A Vibrotactile Sensory Substitution System for Use with Gait Neuroprostheses

Thomas Fuhr, Alexis Godais, and Günther Schmidt
Institute of Automatic Control Engineering, Technische Universität München, Munich, Germany

Abstract

In this paper the design of a sensory substitution system and first experimental experience with paraplegic subjects using the system to display foot load during FES-assisted walking is presented. Miniature vibration motors are used as tactile displays and integrated in an elastic shirt. Intermittent vibration is used to encode three foot load states (*unloaded, floor contact, loaded*) measured by insole pressure sensors. Alternatively, arbitrary sensor signals can serve as information source. Preferred vibration mode and display position have been determined in experiments with 4 paraplegic and 10 neurologically intact subjects, the sensory substitution system has been tested in 3 paraplegic subjects during FES-assisted gait.

Introduction

Complete central lesions not only disable motor but also sensory function of the affected body regions. Functional neuromuscular stimulation can be utilized to partially restore lost motor function. However, to date sensation and proprioception can not be reestablished. Users of neuroprostheses have to rely on their visual and vestibular perception to interpret and control artificially generated movements of their paralyzed limbs.

To improve motor control sensory substitution has been suggested (e.g., [1]) as a means to display artificially assessed postural information at intact body regions utilizing a different sensory modality, such as the auditory, visual, or tactile sense.

Employing the tactile sense has the advantage of not adding conscious load to auditory and visual channels, and being unrecognizable by the environment. Evidence has been presented that subjects can learn to process this information subconsciously after some training [2]. Most commonly, tactile information is displayed by vibrotactile or electrotactile actuators [3], however, only few systems for lower extremity neuroprostheses have been reported. Phillips et al. [2] measured ground reaction forces at heel, toe, medial and lateral mid-foot and displayed these signals at 4 corresponding vibrotactile displays positioned at the chest. Erzin et al. [4] measured knee angles and triggered electrotactile stimuli at the arms in case of insufficient knee extension.

The purpose of this study was to design a sensory substitution system to provide paraplegic subjects with postural information while walking with a newly developed closed-loop gait neuroprosthesis [5]. A major design objective was patient comfort, including minimal demands for donning and doffing, discreetness, small size and low energy consumption.

Design

Analysis

Frontal and tarsal foot loads assessed bilaterally by insole pressure sensors were to be mapped to four tactile displays at the upper body. Miniature vibration motors used in mobile phones were chosen as tactile displays.

To determine vibration parameters and upper body areas to display tactile information, preliminary experiments with 10 neurologically intact (mean age 25 yrs.) and 4 complete paraplegic subjects (mean age 35 yrs.) have been performed. A miniature vibrator (MSF4W, Musasino Corp., Japan, Ø5x14mm) fitted into a square aluminum tube (dimensions: 7x7x20mm) was used.
The following experiments were performed:

1) To determine vibration frequency and intensity characteristics, a motor was analyzed in the frequency and time domain for different supply voltages with an accelerometer. The minimal starting voltage is 1.1V, resulting in a frequency of 75Hz, and can be driven up to 4V (200Hz). A frequency of 130Hz yielded satisfactory results regarding transient time (150ms) and a mild vibration intensity comfortable for the subjects.

2) To determine suitable vibrator positions, human dermatomes C3-C5, and T2-T5; unaffected in our SCI subjects, were zoned into seven ventral (V1-V7) and ten dorsal (D1-D10) regions (Fig. 1). Forearms and lower chest were excluded for reasons of subject comfort. The vibrator was positioned at the center of each region with double-sided adhesive tape and vibrated continuously at 130 Hz. Subjects were asked to rate the position subjectively on a scale from 0 (not acceptable) to 3 (very good). In Fig. 1, results for dorsal and frontal regions are depicted. The darker the region, the higher it was rated on average.

3) Since only 4 to 6 levels of vibrotactile information can be reliably classified [3], it was decided to encode information by discrete levels. Two encoding strategies were tested. Continuous vibration at two frequencies, was applied, and intermittent vibration, in which information is encoded by the frequency toggling between vibrators on and off. Three states were encoded

by a) no vibration, b) low and c) high toggle, or vibration frequencies, respectively.

