ORIGINAL ARTICLE

Gravity magnetic resonance imaging measurement of muscle pump change accompanied by aging and posture

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Abstract

Aim: To date no age-comparative study has been reported about effect of exercise on muscle pump action change, while its effect is suggested to differ in ages. This study aims to clarify the changes in muscle pump action with aging by measuring the muscle and vein area, and blood flow in lower legs.

Methods: Subjects were healthy volunteers and consisted of three groups: young age group ($N = 20$), middle age group ($N = 20$) and old age group ($N = 16$). The lower leg flexor muscle area and popliteal vein area were measured by using T1-weighed magnetic resonance imaging at the condition pre- and post-ankle exercise in three positions. Moreover, popliteal blood flow velocity was also measured using phase contrast magnetic resonance imaging.

Results: The elderly had the highest number of individuals who had exercise habits ($p < .001$). In a multiple linear regression analysis, sitting posture, leg muscle volume, and rate of change in the soleus muscle were significantly related to blood flow velocity change.

Conclusions: No difference was found in the changes in muscle pump action with age. The study results suggested that elderly people with exercise habits might be able to maintain the muscle pump action.

KEYWORDS
aging, blood flow velocity, magnetic resonance imaging, popliteal vein

1 | INTRODUCTION

Chronic lower limb edema (CLE) is highly prevalent in elderly people, leading to various problems. In Japan, 66% of elderly people in long-term care facilities have edema, and lower limb edema accounts for 88% of this (Sato et al., 2015). At walking ability levels, 24% of elderly people with CLE can walk alone, 62% can walk with a cane or walker, and 75% can stay in a sitting posture for a long time (Fukazawa et al., 2013; Oya, 2001). Many elderly people have CLE, and as walking ability decreases, CLE prevalence increases. The occurrence of CLE causes physical effects such as difficulty in walking due to weight and difficulty in moving, and mental effects such as fatigue, anxiety, and discomfort (Kitamura & Shirai, 2014; Greene & Meskell, 2017).

The causes of CLE include disease and disuse. One of the causes of disuse edema is a decrease in muscle pump

action (Hirota, 2012). Disuse edema is caused by aging effects and a decrease of the lower leg muscle pump action due to reduced activity. In clinical settings, nurses recognize disuse CLE as the aging process and tend to underestimate the problems caused by disuse CLE. Moreover, the elderly themselves with CLE also think that CLE cannot be helped. On the other hand, some exercises promoted psychomotor performance (Taheri & Irandoust, 2017) and posture mobility (Irandoust et al., 2019) in elderly. Thus, muscle pump action should be maintained to prevent or reduce CLE (Suehiro et al., 2014).

How is muscle pump action affected by the aging process? It is assumed that to raise the awareness of the disuse CLE in the elderly, it might be important to get this evidence. In several studies, muscle pump action were only measured in young (Kwon, Jung, Kim, Cho, & Yi, 2003; Sochart & Hardinge, 1999) or elderly people (Kawana, Egami, Harada, & Uchida, 2010; Suehiro et al., 2014). A comparison of venous return between generations has been considered. However, no studies comparing young and elderly individuals have revealed any changes in muscle pump action with aging.

In previous studies, muscle pump action was measured by pulsed Doppler ultrasound (Stein, 2016), air plethysmography (Yang, Vandongen, & Stacey, 1999), ambulatory venous pressure (Dixy, Brooke, & McCollum, 2003), and laser tissue blood oxygenation monitor (Mori, Kuniyasu, Fujita, & Watanabe, 2008). However, this measurement using such devices was intended only for changes in venous blood flow before and after exercise. The muscle pump action is an action in which muscle contraction, vein compression, and promotion of venous blood flow occur simultaneously. Magnetic resonance imaging (MRI) can detect venous blood flow and the morphological changes of muscles and veins. Therefore, we employed MRI to measure the compression of muscles and veins and the promotion of blood flow by exercise.

This study aims to clarify the changes in muscle pump action with aging by measuring the muscle pump in young, middle-aged, and elderly people using MRI. Moreover, regarding the influence of gravity, the muscle pump action of the lower leg is supposed to be affected by posture. Thus, the comparison of muscle pump action with aging is needed in supine, sitting and standing positions.

