar flexion.

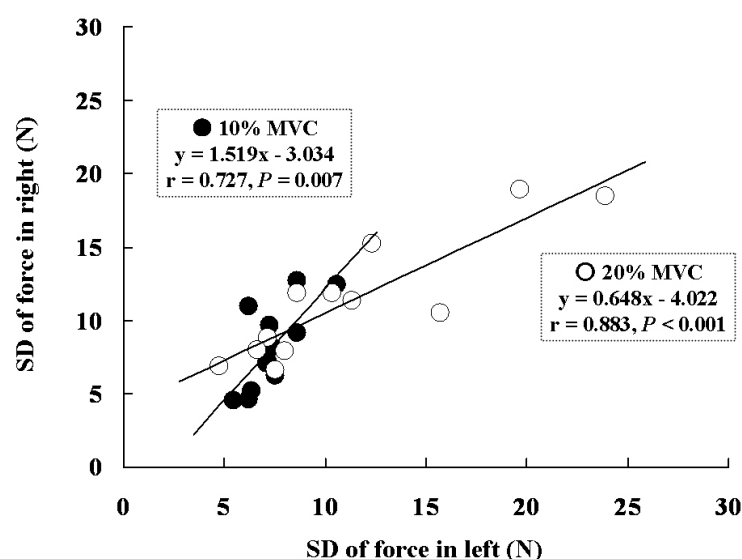


Fig. 11. Relationships regarding force fluctuation during force-matching tasks between the right and left legs (Oshita and Yano, 2010b)

Although there are different control loops for distal and proximal muscles in the cerebellum and reflex pathways, force fluctuations in the plantar flexor muscles were not significantly different between the 2 legs. The present study focuses on investigating the asymmetry of force fluctuations during low-intensity isometric contraction in lower limb muscles. Therefore, the underlying mechanisms of the asymmetry of force fluctuation remain unclear. Future studies are required to determine muscle activity in the antagonist muscle and/or neuromuscular properties (e.g. electromyography, motor unit activity, etc.) in order to clarify the mechanisms of the effects of practice like those reported here.

4. Steadiness in plantar flexion and postural sway

If force fluctuation in the plantar flexors is an important factor for postural stability during quiet standing, the amplitude of force fluctuation will indicate a relationship between ability and postural stability. Thus, in this section, we discuss the relationship between the force steadiness of the plantar flexors and postural sway during quiet standing (Oshita and Yano,

in submitting). Data were obtained from 12 healthy men (age, 21 ± 1 years). Each participant performed the isometric unilateral plantar flexion exercise with their preferred leg. The relationship between force fluctuation during isometric plantar flexion and postural sway during quiet standing was evaluated using linear regression analysis. Figure 12 shows the relationship between postural sway during quiet standing and force fluctuation in plantar flexion. Although postural sway was significantly associated with force fluctuation at 10% MVC, it was not significantly associated with that at 20% MVC. These results suggest that the strategy of motor output in the plantar flexor muscles during low-intensity contraction is different between 10% and 20% MVC; moreover, the fluctuation in motor output in the plantar flexor muscles at 10% MVC was associated with postural sway during quiet standing in young adults.