To determine well distinguishable vibration frequencies, in the first setup 10 neurologically intact subjects were presented pairs of a lower and a higher frequency. Lower vibration frequencies of 75, 95, 115, and 135 Hz were combined with higher frequencies increased by 20, 40, 60, and 80 Hz. Subjects were asked to rate these pairs on a scale from 0 to 3 with respect to differentiability, and to nominate their favourite pair. On average, a lower frequency of 100±8 Hz, and a higher frequency of 155±13 Hz was preferred most.

Secondly, intermittent vibration was applied. Vibration frequency was kept constant at 130Hz. 8 neurologically intact, and 4 paraplegic subjects were presented frequency pairs with a lower toggle frequency of 1, 1.5, 2, and 2.5 Hz, and a second, 1, 1.5, and 2 Hz higher, respectively. Subjects were then asked to rate these pairs. A toggle frequency pair of 1and 2.5Hz was rated best.

4) With favorite positions and toggle frequencies obtained, a re-test was performed to test the subjects' actual ability to interpret the vibration information previously rated best. Blind-folded subjects had to classify vibration patterns (their favorite fast and slow toggle/vibration frequencies) randomly presented 10-12 times at their favorite dorsal and ventral region. Interestingly, the neurologically intact subjects classified the pattern correctly with an error rate of about 10% in both encoding strategies, whereas paraplegic subjects misclassified only one in a total of 42 patterns (intermittent vibration) presented.

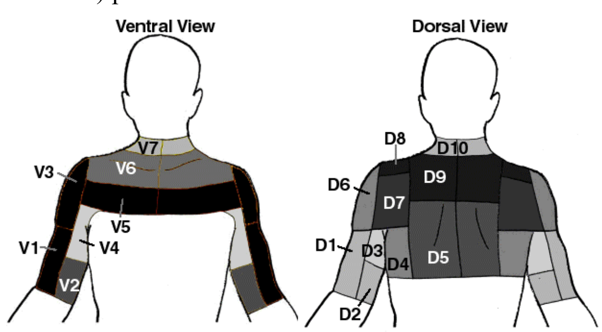

Figure 1: Ventral and dorsal view of the upper body regions tested for vibrator positions. Darker areas indicate higher average rating, i.e. higher preference, based on 4 SCI and 10 neurologically intact subjects.

On the basis of the above findings, dorsal units were positioned close to scapulae (area D9), and ventral units distal of clavicles (area V5). As re-testing of both encoding strategies showed no significant difference in the classification error, and 6 out of 8 subjects preferred intermittent to continuous vibration, the former strategy was chosen. There, a lesser extent of habituation can be expected. Toggle frequencies of 1Hz and 2.5 Hz at a vibration frequency of 130Hz were selected.

System synthesis

Four vibration motors (MSF4W, Musasino Corp., Japan, Ø5x14mm) were placed inside solid aluminum cuboids of size 6x16x24mm to provide a sufficiently large contact area with the skin. Two drillings gave room for the motor and a strain relief. Velcro was attached to the housing to enable rapid mounting to a velcro counterpart on the inside of a tight and elastic shirt.

Figure 2: Sensory substitution shirt with 4 miniature vibrators positioned on the inside close to clavicles and scapulae. Vibration motors (lower right, Ø5x14mm) are housed in a solid aluminum cuboid (upper right, 24x16x6 mm).

An electronic circuit with four timer ICs generating toggle frequencies of 1 Hz and 2.5 Hz is encased in a plastic housing along with 4 AA rechargeable batteries. Vibrators are supplied with 2.5V to obtain a vibration frequency of 130 Hz. 2 digital lines per vibrator are used to set the desired toggle frequency, and are controlled by a PC via the parallel port.

Experimental Evaluation

Sensory substitution protocol

Insole pressure was measured by insoles (Zebris GmbH, Isny, Germany) at left and right frontal and tarsal areas of feet. Two thresholds were used to define the three states *unloaded, floor contact,* and *loaded*. These four channels providing the load state were mapped to ventral and dorsal vibrators of their respective side. Foot load state was updated every 50 ms by the neuroprosthetic control system, and also

Figure 3: Paraplegic subject ready to walk wearing the sensory substitution shirt.

graphically displayed on the control monitor for supervision and on-line modification of thresholds by the experimental staff.