2 | MATERIALS AND METHODS

2.1 | Subjects

We recruited healthy volunteers according to age: young age group, middle age group, and old age group. Subjects were excluded if they had cardiovascular and major musculoskeletal diseases or contraindication for MRI. All enrolled subjects were publicly and comprehensively explained about the study design and protection of their privacy. Young and middle age groups were students or staff at a university. The old age group were community-dwelling individuals introduced from community welfare or healthcare professions.

2.2 | Scan protocol

We used a 0.4 T open-MR system (APERTO Eterna; Hitachi, Ltd., Tokyo, Japan) to scan all subjects (Miyachi, Yamazaki, Ohno, & Miyati, 2019; Ohno, Miyati, Hiratatsu, & Yamasaki, 2017). The height of the MR table can be adjusted from 73.5 to 106.0 cm. Measurement postures were supine, sitting, and standing and were performed randomly. In each posture, plantar flexion of the maximum range of ankle motion (ROAM) was performed for 1 min at 30 times/min in accordance with a metronome. We instructed the subjects not to perform dorsiflexion exercises. Each posture was measured for 1 hr by MRI using the subject's dominant foot. To reduce the burden on the subjects, we performed the measurement only once a day.

First, we measured the cross section of the lower leg during nonplantar flexion of the ankle by T1-weighted imaging (T1WI; time of repetition over time of echo, 183.4/8.6; field of view, 180 mm; slice thickness, 10 mm). Second, we measured the blood flow velocity in the popliteal vein (PV) before exercise by phase contrast imaging (PCI; time of repetition over time of echo, 30/10.7; field of view, 180 mm; slice thickness, 10 mm; velocity encoding, 30–50 cm/s). Third, participants performed exercise for 1 min. Fourth, we measured the blood flow velocity of PV after exercise by PCI. Finally, we measured the cross section of the lower leg during plantar flexion of the ankle by T1WI.

2.3 | Data processing

We used the T1WI to measure the muscle area (gastrocnemius muscle [GAS], soleus muscle [SOL], and other lower leg flexor muscles) and vein area (PV, great saphenous vein [GSV], and small saphenous vein [SSV]) (Figure 1). The measurement was based on the MRI marker (MR-SPOT Packets™ 185, Beekley Medical) affixed 5 cm below the back of the knee. A total of 21 cross sections were measured (eight at the top, one at the marker portion, and 12 at the bottom). To measure the flexor area of the lower leg, we utilized nine consecutive sections below the marker including the marker section. Furthermore, we measured the PV area by using three consecutive sections below the marker and the GSV and SSV areas by using six consecutive sections below the marker.

FIGURE 1 Magnetic resonance imaging (MRI) measuring range and T1-weighted image (T1WI) with muscle and vein region of interest (ROI) set. (a) The measurement was based on the MRI marker affixed 5 cm below the back of the knee. A total of 21 cross sections were measured: eight cross sections at the top, one cross section at the marker portion, and 12 cross sections at the bottom. For the measurement of the flexor area of the lower leg, nine consecutive sections below the marker including the marker section were used. (b) T1WI with muscle and vein ROI set on the T1WI of the cross section at the center of the marker. Muscle area was measured for GAS and SOL. The vein area was measured for the PV and the GSV and SSV. PV, popliteal vein; GAS, gastrocnemius muscle; SOL, soleus muscle; GSV, great saphenous vein; SSV, small saphenous vein
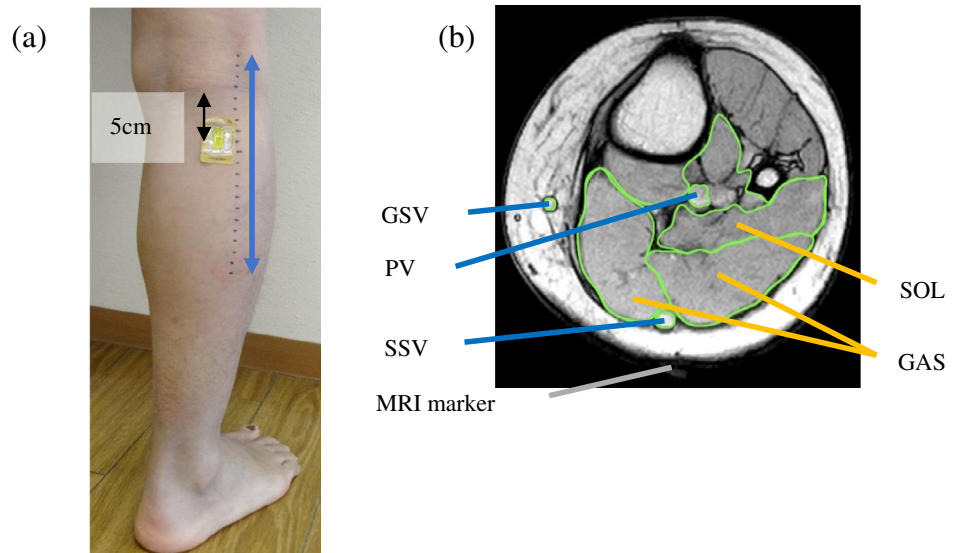
Meanwhile, the blood flow velocity of PV was measured by PCI. The PCI was obtained at the center of the marker section. A pulse wave meter was attached to a finger, and PCI was performed while synchronizing the pulse waves. The measurement time was 1 min and 10–30 s, and it was shorter when the pulse rate was earlier because it depends on the pulse rate.

