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# Sensation thresholds in electrocutaneous stimulation

## Comparison of textile cuff and TENS electrodes

**Abstract:** Acoustic or visual warning signals for workers in hazardous situations might fail under loud and/or low-visibility work situations. A warning system should be developed that uses electrocutaneous stimulation through textile electrodes. Previous work investigated suitable stimulation parameters using TENS electrodes. The aim of this study was to compare TENS and textile cuff electrodes in terms of sensation thresholds, qualitative and spatial sensation. A study on 30 healthy volunteers (f=13, m=17) of mean age of 26.7 years was conducted applying bi-phasic rectangular current pulses to electrodes attached to the upper right arm. The study revealed that perception, attention and intolerance thresholds, qualitative and spatial perception are comparable indicating that future studies with the textile cuff electrodes can be generally based on the previous results with TENS electrodes.

**Keywords:** Electric stimulation, electrode, TENS, smart textile, worker safety, wearable.

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# 1 Introduction

In the field of occupational safety, the warning of workers in hazardous situations is an important task that must work reliably. Current methods use acoustic [1] or visual [2] warning signals. These warnings might fail under loud and/or low-visibility work situations. Therefore, a warning system should be developed that uses electrocutaneous stimulation through textile electrodes.

In our previous work [3] fundamental knowledge was gained on the perception of electrocutaneous stimulation and which stimulation parameters might be suitable for a future warning system. Based on these results, the placement of electrodes at the lateral position of the upper arm, rectangular bi-phasic stimulation pulses of width of 150 µs and amplitudes up to 25 mA were suggested. For this basic research, TENS electrodes have been used.

The aim of the current study is to compare TENS electrodes versus textile cuff electrodes in order to estimate the transferability of the previous TENS results to a wearable electrical warning system. For that purpose, a study with 30 healthy participants was conducted and the sensation thresholds for perception, attention and intolerance in mA as well as the qualitative and spatial sensation have been determined for the two types of electrodes.

# 2 Methods

## 2.1 Study group

The study was approved by the Local Ethics Committee. All subjects signed an informed consent. The following exclusion criteria applied: age less than 18 years or above 65 years, heart disease or pacemaker, severe hypertension, hyperthyroidism, pre-existing neurological diseases (especially epilepsy or pain syndrome), neuro stimulator, diabetes, numbness in the upper arm, psychiatric diseases, implant in the right arm (e.g. splints or screws due to arm fracture), significant skin diseases on the right upper arm, current or past substance abuse, pregnancy or breast feeding or having a regular medication.

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The experiment was conducted in 30 healthy volunteers. The descriptive statistics are shown in Tab. 1. The subjects were advised, to have a sufficient sleep (8 hours), avoid caffeine, nicotine and alcohol, avoid skin cream on the upper arms, drink at least 2 litres and avoid heavy physical exercise in the 24 hours before experiment.

**Table 1:** Descriptive statistics of the study group.

| Property | Quantity |
|---|---|
| Participants | n = 30 |
| Gender | female: 13, male: 17 |
| Age | 26.7±6.1 years (mean±standard deviation) |
| Handedness | righthanded: 28, lefthanded: 2 |
| Arm circumference | 30.3±4.6 cm (mean±standard deviation) |

## 2.2 Experimental setup

We implemented a GUI based experimental control software in LabVIEW allowing for a wide range of stimulation parameters to be set by the operator. This information is transferred to the multifunction I/O device (DAQ NI 6361) via USB (Fig. 1). The output signal of the DAQ is transmitted to the connection block BNC NI-2120, which sends a voltage signal to the isolated bipolar constant current stimulator DS5 (Digitimer Ltd, Hertfordshire, UK). The digital channel selection is sent to the multiplexer D188, which activates one of its 8 output channels realizing that the stimulation is applied to the desired electrode pair. The DS5 converts the voltage input into a current output using the ratio 10V:25mA. The desired current stimulation signal is transferred to the multiplexer D188, which transmits the signal to the desired electrode pair.

