A Study on Estimated Sub-threshold Intensities of Somatosensory Stimuli Based on Somatosensory Evoked Potentials of EEG

Ha-Ju So
Department of Healthcare Engineering
Chonbuk National University
Jeonju-si, Jeonbuk, Korea
hajunala@jbnu.ac.kr

Han-Young Oh
Department of Healthcare Engineering
Chonbuk National University
Jeonju-si, Jeonbuk, Korea
hanyoungoh@jbnu.ac.kr

Seong-Hyun Kim
Division of Biomedical Engineering
Chonbuk National University
Jeonju-si, Jeonbuk, Korea
prite7@empal.com

Dong-Wook Kim
Division of Biomedical Engineering
Chonbuk National University
Jeonju-si, Jeonbuk, Korea
biomed@jbnu.ac.kr

***Abstract*—The present study was conducted to estimate sub-threshold stimulus intensities that can influence the body in performing an objective measurement for individual thresholds of somatosensory stimuli from outside based on brain responses. In order to investigate the relation between brain response and somatosensory stimulation, a hypothesis was set up that sub-threshold stimulus to cause significant postural balance by applying to tibialis anterior tendons would exist between thresholds of the fingers and the tibialis anterior tendons. The experiment was conducted with the somatosensory stimulus and brain wave analysis systems, five male adults were involved. The three kinds of somatosensory stimulation (200 Hz, 250 Hz and 300 Hz) were used, those stimulation was applied to the tibialis anterior tendon of the subjects, and their brain waves were measured at the same time. As a result, we can confirm that fingers were more sensitive to somatosensory stimuli than tibialis anterior tendons and the frequency of somatosensory stimuli and sensitivity to somatosensory stimuli have an inverse correlation. Also, sub-threshold stimulus may derive a significant response from the body.**

Keywords-somatosensory; vibration stimulation; threshold; brain wave

I. Introduction

Human somesthesis is information consisting of senses of touch, pressure, temperature, pain and movement obtained from the receptors distributed on muscles, joints and skin [1-2]. Somesthesis plays an important role in subconscious or automatic adjustment necessary to maintain posture or quickly react to environmental changes. As somesthesis is basic information formed in the human body to maintain a stable posture together with visual and vestibular senses [3-4], attempts to improve the postural balance of the body by stimulating somesthesis continue. Previous studies analyzed the effects of somatosensory stimuli from outside on postural balance in various motions such as quiet standing [5-7] and walking [8-11]. Many previous studies investigating the relation between somatosensory stimuli from outside and postural balance proposed that the somatosensory stimulus has a significant effect on the improvement of postural balance as it activates proprioceptive feedbacks controlling the posture and motions of the body [12-13]. In the meantime, some studies reported that a greater somatosensory stimulus than the threshold stimulus of individuals reduces postural balance as the movement system for postural balance in the body is disturbed [14]. Some reported that the somatosensory stimulus has a low threshold value, compared with other sensory stimuli, causing discomfort or pain in the body whereby the body becomes stressed [15-16]. Studies to estimate the sensory threshold values of individuals relevant to the sensitivity of sensory organs in order to reduce discomfort or pains caused by a somatosensory stimulus, and ones to observe results from the application of a sub-threshold stimulus to the body are underway [17], but they remain insignificant. Previous studies often used the estimated sensory threshold values of individuals for clinical diagnosis and pain-related researches, but many of them depended on the perceptive responses of subjects using a switch or button [18]. Such threshold estimation requires persistent efforts for the subjects under sensory stimulus to perceive a sensory stimulus, and an inaccurate perception of sensory stimulus is difficult to guarantee reliability. Thus, beyond the subjective responses of subjects to a sensory stimulus, there were efforts to determine the perception of a sensory stimulus through objective physiological signals. In this connection, there are previous studies that have observed the perception of a sensory stimulus near threshold using the amplitude of brain waves [19].