2.4 | Posture setting

This study measured three postures, namely, supine, sitting, and standing (Figure 2). In the supine posture, the feet were slightly lifted from the table by using a cushion to prevent compressing the measurement part of the lower leg. In addition, an angle-maintaining plate was arranged to set the angle of the ankle joint in the supine posture without ankle plantar flexion at 90°. In the sitting and standing postures, a 6 cm high wooden plank was inserted under both heels to maintain the ankle plantar flexion.

2.5 | Characteristics of subjects

The subjects were asked about their gender, age, height, medical history, and exercise habits. Exercise habits were defined as exercise more than twice a week for at least 30 min at a time. We interviewed with subjects about routine exercise and its duration and frequency. We used

a multifrequency body composition meter (MC-180, Tanita Co., Ltd.) to measure the body weight, body mass index, and leg muscle volume and to calculate the weight-adjusted leg muscle volume (WLM) obtained from the weight and leg muscle volume of the subjects. Meanwhile, ROAM was measured by applying a goniometer (Tokyo goniometer: Yasuda Seisakusho) to the line connecting the fibula head and the lateral malleolus and the midline of the fifth metatarsal to measure plantar flexion and dorsiflexion, respectively.

2.6 | Analysis

2.6.1 | MRI analysis

The MRIs were analyzed using the image analysis software OsiriX (Pixmeo SARL) (Rosset, Spadola, & Ratib, 2004). All image analyses were performed by one researcher. The measurement target was GAS, SOL, and PV. The value of each item was represented by mean $\pm$ SD.

2.6.2 | Calculation of the rate of change in venous blood flow velocity, leg flexor area, and vein area

