An Inertial Sensor-based Trigger Algorithm for Functional Electrical Stimulation-Assisted Swimming in Paraplegics

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Abstract: Functional electrical stimulation (FES) is used to support gait in stroke patients and to induce cycling motions in paralyzed legs. In the current contribution, we present a method that, for the first time, enables FES-supported swimming in paraplegics. The proposed setup includes a waterproof stimulator, cables, and electrodes. In preliminary experiments, flexion and extension movements of the knee were generated in a completely paralyzed subject to support the propulsion. Furthermore, transcutaneous spinal cord stimulation (tSCS) is used to get a straight swimming position and to reduce spasticity of the lower extremities. The developed setting remained dry and safe during all sessions. The first trials revealed the need for a synchronization of the patient’s arm movements with the artificially induced leg movements to prevent undesired rolling movements of the swimmer. To enable such a synchronized swimming, a trigger algorithm was developed that is based on the roll angle and angular velocity of the trunk. By experimental validation, it was demonstrated that a functional stimulation pattern can be generated during front crawl movements of the upper body. The new setup and methods are currently being tested during the STIMSWIM pilot study with paraplegics. The preliminary results of the first two subjects show an improvement of the swimming speed of approximately 15% for FES/tSCS assisted swimming compared to non-assisted swimming and a clear training effect over the first 7 sessions.

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1. 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 (Tawashy et al., 2009; Brumelli, 2014).

In the majority of cases, SCI 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 the use of arm-crank or wheelchair ergometer or swimming. All these exercises can improve physical fitness by up to 25% with regular exercises (Nash, 2005).

Mobility in the water is often the only experience of unaided body movement (except for the transfer in and from the pool) within an environment that most paralyzed patients enjoy. In addition, there is a plurality of therapeutic effects of swimming for paraplegics described in the literature as an increase in muscle strength, improved coordination, reduction of spasticity and a reduction of contractures (Bromley, 2006).

Functional electrical stimulation (FES) is used successfully in cycling or rowing (Newham and Donaldson, 2007; Gibbons et al., 2016; Wiesener and Schauer, 2017; Schauer, 2017). The corresponding muscles for knee extension and flexion as well as hip extension 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
Fig. 1. The world’s first FES swimming system including a waterproof stimulator, waterproof IMU sensors and waterproof electrodes.

Fig. 2. Photo and construction plan of Axelgaard Ultrastim® snap electrode with oversize water fast backing with an electrode area of 22.9 cm² (Axelgaard, 2004, 2010)

2. THE FES SWIMMING SYSTEM

The first FES swimming system was developed (Fig.1). The stimulator (RehaMove3, Hasomed GmbH, Germany) has a customized firmware and is placed inside a waterproof bag under the swimmer’s T-shirt. For data logging, two inertial motion units (IMU) (MuscleLab, Ergostest Innovation AS, Norway) with internal data storage have been attached between the shoulder blades and at the right arm also using waterproof bags. 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 (see Fig. 3). To fix the snap connector, a transparent film dressing (3M Tegaderm, 3M Co., USA) has been used. In tests with healthy subjects, it has been shown that the connection between cable and electrode must be waterproof as well. Otherwise, parasitic short circuits occur. Therefore, a removable tight silicone tube is used as a cover for the connection between electrode lead and cable.

3. SWIMMING STYLE AND SUPPORTED LEG MUSCLES

The first and most natural question to ask is which leg motion can be and should be induced by FES during what style of swimming. In conventional swimming therapy
for paraplegics, the independence in the water is first achieved on the back since the prone position is more difficult to maintain without muscular control of the hip joints. During the relearn phase, the swimming instructor teaches the patient how to perform precise symmetrical strokes, because asymmetrical strokes easily cause the paralyzed limbs to roll and make it difficult to maintain a straight course (Bromley, 2006). Subsequently, training may focus on several possible swimming techniques for paraplegics with only slight modifications compared to swimming styles of non-paralyzed subjects. For patients with thoracic or lumbar lesion height, Bromley (2006) recommends backstroke, breaststroke, crawl stroke and butterfly stroke, among which the butterfly stroke is the most difficult to learn.

For normal breaststroke in unimpaired swimmers, 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 currently not realizable with FES due to the high number of involved muscle groups. For backstroke and crawl, the so-called flutter kick can be used, which involves mostly the knee extensors and flexors as well as the gluteus muscles. In (Seifert et al., 2011, 2010) 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 to 40-50 degrees and then immediately and quickly extended and then enters the plateau phase.

