

FUNCTIONAL ELECTRICAL STIMULATION ASSISTED SWIMMING FOR PARAPLEGICS

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Abstract: A new method for functional electrical stimulation (FES) assisted swimming has been developed. This includes the development of waterproof electrodes, cables, and a stimulator. In preliminary experiments, an extension and flexion movement of the knee could be induced for a complete paralyzed subject. Furthermore, the developed setting stayed safe and dry during several sessions. To investigate the overall benefit of FES assisted swimming a pilot study was designed which started in 2018. During this study, up to ten complete paraplegic subjects shall be trained to swim with FES assisted leg movement while swimming speed and heart rate are compared to swimming without FES-support. Additionally, the effects of the training on spasticity, the well-being, and the usability of the technology shall be assessed.

Keywords: FES, Swimming, paraplegic

Introduction

A spinal cord injury (SCI) is often associated with paralysis of the lower extremities which means a severe restriction of physical activity and health for the affected subjects. Depending on the level and severity of the injury, this involves a functional limitation of various body sensory and motor functions below the level of lesion. In case of a traumatic SCI, the physical inactivity is in stark contrast to the condition prior to the injury, especially for young patients.

Participation in physical and therapeutic activities following a paraplegia is often limited due to the loss of voluntary motor function and inefficient temperature regulation of the affected extremities, autonomic dysfunction, and early muscle fatigue. In addition, often specially adapted equipment and assistants are needed. Despite all these obstacles, sportive and therapeutic activity after paraplegia can contribute to a reduction in concomitant diseases and to an increase in the emotional well-being of those affected [1, 2].

In the majority of cases, paraplegia results in complete or incomplete paralysis of the lower extremities. Therefore, effective and safe lower extremity training is limited and training exercises of the upper extremities are recommended such as arm-crank ergometer, wheelchair ergometer

or swimming. All these exercises can improve physical fitness by up to 25 % with regular exercises [3]. Mobility in the water is often the only experience of unaided body movement (except for the transfer in and from the pool) within the environment that most paralyzed patients enjoy. In addition, there is a plurality of therapeutic effects described in the literature as an increase of muscle strength, improved coordination, reduction of spasticity and a reduction of contractures [4].

Functional electrical stimulation (FES) is used successfully in FES cycling or rowing [5, 6]. The corresponding muscles for knee extension and flexion or hip extension and flexion are stimulated depending on the crank or joint angle during cycling or triggered by a pull switch while rowing. Due to the combination of arm and leg training, a significantly higher training effect can be achieved. In addition, an improvement in perfusion and lower limb bone density has been observed in some studies [5]. In this paper, we want to present our recent work on the combination of FES assisted swimming in paraplegic patients.

Methods

During the relearn phase of swimming for paraplegics, the independence in the water is first achieved on the back since the prone position is more difficult to maintain without muscle power at the hip joints. Furthermore, symmetrical strokes are taught initially by the swimming instructor during the relearn phase, because asymmetrical swimming techniques cause the paralyzed limbs to roll and the patient finds it difficult in maintaining a straight course [4].

Afterward, there are several possible swimming techniques for paraplegics with slight modifications compared to non-paralyzed subjects. For patients with thoracic or lumbar lesion height [4] recommends backstroke, breaststroke, crawl stroke and butterfly stroke in which the butterfly stroke is the most difficult to learn.

For normal breaststroke in unimpaired subjects, the so-called frog kick is used as leg technique, which includes knee flexors and extensors, thigh adductors and abductors, gluteus and the plantar-flexors. In preliminary tests, we found out that a complex movement like the frog kick is