This study performed an objective measurement of personal threshold for somesthesis from outside, and estimated the intensity of a sub-threshold stimulus that may have an effect on the body by analyzing the somatosensory evoked potentials (SEPs) of brain waves. It supposed that

978-0-7695-4923-1/12 $26.00 © 2012 IEEE
DOI 10.1109/ISDEA.2012.51

there will be an intensity of a sensory stimulus that may influence the body in spite of sub-threshold values among threshold intensities measured on fingers known to be the most sensitive to somesthesis in the body and ankles, and evaluated the effect of the sensory impulse on the body by analyzing the brain waves occurring in the somatosensory area when the subdivided somatosensory stimulus was applied to the body. It is expected that the objective threshold estimates of the somatosensory stimulus and the results on the setting for the sensory impulse intensity drawn by this study, which may influence the body in spite of sub-threshold values, can be used to set a personal specific somatosensory stimulus intensity to be applied to the body to improve postural balance in the next studies.

II. EXPERIMENT PROCESS

This experiment was performed using the somatosensory stimulus and brain wave analysis systems constructed in a darkroom to shut out noises and lights to minimize disruptions from outside.

The somatosensory stimulus system to apply a somatosensory stimulus to subjects was internally manufactured using linear vibration elements that generate mechanical vibration. This system was designed to adjust the intensity of the somatosensory stimulus applied to the body, controlling the electrical characteristics of the input power to drive vibration elements, and to provide a somatosensory stimulus to the exact spot regardless of the individual differences of subjects, using a contractile band type. This experiment used stimuli with vibration frequencies of 250 Hz [20-21], 200 Hz and 300 Hz being the highest in absolute sensitivity regardless of the contact area.

This experiment also used a brain wave collection (Brain-Product) and a brain wave analysis system (BESA) to investigate the response of the body in regards to the inflow of the somatosensory stimulus. Individual disk electrodes were used to collect brain waves, and they were placed at 7 representative regions (F3, F4, C3, Cz, C4, P3 and P4), based on the internationally recognized 10-20 electrode displacement.

The somatosensory stimulus and brain wave analysis systems used for this experiment were synchronized with a trigger signal to observe a change in brain waves resulting from the inflow of the somatosensory stimulus.

The experiment was performed on 5 male adults without neurological diseases. Before starting the experiment, the details of the experiment and significant information were fully explained to subjects with voluntary consent obtained from them. The experiment began with the attachment of electrodes to the scalps of subjects to measure brain waves. Subjects were seated on a chair in a comfortable manner to measure brain waves, and had paste applied on their heads with disk electrodes added to it. Then, somatosensory stimulators were attached to the tibialis anterior tendons and the index fingers of subjects, and the process of increasing or decreasing the intensity of the somatosensory stimulus was repeated, to obtain a perceptible threshold intensity of the somatosensory stimulus [22]. Subdivided somatosensory stimuli between the stimulus intensity obtained from fingers and one from tibialis anterior tendons were flowed in the tibialis anterior tendons of subjects to measure brain waves. The experiment was performed by applying sensory stimulus intensities in a random order to minimize the effects by factors other than sensory stimulus intensity.

This experiment collected brain waves from 7 areas, using a brain wave collection system, for analysis. The sampling rate for the conversion of brain waves from analogue to digital signal was set to 256 Hz. The high pass filter was set to 0.1 Hz and the low pass filter to 70 Hz in order to remove noise that might intrude while measuring brain waves, the whole range of brain waves used in most studies today was collected, and a 60 Hz notch filter was used to remove noise due to the industrial AC.

Brain wave data had an amplitude analysis of SEPs to detect the electrical activities of the brain occurring for a certain period of time in relation to the presentation of the somatosensory stimulus. The amplitude sizes of the SEP at 100 - 150 ms (N150) and 220 - 350 ms (P260) [23] were obtained and compared, based on the marker created at the moment when stimuli were flowed at the measured brain waves. The obtained SEP was interpreted as a change in brain waves by the somatosensory stimulus, compared with the information extracted from stable brain waves.

III. RESULTS

The measurement of the thresholds regarding the somatosensory stimuli applied to the body based on the responses of subjects showed the following results: When somatosensory stimuli of 200 Hz, 250 Hz and 300 Hz were applied to the tibialis anterior tendons, subjects perceived somatosensory stimuli at intensities of 0.11 Vrms, 0.285 Vrms and 0.37 Vrms, respectively. When the same were applied to fingers with a high sensitivity to somesthesis, they perceived somatosensory stimuli at intensities of 0.012 Vrms, 0.017 Vrms and 0.017 Vrms, respectively. When somatosensory stimuli with the same frequency were applied, threshold values measured on fingers were smaller than those of the tibialis anterior tendons. The ratio between thresholds measured on fingers and the tibialis anterior tendons turned out to be 8.8:1 at 200Hz, 16.3:1 at 250Hz and 21.1:1 at 300Hz, indicating that the ratio between two thresholds increased as the frequency increased.

