

## Article

# Effect of Mechanical Stimulation Applied to the Lower-Limb Musculature on Stability and Function of Stair Climbing

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**Abstract:** Mechanical muscle-tendon vibration affects musculature and the nervous system. As the vibrations used in previous studies were varied, consistently determining the effect of mechanical vibration was challenging. Additionally, only a few studies have applied vibrations to dynamic motion. This study investigated whether the vibration based on the sensorimotor response could affect the stability and function of stair climbing. Electroencephalogram (EEG) signals were recorded from the sensorimotor area, and mu rhythms, dependent on the vibration frequencies, were analyzed. Based on the analysis, the vibratory stimulus conditions were set and applied to the Achilles tendon of the lower limb during stair climbing. Simultaneously, electromyogram (EMG) signals from the gastrocnemius lateralis (GL), gastrocnemius medialis (GM), soleus (SOL), and tibialis anterior (TA) were recorded. Activations and co-activations of the shank muscles were analyzed according to the phases of stair climbing. When vibration was applied, the TA activation decreased in the pull-up (PU) phase, and calf muscle activations increased during the forward continuous (FCN) phase. These changes and their degrees differ significantly between stimulus conditions ( $p < 0.05$ ). Co-activation changes, which differed significantly with conditions ( $p < 0.05$ ), appeared mostly in the PU. These results imply that the vibration affects stability and function of stair climbing, suggesting that the vibration characteristics should be considered when they are applied to dynamic movement.

**Keywords:** co-activation; mu rhythm; stair climbing; local vibration

## 1. Introduction

Stair climbing is a motion that combines a forward movement and an ascent performed simultaneously; it requires a stable body support and joint stiffness. Co-activation describes the simultaneous activation or co-contraction in the agonist and antagonist muscles around the joint [1–3]. The role of muscle co-activation is known to be that of increasing joint stiffness of the upper or lower limbs, thereby increasing joint stability [3,4]. For example, Tadayoshi Asaka et al. [5] have confirmed that muscle co-activation increases when standing on an unstable board. In addition, Darainy et al. [6] have reported that subjects use co-contraction control to offset unstable forces in a static state [6]. Solomonow et al. [7] have found that increased co-activation during strong contractions can protect joints and maintain stability. Other studies have reported that co-activation helps in the functional aspects of joints [1,8]. According to Francesco Di Nardo et al. [8], ankle co-activation during level walking can contribute positively to physiological tasks such as foot reversal, balance improvement,

ankle stability control, and knee flexion. In addition, high co-activation can strengthen joints without time delay during sequential movements, helping in counteracting external forces and performing sequential movements [1]. Many previous studies have shown that co-activation contributes to the stability and functionality of movement. Therefore, understanding and controlling co-activation can help improve or assist movement.

Localized vibratory stimulation can be used as a method to affect the stability and functionality of movement by controlling co-activation. Vibrations applied to the limbs affect the sensorimotor cortex through the afferent sensory nerves, resulting in a decrease in mu rhythm [9]. The mu rhythm is an electroencephalogram (EEG) signal of a frequency of 8–13 Hz, generated by the sensorimotor cortex, and is attenuated by vibration, tactile stimulation, and exercise execution [10,11]. Because of this characteristic, it can be used as an index of excitability of the sensorimotor cortex [9,12]. Takayuki Kodama et al. [13] have used the mu rhythm to evaluate the effects of vibratory stimulation-induced kinesthetic illusions. Susanna Lopez et al. [9] reported that a local vibration applied during the isometric contraction of limb muscles can improve the excitability of the sensorimotor cortex. The Ia afferent fiber-induced by vibration activates the  $\alpha$ -motoneurons, resulting in an increase in the electromyogram (EMG), which is indicative of an increase in the muscle contraction force [14,15]. Another previous study has shown that there is an inverse linear correlation between the mu rhythm of the sensorimotor cortex and the force used during isometric contraction [16], and it was reported that the motor-evoked potential (MEP) was changed by local vibrations [17]. Others have shown improved muscle performance through vibratory stimulation applied to the limbs [14,18,19]. Thomas Lapole et al. [19] have reported an increase in joint flexibility due to repeated vibration applied to an Achilles tendon. Bruno P. Couto et al. [18] have applied repeated vibrations of 8 Hz and 26 Hz to two groups, respectively, and they confirmed that the performance of the lower limb muscles was subsequently improved. Finally, Jin Luo et al. [14] have confirmed an increase in the EMG amplitude due to the vibration applied to the elbow joint.

Through these studies, it can be inferred that local vibrations can be used to control the stability and functionality of movements. However, the vibration frequencies and intensities used in previous studies were varied, which made it difficult to objectively compare the effects of vibrational characteristics with each other. Therefore, applying vibrations according to a specific standard is important.

The purpose of this study was to investigate whether the vibratory stimulation selected according to a specific standard affects the stability and functionality of stair climbing. For this purpose, we investigated whether the mu rhythm changed according to the vibration characteristic. Based on this result, vibratory stimulation was applied to the Achilles tendon during stair climbing. Then, for the gait analysis, the activity of shank muscle was measured according to the vibratory stimulation conditions [20]. Changes in the co-activation of the triceps surae according to the applied vibratory stimulation were analyzed.

## 2. Materials and Methods

### 2.1. Subject

This study was conducted on 10 healthy young men with no history of musculoskeletal or nervous system diseases or surgery (Age:  $24.3 \pm 0.7$  years; Height:  $174.3 \pm 1.9$  cm; Weight:  $67.6 \pm 2.3$  kg). All participants were fully informed of the experimental environment and procedures and provided written consent. One day before the experiment, the subjects were asked to rest and refrain from drinking and from exercising excessively, to rule out external factors that present study. For 2 h before the start of the experiment, they were asked to refrain from caffeine intake and smoking. This research was approved by the Institutional Review Board (IRB) of Jeonbuk National University (IRB File No. JBNU 2017-03-011-001).