Using the rate of change, we compared the young, middle-aged, and elderly people. The rates of change in
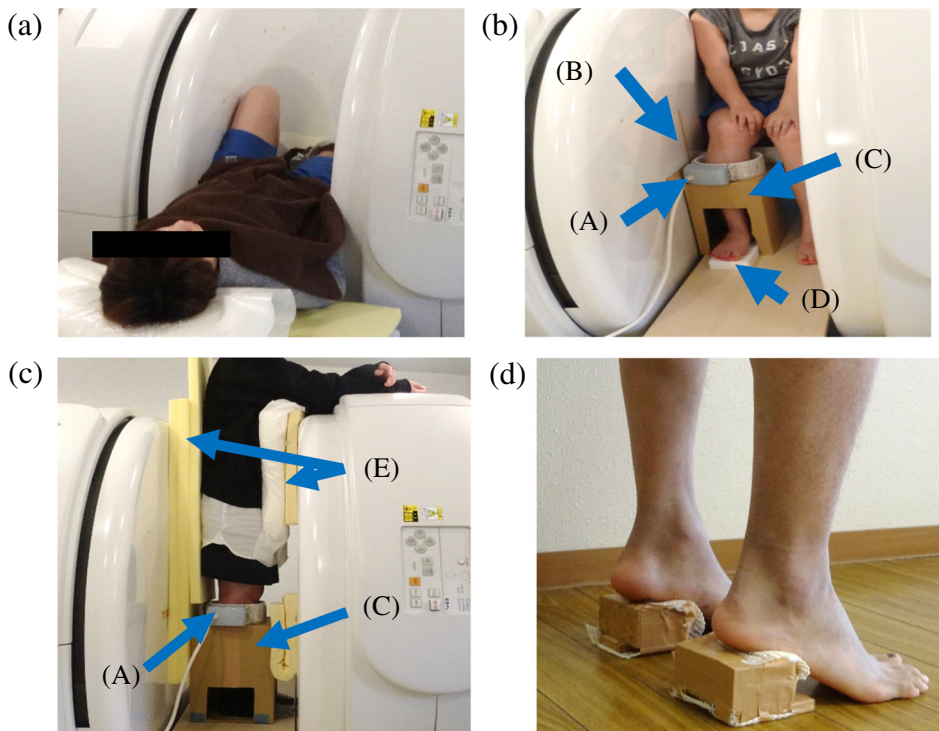
FIGURE 2 Posture setting and using item. (a) Supine posture. The non-measuring limb is placed beside the thigh with the knee joint bent. The hand is placed in a comfortable position for the subject. (b) Sitting posture. The leg and hands are placed in a comfortable position for the subject. The knee joint was adjusted to 105°. (c) Standing posture. A cushion for trunk fixation (E) was used on the trunk to maintain posture. The hands were placed in a comfortable position for the subject. (d) In the sitting and standing posture, a 6 cm high wooden plank was inserted under both heels to keep the ankle plantar flexion. (A) Neck receiving coil. (B) Center of magnetic resonance image. (C) Height adjustment box. (D) Height adjustment plate. (E) Cushion for trunk fixation

the blood flow velocity of PV, flexor muscle area, and vein area were calculated by the following equation. The rate of change was based on 0% when ankle joint non-plantar flexion/before exercise. Rate of change in venous blood flow (%) = (blood flow velocity after ankle plantar flexion [cm/s]−blood flow velocity before ankle plantar flexion [cm/s])/ankle plantar flexion previous blood flow velocity (cm/s) × 100.

Rate of change in flexor muscle area/vein area (%) = (flexor muscle area/vein area after ankle plantar flexion [cm/s]−flexor muscle area/vein area before ankle plantar flexion [cm/s])/ankle plantar flexion from previous flexor muscle area/vein area (cm/s) × 100.

2.6.3 | Statistical analysis

To verify the validity of the exercise in this study, we compared the venous blood flow velocity before and after the exercise. After confirming the normality of the data, we selected an appropriate method from the Wilcoxon signed-rank sum test or the paired t test. The numerical values are shown as the mean ± SD. Then, after the normality and equal variance of the data were confirmed, the age of the subjects was compared by one-way analysis of variance and Tukey–Kramer honestly significant difference test or Games–Howell test, or Kruskal–Wallis test. Exercise habits were compared using the χ^2 test. A multiple linear regression was calculated to predict the rate of change in

blood flow velocity based on generations (young, middle-aged, and elderly), posture (supine, sitting, and standing), leg muscle volume, and rate of change in the muscle cross-sectional area (SOL and GAS). The statistical analysis was conducted using the software SPSS version 25, and the significance level was 5%.

2.6.4 | Ethical considerations

This study was approved by the medical ethics committee of Kanazawa University (approval number 42).

3 | RESULTS

3.1 | Characteristics of the subjects

Table 1 shows the subjects′ characteristics. The ages of the young ($N = 20$), middle-aged ($N = 20$), and elderly ($N = 16$) participants were 23.5 ± 3.2, 47.1 ± 7.4, and 71.6 ± 5.0 years, respectively. The WLM were significantly different between these three groups ($p < .001$). Leg muscle volume and ankle dorsiflexion range tended to decrease with age ($p = .0088$, $p = .073$, respectively). Moreover, four young, six middle-aged, and 14 elderly people had exercise habits; thus, the elderly had the highest number of individuals who had exercise habits ($p < .001$).