TABLE I. THE SUB-THRESHOLD INTENSITIES (μV) OF SOMATOSENSORY STIMULI BASED ON MOMENT THAT SEPS CHANGE

	C3		**Cz**		**C4**	
	N150	***P260***	***N150***	***P260***	***N150***	***P260***
200Hz	51.3	63	57	54.8	36.3	70.3
250Hz	53.5	91.5	65	96	30	96
300Hz	73.8	82.7	79.5	77.5	60	82

The analysis of the SEPs occurred when subdivided somatoenscory stimuli which is based on the thresholds measured on fingers and tibialis anterior tendons were applied to tibialis anterior tendons showed the following results: Table1 shows the intensities of somatosensory stimuli at the moment when a change in SEPs started to arise, compared with the brain waves obtained when stable. When a somatosensory stimulus of 200 Hz was applied, a change in SEPs occurred for the first time at 57.2% for C3, 55.9% for Cz, and 53.3 % for C4. A change in SEPs was observed for the first time at 72.5%, 80.5% and 63%, respectively, when a somatosensory stimulus of 250 Hz was applied, while at 78.2 %, 78.5 % and 71% when a somatosensory stimulus of 300 Hz was applied. Considering that sensory stimuli were applied to the right parts of the body, a change in the SEPs obtained at C4 needs to secure reliability through additional experiments and considerations. As the intensities of sensory stimuli are in the range of 55.9 - 80.5% from intensities at which a change in SEPs was observed for the first time, a significant response can be observed in somatosensory areas regardless of the size of frequency if a sensory stimulus of over 80.5 % is flowed in tibialis anterior tendons with a difference between the thresholds measured on fingers and tibialis anterior tendons. The experiment in this study demonstrated that the application of the sensory stimuli equivalent to approximately 80 % of the difference between the threshold intensities obtained from tibialis anterior tendons and fingers to tibialis anterior tendons could cause SEPs, even though there were differences depending on body parts. This indicates that future studies can use sub-threshold stimuli to have a significant effect on the body without measuring individual SEPs. Despite the fact that additional studies are needed, sub-threshold stimulus intensity can be set for body parts other than the tibialis anterior tendons through an arithmetical calculation using such a process:

$$S[Vrms] = F + \{(A - F) \times 0.805\}$$

Among above, 'S' is intensity of sub-threshold, 'F' is the threshold measured on fingers and 'A' is the threshold measured on tibialis anterior tendons.

IV. Considerations

The purpose of this study is to estimate sub-threshold stimulus intensities that can influence the body in performing an objective measurement for individual thresholds of somatosensory stimuli based on brain responses. A hypothesis was set up that sub-threshold stimulus to cause significant postural balance by applying to tibialis anterior tendons would exist between thresholds of the fingers and the tibialis anterior tendons. To verify this hypothesis, this study subdivided the threshold intensities measured on fingers and tibialis anterior tendons, applied them to tibialis anterior tendons, and collected brain waves. It produced SEPs, which are caused by the application of somatosensory stimuli, from brain waves, and produced a sensory stimulus intensity at the time of occurrence of SEPs, compared with brain waves when stable, which was assumed as a sensory stimulus that can have a significant effect on the body even though it is smaller than the threshold.

