A High-Resolution Surface Electrode Array System for Drop Foot Correction

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Abstract

This paper presents the development and preliminary evaluation of a high-resolution electrode array and its associated hardware and software for drop foot correction. A user-graphical interface allows selection and fine steering of virtual electrode clusters of different shapes and sizes. The system has been evaluated in 12 normal volunteers whilst seated. Each subject underwent two experimental sessions one week apart. During each trial, two different virtual clusters were electronically scanned along the array, whilst angular data of ankle-foot motion was simultaneously recorded. Charts of angular response vs. electrode position were produced using an offline data-analysis tool. The results revealed that patterns of balanced dorsiflexion responses were achieved by most of the participants. However, the data also showed a marked variability in such responses within and between subjects. The results suggest that the use of this array approach may ease the task of finding adequate sites for stimulation in individuals with drop foot.

1. Introduction

Although surface FES presents an attractive orthotic alternative for correction of drop foot, placing the electrodes in the right position is usually described by patients as a time-consuming task which demands a significant effort. In order to ease electrode placement, different investigators have proposed strategies based on surface electrode arrays [1][2][3]. However, problems concerning array design, adequacy of user interfaces, control algorithms and sensors still remain.

This work proposes a FES system based on a large high-resolution surface array to assist electrode positioning in patients with drop foot. The system permits selection of preset virtual electrode clusters (VECs) of different sizes and shapes, which can be scanned throughout a wide range of positions that are not often available when using either a smaller array or an array formed by coarse conductive pads. It has been hypothesised that a balanced dorsiflexion response can be obtained when using this approach.

2. Methods

2.1. Electrode array

A PCB-based flexible 12 x 10 PCB array of square pads (2 mm x 2 mm, interspaced by a distance of 4mm) has been fabricated (Figure 1). The non-electrode parts of the tracks were electrically insulated using insulating varnish. The array has an overall size of 64 mm x 75 mm, large enough to cover the area of the skin, where the conventional active electrode is usually located. Two purpose-built strain relief PCBs were sewn into a backing cloth, to provide the array with fixed connectors. The latter not only prevent the array from overstrectching, but also relieve the strain introduced by the wires connecting the array to the main circuitry.

Figure 1. University of Surrey electrode array

A conductive self-adhesive gel layer AG803 (Amgel Technologies CO, Fallbrook, USA) was used as the electrode-skin interface. Although this gel sticks firmly to the array substrate and skin, it can easily be replaced when necessary.

The pad dimensions and inter-electrode separation were chosen to meet the best possible compromise between array characteristics and conventional PCB fabrication techniques. Finite element modeling studies accounting for array parameters in combination with the gel layer
properties were undertaken before fabrication, in order to test acceptable selectivity and uniformity in current density distribution [4].

2.2. Hardware and software

A microcontroller-based selector box was developed to drive the electrode array. This unit was programmed to distribute the stimuli to preconfigured clusters of electrodes. PhotoMOS relays provide optically isolated connections between the conductive pads and the circuitry. A MicroStim 2V2 stimulator (Odstock Medical Limited, Salisbury UK) was modified, so that the intensity could be automatically regulated by our system. Analog inputs are available for a maximum of 3 sensors. For these preliminary studies, a twin-axis flexible electrogoniometer (SG/110A, Biometrics Ltd, Gwent UK) and its respective instrumentation were coupled to the system.

The hardware communicates with a personal computer (PC) via a serial port (RS-232). A multithreading C++ program provides an interactive environment between the array and the user, data recording capabilities and a platform for automatic algorithms. Electrodes of different sizes and shapes can be selected and controlled through the software. Furthermore, a joystick was added to the hardware, to provide an alternative method for the VEC scanning task. Finally, a data analysis tool was programmed in MATLAB®, enabling creation of different charts of ankle-foot angular response to stimulation for each VEC position, as well as repeatability plots and maps of functional response.

