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Force Control on Fingertip Using EMS to Maintain Light Touch

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***Abstract*—Light touch on a rigid surface with minimal force below a specific threshold reduces postural sway by providing additional sensory cues from the fingertips. The feasibility of maintaining light touch depends on subject characteristics and task difficulty. Therefore, we introduce a method of maintaining light touch by using electrical muscle stimulation (EMS). We applied it in a single-leg standing task involving healthy adult subjects. The subjects stood upright in a single-leg stance on a firm surface and on foam rubber (FR), respectively, under three conditions: no touch (NT, NT-FR), light touch without EMS (LT, LT-FR), and light touch in which EMS was applied based on the contact force (LT-EMS, LT-EMS-FR). The results showed that the force control by EMS helped maintain light touch and reduce postural sway compared with the no-touch condition. The amplitude of postural sway under the touch condition with EMS was equivalent to that under the touch condition without EMS.**

I. Introduction

Light touch on a rigid surface with minimal force below a specific threshold (< 1 N) (the contact force level of light touch insufficient for supporting the human body) reduces postural sway during an upright stance [1]. Studies have investigated the elucidation of this effect from neurophysiological perspectives [2, 3] based on the original physiological findings that the light touch effect on postural stabilization is caused by additional sensory cues from the fingertips that reduce postural sway [1]. Many laboratory experiments based on this finding have shown the practicality of the light touch effect.

Application of the light touch effect has been expanded for various environmental conditions and subjects. In terms of subjects, light touch has been mainly used with healthy young adults [1–9], older adults [5, 8], and stroke patients [9]. In terms of environmental conditions, light touch has been examined from low-difficulty conditions (normal upright standing [3–5, 9] and a tandem position [1, 2, 8]) to high-difficulty conditions (standing on an unstable surface [5], single-leg stance [6], and ground walking in a virtual environment [7]). To receive accurate sensory cues from the fingertips to stabilize postural sway, subjects are required to maintain the contact force of their fingertips with light touch. However, the contact force increases [5, 8] based on age and/or task difficulty, resulting in some subjects being unable to maintain light touch [5, 7]. Therefore, we assume that the feasibility of maintaining light touch depends on these factors.

Methods of maintaining light touch such as auditory or visual feedback have been used to not exceed the threshold of the contact force [3, 8]. However, this feedback only informs the subject of excessive contact force. Accordingly, subjects have to recognize it and adjust the contact force voluntarily, which becomes an attention-demanding precision task [2] that may affect their postural control. Moreover, assumedly, subjects excessively rely on the support surface unconsciously during challenging tasks. In such cases, it is difficult to maintain light touch within a specific threshold with these kinds of feedback. Therefore, we need a new feedback method that maintains light touch without requiring the voluntary adjustment of contact force and that maintains light touch even when a subject excessively relies on the support surface unconsciously.

Electrical muscle stimulation (EMS) is a technique that contracts muscles and induces involuntary movements [10]. This technique can be used for fingertip force control in a closed-loop system. Thus, we hypothesized that EMS can control the contact force of fingertips to maintain light touch. For subjects, involuntary fingertip force control with EMS is not an attention-demanding precision task like with auditory or visual feedback. In this paper, we used this technique to maintain light fingertip contact during a single-leg standing task involving healthy adults. Next, we evaluated whether EMS could control the contact force of fingertips within the threshold and whether maintaining the light touch by EMS would affect the postural sway.

II. Methods

A. Subjects

Eight healthy males (age = 31 ± 6 (SD)) participated in this experiment. All were without neurological or musculoskeletal disorders. They were informed about the experimental protocol and signed a written informed consent form. The study was approved by the local human research ethics committee.

B. Apparatus and procedure

Figure 1 shows the experimental setup. The subjects stood upright on their bare feet in a right single-leg stance on a force plate (400×600 mm, BP400600, AMTI) that computed the center of pressure (COP) position at 1,000 Hz. Eight Vicon motion capture system (Vicon, Vicon Motion Systems) cameras tracked the tri-axial positions of four markers, which were placed on their right anterior pelvis, left anterior pelvis, right posterior pelvis, and left posterior pelvis. The tracking data was recorded at a sampling frequency of 100 Hz.

