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Acute Effect of Somatosensory Stimulation on Gastrocnemius Behavior When Elderly People Climb Stairs

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Climbing stairs is the one of the activities of daily living (ADL) and is more biomechanically demanding than level walking. Recently, local muscle vibration (LMV) has been applied to movement and rehabilitation, and it was revealed that LMV significantly affects muscle activation. However, there have been no investigations of mechanical muscle behavior in real time during the application of LMV. The purpose of this study was to investigate the effects of LMV on muscle behavior and postural stability during stair ascent by the elderly using ultrasound. Fifteen young adults and ten elderly participants were asked to walk and climb stairs. LMV was applied during stair climbing. Center of pressure (COP), electromyography (EMG), and ultrasound data were recorded for each condition. When LMV was applied, a greater root mean square (RMS)-EMG was observed during forward continuance (FCN) along with a shorter fascicle length and larger pennation angle (PA). The COP of elderly participants was greater than that of young adults. When LMV was applied, the COP decreased. These results suggest that LMV affects muscle behavior, leading to more activation during locomotion. In particular, in elderly people with reduced ADL due to aging, LMV may contribute to muscle activation and increase muscle efficiency, improving ADL ability.

1. Introduction

Aging is associated with the involuntary loss of muscle mass, muscle strength, and function related to activities of daily living (ADL). Stair negotiation is one of the important tasks associated with ADL and requires more muscle power and strength than walking. In particular, for elderly people, who may have lost muscle mass due to aging, it can be a hazardous activity.[1,2] A previously study revealed that 74.1% of elderly subjects had difficulties in climbing up stairs and 64.7% of subjects had difficulties in going down stairs.[1]

Several previous research findings on the effects of vibration on muscle activity revealed that vibration stimulation may induce muscle activation.[2–4] Nikooyan and Zadpoor revealed that

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muscle activation can have a significant effect on human mechanical responses under whole body vibration (WBV).[5] However, WBV has some limitations: the difficulty of applying it to targeted muscles in a wide range of trials and the attenuation of the vibratory signal by the time it reaches the intended muscle during its transmission through soft tissue, which may reduce the desired therapeutic effects.[6] Recently, local muscle vibration (LMV) has been used for therapeutic effects and to increase the functionality of muscle as an economically viable and portable alternative to WBV.[2] Other studies have provided evidence that LMV might increase muscle strength as well as muscle mass, bone density, and physical performance.[7]

Although the effects of LMV on musculature are being revealed, most previous studies have investigated the effects from a macroscopic perspective. It is important to reveal the underlying mechanisms such as muscles' mechanical behavior to provide more insight into the effects of LMV and information for rehabilitation, training, and assistance. There are many studies on the acute effect of vibration stimulation,[8,9] but few studies have focused on the changes in the mechanical behavior of muscles during locomotion. In addition, despite many studies on climbing stairs, few studies have measured muscle activity in real time.

Ultrasound imaging in the B-mode is a non-invasive investigation method and has been popular for measuring muscle function *in vivo*. Ultrasound imaging has been used for investigating muscle architecture and dynamic changes in muscles upon their contraction, which can be used to examine the activation of muscle fibers during locomotion.[10–13]

The purpose of this study was to investigate the clinical effectiveness of LMV on the lateral gastrocnemius (LG) muscle in real time via ultrasound imaging. For this purpose, the characteristics of muscle behavior in stance phases in young adult and elderly groups and changes in muscle behavior and postural stability with LMV were examined.

2. Materials and Methods

2.1 Participants

Fifteen healthy young adults (age: 25.5 ± 1.5 years, height: 173.2 ± 2.6 cm, weight: 72.4 ± 4.4 kg) and ten elderly volunteers (age: 76.0 ± 1.7 years, height: 166.7 ± 3.7 cm, weight: 68.0 ± 5.5 kg) who were free from neurological and musculoskeletal disorders with no history of falls or any accidents in the previous year were recruited from Jeonbuk National University and local communities. All participants in the study were informed of the processes and requirements for the study, then completed and signed an informed consent document. This study was approved by the institutional review board of Jeonbuk National University (IRB File No.JBNU 2017-03-011-001).