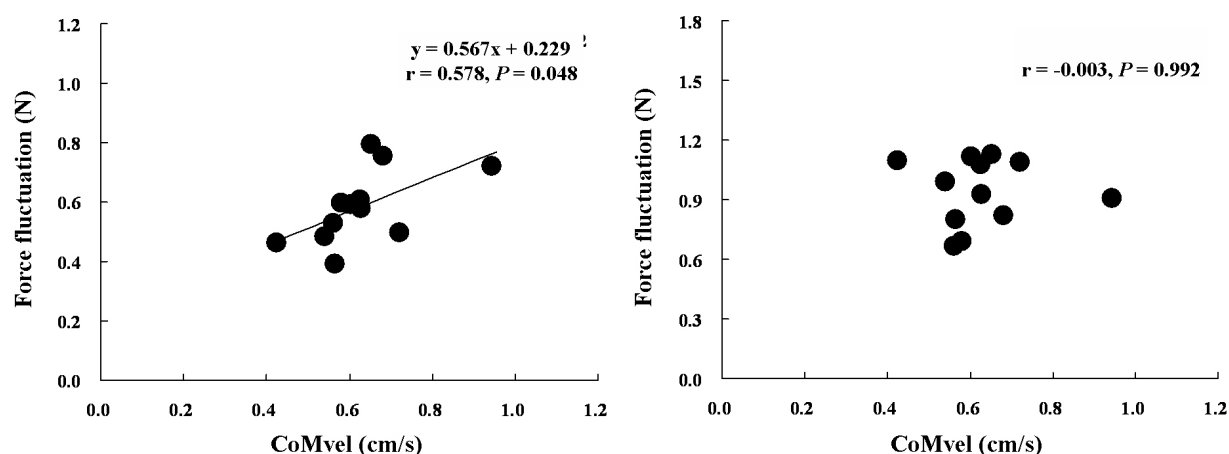


Fig. 12. Relationship between postural sway and force fluctuation during plantar flexion at 10% (left) and 20% (right) MVC

Numerous studies show that the plantar flexor muscles play a significant role in stabilising the body during quiet standing (Masani et al., 2003; Morasso and Schieppati, 1999). Furthermore, we observed a relationship between postural stability during quiet standing and force fluctuations during low-intensity isometric plantar flexion exercise. Therefore, individuals who have greater difficulty controlling plantar flexion force during isometric contraction tend to have greater difficulty controlling their standing posture. We revealed that plantar flexor force fluctuation is associated with postural sway during quiet standing in young adults. These results indicate that the force steadiness in plantar flexor muscles is important for postural stability during quiet standing; this is somewhat consistent with the results of previous studies. Oshita and Yano (2010c) report that force fluctuation during plantar flexion at 20% MVC is associated with postural stability during single-leg quiet standing. Although they report that postural stability is associated with force fluctuation at 20% MVC, the present results show a significant positive correlation between postural sway and force fluctuation at 10% MVC. The discrepancy between these results is thought to be due to the difference in the state of quiet standing. Oshita and Yano (2010c) report that force fluctuation is associated with postural stability during single-leg quiet standing. The activity level of the plantar flexor muscles is approximately 15–20% of MVC during single-leg standing (Sawai et al., 2004); however, it is approximately 10% of MVC during bipedal

standing (Ohnishi et al., 2005; Sawai, et al., 2004). Further, we suggest that the significant correlation between postural stability during quiet standing and the plantar flexor force fluctuation is found only at the corresponding contraction intensities for plantar flexor muscles. Therefore, the present results suggest that the neural strategies for plantar flexor muscles during quiet standing are similar to the strategies for controlling plantar flexor force in young adults.

Although the neural strategies at work in the plantar flexor muscles during quiet standing and those controlling plantar flexion forces are similar, the underlying mechanisms of the effects of steadiness practice on postural stability remain unclear. One possibility is that influence of the co-activation of the antagonist muscle (i.e. tibialis anterior) during both a force-matching task and quiet standing. Benjuya et al. (2004) report that subjects with a large postural sway (i.e. elderly adults) exhibit greater co-activation of the tibialis anterior during quiet standing. During the force steadiness tasks in finger muscles, fluctuations can be produced by alternating activation of the agonist and antagonist muscles (Vallbo and Wessberg, 1993). However, some studies (Burnett et al., 2000; Tracy and Enoka, 2002) report conflicting results in that the co-activation of antagonist muscles does not seem to have a major effect on force fluctuations. Thus, it remains unclear whether co-activation influences force fluctuation and postural stability.

