

# Optimisation of Spatial Electrocutaneous Display Parameters for Sensory Substitution

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**Abstract.** A spatial electrocutaneous display for sensory substitution is being designed. The display will be used to feed back sensory signals from transfemoral prostheses to amputees. The aim is to improve their walking performance. Two experiments have been performed to optimise the display parameters for dynamic, cyclic signals, which are common during walking. From these experiments it became clear that healthy subjects were capable of discerning artificially generated disturbed knee angle patterns from undisturbed patterns. This shows that the electrocutaneous display has the capability to feed back signals from a transfemoral prosthesis.

## 1 Introduction

At the University of Twente in the Netherlands, a spatial electrocutaneous display for sensory substitution is being designed. The objective is to feed back artificial sensory information from a transfemoral prosthesis to a 1-D array of electrodes attached to the skin of the upper leg. This display should increase the amputee's awareness of the prosthesis and improve the amputee's feeling of security [1]. The display could be used for example to feed back the knee angle during the swing phase of locomotion. This enables the amputee to predict if the knee joint will lock at heel contact and support his weight.

A few systems are already patented. In one of them nerve fibres are directly stimulated with electrode cuffs [2]. In another the skin is electrically stimulated when a switch in the prosthetic foot is activated [3].

The research program consists of three phases: In the first phase, the electrode-skin interface is investigated. In the second phase, the display parameters are determined and optimised for the projection of dynamic, cyclic signals, which are common during walking. In the third phase, implementations of electrocutaneous displays are tested in

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a sensory substitution system used by transfemoral amputees. For the second phase, two experiments have been carried out to optimise the display parameters. This paper presents the results of these experiments.

## 2 Methods

In total two experiments have been performed, in which ten healthy and naive subjects volunteered to participate. The experiments have been approved by the medical-ethical committee and all subjects have signed an informed consent. In both experiments, the subjects had to detect artificially generated, disturbed knee angle patterns from a random sequence of 18 disturbed and 72 undisturbed knee angle patterns, displayed on a tactile display. The subjects were instructed to press a reaction button when they believed a disturbance occurred. A laptop was used to measure the subject's reaction and to give the subject auditory feedback. Per trial the detection ratio ( $R_{det}$ ) was calculated, which is defined as the ratio of correctly detected knee angle patterns and the total number of applied patterns. Additionally, the laptop was used to send stimulation patterns to the 8-channel electrocutaneous stimulator.

The subjects were stimulated with 30 Hz bi-phasic current pulses with amplitudes between 0 and 47 mA and pulse widths of 40  $\mu$ s. The amplitude of each channel was adjusted to obtain the same sensation strength for each channel. The knee angle patterns were displayed on a straight array of  $n$  concentric, stainless steel electrodes placed on the medial side of the upper leg. The display was positioned along the longitudinal axis of the upper leg, with the first electrodes being the most distal. The cathode of the electrode consisted of a circular plate with a diameter of 10 mm. The anode consisted of a ring with an outer diameter of 21 mm and an inner diameter of 15 mm. The distance between two adjacent electrodes was 1 cm.

The displayed knee angle patterns were generated with a generic dynamic model. Measurements from Winter [4] were used to calculate the movement of the upper leg and to set the initial conditions of the lower leg. Mechanical parameters of the leg were obtained from Koopman [5]. Only the last 50% of the step cycle (this includes the swing phase) was simulated. The display was switched-off during the other 50% (this includes the stance phase). The knee angle is defined as the angle (in radians) between the extension of the upper leg and the lower leg. Consequently, a fully stretched leg has a knee angle of zero radians. During the swing phase disturbances simulating tripping can be induced by application of a force pulse on the lower end of the lower leg aiming backwards with a strength  $F$ , a duration  $\Delta t$ , and an onset time  $t_0$ . In the experiments  $\Delta t$  was taken 10 ms. For  $t_0=160$  ms (before the maximum knee angle)  $F$  was taken 60, 80 and 100 N. For  $t_0=390$  ms (after the maximum knee angle)  $F$  was taken 250, 300 and 350 N.

The simulated knee angle patterns were sampled at 30 Hz and afterwards converted to stimulation patterns. These stimulation patterns describe which electrodes are activated. The result depends on the number of electrodes ( $n$ ) and the coding ( $c$ ). These display parameters are described in more detail in Section 2.1 and 2.2.

Before the measurements started, the subjects were familiarised with the projection of knee angle patterns. 90 knee angle patterns were displayed on a display of 8 electrodes with  $c=c_{standard}$  (see Section 2.2).

## 2.1 Experiment I: Number of Electrodes ( $n$ )

In the first experiment, the influence of the number of electrodes ( $n$ ) on  $R_{det}$  was measured. The knee angle patterns were projected on a display of respectively  $n=\{2,3,5,8\}$  electrodes. Per subject the measurements were done for each parameter value, which were randomly ordered. This procedure was repeated twice, with the parameter values ordered differently. For  $c$  the standard coding ( $c_{standard}$ ) was used (see Section 2.2 for a more elaborate explanation). From the results the optimal number of electrodes ( $n_{opt}$ ) was determined.

## 2.2 Experiment II: Coding ( $c$ )

In the second experiment  $R_{det}$  was measured for various codings ( $c$ ). The coding determines how the knee angle pattern is converted to a stimulation pattern. It actually consists of three parameters:

1. The mapping method ( $m$ ); this parameter describes which electrodes are activated during a range of knee angles. From previous pilots it was discovered that the activation of one electrode at the time was much less confusing than the simultaneous activation of multiple electrodes. Therefore it was decided to display a linear input signal sequentially. This will be referred to as sequential mapping.
2. The nonlinear mapping method ( $a$ ); this parameter is used to display more detail in certain knee angle ranges. The relation between the normalised input knee angle pattern  $x$  and the output  $y$  is given by equation (1):

$$y = x^a, \quad a \in \langle 0, \rightarrow \rangle, \quad x \in [0,1]. \quad (1)$$

For  $a < 1$  low knee angle values are accentuated, while for  $a > 1$  high knee angle values are accentuated. Taking  $a=1$  results in linear projection.

In the experiment  $a=\{0.5, 1, 2\}$  have been used to measure  $R_{det}$ . These have been proven to be successful parameter values during previous pilots.

3. The filtering parameter ( $A$ ); the filter accentuates disturbances in the knee angle patterns, which frequencies appeared to be above 5 Hz. The filter consists of three cut-off frequencies:  $f_1, f_2$ , and  $f_3$ .  $f_1$  is a zero,  $f_2$  is a pole at 5Hz, and  $f_3$  is a double pole at 15Hz. The maximum amplification  $A$  is determined by

$$A = 20 \cdot (\log(f_2) - \log(f_1)). \quad (2)$$

Pilots showed that useful values for  $A$  were 0 dB (second order low pass filter with  $f_1=5$  Hz) and 12 dB ( $f_1=0.63$  Hz).

The knee angle pattern is first fed through the non-linear mapping, then the filtering and then the mapping method.