## 2.2. Vibratory Perception Threshold Measurement for Vibratory Stimulus Intensity Setting

The vibrational perception threshold of each individual subject was measured to set the local vibratory stimulation intensity for application to mu rhythm measurement and stair climbing. A linear actuator (DMJBRN0934AA; Samsung Electro-Mechanics Co., Ltd., Korea) attached to the Achilles tendon [21] and a function generator (AFG-21 25; Good Will Instrument Co., Ltd., Taipei) were used to apply the local vibratory stimulation. The vibrational perception threshold measurements were made while the subject sat in a chair, relaxed. The vibration intensity was raised slowly from the lowest amplitude and the amplitude at which the subject first felt the vibration was recorded. The vibrational perception threshold was measured in three trials for each of the 14 chosen frequencies from 100–300 Hz, and the average of the three trials was set as the threshold intensity. The sub-threshold intensity was set to a value corresponding to 80% of the threshold intensity. To prevent sensory adaptation to vibration, a five-minute break was given after three trial measurements of one frequency.

## 2.3. Mu Rhythm Measurement for Vibration Frequency Setting

For measuring mu rhythm, EEG scalp electrodes were arranged on C3, Cz, C4, FC4, and CP4 corresponding to the sensorimotor cortex and the right hemisphere according to the 10–20 electrode placement method. The reference electrode was placed on both earlobes. The brain amp MR and the vision recorder (Brain Products GmbH, Germany) was used to measure EEG. EEG measurement was conducted in soundproof dark rooms to eliminate external noise and stimulation caused by light. The experiment was conducted in a comfortable and stable state, with participants seated in chairs. The EEG signals were measured for 60 s per frequency, including non-stimulus. Participants were given five minutes of rest after measuring EEG for one frequency to prevent vibrational sensory adaptation. However, 280 Hz and 300 Hz were excluded from the mu rhythm measurements because some subjects could not feel any vibration at these frequencies when measuring for vibratory perception threshold. Therefore, the mu rhythm was measured for a total of 13 frequencies including non-stimulus.

## 2.4. Mu Rhythm Analysis

To calculate mu rhythm reduction rate, power spectrum analysis for recorded EEG signals was performed using BESA software (BESA GmbH, Germany). In the raw EEG data, the 2 s of EEG signal defined 1 epoch, and the 60 s interval was divided into 30 epochs. Mu rhythm activity for one epoch was calculated as the ratio of mu rhythm (8–13 Hz) to total EEG signal power. Mu rhythm activity for one frequency is calculated as mean value of 30 epochs. Mu rhythm reduction rate was defined as the degree of reduction in mu rhythm activity of the vibratory condition compared to that of the non-stimulus condition.

## 2.5. Stair Climbing Procedure

A five step custom-built wooden staircase with a raise of 16 cm and tread of 30 cm was used in this study. Participants were asked to ascend the stairs at a self-selected velocity and in a step-over-step manner. Before the start of the experiment, the participants repeated climbing the stairs several times to become accustomed to the staircase. EMG measurements were commenced at the start of the stair climbing; at the same time, vibration was applied to the Achilles tendon. Vibratory stimulation conditions were set by a combination of the vibrational intensity (threshold and sub-threshold) and frequencies based on the result of mu rhythm analysis. All the subjects underwent three trials for each vibratory stimulation condition, including non-stimulus.

## 2.6. Electromyogram (EMG) Signal Recording and Processing

A Trigno Wireless EMG System (Delsys Inc., Natick, Massachusetts, USA) was used to collect the EMG signals during stair climbing. EMG is a non-invasive technique for the assessment of the myoelectric signal [22] and useful for understanding muscle activity [23]. The EMG sensors were

attached to the gastrocnemius lateralis (GL), gastrocnemius medialis (GM), soleus (SOL) and tibialis anterior (TA) of the participant's leg [24]. The raw EMG signal was resampled at 1000 Hz, rectified, and smoothed at a cut-off frequency of 6 Hz for Butterworth low-pass fourth-order filter. EMG amplitudes were normalized to the maximum peak of each trial.

### 2.7. EMG and Co-Activation Analysis

The gait cycle of the stair climbing was defined starting from foot contact on the first step of the staircase to the same foot contact on the third step of the staircase. EMG analysis was conducted as follows: the EMG activities of each muscle in each subject measured three times during each vibratory stimulus conditions were ensemble averaged. Then, these ensemble-averaged EMG activities were ensemble averaged to derive a grand ensemble for each vibratory condition. Co-activation was calculated using normalized EMG data of each participant based on the method proposed by Falconer and Winter [3] as follows:

$$\text{Co-activation} = 2 \times \left\{ (\text{Common area}(M_{(a)} \& M_{(b)}) \div (M_{(a)} \text{Area} + M_{(b)} \text{Area})) \right\} \times 100 \quad (1)$$

where  $M_{(a)}$  and  $M_{(b)}$  refer to the agonist and the antagonist muscles, respectively.  $M_{(a)} \text{Area}$  refers to the area below the EMG graph of  $M_{(a)}$ , while  $M_{(b)} \text{Area}$  refers to the area below the EMG graph of  $M_{(b)}$ . Common area represents the area where the graphs of  $M_{(a)}$  and  $M_{(b)}$  overlap. Co-activation was calculated for three muscle groups (TA-GL, TA-GM, and TA-Sol) for each vibratory stimulation condition of each subject. The co-activation analysis was conducted in the same way as the EMG analysis mentioned above. Also, in order to calculate the average of the co-activation of each phase the gait cycle was divided into five phases, by referring to McFayden and Winter [25] (Weight Acceptance (WA, 0%~14%), Pull-Up (PU, 15%~32%), Forward Continuance (FCN, 33%~64%), Foot Clearance (FC, 65%~82%), and Foot Placement (FP, 83%~100%). Processing and analysis of all EMG data and co-activation were done using a custom code written in MATLAB R2018b (The Mathworks Inc., Natick, MA, USA).