This study showed that fingers are more sensitive to a somatosensory stimulus than tibialis anterior tendons are, and fingers and tibialis anterior tendons are less sensitive as the frequency increases. Such results are closely related to the density of somatosensory receptors, and can be accounted for by the characteristics of the receptive stimulus regarding somatosensory receptors. The vibrations used as somatosensory stimuli in this study are perceived by two mechanisms of the body. For the first mechanism, the Meissner corpuscle receptor receives vibrations, which are transmitted to the body using a RA (rapidly adapting) fiber. For the second mechanism, the Pacinian corpuscle receptor receives vibrations, which are transmitted to the body using a PC (Pacinian corpuscle-associated) fiber. A study reported that the RA fiber is sensitive to vibrations of 5 - 100 Hz, and PC fiber to 5 - 1,000 Hz [24], and it can be assumed that the somatosensory stimuli of 200 - 300 Hz used by this study were perceived by the Pacinian corpuscle receptor and the PC fiber. The Pacinian corpuscle receptor is an oval structure observed in the skin, skeletal muscles and articular cavity, whose central nervous system is distorted by an external force, causing an action potential, by which an external force is detected. Since both fingers and tibialis anterior tendons with somatosensory stimuli applied in this study had an anatomical structure with the distributed Pacinian corpuscle receptor, they revealed sensitive responses to somatosensory stimuli. As sensory perception in body parts can be affected by the distribution characteristics of mechanical receptors, innervation density and the buffering of subcutaneous tissues [25], even the same stimulus can bring about a difference in perception depending on the parts, and expecially, fingers showed high sensitivity to the somatosensory stimulus since they have high innervation density compared with tibialis anterior tendons. The result of this study in which fingers demonstrated high sensitivity coincides with that of the previous study pertaining to the sensitivity of vibration sense [26]. The reason why the ratio between the thresholds measured on fingers and tibialis anterior tendons increased as the frequency of the somatosensory stimulus grew is that the threshold obtained from tibialis anterior tendons was smaller than that from fingers. In the meantime, the thresholds measured on fingers and tibialis anterior tendons increased as the frequency grew, showing an inverse correlation between frequency and sensitivity. However, this is contrary to the result of the precedent study, which shows that the sensory threshold decreases as the frequency increases [25]. Thus, additional studies and consideration are needed since the perception of sensory stimulus thresholds can be affected by various factors such as the characteristics and application of a sensory stimulus.

Based on the thresholds obtained from fingers being very sensitive to a somatosensory stimulus and tibialis anterior tendons with a somatosensory stimulus entered to maintain postural balance, the comparison of those SEPs obtained by applying the subdivided somatosensory stimuli to tibialis anterior tendons showed that SEPs occurred even when sensory stimuli smaller than thresholds obtained from tibialis anterior tendons were applied, and the use of a sub-threshold stimulus could derive significant responses from the body. This increases the possibility to use sub-threshold stimuli together with the efforts made to stimulate somesthesis using noise resonance with white noise applied except sensory stimuli in the previous studies intended to improve the postural balance of the body using sub-threshold stimuli [27-28]. Such results are different from the common physiological understanding that stimuli smaller than sensory thresholds cannot cause physiological responses. This can be accounted for by the anatomical structure of tibialis anterior tendons to which the somatosensory stimulus is applied. Various receptors are distributed in the tibialis anterior tendons, which produce action potentials by external stimuli. The intensity of stimuli sufficient enough to produce action potential is called 'threshold'. In general, a single receptor does not respond to the stimuli smaller than the threshold as it complies with the all-or-none law. However, tibialis anterior tendons are excluded from the application of the all-or-none law for single receptors as they have an anatomical structure in which single structures are gathered. In other words, on the assumption that stimulus intensity at which most of the receptors distributed in tibialis anterior tendons are activated is threshold, some single receptors have individual thresholds smaller than this intensity, and the combination of responses for these receptors produce physiological responses.

Subject 1 reported in subjects' responses that the perception of a somatosensory stimulus was not clear when measuring the thresholds of the somatosensory stimulus. Even though repetitive experiments and sufficient rest were provided, Subject 1 demonstrated a great deviation in thresholds of somatosensory stimuli. This can be accounted for by a precedent study in which the size of muscles and the distribution of subcutaneous fats have influence on sensory perception [29]. The BMI index of Subject 1 was 31.02 higher than other subjects, from which it is supposed that his physical characteristics had an effect on somatosensory perception. Since the threshold of the somatosensory stimulus could not be calculated, data for Subject 1 were excluded from the analysis of results for this experiment. However, the intensity of the sensory stimulus at which a change in SEPs is observed for the first time existed within the range of 55.5 % - 94.5 % in data for Subject 1 as well showing that stimuli smaller in intensity than the threshold could draw responses from the body.