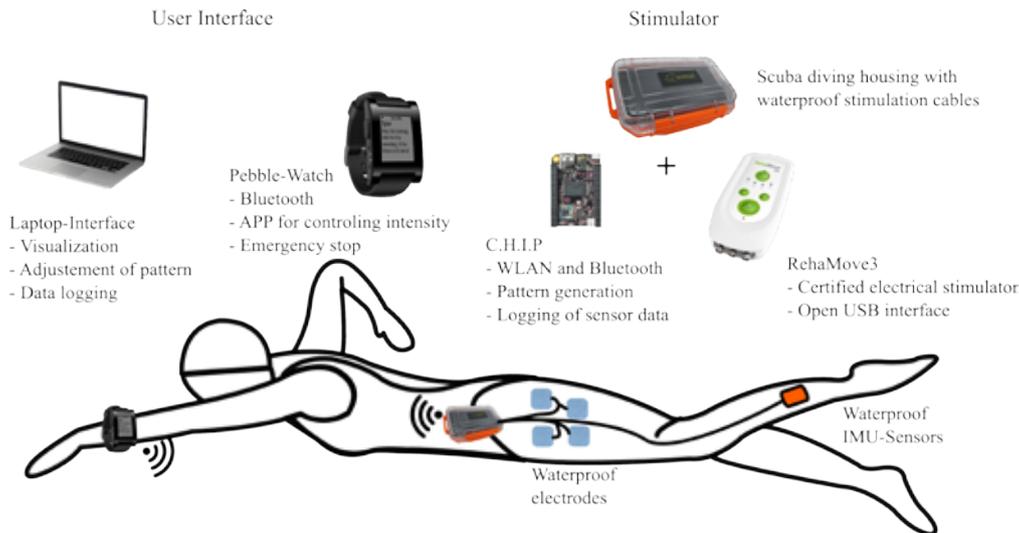


Figure 1: Experimental FES swimming setting including the waterproof stimulator (Hasomed RehaMove3, CHIP embedded PC, scuba diving housing) the user interface (Pebble I smartwatch, Laptop), waterproof IMU sensors and waterproof electrodes.

not realizable with FES. For backstroke and crawl, the so-called flutter kick can be used for the lower legs with FES support. For this technique, the knee extensors and flexors and the gluteus are mostly involved. In [7, 8] the knee angle course for healthy non-expert swimmers for crawl is analyzed. Here, after a short and strong extension phase, a plateau phase can be observed where the knee joint is fully extended. During the plateau phase, the other knee is flexed until 40-50 degrees and then directly extended until the plateau phase. To reproduce this movement for paraplegic patients a periodic stimulation pattern is used which is shown in Fig 3. The pulse width is kept constant at a level of 300-400 μs while the current amplitude of the biphasic pulses is ramped on and off.

To our best knowledge, there is no study or work on FES in water to produce a functional movement. There are several works on Iontophoresis for the transdermal delivery of pharmaceuticals using low DC currents. Furthermore, in [9] waterproof surface EMG electrodes are used to compare EMG signals on land and in water. Here, standard EMG electrodes are fixed and waterproofed using 3M Tegaderm as a waterproof oversize backing. Due to the fact that chlorinated water in swimming pools has a conductance of 2.5-3 mS/cm which results in resistance of 333-400 Ohm a direct stimulation with non-waterproof electrodes would produce a parasitic short circuit between electrodes during stimulation.

Therefore, Axelgaard Manufacturing developed a waterproof electrode with a snap connector which stays waterproof over at least 30 minutes (see Fig. 4). To fix the snap connector a 3M Tegaderm adhesive has been used. In tests with healthy subjects, it has been shown that the connection between cable and electrode must be waterproof as well. Therefore, a tight silicone tube is used as a cover for the connection between electrode and cable.

During preliminary tests for the STIMSWIM pilot study, an experimental FES swimming setting was developed (Fig.1). For the stimulator, the RehaMove3 (Hasomed GmbH, Ger-

many) is used in combination with a wireless embedded PC which executes the stimulation pattern and collects sensor measurements. The stimulation is controlled via a Kivy App running on a standard laptop. In the water, the subject can control the stimulation via a customized smartwatch App.

Preliminary experimental results

To find the best swimming technique and stimulation setting several preliminary tests have been executed with one paraplegic subject under medical supervision of the Unfallkrankenhaus Berlin¹. The participant gave written informed consent.

The stimulation of the gluteus was excluded due to the fact that it is not possible to place the electrodes on a paraplegic without help. Furthermore, the hip position of a paraplegic in backstroke swimming technique depends on the level of control over the waist and hip. In preliminary tests, we found out that the lower the hip the less propulsion which can be achieved by stimulating the knee flexors and extensors. As a result crawl stroke was decided to be used in combination with FES for the planned study. Furthermore, during tests with floats at the ankle a default upward movement of the ankle could be observed for crawl stroke which results in a more streamlined position in the water. In Fig. 4 three photos in the sagittal plane are displayed which show the different states of the stimulation. During this test, the subject was asked not to swim with his arms to get a stable position. During the trial underwater video data has been captured using a waterproof GoPro action camera. Using the video data the left knee angle was tracked as shown in Fig. 3 using the video processing software Kinovea. Compared to [7, 8] the plateau phase of the knee