2.2 Experimental instruments and measurements

2.2.1 Staircase

A custom-built staircase consisting of five steps with standard dimensions (step height: 16 cm, step width: 180 cm, step depth: 30 cm) was used in this study. Four force platforms

(4060-08, Bertec Corp., USA) were used to measure the ground reaction force (GRF) and center of pressure (COP). Two force platforms were embedded on the ground, and the third and fourth force platforms were embedded in the first and third steps of the staircase, respectively.

2.2.2 Electromyography (EMG)

EMG data were collected using a Trigno™ Wireless EMG system (Delsys Inc., USA). Prior to EMG sensor attachment, the skin was cleaned with disposable ethanol swabs. The sensor configuration was used in active mode and placed on the LG muscle. The EMG signals for the LG muscle were sampled at 1118 Hz while participants climbed the stairs.

2.2.3 Measurement of GRF and COP

By using commercial motion capture software (First Principles, Northern Digital Inc., Canada), signals from force platforms were sampled at 1000 Hz and raw GRF and COP data were recorded.

2.2.4 Ultrasound imaging recording

A PC-based ultrasound system (Accuvix V10, Samsung Medison Co., Ltd., Rep. of Korea), which offers on-board image archival capabilities, as well as DICOM 3.0, was used to image the LG muscle fascicles in the sagittal plane. In this experiment, we used a linear ultrasound probe (L5-13IS, Samsung Medison) at a center frequency of 8.0 MHz and with a field of view of 38.4 mm in B-mode. The probe was securely fixed to the leg in the midsagittal plane of the LG muscle with a custom-built fixation device (Fig. 1) and securely bandaged with 3M Micropore™ surgical tape (Fig. 2). All ultrasound images were captured in Cineloop mode to a depth of 30 mm at 25 frames/s during stair ascent.

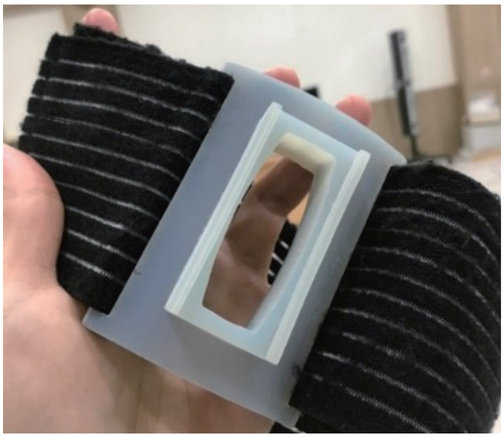

Fig. 1. (Color online) Custom-built probe fixation device.

Fig. 2. (Color online) Probe placed on LG muscle fascicles in the sagittal plane.

2.3 Data analyses

2.3.1 EMG analysis

By using EMGworks Analysis software (Delsys Inc., USA), the EMG signals were resampled at 1000 Hz and then subjected to root mean square (RMS) smoothing.(14) The RMS-EMG during the stance phase was time normalized from 0 to 100%, and the RMS-EMS amplitude was normalized by the peak RMS-EMS value.

2.3.2 COP analysis

The COP was calculated from the moment the foot touched the ground to when the ipsilateral leg lifted up.(15) The COP was analyzed by dividing it into the anterior-posterior (AP) and medial-lateral (ML) values. The RMS-AP and RMS-ML values were calculated as follows:

$$\text{RMS-AP} = \sum_{i=1}^{n-1} \sqrt{\left(x_i - x_{i-1}\right)^2}\,, \tag{1}$$

$$\text{RMS-ML} = \sum_{i=1}^{n-1} \sqrt{\left(y_i - y_{i-1}\right)^2}\,, \tag{2}$$

where n is the total number of samples, i is the sample number, x is the COP coordinate in the AP direction, and y is the COP coordinate in the ML direction.