### 2.8. Statistical Analysis

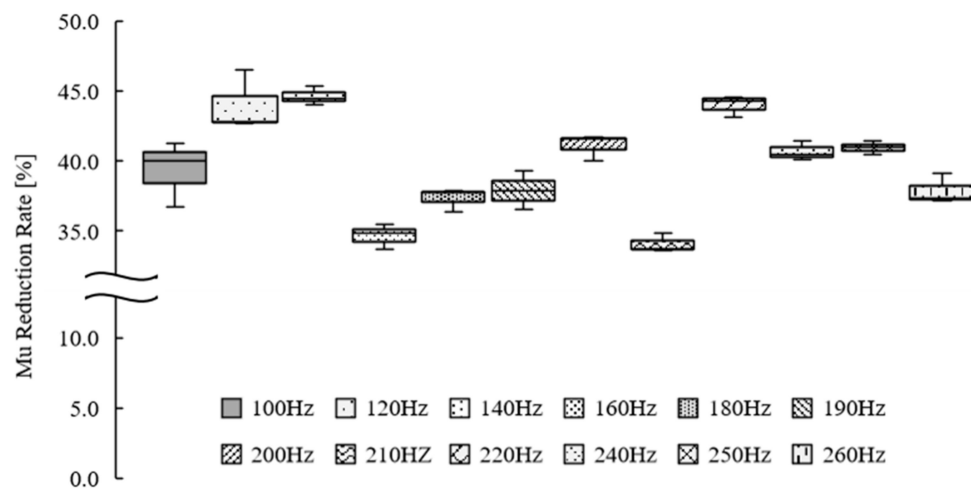
SPSS 20 (IBM SPSS Statistics, Armonk, New York, USA) was used for statistical analysis. Paired *t*-tests were performed to confirm the statistical significance between the mu rhythm reduction rates dependent on different frequencies ( $p < 0.05$ ). The statistical analysis of the EMG activity in each muscle was performed paired *t*-test to confirm the statistical significance between different vibratory stimulation conditions within the gait phase. This statistical analysis was performed on all muscles. The Friedman test was used to compare the co-activation values during each phase of gait cycle and to analyze the differences according to the vibratory stimulation conditions. Post hoc analyses were performed using the Wilcoxon signed-rank test and statistical significance was defined at  $p < 0.05$ .

## 3. Results

### 3.1. Changing the Mu Rhythm Using Localized Vibrations

The mean of the mu rhythm reduction rate for all vibration frequencies is shown in Figure 1 and the statistical significance between each frequency is shown in Table 1. A statistical significance was found at most frequencies ( $p < 0.05$ ). As shown in Figure 1, among these frequencies, a mu rhythm reduction rate of 140 Hz was the highest and 210 Hz was the lowest. Based on these results, the vibratory conditions were chosen. 'None' is a condition under which no vibration was applied; the 140 Hz frequency is set as 'Max', and the 210 Hz frequency is set as 'Min'. All vibratory conditions were applied with threshold intensity (Th-) and the sub-threshold intensity (Sub-). Therefore, vibration stimulation conditions were set as follows; 'Th-Max' and 'Th-Min' applied as the threshold intensity

(Th-), 'Sub-Max' and 'Sub-Min' applied as the Sub-threshold intensity (Sub-) and 'None' with no vibration applied.



**Figure 1.** Mean ( $\pm$  standard deviation) of mu rhythm reduction rate (through paired *t*-test) according to localized vibration frequencies.

**Table 1.** Result of paired *t*-test of the mu rhythm reduction rate, \* indicates a statistical significance between vibrational frequencies ( $p < 0.05$ ).