V. CONCLUSIONS

The purpose of this study was to provide an objective estimation of sub-threshold stimulus intensities that can influence the body, based on brain responses. A hypothesis was established whereby sensory stimuli smaller than the thresholds of tibialis anterior tendons between those thresholds obtained from the fingers and the tibialis anterior tendons, and the experiment was performed with the following results:

1. When somatosensory stimuli with the same frequency were used, fingers were more sensitive to somatosensory stimuli than tibialis anterior tendons were, and the frequency of somatosensory stimuli and sensitivity to somatosensory stimuli have an inverse correlation.

2. When sensory stimuli equivalent to 80 % of the difference for threshold intensities obtained from tibialis anterior tendons and fingers were applied to tibialis anterior tendons, a change in SEPs was observed, showing that a sub-threshold stimulus may derive a significant response from the body.

The experimental results above can be used as basic data for the use of sub-threshold stimuli in deriving a significant response from the body using the somatosensory stimuli input, and also as a standard for setting the intensity of a sub-threshold stimulus. If additional studies related to this study are performed in the future, the application of a somatosensory stimulus to the body taking into consideration personal characteristics, and various interface designs using senses are expected.

ACKNOWLEDGMENT

This work was supported by the Grant of the Korean Ministry of Education, Science and Technology. [Mid – Career Researcher Program (1201000345)]

REFERENCES

[1] T. Mergner, and T. Rosemeier, " Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions : a conceptual model" , Brain Research Reviews, Vol.28, No.1-2, p.118-135, 1998.

[2] K.O. Berg, B.E. Maki, J.I. Williams, P.J. Holliday and S.L. Wood-Dauphinee, "Clinical and laboratory measures of postural balance in an elderly population", Archives of Physical Medicine and Rehabilitation, Vol.73, No.11, p.1073-1080, 1992.

[3] A.E. Patla, E. Niechwiej, V. Racco and M.A. Goodale, "Understanding the contribution of binocular vision to the control of adaptive locomotion", Experimental Brain Research, Vol.142, No.4, p.551-561, 2002.

[4] F.B. Horak, L.M. Nashner and H.C. Diener HC, "Postural strategies associated with somatosensory and vestibular loss", Experimental Brain Research, Vol.82, No.1, p.167-177, 1990.

[5] P.F. Meyer PF, L.I. Oddsson and C.J. De Luca CJ, "Reduced plantar sensitivity alters postural responses to lateral perturbations of balance", Experimental Brain Research, Vol.157, No.4, p.526-536, 2004.

[6] F.B. Horak, R. Dickstein and R.J. Peterka RJ, "Diabetic neuropathy and surface sway-referencing disrupt somatosensory information for postural stability in stance", Somatosensory and Motor Research, Vol.19, No.4, p.316-326, 2002.

[7] G.G. Simoneau, J.S. Ulbrecht, J.A. Derr, M.B. Becker and P.R. Cavanagh, "Postural instability in patients with diabetic sensory neuropathy", Diabetes Care, Vol.17, No.12, p.1411-1421, 1994.

[8] S.D. Perry, W.E. McIlroy and B.E. Maki, "The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation", Brain research, Vol.22, No.2, p.401-406, 2000.

[9] P.F. Meyer, L.I. Oddsson and C.J. De Luca, "The role of plantar cutaneous sensation in unperturbed stance", Experimental Brain Research, Vol.156, No.4, p.505-512, 2004.

[10] M.C. Do, B. Bussel and Y. Breniere, "Influence of plantar cutaneous afferents on early compensatory reactions to forward fall", Experimental Brain Research, Vol.79, No.2, p.319-324, 1990.

[11] E. Eils, S. Behrens, O. Mers, L. Thorwesten, K. Völker and D. Rosenbaum, "Reduced plantar sensation causes a cautious walking pattern", Gait Posture, Vol.20, No.1, p.54-60, 2004.

[12] P. Cordo, V.S. Gurfinkel, L. Bevan and G.K. Kerr, "Proprioceptive consequences of tendon vibration during movement", Journal of Neurophysiology, Vol.74, No.4, p.1675-1688, 1995.