2.3. Experimental method

Approval for the experiments was granted by the University and the local NHS research Ethics Committees. Twelve normal volunteers (6 females, 6 males, mean 29.5 SD 9.3 years old) participated in the study. Each participant underwent two trials separated by a period of one week. During each session, the subject was asked to stand with hips/knees extended and both feet in a neutral position over a personalised template. The electrogoniometer was then attached between the shank and the lateral aspect of the right foot. The sensor was calibrated, and then the subject sat with both legs in a comfortable position, with their feet hanging freely over a plastic support. The positions of the chair and the support were both noted to minimise systematic errors in the measurements taken in subsequent trials.

The array was then carefully attached below the head of the fibula, and secured with a neoprene bandage. A conventional pre-gelled (50 mm x 50 mm) return electrode was placed approximately six fingers breadth distally to the tibial tuberosity, over the muscle belly of tibialis anterior.

Two virtual electrode clusters (VEC1 ≈ 40mm x 40mm, 6 x 6 electrodes, and VEC2 ≈ 50mm x 50mm, 8 x 8 electrodes) were electronically configured to emulate two different sizes of conventional electrodes. The threshold of maximum intensity tolerated by the volunteer was then determined for both VECs. The VEC to be scanned first was randomly selected. Ankle-foot angle data were collected, while an automatic algorithm sequentially tested each possible cluster position within the array for various steps of intensity until the tolerance threshold. The stimuli applied consisted of a biphasic asymmetric waveform at 40 Hz (pulse duration 300µsec, current 0-100 mA). For each step, the stimulation was maintained for 650 ms, except for the last step, where it was maintained for 2 seconds. Resting periods of 6 seconds were allowed between cluster positions to minimise the effects of fatigue. Finally, the next VEC was tested using the same procedure. A resting period of 10 minutes was allowed between the evaluation of both clusters.

3. Results

Despite the lack of a quantitative definition of balanced dorsiflexion within the FES community, it was initially taken to be motion of the ankle-foot beyond 0° of dorsiflexion and between 0° and 10° of eversion. In this context, favourable responses were observed for all the participants in both sessions when testing VEC1 and VEC2, yet all the subjects reported that VEC2 produced a more comfortable sensation. In addition, nine out of the twelve subjects did not exceed more than 5° of eversion.

Figure 2 shows a subset of the charts of balanced dorsiflexion response for subject 5. In the plots each cell represents a tested VEC1 shift. For plots a) and b), the colour scale indicates the minimum number of stimulator steps necessary to achieve the desired response. The dark blue zones indicate that non-ideal responses (either weak or exaggerated) were attained in those particular positions.
Figure 2. VEC1 testing for subject 5. a) Plot of response for session 1. b) Plot of response for session 2. c) Repeatability plot for sessions 1 and 2. Plot c) reflects the repeatability of cluster positions producing or not a balanced response. The white cells show VEC1 positions for which balanced responses were repeatedly achieved. Likewise, black regions illustrate common positions for which no-response was found during both sessions. This suggests that although the overall patterns may differ from day to day for each subject, some of the clusters may produce a similar response during future trials. This behaviour was observed in all the charts obtained from all the subjects. Conversely, the grey areas portray balance responses found during one of the sessions only. It was also observed that patterns of VEC position to response were also variable between subjects using both configurations. The electrode array was also tested using different sizes of return electrodes. The information collected is currently being analysed.

4. Discussion and Conclusions

An approach based on a large high-resolution electrode array for drop foot correction has been developed. By fine scanning of electrode position, balanced ankle-foot angular responses were obtained at various VECs positions. The latter were not fully repeatable within and between subjects. Some of them overlapped suggesting the likelihood of reappearance in future sessions, although not critical to the clinical use of the array.

Work is currently being carried out to evaluate the use of the system by post-stroke and multiple sclerosis patients (e.g. use of joystick to find the optimal position). Future directions will consider the design and development of self-contained stimulator/array sleeves that can be worn on the shank, automated algorithms, and the assessment of the response to stimulation when using this approach during walking.

References

[4] Hernandez M, Ewins D. 2D finite element modelling of current density distribution during the application of electrical stimulation using surface arrays. 3rd European Medical and Biological Engineering Conference EMBEC05, Prague, Czech Republic. 2005

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