Motor and sensor recovery in a paraplegic by transcutaneous spinal cord stimulation in water

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Abstract: A spinal cord injury is associated with a loss or reduction of motor and sensor function. During the rehabilitation process, gait training and standing exercise play a significant role in partial restoration of motor ability. In this paper we introduce a case study, which determines the effects of transcutaneous spinal cord stimulation (tSCS) during locomotion attempts in water. Within eight weeks a paraplegic subject conducted 14 training sessions involving tSCS and one session containing a combination of tSCS and functional electrical stimulation (FES). For assessment purposes, inertial sensor units (IMUs) and electromyography (EMG) sensors were used in water during locomotion.

I. Introduction

A traumatic spinal cord injury (SCI) results in limitations of motor and sensor functions. Depending on the severity of the injury, SCI can lead to complete paralysis of the lower extremities. Achievements in robotic supported gait training have been accomplished in the past. Furthermore, with the application of an implanted pulse generator, which stimulates the spinal cord epidurally, a promising step towards motor function rehabilitation has been taken. However, after implantation, intensive training, involving robotic support must be conducted to regain motor function. This requires intense therapeutic support as well as expensive equipment. Additionally, the patient needs to undergo surgery with all involving risks.

Here, we introduce a method, which uses transcutaneous spinal cord stimulation (tSCS) during a locomotion initiation training in water. This technique reduces spasticity [1] and amplifies weak residual motor functions [2]. In a case study, the setup was tested on a paraplegic patient. In order to reduce the required muscular strength to a minimum and to make use of weight lifting characteristic of water, the study was conducted in a pool. In addition, setting up the study in water minimizes the risk of injury and, therefore, the required manual support.

II. Material and methods

In this case study, a female AIS B (motor complete and sensor incomplete paralysis) patient (age 31) with lesion level TH1-TH3 carried out an individual training based on tSCS. Floating aids were used to secure the subject. Within eight weeks 14 training sessions were conducted. In an additional session tSCS was combined with functional electrical stimulation (FES) of the knee extensors. For tSCS, waterproof adhesive electrodes are attached to the abdomen and back. The electrode position and stimulation intensity at the back have been determined according to [1]. While locomotion initiation training, the stimulation frequency is adjusted to 30 Hz according to [2]. FES of knee extensor muscles is done by means of safety silicone electrodes strapped to the subject's thighs. The stimulation frequency corresponds to the frequency used for tSCS. Intensities in the range of 5 to 40 mA are applied depending on the fatigue level. The subject's legs are bilaterally stimulated. In order to take a step, FES is turned off on the corresponding leg during swing phase. The CE-certified stimulator RehaMove3 (Hasomed GmbH, Germany), with customized firmware, controls the different stimulation channels. The device is placed in a waterproof diving bag.

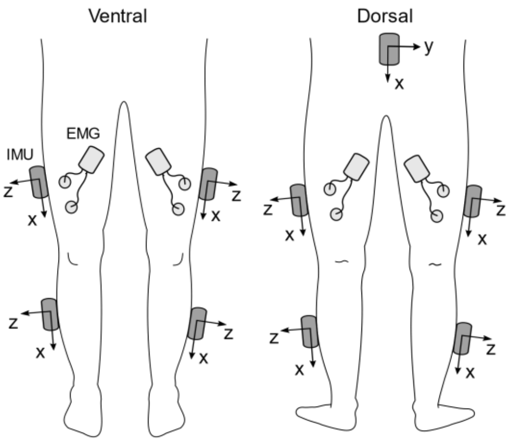

Figure 1: The IMUs are attached bilaterally on the exterior thigh and shank, as well as centrally on the lower back. EMG sensors measure the muscular activity of hamstrings and quadriceps.

To monitor the effects of stimulation on the subject's locomotion ("gait"), a wireless sensor setup is used. The sensor system WaveTrack (Cometa srl, Italy) is a water-proof system consisting of several time-synchronized inertial measurement units (IMUs) and electromyography (EMG) sensors, which are attached to the subject's lower limbs and back. The positions of the different sensors are shown in Fig. 1. The joint angles of both knees and hips and volitional muscular activity are calculated from the recorded data for validating the subject's progress during training and stimulation.