[13] R. Roll, J.L. Velay and J.P. Roll, "Eye and neck proprioceptive messages contribute to the spatial coding of retinal input in visually oriented activities", Experimental Brain Research, Vol.85, No.2, p.423-431, 1991.

[14] P. Simeonov, H. Hsiao, J. Powers, D. Ammons, T. Kau and A. Amendola, "Postural stability effects of random vibration at the feet of construction workers in simulated elevation", Applied Ergonomics, Vol.42, No.5, p.672-681, 2011.

[15] K.A. Kaczmarek, J.G. Webster, P. Bach-y-Rita and W.J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems", IEEE Transaction on Biomedical Engineering, Vol.38, No.1, p.1-16, 1991.

[16] G.F. Shannon, "A comparison of alternative means of providing sensory feedback on upper limb prostheses", Medical and Biological Engineering and Computing, Vol.14, No.3, p.289-294, 1976.

[17] A. Chatterjee, P. Chaubey, J. Martin and N. Thakor, "Testing a Prosthetic Haptic Feedback Simulator with an Interactive Force Matching Task", Americal Academy of Orthotists & Prosthetists, Vol.20, No.2, p.27-66, 2008.

[18] M. Ushio, T. Murofushi, Y. Chihara, S. Iwasaki, T. Yamaguchi and K. Kaga, "Testing of vibratory thresholds as a clinical examination for patients with unsteadiness due to somatosensory disorders", Gait & Posture, Vol.28, No.4, p.552-558, 2008.

[19] K. Linkenkaer-Hansen, V.V. Nikulin, S. Palva, J.R. Iimoniemi, and J.M. Palva, "Prestimulus Oscillations Enhance Psychophysical Performance in Humans", The Journal of Neuroscience, Vol.24, No.45, p.10186-10190, 2004.

[20] S.J. Bolanowski, G.A. Gescheider, R.T. Verrillo and C.M. Checkosky, "Four channels mediate the mechanical aspects of touch", Journal of the Acoustical Society of America, Vol.84, No.5, p.1680-1694, 1988.

[21] G.A. Gescheider, S.J. Bolanowski, J.V. Pope and R.T. Verrillo, "A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation", Somatosensory and Motor Research, Vol.19, No.2, p.114-124, 2002.

[22] D. Yarnitsky and E. Sprecher, "Thermal testing: normative data and repeatability for various test algorithms", Journal of the Neurological Sciences, Vol.125, No.1, p.39-45, 1994.

[23] M. Reinacher, R. Becker, A. Villringer and P. Ritter, "Oscillatory brain states interact with late cognitive components of the somatosensory evoked potential", Journal of Neuroscience Methods, Vol.183, No.1, p.49-56, 2009.

[24] R.T. Verrillo, A.J. Fraioli and R.L. Smith, "Sensation magnitude of vibrotactile stimuli", Attention, Perception, & Psychophysics, Vol.6, No.6, p.366-372, 1969.

[25] J.W. Morley and M.J. Rowe MJ, "Perceived pitch of vibrotactile stimuli: effects of vibration amplitude, and implications for vibration frequency coding", The Journal of Physiology, Vol.431, p.403-416, 1990.

[26] R.W. Cholewiak, J.C. Brill and A. Schwab, "Vibrotactile localization on the abdomen: effects of place and space", Perception & Psychophysics, Vol.66, No.6, p.970-987, 2004.

[27] J.J. Collins, A.A. Priplata, D.C. Gravelle, J. Niemi, J. Harry and L.A. Lipsitz, "Noise-enhanced human sensorimotor function", IEEE Engineering in Medicine and Biology Magazine, Vol.22, No.2, p.76-83, 2003.

[28] A. Priplata, J. Niemi, M. Salen, J. Harry, L.A. Lipsitz and J.J. Collins, "Noise-enhanced human balance control", Physical Review Letters, Vol.89, No.23, p.238101(1)-(4), 2002.

[29] G. Savic, E.M. Bergström, N.J. Davey, P.H. Ellaway, H.L. Frankel, A. Jamous and A. Nicotra, "Quantitative sensory tests (perceptual thresholds) in patients with spinal cord injury", Journal of Rehabilitation Research and Development, Vol.44, No.1, p.77-82, 2007.