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Static standing trunk sway assessment in amputees – effects of sub-threshold stimulation

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Abstract: Sub-threshold electrical stimulation can enhance the sensitivity of the human somatosensory system to improve the balance control capability of elderly was shown in recent rehabilitation articles. The purpose of this study was to evaluate the postural sway of trans-tibial amputees when performing single leg quiet standing on firm surface. Four unilateral trans-tibial amputees who consecutively wore prosthetics over 2 years were recruited in this study. Subjects performed single leg quiet standing trails with sub-threshold electrical stimulation applied at the quadriceps muscle during the trails. Spatial co-ordinates for the determination kinematic data (sway distance) of the center of mass (COM) on second sacral (S2) were collected using an ultrasound-based Zebris CMS-HS system. The single leg quiet standing test is measure considered to assess postural steadiness in a static position by a spatial measurement. The common notion is that a better postural steadiness, i.e. less postural sway, allows for longer time single leg quiet standing. However, there is lack of evidence how postural steadiness during single leg quiet standing changes over time. In this article, we hypothesized that the static balance of single leg quiet standing could be improved for providing proprioceptive neuromuscular facilitation using sub-sensory stimulation in amputees. To test this hypothesis, a computerized sub-threshold low-level electrical stimulation device was developed and proposed for clinical study. Experimental results show that reduction in all of the postural sway indices (constant time sway length, max sway distance and average sway distance) and increase in single leg support time index during single leg quiet standing by applying sub-sensory stimulation. The single leg quiet standing test findings suggest that sub-threshold electrical stimulation rehabilitation strategies may be effective in improving static balance performance for amputees.

Key words: Somatosensory, static balance, sub-threshold.

INTRODUCTION

Balance is a critical functional capability that greatly influences our ability to perform activity of daily living. Recent studies proved that tactile stimulation in foot sole contributes to the coding and the spatial representation of body posture (Roll *et al.* 2002). Several clinical studies show that the sub-threshold low-level noise stimulation (electrical or mechanical) can enhance the sensitivity of the human somatosensory system (Gravelle *et al.* 2002; Priplata *et al.* 2000, 2003). In this study, we examined the effects of sub-threshold low-level input to the somatosensory system on static balance control in amputees. We hypothesized that the static balance performance of amputee during single leg quiet standing could be improved by applying sub-threshold electrical stimulation. To test this hypothesis, a sub-threshold low-level electrical stimulation device was developed and a series of tests on amputee subjects were conducted.

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MATERIAL AND METHOD

In this study, the static balance performance of amputee during single leg quiet standing by applying sub-threshold electrical stimulation was tested as shown in Figure 1. The proposed sub-sensory low-level stimulation unit is an electrical stimulation device in which the stimulation signal is controlled based on the cutaneous sensation

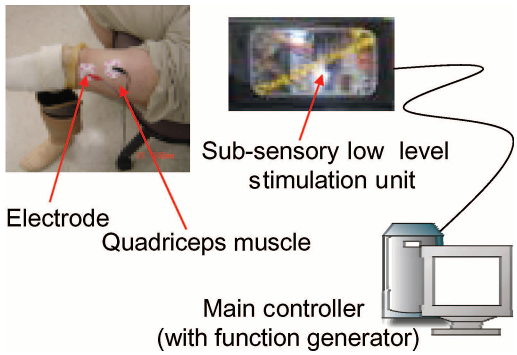

Figure 1 The position of the electrodes on quadriceps muscle of transtibial amputee subject.

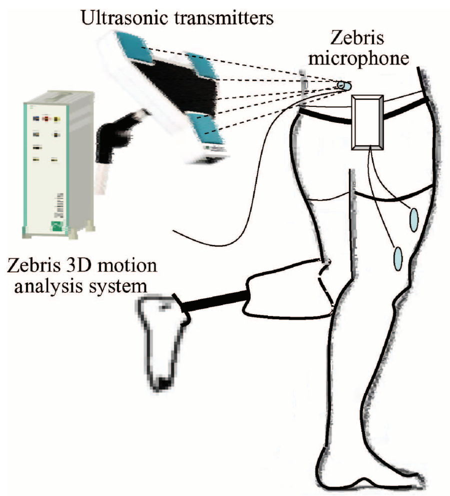

Figure 2 The schematic diagram for quiet single leg standing test setup.

threshold of each individual subject. The cutaneous sensation threshold of each subject is confirmed prior to testing. The stimulation signal was set to be 90% of subject's cutaneous sensation threshold for control purpose. A built-in stimulation current limiter is also designed to stabilize the stimulation current signal during the experiment. To monitor the performance of the current limiter, a digital readout can be shown on the controller's screen during the stimulation period. A function generator to produce the triangular wave signal with appropriate frequency and amplitude was used. The sub-threshold triangular signals were applied through surface electrodes on quadriceps of the subject's lower extremity. The sub-threshold low-level stimulation unit comprises of 8051 single chip microcomputer (AT89C52, Atmel Corporation, USA), signal amplifier, A/D converter, RAM and 9 V power supplier. The low-level signal used in this study is a triangular waveform with 0–60 mA in amplitude and 500 msec in period. The electrodes were rectangular (4 × 4.8 cm) self-adhesive gel pads, aligned with the longitudinal axis along the joint axis line formed by the femoral and tibial condoyle (Figure 2). The sub-threshold low-level stimulation signal was applied for the entire duration of the stimulation trial.