2.3.3 Ultrasound imaging analysis

Recorded ultrasound images were transferred to a desktop computer for offline analysis. Then, the pennation angle (PA) and fascicle length (FL) were calculated using Ultra Track software.(11)

Muscle FL was defined as the straight line between the superficial aponeuroses and the deep aponeuroses parallel to the lines of collagenous tissue visible on the image. PA (β) is the angle at which a fascicle leaves the deep aponeurosis and intersects the theoretical superficial aponeurosis.(16) Images were selected so that fascicles were visible near the deep aponeurosis. However, the fascicle was often not visible in its entirety, in which case its intercept with the superficial aponeurosis was extrapolated as illustrated in Fig. 3.(16)

In the experiment, we used Eq. (3) to estimate FL, where h, L_1, and α data were obtained from Ultra Track software.(16)

$$Estimated\ FL = L_1 + \frac{h}{\sin e(\alpha)} \tag{3}$$

Here, h is the length between the superficial aponeurosis and the end point of the visible FL. α is the angle at the intersection point between the line of superficial aponeurosis and the invisible

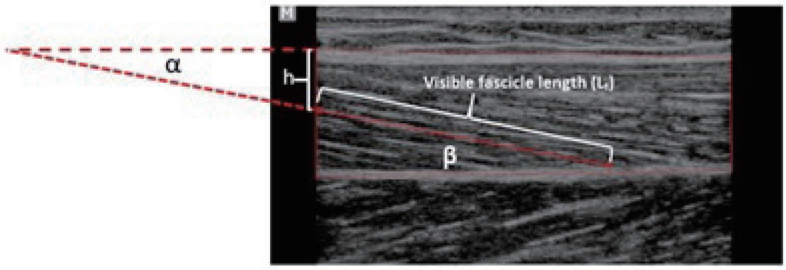

Fig. 3. (Color online) Ultrasound images of LG muscle of representative elderly participant. Muscle lengths of the visible FL (L_1) and PA (β) were measured. The thin line represents superficial and deep aponeuroses. The PA (β) is the angle between FL and deep aponeuroses.

line as shown in Fig. 3. Changes in FL were calculated using FL obtained while the subject was standing in a natural position as a reference.

2.4 Procedure and stair ascent cycle selection

Participants were asked to ascend the stairs three times. LMV stimulations were applied randomly during stair ascent. The stance phase of stair ascent was selected as the analysis segment using the GRF of the fourth platform. During stair climbing, the leg moved in a cyclic pattern.[17] The cycle for the stance phase is divided into three sub-phases: weight acceptance (WA), in which the entire body is shifting into the optimal position before pull-up (PU); PU, in which the body moves to fully support it on the next step; and forward continuance (FCN), in which the body prepares for the swing phase after a step has been completed.

2.5 Statistical analyses

The mean of the results of three trials was used for all parameters, which was calculated for each sub-phase. Statistical analyses were performed using SPSS statistics 25 (IMB Corp., USA). The Shapiro–Wilk test was performed to confirm the normality of the changes in FL, RMS-EMG, PA, and COP in both the young adult and elderly groups. The level of normality was set at $p > 0.05$. A paired sample t-test was performed for the normal data, whereas the Wilcoxon signed rank test was performed on the non-normal data to compare the significance of differences between the cases of LMV and no vibration for both groups. The significance level was set to $p < 0.05$.

3. Results

3.1 Muscle behavior while climbing stairs

The average times of stair climbing in the stance phase for the young adult and elderly groups were 0.820 ± 0.09 s and 0.979 ± 0.08 s, respectively. The changes in RMS-EMG, FL, and PA of the young adult and elderly groups are shown in Table 1.

Table 1
RMS-EMG activation (%), FL (cm), and PA (degree) of young adult and elderly groups.