Experimental protocol

Three complete SCI patients were asked to wear the shirt during a total of 9 walking sessions using the gait neuroprosthesis described in [5]. After standing-up, load thresholds for each channel were set individually to signal the state *floor contact*, when the subjects stood upright with their weight transferred to the legs as much as possible. They were then asked to shift weight to left or right leg, and to toes or heels to set the second threshold to signal *loaded* at the left, right, ventral or dorsal vibrators, respectively. Then, the subject started to walk. After every walk they were asked if

a) vibration was comfortable,
b) vibrotactile information correlated with the visually observed state of their feet, and
c) they could profit from the additional information.

Discussion and Conclusions

The technical goals of this study were satisfied. The sensory substitution shirt is easy to use and adds only little extra effort to donning and doffing time. The vibrators in the shirt do neither compromise cosmesis nor range of motion. By involving our paraplegic subjects in the design process from the very beginning, it was possible to tailor the system to their specific needs. The system has become an integral part of the groups' closed-loop gait neuroprosthesis, and has been frequently used in experiments.. By displaying sensor signals required by the control system also to the patients, their improved knowledge of the state of the neuroprosthesis is expected to improve walking performance.

Our patients appreciated the possibility to 'feel' the state of their feet, however, stated that walking with the neuroprosthesis demanded too much conscious effort to interpret the vibrotactile information at the same time. They also admitted they were confused by the amount of tactile information, and that it was difficult to distinguish the state of a single vibrator with all four vibrators active at different toggle frequencies. This observation was also described in [2], however, it was suggested that continued use and training could significantly improve walking performance.

We encoded floor contact by the presence of vibration, to signal the necessity of increased attention in the absence of vibration, as during the swing phase of gait. In this way, if vibrators failed due to technical problems, no vibration also indicated a problem. The chosen lower toggle frequency of 1 Hz induces a worst-case time delay of 500ms, before *floor contact* can be detected by the subjects. As initial floor contact is of special interest at the end of the swing phase this delay might not be tolerable.

In conclusion, we have changed the encoding strategy, and decreased the amount of information displayed. The system is now only notifying a single state, floor contact, per leg by continuous vibration of 130 Hz, and will be tested in our next experiments. Additionally, the transmission of other postural information will be investigated. In another study [4], knee angle has been monitored to warn patients using a gait neuroprosthesis if the supporting leg was not extended sufficiently. Displaying the extension state of the knee in combination with the knee extension controller described in [5] could help to further improve walking performance.

Experimental sessions carried out in our lab only once a week are not sufficient. to learn to subconsciously process the additional information from the sensory substitution system. We therefore currently extend the system to be used as a stand-alone system by our paraplegic subjects at home. A user-modifiable voltage threshold will be provided to switch vibration states in order to allow arbitrary signals such as foot switches or goniometers to serve as information sources without the need of a control PC.

More experiments have to be performed to provide significant evidence that sensory substitution does actually improve walking performance.

References

[1] Riso, R. (1998) *Perspectives on the role of natural sensors for cognitive feedback in neuromotor prostheses.* Automedica 16:329-353

[2] Phillips, C.A., Koubek, R.J., and Hendershot, D.M. (1991) *Walking while using a sensory tactile feedback system: potential use with a functional electrical stimulation orthosis*. J. Biomed. Eng. 13:91-96

[3] Kaczmarek, K.A., Webster, J.G., Bach-y-Rita, P., and Tompkins, W.J. (1991) *Electrotactile and Vibrotactile Displays for Sensory Substitution Systems*. IEEE-TRE 38:1-16

[4] Erzin, R., Bajd, T., Kralj, A., Savrim, R., Benko, H. (1996) *Influence of Sensory biofeedback on FES assisted walking.* Elektroteh. Vestn. 63:53

[5] Fuhr, T., Quintern, J., Riener, R., Schmidt, G., *Walk! – Experiments with a Cooperative Neuroprosthetic System for the Restoration of Gait.* Proc. 6th Ann. Conf. IFESS, June 16-20, 2001, Cleveland, OH, USA

Acknowledgments:

The authors would like to thank their patients for participating in this study, T. Stoeber, J. Gradl, and H. Kubick, lab technicians, for the electronic and mechanic implementation of the devices. This study was funded in part by the German Research Foundation within the Collaborative Research Center 'Sensory Motor Systems', SFB 462, project A1.