To obtain the contact force during light touch, a tactile force sensor (9-mm diameter, T40S1-WM155-K1-P1A-C100, Touchence) was attached to the parallel bar (TB-534-02, Takada bed) laterally on the subjects' right side and adjusted to the height of their waist. It measured the tri-axial contact force of each subject's right index finger at 40 Hz. The contact force was transmitted to a PC through an amplifier (AMC3-

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565603, Touchence) and a microcontroller (EBS-001-1, Touchence). Another microcontroller (Arduino Uno, Arduino) connected to the PC sent a trigger to the function generator (SEN-8203, Nihon Kohden) to apply the EMS. The EMS was applied using a function generator and isolator (SS104-J, Nihon Kohden). A pair of disposable electrodes (F-150M, Nihon Kohden) were placed on the extensor digitorum muscle of the subject's right forearm (Figure 2). Before the experiment, the intensity was calibrated for each user to prevent pain from the EMS. Based on the JIS standard (electric therapy apparatus for home use, JIS C 9335-2-209: 2018) and the design guideline [11], we set the maximum pulse width to 100 μs, the maximum frequency to 200 Hz, and the maximum current to 20 mA.

We used proportional control of the pulse frequency (f) to change the intensity of the EMS based on the contact force. We controlled the f (Hz) of the EMS to the extensor digitorum muscle as follows:

$$f = \begin{cases} 200 & (Fz \geq 1.5) \\ 200\,Fz\text{-}100 & (0.5 \leq Fz \leq 1.5) \\ 0 & (0 \leq Fz \leq 0.5) \end{cases}, \tag{1}$$

where Fz (N) is the current contact force of the fingertip in the vertical direction. If the current contact force was more than 0.5 N, the EMS was involuntarily applied to extend the right index finger to maintain light touch below 1 N.

We evaluated muscle activity during the single-leg upright task. The subjects wore electromyography (EMG) sensors (Delsys, Trigno Wireless System) on the tibialis anterior (TA) and the gastrocnemius (GA) lateralis muscles. The sampling rate was 1,000 Hz.

C. Protocol

Prior to the single-leg standing tasks, the subjects performed maximum voluntary muscle contractions (MVCs) of plantar flexion and dorsiflexion of the ankle. To obtain the MVC value in TA, they stood upright and raised their right toe with maximum force to resist the force applied by the investigator. To obtain the MVC value in GA, they raised their right heel with maximum force similarly. Each MVC task was performed twice every five seconds.

The single-leg stance tasks consisted of six conditions: (1) no touch (NT), (2) light touch (LT), (3) light touch in which EMS was applied based on the contact force (LT-EMS), (4) no touch on the foam rubber (FR) (410×500×60 mm, AMB-ELITE, SAKAI Medical) placed on the force plate (NT-FR), (5) light touch on the FR (LT-FR), and (6) light touch on the FR in which EMS was applied based on the contact force (LT-FR-EMS). The first three conditions were classified as low-difficulty conditions, and the other conditions were high-difficulty conditions. Under the no-touch conditions ((1) and (4)), subjects stood with their arms hanging down at their sides. Under the light touch conditions ((2), (3), (5), and (6)), they touched their right index finger to the force sensor and tried to maintain light touch while standing. Prior to the experiment, they were instructed to contact the force sensor with as little force as possible while visual feedback on a monitor would inform them of the strength of the contact force.