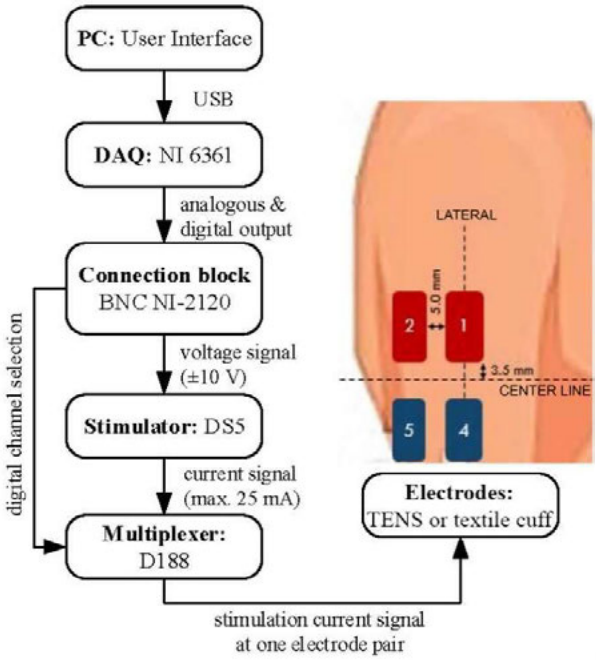


**Figure 1:** Experimental setup with electrode positions (red: anode, blue: cathode). Electrode pair 3-6 is located posterior of the upper right arm.

## 2.3 Experimental paradigm

### 2.3.1 Preparation

Six TENS electrodes of size 25 mm x 27 mm were arranged to an electrode matrix according to the configuration on the textile cuff (Fig. 2, lower left). The electrodes of the textile cuff consist of silver coated knitted fabric covered by carbon black filled silicon. The textile cuff is stretchable and thus the horizontal distance between the electrodes changes in dependence of the arm circumference. Consequently, three TENS electrode matrices were prepared with vertical distance of 7.0 mm between upper and lower electrode and horizontal distance of 5.0 mm, 7.5 mm and 10.0 mm between the neighbouring electrodes.

The centre line between elbow and shoulder joint as well as the lateral point with upper and lower edge of the cuff were marked on the right upper arm of the participant. In order to reduce the transition impedance between the skin and the electrodes, the right upper arm of the participant was cleaned and moistened with a wet towel. The circumference of the


**Figure 2:** Textile cuff attached to the upper right arm with electrode connectors (upper left) and electrodes (lower left) made of knitted fabric coated with silver covered by carbon black filled silicon.

subject's arm along the midline was measured. The textile cuff was placed on the right upper arm where electrode pair 1-4 (Fig. 2) was placed on the lateral side and arm's midpoint. The horizontal distance between two electrode connectors (Fig. 2, upper left) was measured and the best fitting electrode matrix from the three prepared ones was selected.

The participant was asked to sit in a relaxed position, to relax the arm, to keep the view away from the experimental devices and to concentrate on the sensation of the stimulation. During the experiment, the arm was positioned in a relaxed and bent position on a table. The experiment was conducted at a room temperature of ~23°C.

### 2.3.2 Threshold determination

The data of threshold were recorded as soon as the subject responded to the three states of: perception, attention and intolerance. The perception threshold $A_p$ denotes the smallest amplitude, where the participant can sense the stimulation signal. The attention threshold $A_a$, denotes the amplitude where the intensity of the sensation is strong enough to catch the participant's attention. The intolerance threshold $A_i$ denotes the amplitude from which the participant senses the stimulation as inconvenient. If muscle twitching occurred, the measurement series was stopped and the current amplitude value was noted. Muscle twitches are not desired in the current study for the use of the stimulation in a warning system. The subjects were required to report the sensation they felt qualitatively and spatially according to the sensation categories of the questionnaire summarized in Tab. 2.

**Table 2:** Sensation categories of the questionnaire.

| Qualitative sensation | | Spatial sensation | |
|---|---|---|---|
| □ Knocking | □ Muscle twitch | □ Between electrodes | □ Extended beyond electrode |
| □ Scratching | □ Tickling | □ Upper electrode | □ At another part of the body |
| □ Stinging | □ Itching | □ Lower electrode | |
| □ Painful | □ Pinching | | |

At the beginning, the abovementioned definitions of the thresholds and the sensation categories of the questionnaire were explained to the participant and questions from the participant were answered. After that a single bi-phasic stimulation pulse of pulse width $t_p = 150$ µs was applied to the participants upper right arm at electrode pair 1-4. The amplitude was increased gradually (steps of 0.1 mA, 0.2 mA or 0.5 mA).

The threshold determination was conducted according to the following scheme:

- Adaptation phase: A-A-B-B-B-B-A-A
- Evaluation phase: B-B-A-A-A-A-B-B,

where A means that the textile cuff is placed at the subject's arm and B refers to the TENS electrodes. At each A or B, the three thresholds are determined for the pairs 1-4, 2-5, and 3-6, separately. This lead to an overall experiment duration of approximately one hour and 40 minutes. The adaptation phase had the aim that the participants get trained to the new feeling of current stimulation, the reporting of the thresholds as well as the qualitative and spatial sensation. For analysis, the results of the evaluation phase were used. The participant was not informed about the aim of the two different phases in order to avoid a participant related bias.

Lastly, the skin was observed for irritations (e.g. red skin) after the electrodes have been removed and participant's experience was evaluated.