Values	Sub-phase	Young Adult				Elderly			
		Control	180 Hz	190 Hz	250 Hz	Control	180 Hz	190 Hz	250 Hz
RMS-EMG	WA	9.829 ±1.26	14.952* ±2.45	10.058 ±1.71	12.772* ±2.69	7.201 ±0.96	7.266 ±0.93	7.320 ±0.71	11.200* ±2.10
	PU	11.868 ±1.86	15.793* ±3.01	12.803* ±2.67	20.735* ±3.10	7.665 ±1.06	8.297 ±1.52	10.230* ±1.48	12.330* ±1.86
	FCN	78.166 ±24.21	81.101* ±23.41	84.668 ±3.3.81	79.666* ±23.79	84.210 ±38.96	84.693 ±40.24	88.193 ±38.34	87.910* ±41.51
FL Change	WA	−0.345 ±0.050	−0.495 ±0.133	−0.549* ±0.026	−0.583* ±0.041	−0.807 ±0.086	−1.725* ±0.051	−1.405* ±0.101	−1.374* ±0.057
	PU	−0.326 ±0.057	−0.291 ±0.131	−0.407* ±0.063	−0.460* ±0.059	−0.257 ±0.139	−1.551* ±0.045	−1.378* ±0.074	−1.337* ±0.049
	FCN	−0.808 ±0.151	−1.416* ±0.307	−0.967* ±0.204	−1.066* ±0.128	−1.386 ±0.334	−2.125* ±0.152	−1.921* ±0.091	−2.113* ±0.184
PA	WA	0.152 ±0.001	0.158* ±0.002	0.154 ±0.001	0.165* ±0.001	0.149 ±0.001	0.157* ±0.001	0.152 ±0.001	0.158* ±0.001
	PU	0.147 ±0.001	0.151* ±0.001	0.150 ±0.001	0.156* ±0.001	0.141 ±0.002	0.154* ±0.001	0.152* ±0.001	0.157* ±0.001
	FCN	0.159 ±0.004	0.171* ±0.006	0.159* ±0.002	0.165* ±0.002	0.163 ±0.15	0.171* ±0.16	0.167* ±0.16	0.176* ±0.17

Results are presented as mean ± standard deviation.
When non-normality was observed, a Wilcoxon signed rank test was performed, whereas a paired sample t-test was performed when normality was confirmed.
*$p < 0.05$, indicating a statistical difference between the control (non-stimulation) and stimulation.
FL is decreased compared with the reference data.

During WA, the change in FL of the elderly group was greater than that of the young adult group, whereas RMS-EMG for the young adult group was greater than that for the elderly group. During PU, compared with their values in WA, FL slightly increased, PA decreased, and RMS-EMG slightly increased for both groups. Then during FCN, FL suddenly decreased, which was followed by the greatest PA observed. Furthermore, the peak values of RMS-EMG were observed during FCN in both groups. The results show that the LG muscle became active during FCN, as also reported by Spanjaard *et al.*[18]

3.2 Changes in muscle behavior during LMV stimulation

During WA, when LMV was applied, FL of the elderly group decreased to about half of that of the control, while FL of the young adult group also decreased but the decrease was less than that in the elderly group. PA became larger than the control in both groups but the change in PA of the elderly group was greater than that of the young adult group. RMS-EMG of both groups increased. For this phase, the frequency of 250 Hz provided the greatest RMS-EMG for the elderly group, whereas 180 Hz provided the greatest RMS-EMG for the young adult group.

During PU, FL of the elderly group decreased to less than the control value, whereas it remained almost constant for the young adult group. PA was larger for the elderly group than for the young adult group. The degree of change in RMS-EMG of the young adult group was larger than that of the elderly group. During PU, the frequency of 250 Hz provided the greatest RMS-EMG in both groups.

During FCN, FL rapidly decreased in both groups. FL of the elderly group was 1.5 times shorter than the control, whereas FL of the young adult group was slightly shorter than the control. Similar to the control, the muscle became active due to plantar ankle movement, which led to PU progression, and the peak values of RMS-EMG, FL, and PA were observed in this phase. The frequency of 250 Hz provided the greatest RMS-EMG for the elderly group, whereas 180 Hz provided the greatest RMS-EMG for the young adult group.