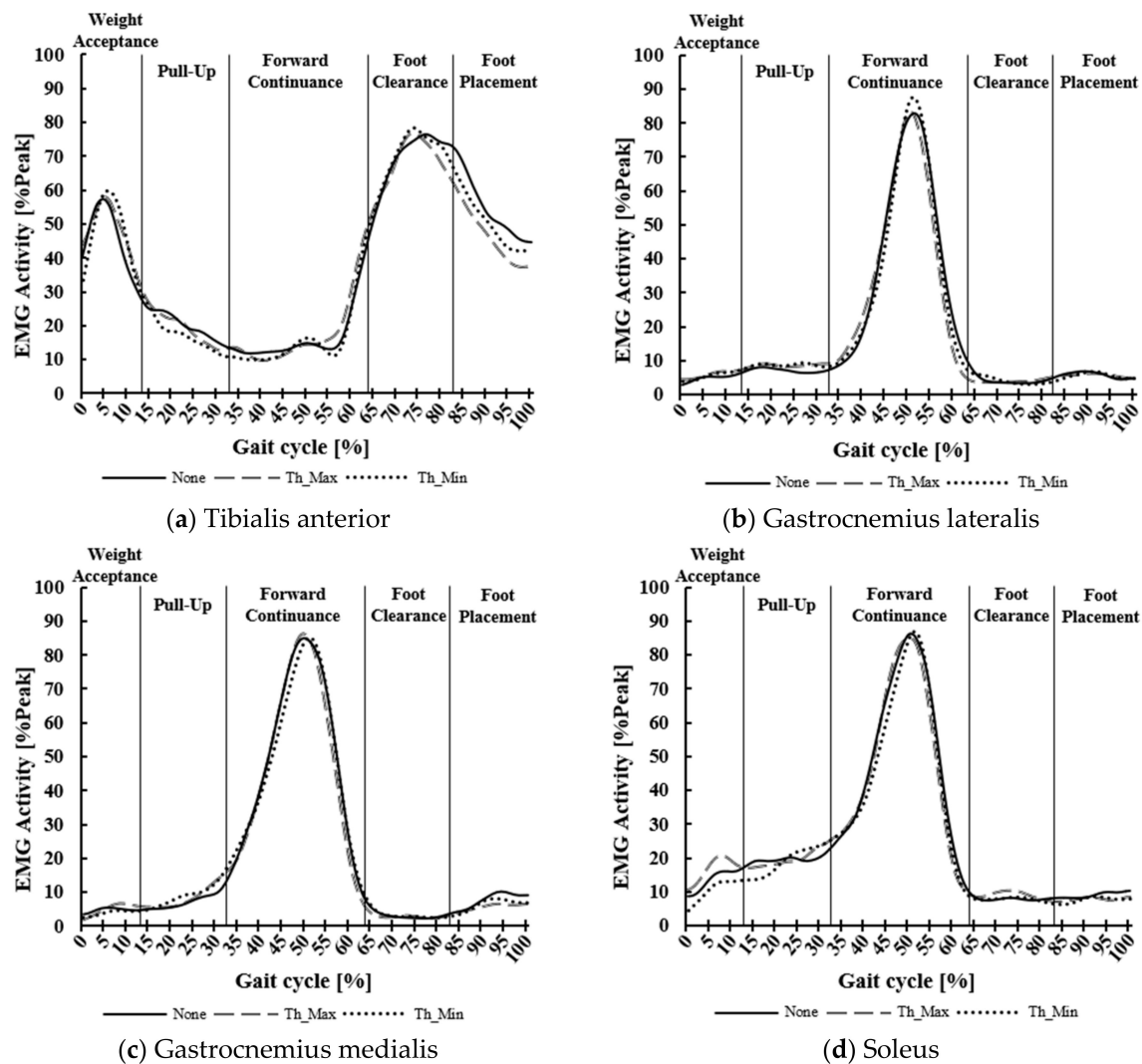
Frequencies	100 Hz	120 Hz	140 Hz	160 Hz	180 Hz	190 Hz	200 Hz	210 Hz	220 Hz	240 Hz	250 Hz	260 Hz
100 Hz		*		*								
120 Hz			*	*	*	*	*	*				*
140 Hz				*	*	*	*	*	*	*	*	*
160 Hz					*	*	*	*	*	*	*	*
180 Hz						*	*	*	*	*	*	*
190 Hz							*	*	*	*	*	*
200 Hz								*	*	*	*	*
210 Hz									*	*	*	*
220 Hz										*	*	*
240 Hz											*	*
250 Hz												*
260 Hz												

\* Indicates statistical significance between vibration frequencies ( $p < 0.05$ ).

### 3.2. Changes in Muscle Activity According to the Local Vibratory Stimulation Conditions

Figures 2 and 3 show patterns of muscle activity according to the local vibratory stimulation conditions. Tables S1 and S2 show the mean and standard deviations of the vibrational stimulus conditions according to the gait phase, and the statistical significance between the conditions (See Supplementary Material).