To evaluate the balance performance, a commercial force measurement system (Model CMS-HS, Zebris Medizintechnik GmbH., Isny im Allgäu, Germany) was utilized. Sampling rate for Zebris motion analysis system for measurement data collection is 50 Hz. The sampling rate for Zebris instrumented insole to measure the temporal responses is 100 Hz. The stimulation output signal is a triangular waveform with 500 ms in period (i.e., 2 Hz). The sway pattern of the center of mass (COM) on second sacral (S2) was measured. A passive marker consists of a small ultrasonic microphone and was connected to the control unit of Zebris system. Three sequential active ultrasonic transmitters in the measuring unit of Zebris system send continuous pluses during operation. The distance between transmitter and the passive marker was determined through the running time of the pulse. By triangulation the absolute 3D coordinates of the center of gravity of the subject can be determined.

PATIENT SELECTION

Four lower extremity amputees (three males and one female), age 24–48 years, mean age 35.25 ± 11.59 years, height 162.75 ± 5.19 cm, weight 61.50 ± 7.23 kg, volunteered to participate in this study are listed in Table 1. Potential subjects were randomly selected and contacted from a database of Department of Physical Medicine and Rehabilitation Hospital, Chung Shan Medical University, Taichung, Taiwan. A self-reported medical history screened potential participants for orthopedic or neurological conditions such as Parkinson's disease, peripheral neuropathy, stroke, disabling arthritis, uncorrected visual problems, dizziness or vertigo, use of assistive walking devices, joint injury, and joint implants. Subjects who reported these conditions were excluded from the study. The study was approved by the ethics committee of cooperation hospital. All subjects signed an informed consent before entering the study.

Subjects were asked to maintain balance without sub-threshold low-level stimulation (control group) and with sub-threshold low-level stimulation (experimental group) on the sound side leg for as long as they could, with arms across their chest and with a steady forward focus. Subjects were allowed to raise their arms out to the side if needed for balance. Subjects maintained a small amount of flexion in their stance knee joint during the balance task and were performed with the subject in single leg quiet standing position. Subjects performed two to three practice trials before data were recorded by Zebris force measurement system. The single-leg balance task was performed six times, without sub-threshold low-level stimulation applied in random order during three of the six trials. Sit-down rest for 15 minutes was provided every trial.

Table 1 **Demographic data of participants**

	Subject I	Subject II	Subject III	Subject IV	Average
Prosthetics wearing (yrs)	12	18	10	1.5	10.38 ± 6.82
Sex	Male	Male	Female	Male	–
Age (yrs)	24	42	27	48	35.25 ± 11.59
Height (cm)	165	165	155	166	162.75 ± 5.19
Weight (kg)	55	65	56	70	61.50 ± 7.23
Affective side	Left	Right	Right	Right	–

Table 2 **Comparison of static balance performance indices under single leg quiet standing with and without stimulation**

Index	Control Group (Without Stimulation)	Experiment Group (With Stimulation)	Improvement Ratio (%)
HTI (s)	3.34 ± 2.10	7.76 ± 4.62	132.34
SLI (mm)	241.79 ± 83.71	235.69 ± 167.26	2.52
MSDI (mm)	128.08 ± 66.66	70.94 ± 34.61	44.61
ASDI (mm)	71.67 ± 29.59	27.63 ± 13.05	61.45

Improvement Ratio = |(Without stimulation − with stimulation)| / (Without stimulation) HTI: holding time index; SLI: constant time sway length index; MSDI: max. sway distance index; ASDI: average sway distance index.

TREATMENT PROTOCOL

In this study, the sub-threshold low-level signal was used to assess its effects to the somatosentory system on static balance performance during single leg quiet standing in amputees. At the outset of the testing session, each subject was asked to determine his or her threshold of tactile perception quadriceps muscle of the sound side. A potentiometer was used to adjust the amplitude of the low-level signal output. Thus, the applied low-level signals were sub-threshold, and subjects could not distinguish between low-level and control trials. The low-level signal used in this study is a triangular waveform with 0–60 mA in amplitude and 500 ms in period.

During the three stimulation trials, electrical input was applied through surface electrodes on the lateral aspects of the subject's quadriceps muscle in the sound side leg. The amplitude of stimulation signal was well below the cutaneous sensation threshold of all subjects, as confirmed by a threshold measurement prior to testing. To provide the safety measure for preventing subject's falling during the experiments, a safety harness was used for all subjects. The harness was suspended from the ceiling and was adjusted so that it was not supporting the subject's weight but would catch the subject if they completely lost balance. During the three stimulation trials, electrical input was applied through surface electrodes on the lateral aspects of the subject's quadriceps muscle in the sound side leg. The electrical stimulation signal was applied for the entire duration of the stimulation trial. The stimulation amplitude was well below the cutaneous sensation threshold of all subjects, as confirmed by a threshold measurement prior to testing.