3.3 Changes in COP during LMV stimulation

RMS-AP and RMS-ML for the elderly and young adult groups during LMV stimulation are shown in Table 2. During stair climbing, in all sub-stance phases, RMS-AP and RMS-ML of the elderly group were greater than those of the young adult group. When LMV was applied during WA, RMS-AP and RMS-ML of both groups tended to decrease for all frequencies, although statistical significance was not observed. During PU, RMS-ML was constant in the young adult group, whereas in the elderly group, it decreased for all frequencies, particularly RMS-ML, which decreased to about half of the control. During FCN, RMS-AP and RMS-ML of the young adult group also remained nearly constant. Meanwhile, RMS-ML of the elderly group slightly increased and RMS-AP remained almost unchanged, similarly to those of the young adults.

4. Discussion

4.1 Characteristics of muscle behavior during stair climbing in the elderly

During stair climbing, RMS-EMG and PA increased and FL decreased for both groups. When LG became active in the FCN phase, RMS-EMG and PA were observed to be larger and

Table 2
RMS-COP (cm) during stance phase of young adult and elderly groups.

Sub-phase	COP	Young Adult				Elderly			
		Control	180 Hz	190 Hz	250 Hz	Control	180 Hz	190 Hz	250 Hz
WA	RMS-ML	1.039 ±0.430	0.789 ±0.471	1.026 ±0.428	0.803 ±0.317	1.428 ±0.279	1.364 ±0.693	1.326 ±0.718	1.717 ±1.468
	RMS-AP	1.199 ±0.666	1.096 ±0.663	1.369* ±0.659	1.024 ±0.594	1.669 ±0.614	1.659 ±0.457	1.519 ±0.665	1.544 ±0.562
PU	RMS-ML	0.042 ±0.005	0.043 ±0.014	0.045 ±0.010	0.040 ±0.014	0.137 ±0.228	0.066 ±0.055	0.089 ±0.120	0.074 ±0.081
	RMS-AP	0.075 ±0.041	0.067 ±0.029	0.070 ±0.021	0.069 ±0.026	0.106 ±0.065	0.073 ±0.036	0.101 ±0.090	0.822 ±0.28
FCN	RMS-ML	0.165 ±0.071	0.153 ±0.084	0.170 ±0.084	0.160 ±0.099	0.181 ±0.055	0.215 ±0.107	0.232 ±0.113	0.186 ±0.062
	RMS-AP	0.245 ±0.057	0.222 ±0.087	0.242 ±0.056	0.225 ±0.090	0.312 ±0.035	0.301 ±0.055	0.304 ±0.053	0.291 ±0.054

Results are presented as mean ± standard deviation. AP: Antero-posterior. ML: Medio-lateral.
When non-normality was observed, a Wilcoxon signed rank test was performed, whereas a paired sample t-test was performed when normality was confirmed.
*$p < 0.05$, indicating a statistical difference between the control (non-stimulation) and stimulation.
FL is decreased compared with the reference data.

FL was observed to be shorter in the elderly group. This means that the muscle behavior of both groups is the same, but the degree to which muscle behavior is performed is different. These differences between the two groups might be due to age-related changes in neuromuscular function and physical activity, in accordance with previous studies.(19) In addition, muscle weakness in elderly people is a factor related to aging that increases muscle activity according to the results of a laboratory-based study.(20)

4.2 Effects of LMV on muscle behavior during stair ascent

The main finding of this study is that LMV might contribute to changes in muscle behavior. When LMV was applied, FL decreased in both groups, especially the elderly group, in which it roughly halved. Thus, it can be seen that LMV can affect elderly people more than young adults. Moreover, an increase in PA was followed by a decrease in FL, consistent with the results of Lichtwark *et al.*(13)

The shortened FL during LMV stimulation may maximize the efficiency of muscle work. The total energetic cost is minimized when FL reaches the optimal length. The optimal length is defined as the value of FL providing the maximal efficiency. According to Lichtwark and Wilson,(21) a broad range of muscle FLs can achieve close to optimal efficiency during locomotion and FL can be decreased to maximize the efficiency. Therefore, LMV may contribute to maximizing the efficiency of muscle mechanics during stair climbing in the elderly.