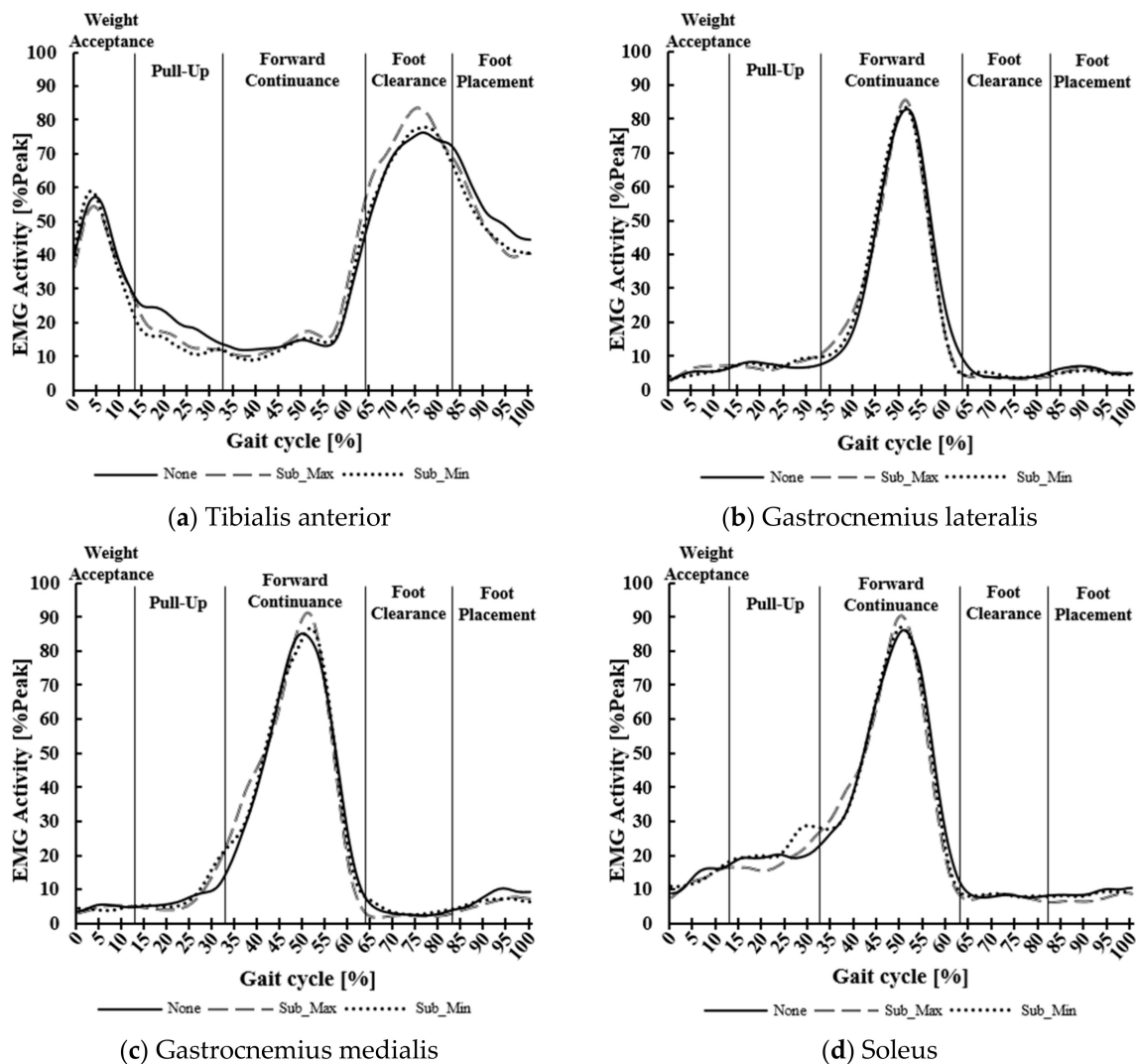
At the threshold intensity, TA showed that Min was lowest at 16.4% in the PU phase (Table S1), and that the amplitude of Max and Min decreased in the swing phase (FC and FP phase) faster than that of None. GL showed that Min had the highest peaks at 87.6% compared with other vibratory conditions in FCN phase, and for GM and SOL we could not confirm a difference due to vibratory conditions.



**Figure 2.** Mean of electromyogram (EMG) activity of all participants in the vibrational stimulation conditions at the threshold intensity: (a) Tibialis Anterior (TA), (b) Gastrocnemius Lateralis (GL), (c) Gastrocnemius Medialis (GM), (d) Soleus (SOL). ‘Th-Max’ means a vibration of 140 Hz was applied at the threshold intensity, while ‘Th-Min’ means a vibration of 210 Hz was applied at the threshold intensity. The solid line indicates the gait phase (Weight Acceptance (WA, 0%~14%), Pull-Up (PU, 15%~32%), Forward Continuance (FCN, 33%~64%), Foot Clearance (FC, 65%~82%), Foot Placement (FP, 83%~100%)).

At sub-threshold intensity, Tibialis anterior muscle (TA) showed lower activity in Max (15%) and Min (13.4%) than in None during the PU phase (Table S2). The maximum peak appeared in the FC phase (Figure 3a). Early decreases in the EMG activity were observed in the FP phase. The triceps muscle of the calf (i.e., GL, GM, and SOL) showed enhanced peak activity under all vibratory conditions, and muscle activity was increased between the PU and the FCN phases (Figure 3a–c).



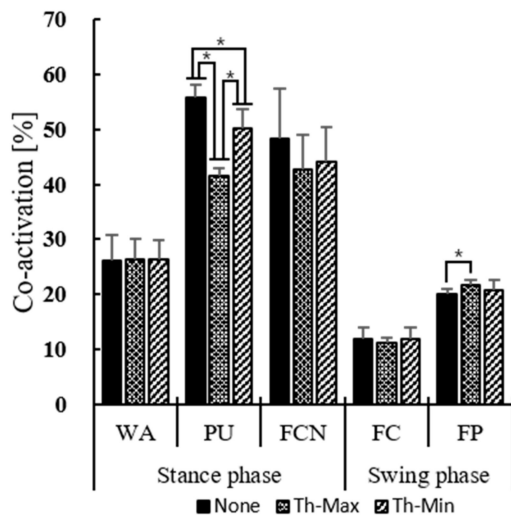


**Figure 3.** Mean of EMG activity of all participants in vibration stimulation conditions at sub-threshold intensity: (a) Tibialis anterior, (b) Gastrocnemius lateralis, (c) Gastrocnemius medialis, (d) Soleus. ‘Sub-Max’ means a vibration of 140 Hz was applied at sub-threshold intensity, while ‘Sub-Min’ means a vibration of 210 Hz was applied at sub-threshold intensity. The solid line indicates the gait phase (Weight Acceptance (WA, 0%~14%), Pull-Up (PU, 15%~32%), Forward Continuance (FCN, 33%~64%), Foot Clearance (FC, 65%~82%), Foot Placement (FP, 83%~100%)).