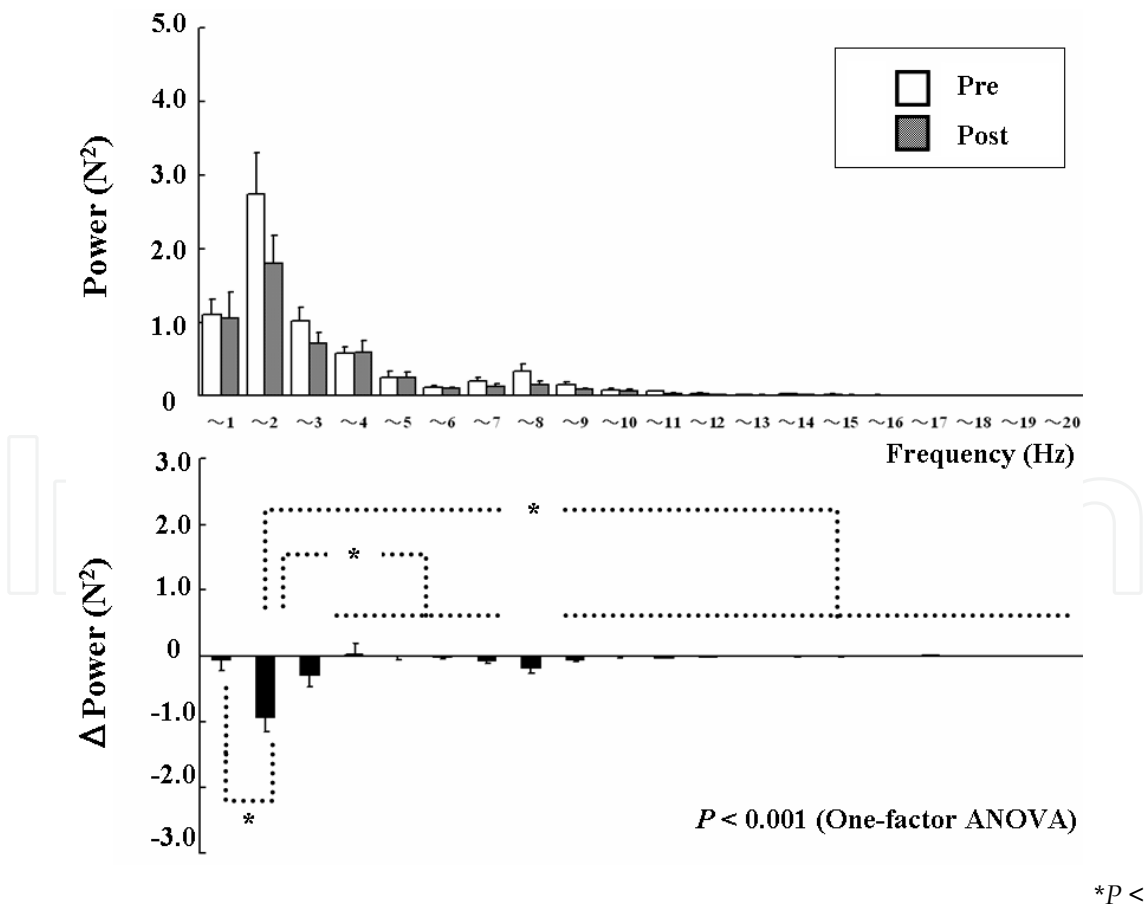


Fig. 13. Power spectral analysis of force fluctuation before and after steadiness practice (Oshita and Yano, 2011b)

Another possibility is that Ia afferent function has the capacity to modulate force fluctuations and postural stability. Ia afferent inputs contribute to force fluctuations in the low-frequency range. Yoshitake et al. (2004) report force fluctuations in the plantar flexor muscles at <2 Hz during low-level contractions (<10% MVC) after prolonged Achilles tendon vibration, a factor known to influence Ia afferent function. Oshita and Yano (2011b) found a reduction in force fluctuation in the frequency range of <2 Hz after force steadiness practice (Fig. 13). Furthermore, postural stability during quiet standing is also influenced by the efficacy of Ia afferent function as reflected by the amplitude of the H-reflex (Tokuno et al., 2007; Tokuno et al., 2008). Thus, force fluctuations might be associated with postural sway as a result of the contribution of Ia afferent function. Future studies are required to determine muscle activity in the antagonist muscle and/or neuromuscular properties (e.g. electromyography, motor unit activity, etc.) in order to clarify the mechanisms of practice effects like those reported here.

In summary, the present results indicate that the significant correlation between postural stability during quiet standing and force fluctuation during plantar flexion is found only at the corresponding contraction intensities for the plantar flexor muscles in young adults. Furthermore, the present results suggest that the neural strategies for plantar flexor muscles during quiet standing are similar to those controlling the plantar flexor force in young adults.