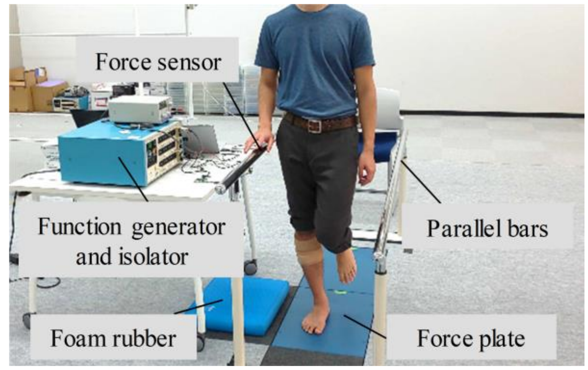

Fig. 1. Experimental setup.

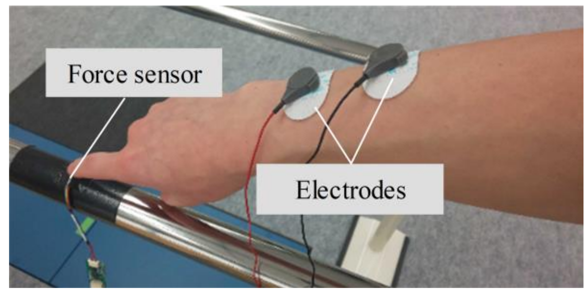

Fig. 2. Method of attaching the electrodes to apply the EMS.

Each trial was 40 seconds long, and the subjects took a 1-minute break between each trial. The trials were performed from low-difficulty conditions to high-difficulty conditions. At each difficulty level, the no-touch conditions ((1) and (4)) were performed first, and the order of the other conditions were randomized. If the subjects could not hold their posture for 40 s, the trial was repeated after the break. If they also failed the second trial, the trial under the applicable condition was considered "failed," and we moved to the next condition. All data between 5–35 seconds was used for analysis, and the other parts were eliminated.

D. Analysis

We investigated the targeted subjects who were necessary to control the contact force using EMS by first calculating the number of samples of contact force (Fz) that exceeded 0.5 N. Next, we classified the subjects into a group to whom the EMS was applied more than ten times and the other group to whom the EMS was applied less than ten times. We targeted the former group and used their data for analysis. Then, we calculated the duration of contact force over 0.5 N under each condition for targeted subjects.

Each data item recorded during the 30 s was divided into six segments every 5 s. The contact force data in the vertical direction was low-pass-filtered with a Butterworth digital filter with a cut-off frequency of 5 Hz. We compared the contact force between conditions by calculating the median for each 5-second segment.

The COP data was low-pass filtered with a Butterworth digital filter with a cut-off frequency of 10 Hz. We evaluated the postural sway values by calculating the root mean square (RMS) area as follows:

TABLE I. NUMBER OF SAMPLES FOR WHICH F_Z EXCEEDED 0.5 N UNDER EACH CONDITION FOR ALL SUBJECTS

	Low difficulty condition		High difficulty condition	
	LT	LT-EMS	LT-FR	LT-EMS-FR
A	12	38	13	28
B	0	0	0	1
C	0	0	4	0
D	2	0	66	1
E	3	5	46	2
F	0	0	3	1
G	0	2	38	8
H	0	0	0	2

$$\text{COP RMS area (mm}^2) = \pi\left(\frac{1}{n}\sum_{i=1}^{n}\sqrt{(\text{COP}_{x_i} - \text{COP}_{x_m})^2 + (\text{COP}_{y_i} - \text{COP}_{y_m})^2}\right)^2, \quad (2)$$

where $\text{COP}x_i$, $\text{COP}y_i$ represents the amplitude of the COP in the frontal plane and the sagittal plane in the i th sample, respectively, and $\text{COP}x_\text{m}$, $\text{COP}y_\text{m}$ represents the mean amplitude of the COP for each 5-second segment. The tracked position data was low-pass-filtered with a Butterworth digital filter with a cut-off frequency of 10 Hz. We also evaluated the postural sway values around the pelvis by calculating the center of mass (COM) of the four pelvis markers and the COM norm as follows:

$$\text{COM norm(mm)} = \sqrt{(\text{COM}_{x_i} - \text{COM}_{x_m})^2 + (\text{COM}_{y_i} - \text{COM}_{y_m})^2 + (\text{COM}_{z_i} - \text{COM}_{z_m})^2}, \quad (3)$$

where COM_i represents the mean amplitude of the position of the four pelvis markers in the i th sample, and COP_m expresses the mean amplitude of the COM for each 5-second segment.