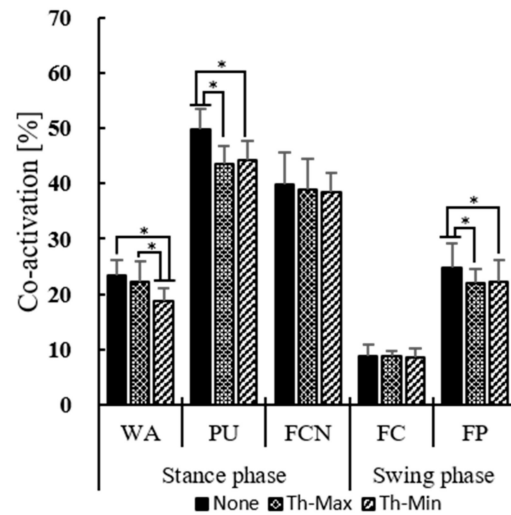
### 3.3. Co-Activation Differences with Vibration Conditions and Phases of Gait Cycle

The change in co-activation with vibration conditions was different for each gait phase, as shown in Figures 4 and 5. Co-activation was mostly at its highest in the PU phase and at its lowest in the FC phase. At the threshold intensity (Figure 4), the TA-GL group showed reduced co-activation during the PU and the FCN phases. During the PU phase, Th-Max decreased by 14.1% and Th-Min by 5.6% ( $p < 0.05$ ). In the FCN phase, Th-Max was reduced by 5.7% and Th-Min by 4.4% compared with None, but was not significant. For the TA-GM group, co-activation decreased in the WA, the PU and the FP phases. Th-Max decreased by 6.2% for the PU phase and by 2.9% for FP phase ( $p < 0.05$ ). Th-Min decreased by 4.6% for the WA phase, 5.5% for the PU phase, and 2.7% for the FP phase, respectively ( $p < 0.05$ ). Co-activation in the TA-SOL group was reduced by 7.3% in Min during the WA phase ( $p < 0.05$ ). Also, during the PU phase, Th-Max and Th-Min decreased by 12.4% and by 11% compared with None, respectively ( $p < 0.05$ ). At Sub-threshold intensity (Figure 5), the TA-GL group showed increased co-activation in the Sub-Min during the PU phase (by 4.4%,  $p < 0.05$ ), while co-activation in

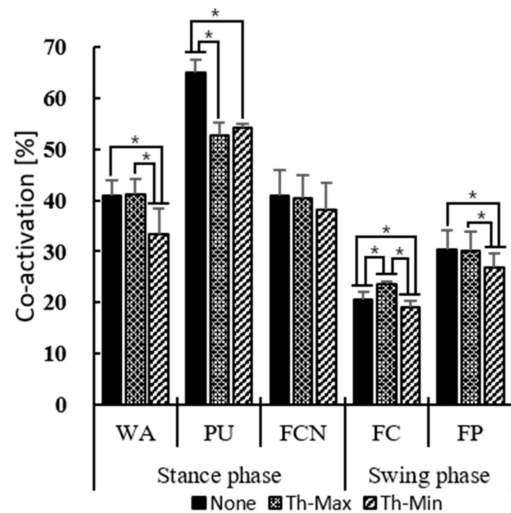
the FC phase was reduced by 3.2% in the Sub-Max ( $p < 0.05$ ). For the TA-GM group, the Sub-Max and Sub-Min in the PU phase increased by 4.3% and by 11.2% compared with None, respectively ( $p < 0.05$ ). Co-activation of Max in the FC phase decreased by 3% ( $p < 0.05$ ). TA-SOL group showed reduced co-activation in the Sub-Max (by 8.1%) and Sub-Min (by 11.5%) compared with None during the PU phase and Sub-Min resulted in the lowest co-activation ( $p < 0.05$ ).



(a) TA-GL group



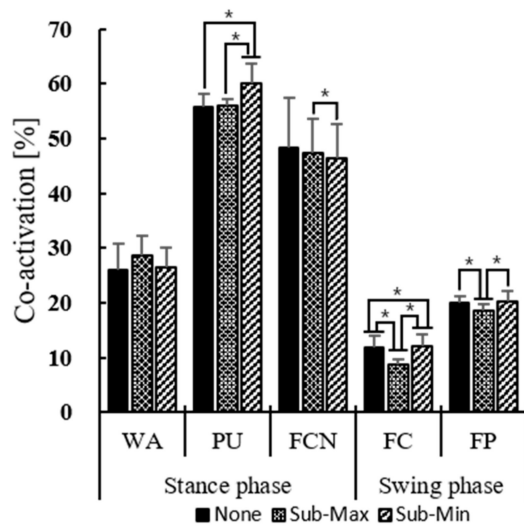
(b) TA-GM group



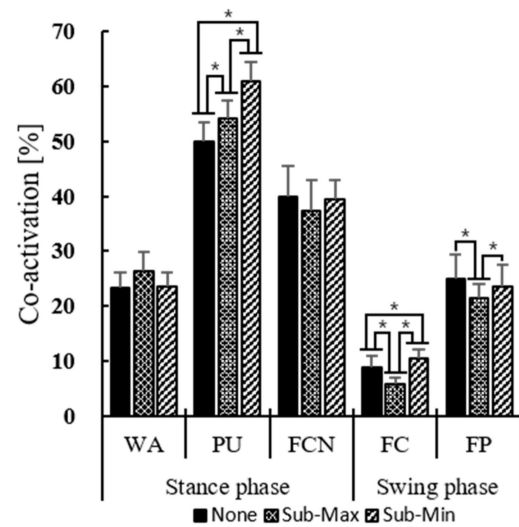
(c) TA-SOL group

**Figure 4.** Mean value ( $\pm$  standard deviation) of co-activation of each gait phase according to the vibratory stimulation conditions at threshold intensity of each muscle group: (a) TA-GL group, (b) TA-GM group, (c) TA-SOL group, \* indicates statistical significance through post-hoc tests between vibratory stimulus conditions ( $p < 0.05$ ).