5. Steadiness practice reduces force fluctuation and postural sway

In section 4, we found a significant correlation between postural stability during quiet standing and force fluctuation in plantar flexion. If the force fluctuation in the plantar flexor muscles is reduced by steadiness practice, postural sway during quiet standing would also be reduced. This is because the results presented in section 4 suggest that the neural strategies employed by the plantar flexor muscles during quiet standing are similar to those controlling plantar flexion forces in young adults. Thus, in this section, we discuss the effects of steadiness practice in the plantar flexor muscles on force fluctuation during isometric contraction and postural sway during quiet standing (Oshita and Yano, 2011c).

Data were obtained from 21 healthy men (age, 21 ± 1 years). Participants were randomly assigned to a practice group ($n = 14$) and a non-exercising control group ($n = 7$). Practice groups were divided according to the frequency of practice: for 4 weeks, 7 participants practiced once a week while the other 7 practiced twice a week. Participants performed a strength test, force-matching tasks, and a postural stability test before and 4 weeks after the practice program. Strength was assessed by measuring MVC force. Force-matching tasks were performed to maintain isometric contraction. Steady contraction practice was performed as an isometric plantar flexion exercise under conditions identical to those in the experimental session. All practice was performed in the laboratory under supervision with emphasis on performing steady contractions. Practice consisted of 5 sets of practice per session. Verbal encouragement was provided during the sessions. The practice session consisted of the steady contraction task that lasted for 60 s (30 s at 10% and 20% MVC each) followed by a 30-s rest period.

Although MVC values were not significantly different before and after the practice period in the practice group, force fluctuation was significantly lower. Although the practice itself reduced force fluctuation, the frequency of practice did not have an effect (Table 1). Furthermore, there was no statistically significant interaction between practice intervention

and frequency (Table 1). These results indicate that force fluctuation is reduced by low-intensity force steadiness practice but does not change the MVC. Moreover, no effect of practice frequency (one or two time per week) was observed between groups.

Strength and steadiness practice reduce force fluctuation during the voluntary contraction of the distal muscles of the upper and lower limbs. Keen et al. (1994) found that 4 weeks of strength practice with the first dorsal interosseous muscle with a heavy load (80% of maximum) in 10 young adults (aged 18–27 years) reduced force fluctuation during isometric contraction at 50% MVC. Patten and Kamen (2000) report that the ability of 6 young adults (aged 18–22 years) to match a force trajectory requiring force modulation up to 60% MVC in the dorsiflexor muscles improved after 2 weeks of isometric force modulation training.

| | | | | Practice group | | ANOVA | | |
|-------------------|---------------|--------|------|----------------|---------------|------------------|------------------|------------------|
| | | | | Once a week | Twice a week | Frequency | Pre - Post | Interaction |
| Muscle strength | Right | (N) | Pre | 470.6 ± 187.9 | 538.0 ± 252.9 | <i>P</i> = 0.730 | <i>P</i> = 0.370 | <i>P</i> = 0.174 |
| | | | Post | 509.2 ± 164.3 | 529.6 ± 246.5 | | | |
| | Left | (N) | Pre | 474.7 ± 165.2 | 548.6 ± 238.0 | <i>P</i> = 0.600 | <i>P</i> = 0.722 | <i>P</i> = 0.614 |
| | | | Post | 496.1 ± 165.3 | 544.9 ± 222.2 | | | |
| Force Fluctuation | 10% MVC Right | (N) | Pre | 0.559 ± 0.088 | 0.695 ± 0.279 | <i>P</i> = 0.468 | <i>P</i> = 0.050 | <i>P</i> = 0.318 |
| | | | Post | 0.518 ± 0.157 | 0.468 ± 0.086 | | | |
| | 10% MVC Left | (N) | Pre | 0.540 ± 0.055 | 0.782 ± 0.262 | <i>P</i> = 0.291 | <i>P</i> < 0.001 | <i>P</i> = 0.053 |
| | | | Post | 0.427 ± 0.046 | 0.426 ± 0.127 | | | |
| | 20% MVC Right | (N) | Pre | 0.880 ± 0.056 | 1.142 ± 0.457 | <i>P</i> = 0.297 | <i>P</i> < 0.001 | <i>P</i> = 0.253 |
| | | | Post | 0.720 ± 0.087 | 0.901 ± 0.399 | | | |
| | 20% MVC Left | (N) | Pre | 1.096 ± 0.013 | 1.237 ± 0.327 | <i>P</i> = 0.604 | <i>P</i> < 0.001 | <i>P</i> = 0.456 |
| | | | Post | 0.758 ± 0.120 | 0.715 ± 0.227 | | | |
| Postural sway | CoM velocity | (cm/s) | Pre | 0.593 ± 0.095 | 0.607 ± 0.060 | <i>P</i> = 0.690 | <i>P</i> = 0.004 | <i>P</i> = 0.655 |
| | | | Post | 0.539 ± 0.045 | 0.530 ± 0.043 | | | |