TABLE 1 Characteristics of the subjects

	Young	Middle	Elderly	*p*
Gender (M/F)	10/10	10/10	8/8	1.000[a]
Age (years)	23.5 ± 3.2	47.1 ± 7.4	71.6 ± 5.0	<.001[b]
BMI (kg/m^2)	21.6 ± 3.6	22.7 ± 3.6	22.3 ± 2.8	.287[b]
Leg muscle (kg)	17.1 ± 4.1	15.6 ± 3.7	14.3 ± 3.6	.088[b]
WLM	29.0 ± 3.0	26.1 ± 2.7	25.1 ± 3.2	<.001[c]
ROAM (°)				
Plantar flexion	54.9 ± 5.9	53.6 ± 8.8	52.1 ± 4.2	.486[d]
Dorsiflexion	19.3 ± 6.4	20.9 ± 8.8	15.1 ± 8.0	.073[c]
Exercise habits(N)	4/16	6/14	14/2	<.001[a]

Note: Values are mean ± *SD*. *N* = 56.
Abbreviations: BMI, body mass index; ROAM, range of ankle motion; WLM = weight-adjusted leg muscle volume.
[a]χ^2 test.
[b]Kruskal-Wallis test.
[c]Tukey–Kramer honestly significant difference test.
[d]Games-Howell test.

The cross-sectional areas of the SSV before ankle exercise were significantly different in the sitting posture (*p* = .010) and in the standing posture (*p* = .025) (Figure 3).

3.2 | Generational comparison of muscle pump action

The PV blood flow velocity increased significantly after exercise compared with that before exercise at all ages and postures (*p* < .01).

A multiple linear regression was calculated to predict the rate of change in blood flow velocity based on generations (middle-aged and elderly), posture (supine and sitting), leg muscle volume, and rate of change in muscle cross-sectional area (SOL and GAS) (Table 2). Sitting posture, leg muscle volume, and the rate of change in SOL were significant predictors of blood flow velocity change.

4 | DISCUSSION

In this study, we performed an ankle plantar flexion exercise for 1 min (30 times/min). In comparing blood flow velocities before and after ankle plantar flexion exercise, the blood flow velocities after the exercise increased significantly at all generations and postures. In the rate of change in blood flow velocity by posture, the blood flow velocity increased to 55–90%, 30–40%, and 90–135% in the supine, sitting, and standing postures, respectively. Regarding the changes in venous blood flow velocity due to exercise, Kwon et al. (2003) reported that the rate of

change in the peak velocity of femoral venous blood flow was 104% by performing ankle plantar flexion in a supine posture. Meanwhile, Stein (2016) reported that the rate of change in the peak velocity of PV blood flow was 118% when performing ankle dorsiflexion in a supine posture. Comparing the results of these previous studies with the results of the current study, the rate of change in venous blood flow velocity was similar, although body posture and exercise methods had differences. The ankle plantar flexion exercise performed in this study is an appropriate exercise to promote muscle pump action.

Measurements of muscle pump action effects have been limited to specific ages. For instance, Suehiro et al. (2014) investigated elderly people with an average age of 75 years, and Kwon et al. (2003) investigated young people with an average age of 21 years. The current study is the first one to investigate the changes in muscle pump action with age in young, middle-aged, and elderly people. In this study, a multiple linear regression showed that aging had no significant effect on the change of blood flow velocity, considering that the elderly people maintained leg muscle volume, ROAM, and exercise habits required for the pumping action.

In this study, leg muscle volume tended to be lower in elderly people than in young people. However, the leg muscle volume measured by Tanimoto et al. (2010) was 13.1 kg, whereas that of the elderly in the current study was 14.4 ± 3.6 kg, which was larger than that measured by Tanimoto.