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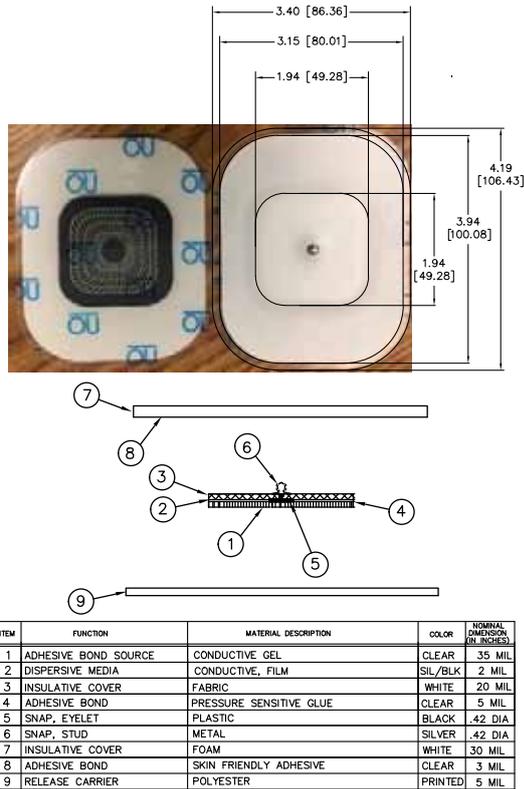


Figure 2: Photo and construction plan of Axelgaard Ultrastim® snap electrode with oversize water fast backing with an electrode area of 22.9 cm² [10, 11]

angle after the full extension is reduced. Due to the missing arm movement, the knee moves automatically to the rest angle of 90 degree. During swimming with arms knee angle tracking was not possible due to the swimming speed and role movement of the trunk. Furthermore, the reached minimum flexion angles are 20 degrees higher compared to non-paralyzed swimmers. The stimulation setting including the stimulator, cables, and electrodes stayed dry over the full trial duration of 30 minutes. We found out that the synchronization of the knee extension with the contralateral elbow extension in the case of crawl stroke is needed to increase the swimming speed and effectiveness. Furthermore, if the arm movement is synchronized to the leg movement then the rolling of the body around the longitudinal axis is minimized. Therefore, we plan for the next trials to sense the arm motion by an inertial sensor to control the stimulation of the leg, or to provide a sensory stimulation to the swimmer to inform him/her about the movement of the stimulated leg as biofeedback. In addition, the influence of the Hamstring stimulation was rated quite low compared to the propulsion produced by the Quadriceps only. Therefore, for the planned study either quadriceps only or the combination of quadriceps and hamstrings shall be stimulated.

The STIMSWIM pilot study

The STIMSWIM pilot study shall investigate the technical feasibility of FES to support swimming motions by the legs

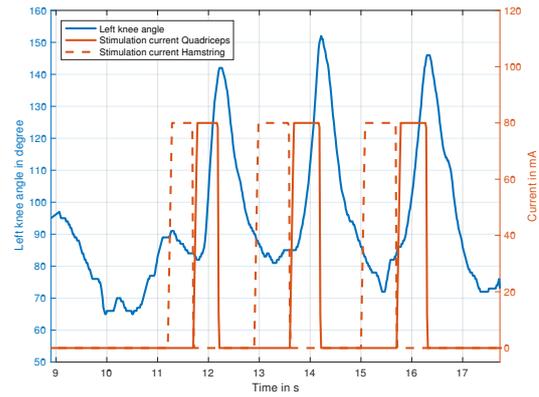


Figure 3: Left knee angle for three consecutive strokes during stimulation of the Quadriceps and Hamstring muscle group.