SINGLE LEG QUIET STANDING BALANCE INDICES

Four different static balance performance indices were defined and used for assessment. One index is time-related measure and other three indices were body sway-related measures. The detailed definition of each balance index was elaborated as follows. (1) Holding Time Index (HTI): total duration in which the subject maintains balance on a single leg; (2) Constant Time Sway Length Index (SLI): total distance between consecutive point on the COM trajectory over a constant time interval; (3) Max. Sway Distance Index (MSDI): the maximum sway distance is defined as the point that has the longest distance from the origin point on the COM trajectory; (4) Average Sway Distance Index (ASDI): the average sway distance is defined as the summation of sway length between origin point to each sampling point on the COM trajectory divided by the total number of sampling.

RESULTS AND DISCUSSION

From the results of the quiet standing balance tests, the single leg stand holding time (HTI) of four subjects increased with sub-threshold low-level electrical stimulation, indicating an overall improvement in balance performance in the stimulation condition. Besides, the constant time sway length index (SLI), max sway distance index (MSDI) and the average sway distance index (ASDI) were found decreased for four subjects as shown in Table 2. The improvement ratio of four balance performance indices across subjects for single leg quiet standing tests resulted in a 132.34% in HTI, 2.52% in SLI, 44.61% in MSDI, and 61.45% in ASDI respectively. For each of these measures of the four subjects showed improvement with electrical stimulation.

This study demonstrated that imperceptible low-level electrical stimulation with triangular waveform, when applied to the quadriceps, could enhance the static balance performance of lower extremity amputee patients. This improvement was demonstrated in single leg quiet standing test condition. The fact that balance performance was improved in task when sub-threshold low-level electrical stimulation was applied demonstrates an overall reduction in postural sway and increase in single leg support time, and suggests that balance perturbations in any task might be more easily overcome with the application of low-level electrical stimulation signals. From Table 1, the improvement ratio of static balance performance indices noted in this study is 132.34%. The significant improvement was shown in single leg support time index (HTI).

A promising rehabilitation strategy using low-level noise stimulation (either electrical or mechanical) has recently been shown to improve the sensitivity of the human somatosensory system (Dhruv *et al.* 2002; Liu *et al.* 2002). In addition, noise-based sensory enhancement to improve human balance control for healthy elderly adults was reported (Gravelle *et al.* 2002; Priplata *et al.* 2003). In this study, we extended the effect of low-level electrical inputs, instead of noise, applied to the quadriceps muscle on the amputee subjects. The result of this study suggests that sub-threshold low-level electrical stimulation even with triangular waveform can enhance static balance performance. The comparison of sub-threshold low-level electrical stimulation with different waveforms (i.e., noise, triangular, etc.) on amputee's balance performance will be followed.

The sub-threshold low-level electrical stimulation used in this study is likely effective in enhancing the function of the human sensor-motor system because of the electrical nature of information transfer in sensory neurons. Low-level electrical signals can cause small changes in receptor transmembrane potentials. This depolarization in the local membrane potential brings the neuron closer to threshold, thus making it more likely to fire an action potential in the presence of a weak signal. The electrical depolarization when combined with graded potentials from mechanical stimuli could provide a mechanism by which normally sub-threshold mechanical stimuli become detectable in the presence of electrical low-level signal.

CONCLUSIONS

This pilot study suggests that sub-threshold low-level electrical stimulation strategies may be effective in improving static balance control in lower extremity amputees. A device designed with sub-threshold low-level electrical stimulation functions was used for this study. The experimental results suggested that proposed proprioceptive biofeedback implementations can be effective in achieving static balance for amputees. In the future, the proposed device may be redesigned as a wearable prosthetic that may potentially reduce the frequency and severity of falls for lower extremity amputees.

The results have important implications on the design of rehabilitation training protocols for individuals with amputee. However, extensive research is still necessary to further validate the results and their implications. Future studies should include larger randomly controlled groups, which will further analyze and compare the changes induced by the different training protocols, and will provide more information concerning the effect of sub-threshold low electrical stimulation strategies on various patient subgroups. Further research should also investigate other important related issues such as long-term effect of training technique and relation between intensity of training and response. Furthermore, it indicates that for some important gait parameters, which include functional walking ability, stride length, percentage of single stance period, and EMG muscular activity, treadmill training may induce changes not obtained by conventional gait training. Additional research with larger study groups and long-term information gathering is recommended to further evaluate the effectiveness of visual-auditory biofeedback in the early stages of amputee rehabilitation. In the future, the proposed device may be redesigned as a wearable prosthetic that may potentially reduce the frequency and severity of falls for lower extremity amputee patients.

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