Dixy et al. (2003) studied the relationship between ROAM and muscle pump action in chronic venous disorders in subjects with a mean age of 60 years. The muscle pump action was significantly promoted in the group
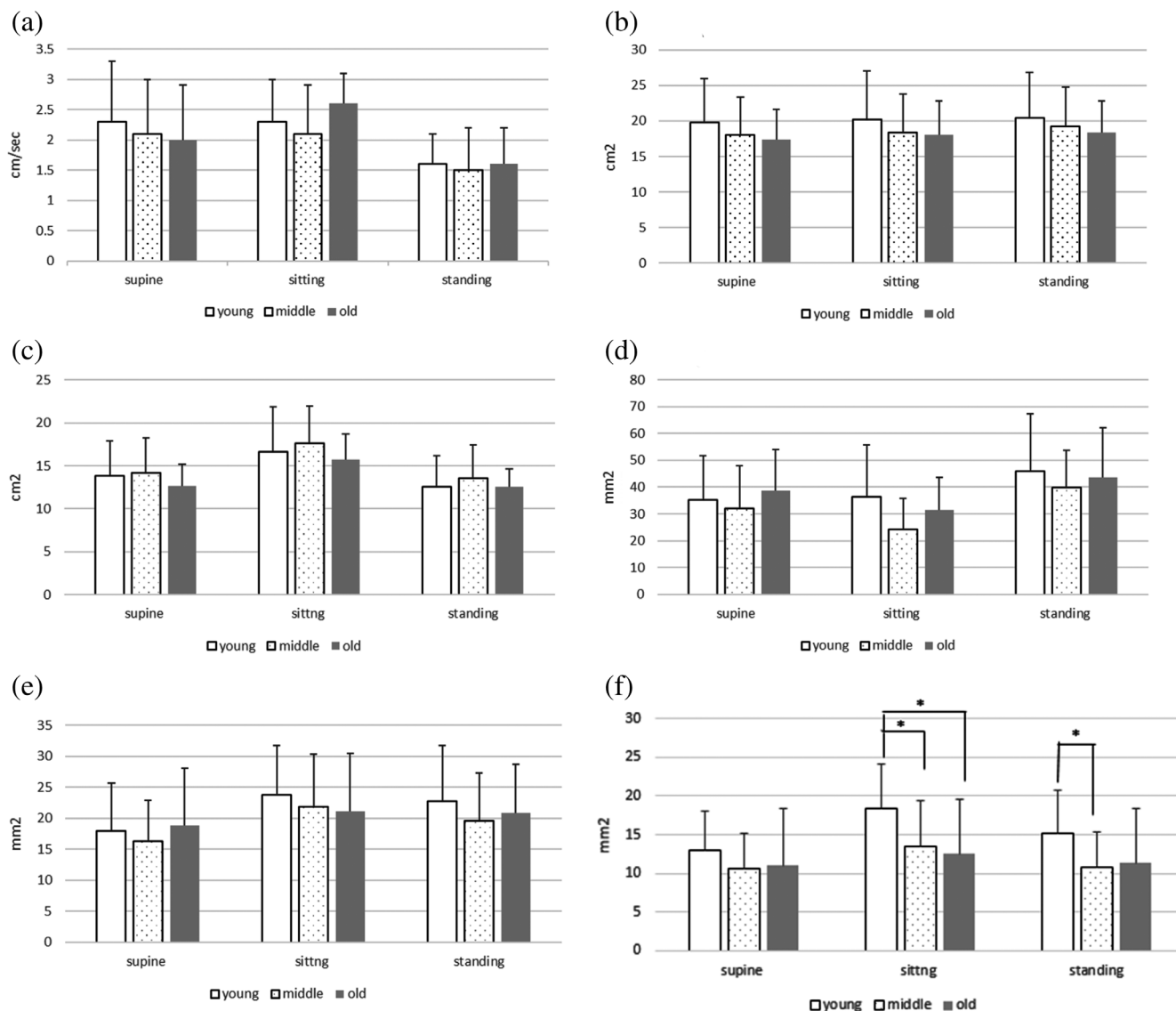
FIGURE 3 Comparison of each magnetic resonance imaging parameter before ankle exercise in each position by age groups. (a) PV blood flow, (b) GAS area, (c) SOL area, (d) PV area, (e) GSV area and (f) SSV area. One-way analysis of variance and Tukey–Kramer honest significant difference test or Games–Howell test, or Kruskal–Wallis test. *Indicates a statistically significant difference ($p = .01$). PV, popliteal vein; GAS, gastrocnemius muscle; SOL, soleus muscle; GSV, great saphenous vein; SSV, small saphenous vein

with $61.3° ± 6.6°$ of ROAM (plantar flexion + dorsiflexion) than in the group with $40.9° ± 9.4°$. For the elderly in this study, the ROAM (plantar flexion + dorsiflexion) was $67.3° ± 10.8°$, which is higher than that in the study of Dixy et al. Lowering the ROAM may also reduce muscle pump action. In this study, the ROAM was not significantly different between the ages, and the muscle pump action was maintained because it was greater than the previous study.