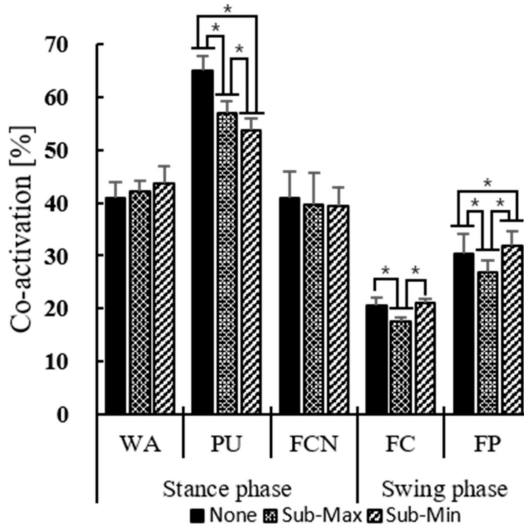




(a) TA-GL group



(b) TA-GM group



(c) TA-SOL group

**Figure 5.** Mean value ( $\pm$  standard deviation) of co-activation of each gait phase according to the vibratory stimulation conditions at the sub-threshold intensity of each muscle group: (a) TA-GL group, (b) TA-GM group, (c) TA-SOL group, \* indicates statistical significance through post-hoc tests between vibratory stimulus conditions ( $p < 0.05$ ).

#### 4. Discussion

This study investigated changes in the mu rhythm with vibration frequency, and changes in the EMG and co-activation caused by the local vibratory characteristics based on the mu rhythm and the perception thresholds during stair climbing.

##### 4.1. Effect of Vibration Frequency on Mu Rhythm

To set vibratory conditions for the Achilles tendon during stair climbing, mu rhythm reduction rate according to vibration frequencies was analyzed. As a result, it was confirmed that the mu rhythm reduction rate differs according to the applied vibration frequencies (Figure 1). This means that the vibratory stimulus applied to the Achilles tendon affected the sensorimotor cortex, and that acceptance of the vibratory sense in the Achilles tendon varies according to vibration frequencies. Depending on

the distribution and density of the receptor [26] and the frequency of firing [12], the vibration frequency and sensing capacity to be detected vary, and the amount of information transmitted through the Ia afferent differs. Therefore, a difference occurs in the signal transmitted to the sensorimotor cortex according to vibration frequency, while a difference in the mu rhythm reduction rate occurs in response to changes in the vibration frequency. This is in line with the previous study, which reported that the somatosensory response to vibrotactile stimuli is frequency-dependent [27]. In addition, Barbara Marconi et al. [28] have confirmed that vibrations that were repeatedly applied to the flexor carpi radialis muscles during voluntary contractions can induce excitatory changes in the primary motor cortex. Sabine Siggelkow et al. [29] have also shown an increase in MEP due to vibrations of 80 and 120 Hz applied to the extensor carpi radialis muscle. In addition, Kossev A et al. [30] have reported that the MEP of the transcranial magnetic stimulation was enhanced by vibrations applied to the extensor carpi radialis muscles. An increase of MEP occurs with increased excitability of the motoneuron pool, and there are also changes in the cortical responsiveness and in the operation of the intracortical circuits [31]. MEP varies with vibration frequency, and a change in MEP implies a decrease or an increase in the number of motor neurons that can respond to the excitation of a given motor neuron pool [32]. Therefore, in this study, the change in mu rhythm indicates that vibration applied to the Achilles tendon induced an excitatory change in the sensorimotor cortex, which affects both the motor neuron pool excitability and the target muscle activity.

#### *4.2. Effect of Vibratory Stimulation Conditions on EMG Activation*

Under all stimulation conditions, including non-stimulus, two specific patterns of muscle activity were confirmed during stair climbing. For the TA, the maximum activity appeared in the WA and FC phases. During the WA phase, the body weight is transferred to the leading leg to help with the swing of the trailing leg. At this time, the TA serves to pull the body forward to prepare for weight acceptance. In the FC phase, the TA serves by preventing a foot drop for ensuring foot clearance. For the triceps surae (i.e., GL, GM and Sol), the maximum activity appeared in the FCN phase. In the FCN phase, the body moves forward and the toe-off of the leading leg occurs in the last part of this phase. The maximal activity of the triceps surae is caused by the plantarflexion for performing the toe-off and supporting the body.

When vibratory stimulation was applied, a change in the EMG activation was observed according to the local vibratory conditions (Figures 2 and 3).

TA did not significantly change in the WA phase, whereas it showed decreased activity in the PU phase and reached a peak in the FC phase. The vibratory conditions that showed decreased activation in the PU phase were Th-Min, Sub-Max, and Sub-min (Figures 2a and 3a). In the PU phase, the ankle joint is approaching the standing posture, with decreased dorsiflexion and extension of the knee and hip joint [33,34]. Decreased TA activity is thought to facilitate coordination with other joint movements during the pull-up. Sub-Max was the vibratory condition that showed the highest peak during the FC phase. This ensures toe-clearance and a stable swing by maintaining dorsiflexion of the ankle joint.

GL, GM, and SOL show increased muscle activity between the PU and FCN phases at sub-threshold intensity conditions (Figure 3b–d). This phase is when the trailing leg begins to swing after the toe-off, and the leading leg performs single-limb support. While the ankle joint is in dorsiflexion, the trailing leg moves upwards to the next step and the body begins to move forward. Thus, the increased muscle activity under vibratory conditions will help in preventing the body from collapsing forward and in maintaining a stable foot support. In addition, the maximum peak appears in the FCN phase. The local vibratory stimulation will help to push upward and support the body by facilitating the plantarflexion of the leading leg.