Increased PA during LMV application is related to muscle cross section area (CSA), which is also supported by the finding of Kawakami *et al.*(22) PA became greater than the control value. This led to an increase in CSA per unit volume, which affected the force-producing capacity and muscle efficiency. Moreover, in our study, a greater RMS-EMG induced by LMV was observed, similar to in previous reports,(9) which confirmed that LMV can increase the efficiency of muscles during locomotion.

4.3 Effects of LMV on postural stability in the elderly

During the stance phase, RMS-COP in the AP and ML directions was larger for the elderly group than for the young adult group. This indicates that elderly people have higher postural sway than young adults. This is because the reduced ability to adapt to changes and maintain balance in a new environment is caused by the age-related decline in the sensory system.(23)

During WA, the difference in RMS-ML between both groups was 0.39 cm and that in RMS-AP was 0.47 cm. During FCN, the difference in RMS-ML was 0.016 cm and that in RMS-AP was 0.067 cm. During PU, the difference in RMS-ML was 0.10 cm and that in RMS-AP was 0.067 cm. These results might be due to the direction of movement. Forward locomotion occurs predominantly in WA and FCN, whereas sideways locomotion occurs in PU. RMS-ML is three times larger than RMS-AP in PU, and RMS-AP is four times larger than RMS-ML in FCN and 1.2 times larger in WA. That is, the difference between AP and ML is high only in the single-limb support phase.

When LMV was applied during stair climbing, both RMS-AP and RMS-ML tended to decrease. In particular, RMS-ML was markedly reduced in PU. The ML direction is important as it is associated with increased risk of falling.(24) According to Eklund and Hagbarth,(25) vibration might induce the spindle primaries that alternately drive the α-motoneurons of muscle. Thus, the reduction of RMS-AP and RMS-ML might be because antagonist muscle co-activation provides mechanical stability by stiffening the joints,(26) which may result from LMV contributing to the activation of the afferent nerve. In other words, during LMV application, the surrounding muscle contracts and provides more reinforcement. This in turn might induce stiffening of the joint, resulting in greater balance and stability, demonstrating that LMV can be used to restore balance and increase stability.

In this study, by ultrasound imaging, the muscle behavior and postural stability of groups of elderly people and young adults, and changes in them induced by LMV, were investigated in real time. As a result, the features of muscle behavior and postural stability of the elderly during stair climbing and the effect of LMV were revealed. The number of elderly participants in this study was small. Therefore, further study involving more participants is necessary to investigate muscle-tendon complex and muscle co-activation to provide further insight into mechanical muscle behavior.

5. Conclusion

In this study, by ultrasound imaging, the effects of LMV on the muscle behavior and postural stability of elderly people during stair ascent were investigated. To do this, RMS-EMG, FL, and PA of a group of elderly people were examined in comparison with those of a group of young adults. It was found that the muscle behavior of both groups was similar, but some aspects of muscle behavior were more pronounced in the group of elderly people, particularly in the FCN sub-phase. Regarding postural stability, elderly people have greater postural sway than young adults in all directions.

When LMV was applied to the LG muscle during stair ascent, muscle activation, PA, and FL contraction increased. Furthermore, RMS-ML and RMS-AP of the elderly group decreased, particularly RMS-ML in the PU sub-phase.

The results of our study suggest that LMV can induce greater activity of muscles and be used as an approach to restoring balance and increasing stability. In particular, real time changes in muscle behavior caused by vibration stimulation revealed the ability of LMV to help develop effective rehabilitation techniques and therapeutic tools to help restore mobility. Furthermore, this study provides theoretical support to establish therapy using LMV for elderly and/or disabled people.

Acknowledgments

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