Table 1. Changes in muscle strength and force fluctuation due to steadiness practice in the practice group (Oshita and Yano, 2011c)

These previous findings corroborate those of the present study. Both the existing literature and present results indicate that strength and steadiness training interventions consistently reduce fluctuations during the low-to-moderate-intensity contractions of the distal muscles of the upper and lower limbs. Furthermore, even though the frequency of practice was relatively low (once a week), it was sufficient to reduce the force fluctuation in the present study.

We also showed that steadiness practice in the plantar flexor muscles reduces the postural sway during quiet standing. In a study involving the upper limbs, Ranganathan et al. (2001) found that skilled finger movement practice improves both the steadiness of the hand muscle and Purdue pegboard test scores. Kornatz et al. (2005) also found that steadiness practice in hand muscles improves the steadiness of the hand muscles and Purdue pegboard test scores. The results of these previous studies led us to hypothesise that steadiness practice in the plantar flexor muscles decreases the force fluctuations of the plantar flexor muscles and improves postural stability. The results of the present study demonstrate that steadiness practice in the plantar flexor muscles reduces postural sway during quiet standing. Therefore, this suggests that the neural strategies employed by the plantar flexor

muscles during quiet standing and those controlling plantar flexion forces in young adults are similar.

Figure 14 shows the relationship between pre-practice postural sway and changes in steadiness. Linear regression analysis revealed a significant relationship between pre-practice postural sway and the change in postural sway due to steadiness practice. This result indicates that subjects exhibiting relatively large pre-practice postural sway also exhibit greater reductions in postural sway following force steadiness practice in the plantar flexor muscles. Thus, the effects of practice on postural stability are dependent on pre-practice postural stability. This finding is also consistent with the findings of other reports demonstrating that improvements in steadiness are more frequent in subjects with low initial steadiness levels (Manini et al., 2005; Tracy et al., 2004); this strengthens the notion that the effectiveness of training is dependent on the initial level of steadiness.

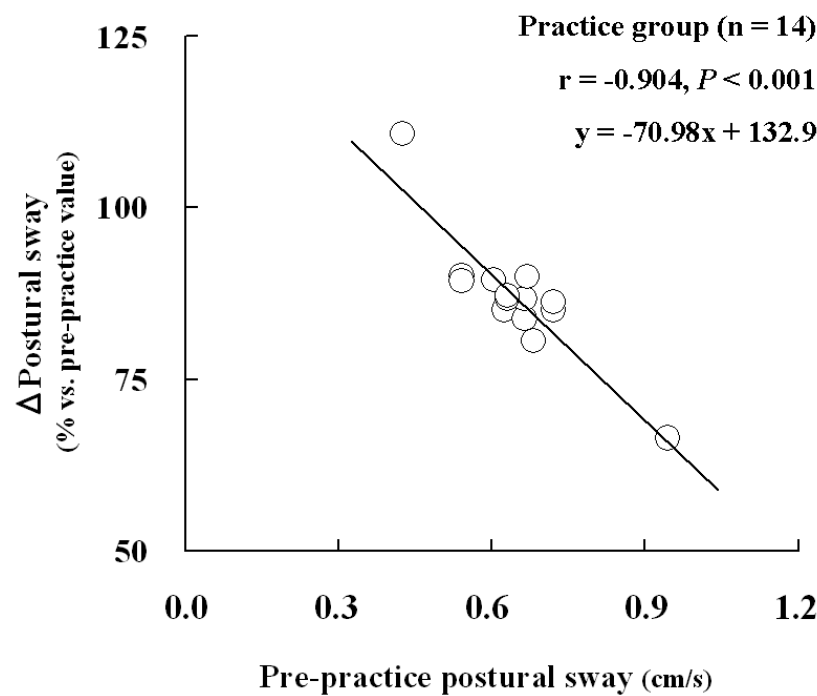


Fig. 14. Relationship between baseline postural sway and changes in postural sway (Oshita and Yano, 2011c)