#### 4.3. Changes in the Co-Activation by Localized Vibratory Stimuli during Stair Climbing

To investigate the effect of the localized vibratory stimulation on the stability and function of stair climbing, co-activation was analyzed across stair-climbing phases, muscle groups and stimulation intensities.

At the threshold intensity condition, a reduced co-activation appeared predominantly in the phases WA, PU and FCN. During the WA phase, the body weight is transferred to the leading leg, and the joint flexion of the hip and knee begins to decrease [33,35]; then, the joint extension of the hip and knee develops in the PU phase, and subsequently the transition of the ankle joint from dorsiflexion to plantarflexion occurs in the FCN phase. An increase of co-activation translates into improved joint protection and stability through an increase in joint stiffness [4]. However, excessive co-activation has been reported to reduce the degree of joint freedom resulting from stiff posture [36]. In other words, a decrease of co-activation means a decrease in joint stiffness, resulting in an increase in the degree of joint freedom. All three joints are extending during the phases WA, PU and FCN. Thus, a reduced co-activation means that an extension of the lower limb segments will be achieved harmoniously and that the local vibratory stimulation contributes positively to joint extension. Even if a reduced co-activation decreases the stability of stair climbing, the stability of stair ascending will not be harmed because the extension of the femur muscles in the leading leg and the plantarflexion of the calf muscles in the trailing leg perform the body lift.

At the sub-threshold intensity conditions, an increased co-activation appeared predominantly in the phases of WA and PU, except for the PU phase of the TA-SOL group. During the PU phase, the upright alignment of the lower limb segments is achieved while decreasing the dorsiflexion. The localized vibratory stimulation in the initial PU phase facilitates the shank upright alignment by reducing TA activity, and in the later PU phase, it facilitates a rapid increase in activity of the gastrocnemius muscle (Figure 3), which contributes to providing joint stiffness for the vertical movement of the trunk. In contrast, the co-activation of the TA-SOL group decreased. This is presumed to occur due to the difference in the type of contraction in the muscle during movement. M. Spanjaard et al. [37] have reported that the GM fascicle exhibits a near-isometric behavior when the GM muscles are activated during stair climbing. Masaki Ishikawa et al. [38] have shown that the GM fascicle was stretched during early single-limb support during level walking and remained isometrical in a later stance phase. By contrast, Sol's fascicle reportedly continued to lengthen until the end of the single-limb support. O. S. Mian et al. [39] have reported that the GL's tendinous tissue, the muscle-tendon complex, and fascicle were passively shortened by the TA movement immediately after initial contact and extended to a later stance. Thus, it can be expected that there will be a difference in the contraction method or state of the muscles according to the movement performed by a person and that the change in co-activation due to vibratory stimulation may be different for each muscle group.

In the swing phase (i.e., the FC phase), co-activation was decreased by the sub-max. This decrease in co-activation can be interpreted as an increase in the degree of joint freedom, along with a decrease in the dorsiflexion of the ankle. The common area of co-activation refers to the area where two muscles, which are in an agonist-antagonist relation, are activated simultaneously. During the FC phase, TA takes on the role of the agonist muscle, peaks are observed, and the EMG increases under vibratory conditions. The GL and GM act as antagonists during this phase, and do not show changes in the EMG due to vibration. In other words, the decrease in co-activation by vibratory stimulation during the FC phase is due to the increase in the TA activation, which enables the ankle joint to maintain dorsiflexion and achieve sufficient foot clearance.

The effect of the local vibratory stimulation on the stability and function of stair climbing is apparent in the PU phase. Threshold and sub-threshold intensities seem to affect the degree of joint freedom and joint stiffness, respectively, and can be controlled to an extent by varying the vibration frequency. In particular, the Th-Max and Sub-min stimuli have the greatest influence. However, in previous studies, Simeonov et al. [40] have reported that supra-sensory mechanical vibrations applied to construction workers' feet may increase the risk of loss of balance. Pope et al. [41] have

confirmed that a sensory stimulus above our tolerated level may cause discomfort. Furthermore, Priplate et al. [42,43] have found that a sub-threshold mechanical vibrational stimulation increased the detection of plantar pressure changes, resulting in decreased postural shaking in elderly and peripheral neuropathy patients.

In this study, changes in EMG activity and co-activation during stair climbing were identified when a mu rhythm-based vibratory stimulation was applied. These results suggest that localized vibratory stimulation can help improve the function and stability of stair climbing. However, since this study examined only the parameters of the muscles, it is difficult to identify changes in kinetic and kinematic factors such as joint angle, moment, and power during the performance of the motion. In future studies, if the analysis of kinetic, kinematic, and spatiotemporal variables is added using a three-dimensional motion analysis system, the effect of the local vibratory stimulation on stair climbing may be understood in more detail.

## 5. Conclusions

In this study, local vibratory stimulation set by the mu rhythm was applied during stair climbing, and changes in the lower leg musculature were confirmed through co-activation and EMG activity.

There was a difference in the mu rhythm reduction depending on the vibration frequencies, and the local vibration based on the mu rhythm reduction rate resulted in a change in muscle activity and co-activation during stair climbing. Changes in co-activation were confirmed to be affected by the phases of the gait cycle, vibration frequency and intensity, and muscle groups. It was determined that local vibratory stimulation selected with a mu rhythm reduction rate can contribute to the stability and function of stair climbing.

Thus, when applying vibration to dynamic tasks such as stair climbing, first, it is necessary to derive appropriate vibration characteristics, notable frequency and stimulus intensity to the body part to which vibration is applied, and then apply vibration in consideration of the motion performed. These results could then be utilized as a reference for rehabilitation, clinical treatment or research for which vibration is applied.

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