The joint angle evaluation is based on orientation estimation using quaternions. Magnetometer data are not reliable due to the vast disturbances during underwater measurements. Therefore, an accelerometer- and gyroscope-based estimation algorithm is applied to determine the relative orientation between two IMU-sensors. The compensation of heading errors resulting from absent magnetometer data reposes on kinematic constraint and non-varying joint axes. Knee and hip are assumed as approximate hinge joints [3]. For evaluating the subject's movements under tSCS, the volitional muscular activity has to be extracted from the EMG signal. This is achieved by isolating the inter-pulse-intervals (IPI) between the stimulation artifacts, followed by a high-pass-filter and calcu-lation of the mean value of the rectified filter output in each IPI. [4]

III. Results

After the first training sessions, the subject noticed an improvement of sensory function in the right leg below the level of lesion. This sensor recovery lasts up to this day. Furthermore, the subject's trunk stability increased leading to an improvement in balance during daily routines. When starting the therapy sessions, two people were required to guide the subject through the pool. She was not able to walk on her own and had to be manually supported during walking attempts. However, after the therapy the subject was capable of walking in the pool almost independently, only requiring occasional help of another person to follow a straight line. This applies for walks while tSCS, as well as for those without any stimulation turned on. The results of EMG processing and joint angle analysis are shown in Fig. 2. Note that knee and hip angles are defined zero in a fully extended upright standing position and knee angles are defined negatively. Note further, that the maximum value of the EMG without tSCS is set to one. All data shown in the results were recorded at the end of the study.

IV. Discussion and conclusions

At the end of the study, voluntary control of the left hip, knee and ankle joint could be observed in water during locomotion also without tSCS. Corresponding to the observations, the volitional muscular activity improved under tSCS. As shown in Fig. 2, the activity of the left quadriceps improved by 300 percent, when tSCS was turned on. Furthermore, an enhancement in the range of movement was monitored, demonstrated by a more outspread distribution of the cyclograms. Overall, a combination of tSCS and FES leads to a more upright posture and fully extended knee joint in the stance phase resulting in a shifted cyclogram towards smaller joint angles, which are more similar to observations on healthy subjects. Thus, the outcome of this case study indicates that using a combination of tSCS and FES might be a useful therapeutic tool for locomotion initiation and gait training in water. However, further research and more subjects are needed to quantify the results.

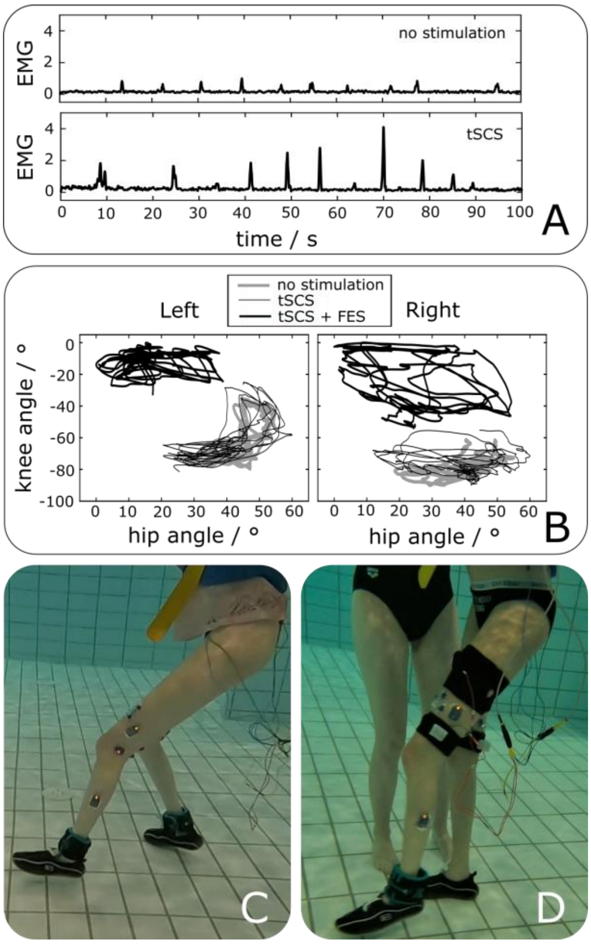

Figure 2: A shows the EMG of the left quadriceps while walking using tSCS vs. no stimulation. In B, a cyclogram for each body side picturing joint angles during a five steps movement is displayed. Additionally, two photos show step initialization using tSCS (C) vs. tSCS in combination with FES (D).

AUTHOR'S STATEMENT

Research funding: This work was supported by the Berlin Senate Department for Economics, Energy and Public Enterprises via the funded validation project "Pilotprojekt Validierungsförderung" and by the Stiftung Industrieforschung within the project "Forum Junge Spitzenforscher – Mobilität". Conflict of interest: CW and TS are co-founders of SensorStim Neurotechnology GmbH, which is startup developing FES stimulation devices. All other authors declare that they have no competing interests. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The study was approved by the ethical committee of the Berlin Chamber of Physicians. We like to thank Diethad Steube and Marco Spiegel for giving us access to the therapeutic pool at the ZAR Berlin.

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