A significant difference was found between the age groups with and without exercise habits. According to the Ministry of Health, Labor, and Welfare, the percentage of people aged 20–64 years who had exercise habits was 18.7%

and those of 65 years or more was 39.3% (Ministry of Health, Labor, and Welfare, 2018). In our study, 25% (10/40) of the subjects in the young and middle-aged groups had exercise habits and 87.5% (14/16) of the elderly group subjects had exercise habits. Therefore, the elderly in this study did not demonstrate a decrease in muscle pump action due to aging because the exercise habits, leg muscle volume, and ankle plantar flexion excursion were maintained. In future, the muscle pump action of those who have decreased leg muscle volume or ROAM or those who have edema needs to be measured.

According to this study result by using MRI measuring, leg muscle volume, and the rate of change in SOL

TABLE 2 Effective independent variables for change of blood flow velocity

	Unstandardized coefficients		Standardized coefficients			95% CI of B	
	B	*SE*	**β**	**t**	***p***	**Lower limit**	**Upper limit**
Constant	183.353	30.796		5.954	<.001	122.5336	244.1729
Middle	13.695	14.603	.076	0.938	.35	−15.1441	42.53485
Elderly	−4.961	16.128	−.026	−0.308	.759	−36.8128	26.89154
Supine	−26.882	15.682	−.147	−1.714	.088	−57.8527	4.087958
Sitting	−59.151	16.959	−.324	−3.488	.001	−92.6442	−25.6585
Leg muscle volume	−6.096	1.659	−.276	−3.675	<.001	−9.3722	−2.8207
Rate of change GAS	0.131	1.058	.009	0.124	.902	−1.95795	2.219348
Rate of change SOL	1.384	0.671	.17	2.062	.041	0.058514	2.70882

Note: A significant regression equation was found ($F_{7,160} = 6.464$, $p < .001$)], with an R^2 of .220.
GAS, gastrocnemius muscle; SOL, soleus muscle.

were significant predictors of blood flow velocity change. This suggested that intervention exercise to increase the leg muscle, especially SOL, might effect on the prevention or management of CLE. Measuring muscle pump action might be useful for nurses to assess the muscle pump action level and evaluate intervention which promote venous return to manage CLE. We consider that MRI is not the suitable equipment for point of care. Thus, we need to develop an easier device and method to measuring muscle pump action at the bedside in the future.

There were some limitations in this study. The sample selection was nonprobability sampling and number of subjects in each group was small. Considering that the measuring table is high (73.5–106.0 cm), elderly people with reduced walking ability cannot be measured safely. Hence, measuring elderly people with leg muscle volume or reduced ROAM was impossible. Measurement of muscle pump action in targeting elderly people with reduced walking ability or who have edema is necessary. Therefore, we must try to conduct the study for increasing the safety of the measurement or changing the measurement equipment. MRI analysis was performed by one specific researcher for all image processing. Given that the target image was not blinded, a detection bias might have occurred.

5 | CONCLUSIONS

To clarify the changes in muscle pump action based on age and body posture, we measured the muscle pump action of 20 young, 20 middle-aged, and 16 elderly people in supine, sitting, and standing postures. As a result of the multivariate analysis, no difference was found in the changes in muscle pump action with age, but a difference was found in the muscle pump action change with body posture. The study results suggest that elderly people may

be able to maintain their muscle pump action when they have exercise habits, leg muscle volume, and ROAM.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Study design: N.O., T.S., T.F., T.M. and J.S.
Data collection and analysis: T.F., N.O. and T.S.
Manuscript authorship: T.F., K.O. and J.S.
Critical manuscript revisions: J.S., K.O., N.O. and T.M.

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