## 2.4 Statistics

The individual mean amplitudes of the thresholds were calculated from the evaluation phase. In order to visualize possible differences between TENS and textile cuff electrodes regarding perception, attention and intolerance thresholds results are shown in form of boxplots. Additionally, a Wilcoxon rank sum test ($\alpha = 0.0055$, Bonferroni corrected) is used to compare the threshold distributions of TENS vs. textile cuff with the null hypothesis that there is no difference, i.e. a symmetric distribution around zero.

A stacked bar graph was chosen to show the absolute frequency distribution of qualitative and spatial perception types in all 30 participants.

# 3 Results and Discussion

## 3.1 Thresholds

Fig. 3 shows the distribution of the individual mean perception, attention and intolerance thresholds of the study group for electrode pair 3-6 in form of boxplots. The electrode pairs 1-4 and 2-5 show comparable behaviour of the thresholds and are therefore not visualized here. The boxplots indicate in general similar thresholds for the TENS and textile cuff

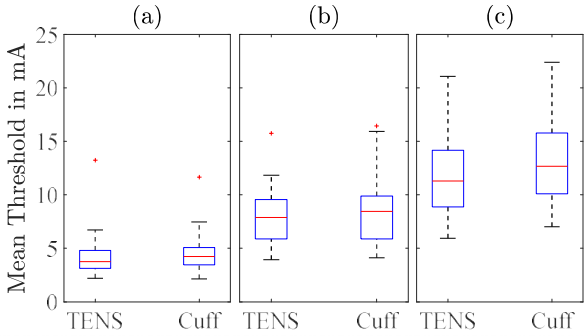


**Figure 3:** Boxplots of distribution of individual mean values of perception (a), attention (b) and intolerance threshold (c) in mA for TENS vs. textile cuff electrode pair 3-6.

electrodes. However, the Wilcoxon test indicated a difference between TENS and textile cuff at attention (p=0.005) and intolerance (p=0.001) threshold. This might be caused by the right-skewed distribution of the attention threshold for the cuff (Fig. 3 b) and the small shift towards higher intolerance thresholds for the cuff (Fig. 3 c). For the other electrode pairs and thresholds no significant difference was found (Tab. 3).

**Table 3:** p-values of Wilcoxon rank sum test for comparison of sensation thresholds of TENS vs. textile cuff at the three different electrode pairs.

| Threshold \ Electrode pair | 1-4 | 2-5 | 3-6 |
|---|---|---|---|
| Perception | 0.87 | 0.18 | 0.18 |
| Attention | 0.17 | 0.38 | 0.005* |
| Intolerance | 0.12 | 0.12 | 0.001* |

## 3.2 Qualitative and spatial sensation

Fig. 4 shows the qualitative and spatial sensation distributions as stacked bar graphs for TENS electrode pair 3-6. The distributions for the textile cuff are similar and therefore not visualized here. The behaviour is very similar for electrode pairs 1-4 and 2-5. The results indicate that also the sensations for TENS and textile cuff electrodes are comparable. The most frequent qualitative perception at $A_p$ and $A_a$ is 'Knocking', and at $A_i$ 'Stinging' and 'Muscle Twitch'. The spatial sensation is always located at one of the electrodes or between the electrodes.

# 4 Conclusion

The study indicates that future studies with the textile cuff electrodes can be generally based on the previous results with

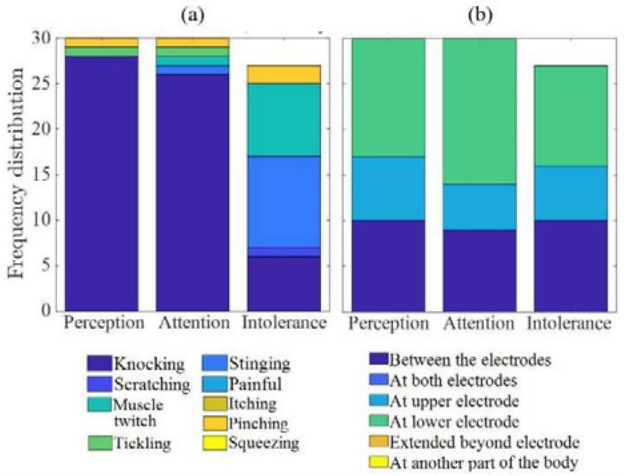


**Figure 4:** Distribution of qualitative (a) and spatial perception (b) for TENS electrode pair 3-6. The intolerance threshold shows three cases less, as 2 participants showed $A_i$ >25 mA and one muscle twitching at $A_a$.

TENS electrodes, but slightly increased thresholds might be present for the textile cuff electrodes for varying electrode positions around the upper arm.

### Author Statement

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