As indicated in section 4, multiple factors influence the relationship between force steadiness and postural stability. Although we focused on whether force steadiness practice in the plantar flexor muscles improves postural stability during quiet standing, we demonstrated the functional significance of force fluctuations during voluntary contraction. From the perspective of exercise prescription, the results reported in this section also suggest that even low-frequency, (once a week) low-intensity (within 20% MVC) steadiness practice is an effective method for improving human movement.

6. Conclusion

This chapter discussed the relationship between force steadiness in lower limb muscles and postural stability during quiet standing. Although previous studies suggest that the

asymmetry of leg muscle functions might affect the human movements (Skelton et al., 2002; Oshita et al., 2009), no significant differences in force steadiness during isometric knee extension or plantar flexion were observed between the 2 legs as shown in section 3. In section 4, a significant correlation between postural stability during quiet standing and force fluctuation during plantar flexion was found only at the corresponding contraction intensities of the plantar flexor muscles in young adults. Furthermore, in section 5, we found that steadiness practice in plantar flexor muscles improves postural stability during quiet standing and that the effects of practice are dependent on pre-practice postural stability. These results will provide useful information to design a training program for postural stability. Usually, the goal of many training programs is improvement of postural stability by an increase in muscle strength (Anderson and Behm, 2005; Holviala et al., 2006). Certainly, strength of the main working muscles to support self body weight is thought to be the most important factor for postural stability. However, MVC in the plantar flexor did not relate with posture sway in our report (Oshita and Yano, 2010c). Further, Kouzaki et al. (2007) reported that postural sway during bipedal quiet standing increases following bed rest despite maintenance of the muscle volume of the main working muscle for human postural standing by strength training. These results indicate that not only muscle strength but also force steadiness is an important factor for postural stability. From the perspective of exercise prescription, the results described in section 5 also suggest that even low-frequency (once a week), low-intensity (within 20% MVC) steadiness practice is an effective method for improving human movement. Therefore, this chapter demonstrates the functional significance of force fluctuations in lower limb muscles.

7. Future direction

So far we have focused on clarifying the relations between postural stability and force steadiness in healthy young men. Regarding the force steadiness, the following investigations are also required:

- To clarify the relationship between force steadiness and various human movements (i.e., walking, to go up (down) stairs, dynamic postural stability, and so on)
- To measure the force steadiness in multiple generations and, possibly, in individuals with neurological disorders.

In particular, unsteady movement or large variability in force output in elderly adults (Galganski, et al., 1993) might lead to difficulties in the performance of daily activities (Kornatz, et al., 2005). By examining the relations between force steadiness and human movement in multiple generations, the findings would more clarify the functional significance of force steadiness and might lead to an understanding of the physiological mechanisms of deteriorations in movement in elderly adult or individuals with neurological disorders.

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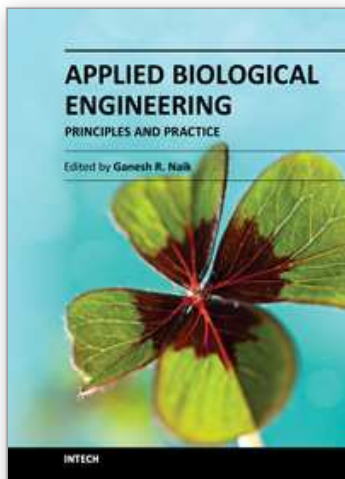
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Biological engineering is a field of engineering in which the emphasis is on life and life-sustaining systems. Biological engineering is an emerging discipline that encompasses engineering theory and practice connected to and derived from the science of biology. The most important trend in biological engineering is the dynamic range of scales at which biotechnology is now able to integrate with biological processes. An explosion in micro/nanoscale technology is allowing the manufacture of nanoparticles for drug delivery into cells, miniaturized implantable microsenors for medical diagnostics, and micro-engineered robots for on-board tissue repairs. This book aims to provide an updated overview of the recent developments in biological engineering from diverse aspects and various applications in clinical and experimental research.

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