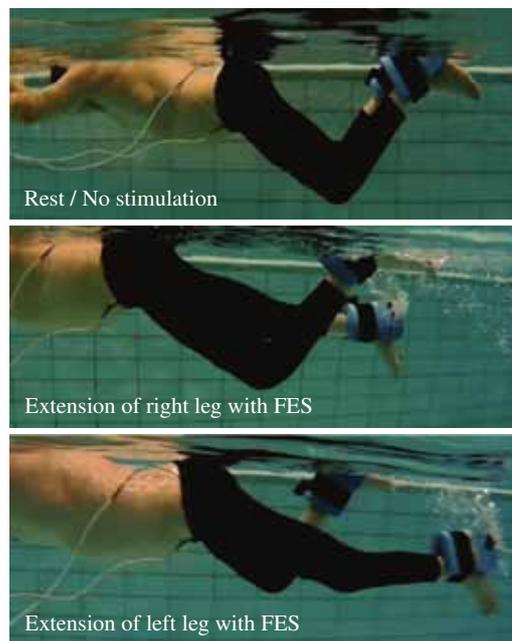


Figure 4: Experiment with a paraplegic subject (Th5, ASIA scale A) with floats at the feet with asynchronous stimulation of the left and right quadriceps and hamstrings.

in up to 10 subjects with complete paralysis of the lower extremities after spinal trauma. The subjects have to be over 18 years and must give written informed consent. There are three main questions which shall be answered within this trial. Does the swimming speed increase compared to non-assisted swimming? 2. Does the general well-being of the subject improve during the trial? 3. How is the acceptance of the technology by the user? The trial comprises of a land and a swimming phase. After the recruitment and initial assessment, the subject is asked to carry out a four-week FES cycling training. During the land training, he/she is asked to train at least three times a week for 30 minutes with a standard RehaMove FES cycling ergometer. At the beginning and end of this training phase, the thigh diameter and maximum cycling power are assessed. This preliminary FES cycling training is needed to build up a defined baseline for the swimming trial. During the swimming phase, the

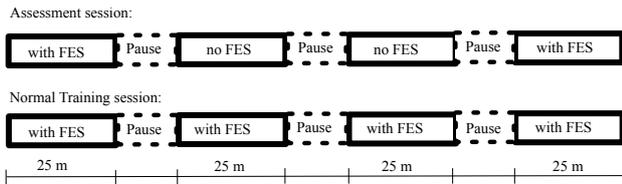


Figure 5: Comparison of assessment and training session. For each assessment session, the subject shall swim the same distance while the time needed is measured. The distance of each swimming trial will be fixed to 25 m.

FES cycling shall be reduced to two times a week.

Table 1: Trial plan for the swim training during the STIMSWIM study. A means training with FES and B without.

ID	Time after assessment	Assessment
T0	Four weeks after recruitment/assessment and FES cycling training (3 times a week)	Execution of Modified Ashworth Scale Test, Measurement of swim distance and speed with and without FES (ABBA)
T1	After 4-6 training sessions (maximum 30 days after last assessment)	Execution of Modified Ashworth Scale Test, Measurement of swim distance and speed with and without FES (ABBA)
T2	After 8-12 training sessions (maximum 30 days after last assessment)	Execution of Modified Ashworth Scale Test, Measurement of swim distance and speed with and without FES (ABBA)
T3	After 12-18 training sessions (maximum 30 days after last assessment)	Execution of Modified Ashworth Scale Test, Measurement of swim distance and speed with and without FES (ABBA)

Afterward, the swimming training starts which follows the trial protocol shown in Tab.1. The swimming assessment consist of a strict ABBA pattern to eliminate the effect of fatigue. Furthermore, the swimming trials of an assessment session either with FES or without are separated by a five-minute pause. In between the assessment, the subjects shall train with FES only in four separate training blocks as shown in Fig. 5. The training is supervised by a pool attendant to eliminate the risk of severe events. At the beginning and end of each assessment, the spasticity shall be specified using the Modified Ashworth Scale test. Furthermore, the subject is asked to fill in a questionnaire about his/her well-being and the usability of the FES swimming training. At the moment 3 subjects could be recruited and we started the FES cycling training. The study shall be finalized by the end of this year.

Discussion

A new concept for FES assisted swimming for paraplegics was proposed which uses a waterproof stimulator and electrodes to produce a swimming movement of the paralyzed legs. During experiments, a periodic FES induced extension and flexion of the knee could be shown which produced a

propulsion movement in the water. To assess the improvement in speed, swimming distance and well-being a pilot trial was set up. If it is possible to show that an effective swimming training including the paralyzed legs can be realized a completely new aqua therapy for paraplegics can be built up. In addition, the stimulation could also be used recreationally by paraplegics for diving. Furthermore, it is conceivable that not only complete paraplegic patients but also incomplete paraplegic patients or stroke patients could benefit from an FES-assisted gait therapy in water. An improvement in physical functions and walking ability in manual underwater training has been shown in several studies [12, 13].

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