A bandpass filter (1–500 Hz) rectified the EMG data by calculating the RMS over a 100-ms window. In the MVC tasks, we set the maximum EMG value as the MVC value. The data was normalized by the MVC value. We calculated the median for each 5-second segment.

We conducted the Wilcoxon Rank-Sum test to compare the medians of contact force under the conditions with and without EMS. To compare the mean postural sway values (COP RMS area and COM norm) and the mean of the EMG activity under the NT-FR, LT-FR, and LT-EMS-FR conditions, we used a one-way analysis of variance, then conducted post-hoc multiple comparisons using Tukey-Kramer tests.

III. RESULTS

Under low-difficulty conditions (standing on a firm surface), all the subjects could keep upright in the single-leg stance for 40 s. However, under the high-difficulty conditions, two of them failed the trial under the no-touch condition. Table 1 shows the number of samples in which Fz exceeded 0.5 N under each condition. Under the low-difficulty conditions (LT and LT-EMS), EMS was applied more than ten times to only one subject. Under the high-difficulty conditions (LT-FR and LT-EMS-FR), EMS was applied more than ten times to four subjects. To evaluate whether EMS controlled the contact force, we targeted four subjects (A, D, E, and G) under both the LT-FR and LT-EMS-FR conditions.

Figure 3 shows box plots of the duration of the contact force (Fz) over 0.5 N under the LT-FR and LT-EMS-FR conditions for the targeted subjects. The duration was significantly shorter under the LT-EMS-FR condition than under the LT-FR condition. Figure 4 shows box plots of the contact force under the LT-FR and LT-EMS-FR conditions for the targeted subjects. There were 30 data items for each condition (six segments × five subjects). The results showed a significant difference ($p < 0.01$).

Figure 5 shows box plots in the COP RMS area under the NT-FR, LT-FR, and LT-EMS-FR conditions for the targeted

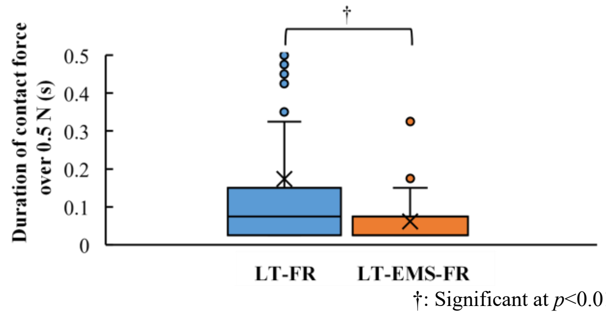

Fig. 3. Box plots of the duration of contact force over 0.5 N under LT-FR and LT-EMS-FR conditions for targeted subjects. The cross symbol (×) indicates the average value.

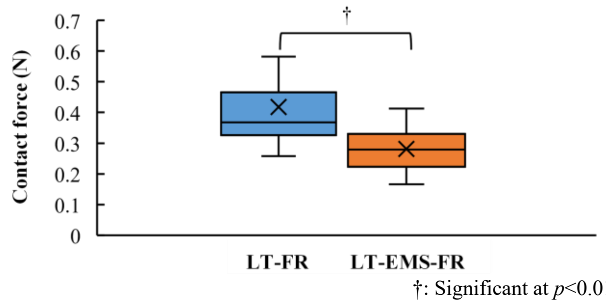

Fig. 4. Box plots of the contact force under LT-FR and LT-EMS-FR conditions for targeted subjects.

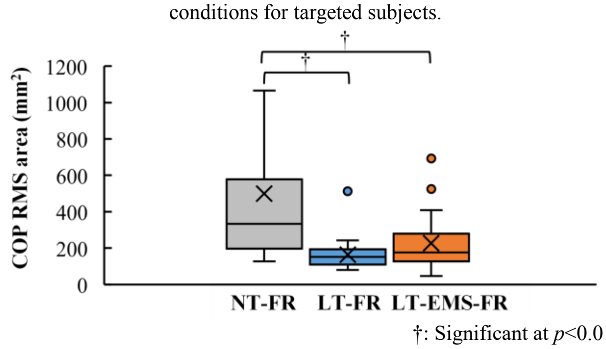

Fig. 5. Box plots of the COP RMS area under NT, LT-FR, and LT-EMS-FR conditions for targeted subjects.

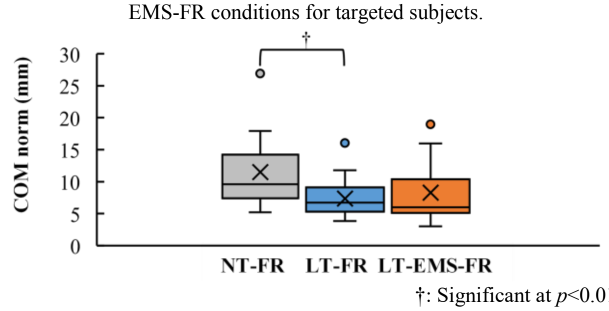

Fig. 6. Box plots of the COM norm under NT, LT-FR, and LT-EMS-FR conditions for targeted subjects.

subjects. There were significant differences between NT-FR and LT-FR and between NT-FR and LT-EMS-FR ($p < 0.01$). The COP RMS area was significantly reduced under both LT-FR and LT-EMS-FR conditions compared with that under the NT-FR condition. Figure 6 shows box plots of the COM norm under the NT-FR, LT-FR, and LT-EMS-FR conditions for the targeted subjects. The results showed a significant difference between NT-FR and LT-FR ($p < 0.01$).

Figure 7 shows box plots of the muscle activity of the tibialis anterior (TA) and the gastrocnemius (GA) lateralis muscles under the NT-FR, LT-FR, and LT-EMS-FR conditions for the targeted subjects. The results of EMG in TA showed significant differences between NT-FR and LT-FR ($p < 0.01$)

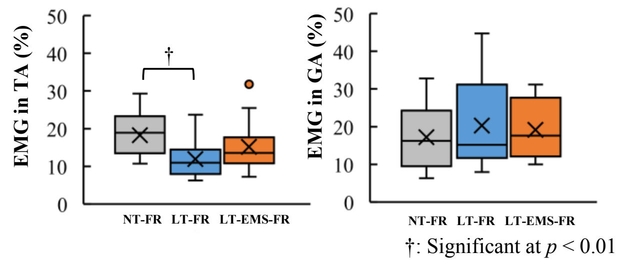

Fig. 7. Box plots of the muscle activity of TA and GA under NT, LT-FR, and LT-EMS-FR conditions for targeted subjects.

IV. Discussion

We evaluated whether EMS could control the contact force of fingertips to maintain light touch and whether maintaining light touch by EMS would affect the postural sway. The results indicated that applying EMS to the index finger extensor muscle reduced both the duration of the contact force over 0.5 N and the amplitude of the contact force, demonstrating that EMS controlled the contact force to maintain light touch. In addition, the effect of reducing the postural sway was seen in the COP RMS area under the touch condition with EMS and under the touch condition without EMS, suggesting that the intervention of involuntary movement by EMS would not have adversely affected postural control. Contact force control using EMS could help maintain light touch below 1 N and improve postural control ability under conditions with stronger contact force (e.g., more difficult tasks, older subjects, etc.).

The pelvic sway was not significantly reduced under the EMS condition compared with under the no-touch condition. We considered that some subjects may have paid too much attention to the force control. In the interview after the experiment, one subject (Subject A) reported that he adjusted the contact force by targeting the threshold the EMS was applied at (0.5 N). This may be an attention-demanding precision task that affects their postural control.

Muscle activity with EMS showed values similar to no-touch and touch-without-EMS conditions. We assume that standing on the FR is a challenging task that increases ankle joint movement, resulting in muscle activity that did not greatly reduce even by light touch.

In conclusion, we showed that force control by EMS helped maintain light touch and reduce postural sway compared with the no-touch condition. The amplitude of postural sway under the touch condition with EMS was equivalent to that under the touch condition without EMS. However, there were some limitations. First, the subjects were healthy adults, and we applied EMS to only four of them to maintain light touch under an unstable surface condition. Next, regarding the experimental instructions, we asked subjects to touch the force sensor with as little force as possible, resulting in too much attention being paid to the contact force. The intervention of involuntary movement by EMS is considered to be more effective when attention is paid to postural stability, as subjects tend to rely more on a support surface.

In future work, we will explore a wider range of subject characteristics and task difficulties in which maintaining light touch is difficult, and we will determine the fields of light touch maintenance that EMS is applicable to.

References

[1] J. R. Lackner, E. Rabin, and P. DiZio, “Stabilization of posture by precision touch of the index finger with rigid and flexible filaments,” Exp. Brain Res., vol. 139, pp. 454–464, 2001.

[2] D. Kaulmann, M. Saveriano, D. Lee, J. Hermsdörfer, and L. Johannsen, “Stabilization of body balance with Light Touch following a mechanical perturbation: Adaption of sway and disruption of right posterior parietal cortex by cTBS,” PLoS ONE, vol. 15, no. 7, pp. e0233988, 2020.

[3] T. Ishigaki, K. Ueta, R. Imai, and S. Morioka, “EEG frequency analysis of cortical brain activities induced by effect of light touch,” Exp. Brain Res., vol. 234, pp. 1429–1440, 2016.

[4] M. Renato, L. S. Bedo Bruno, O. Santos Luciana, A. Batistela Rosangela, R. P. Santiago Paulo, and E. Mauerberg-deCastro, “Additional haptic information provided by anchors reduces postural sway in young adults less than does light touch,” Frontiers in Neuroscience, vol. 12, pp. 346, 2018.

[5] F. Tremblay, A. C. Mireault, L. Dessureault, H. Manning, and H. Sveistrup, “Postural stabilization from fingertip contact,” Exp. Brain Res., vol. 164, pp. 155–164, 2005.

[6] K. Oshita and S. Yano, “Effect and immediate after-effect of lightly gripping the cane on postural sway,” J. Physiol. Anthropol., vol. 35-14, pp. 1–8, 2016.

[7] D. M. Stramel, R. M. Carrera, S. A. Rahok, J. Stein, and S. K. Agrawal, "Effects of a person-following light-touch device during overground walking with visual perturbations in a virtual reality environment," in IEEE Robotics and Automation Letters, vol. 4, no. 4, pp. 4139–4146, 2019.

[8] A. M. F. Berela, S. Caporicci, and J. A. Barela, “Contribution of fingertip light touch on postural stabilization of older adults,” In: F. Barbieri and R. Vitório (eds), Locomotion and Posture in Older Adults, Springer, Cham., pp. 209–218, 2017.

[9] B. P. Cunha, S. R. Alouche, I. M. Araujo, and S. M. Freitas, “Individuals with post-stroke hemiparesis are able to use additional sensory information to reduce postural sway,” Neurosci. Lett., vol. 513, no. 1, pp. 6–11, 2012.

[10] E. Tamaki, T. Miyaki, and J. Rekimoto, “PossessedHand: techniques for controlling human hands using electrical muscles stimuli,” In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 543–552, 2011.

[11] M. Kono, T. Takahashi, H. Nakamura, T. Miyaki, and J. Rekimoto, “Design guideline for developing safe systems that apply electricity to the human body,” ACM Trans. Comput.-Hum. Interact., vol. 25, no. 3, 2018.