To find the best swimming technique and stimulation setting, several preliminary tests have been executed with a paraplegic subject (ASIA impairment scale A, lesion level T5/6) under medical supervision of the Unfallkrankenhaus Berlin. The participant gave written informed consent.

The stimulation of the gluteus was excluded since a paraplegic would not be able to place the electrodes on that muscle without assistance. 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 is, the less propulsion can be achieved by stimulating the knee flexors and extensors. Therefore, we decided to use crawl strokes in combination with FES-induced flutter kicks for the planned study. Furthermore, preliminary tests revealed that attaching floats to the ankle joints leads to a default upward movement of the ankle, which results in a more streamlined position in the water.

In Fig. 3 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 camera. During all trials, the influence of the Hamstring stimulation was rated quite low compared to the propulsion produced by the quadriceps. After an extension, the knee automatically flexes itself back if floats at the ankle are used. Hence, during the subsequently reported trials only the quadriceps muscle groups were stimulated periodically for 0.5 s at 25 Hz with a adjustable pulse width of 0-500 μs and current amplitude of 0-100 mA.

Furthermore, transcutaneous spinal cord stimulation (tSCS) was applied at a level of 40 mA and 1 ms pulse width at a frequency of 50 Hz over the T11/12 region at the spinal cord (Hofstoetter et al., 2014). The level was chosen to produce a sensory stimulation of the lower extremity nerves for spasticity reduction. At the same time, the trunk musculature is activated at a motor level by the tSCS. The latter shall improve trunk stability and straighten the upper body and hip.

Analyzing the video data and comparing the knee angles to Seifert et al. (2011, 2010) the plateau phase of the knee angle after the full extension is reduced and due to the floats and the used stimulation pattern. The knee moves automatically to the rest angle of 90 degree. Furthermore, the reached minimum flexion angles are 20 degrees higher compared to non-paralyzed swimmers.

Using the IMU sensors the roll angle of the upper trunk and the right arm inclination angle were measured during the swimming experiments, as presented in Fig. 4. According to Psycharakis and Sanders (2010), the measured or observed roll angle is in the range of non-expert swimmers. Furthermore, the arm inclination angle is synchronous to the upper trunk roll angle. From video analysis, the trunk and hip roll angle performs similar, since no synchronization of arm and leg movement is performed. Psycharakis and Sanders (2010) described an decrease of the hip roll angle compared to the upper trunk roll angle with increasing swimming velocity and with synchronous arm and leg.
movement. Therefore, a major result of these preliminary experiments is that, in the case of crawl stroke, the knee extension should be synchronized with the contralateral arm movement to increase the swimming speed and effectiveness. Beside the experimental results for the swimming style the stimulation setting including the stimulator, cables, and electrodes stayed dry over the full trial duration of 30 minutes in all experiments.

4. ROLL-ANGLE-TRIGGERED STIMULATION

To address the need for synchronization of the leg movements with the arm movements, a method was developed that uses the roll angle and angular velocity of the trunk to trigger the stimulation of the legs. The roll angle of the trunk is defined as the angle between the mediolateral axis of the trunk and the horizontal plane, as illustrated in Fig. 5. During front crawl swimming, this angle typically varies periodically in the range of ±50° for expert swimmers and in the range of ±30° for non-experts swimmers (cf. (Callaway et al., 2009; Bächlin et al., 2009)). An IMU is attached to the back such that the intrinsic x-axis of the IMU is aligned with the longitudinal axis of the trunk and the intrinsic y-axis of the IMU points mediolaterally to the right-hand side of the subject. Therefore, the roll angle can be calculated via the following procedure.

In a first step, the orientation of the IMU is determined from the measured acceleration and angular rate. To this end, we employ the algorithm proposed by Seel and Ruppin (2017), which yields a quaternion $\mathbf{q}(k)$ at every time index $k$. This quaternion describes the orientation of the intrinsic sensor frame $\mathcal{S}$ of the IMU with respect to a fixed inertial reference frame $\mathcal{E}$ with vertical $z$-axis. Note that the algorithm is modular and that we refrain from using the magnetometer-based corrections described by Seel and Ruppin (2017) information since the azimuth (heading) information is not needed. The $y$-axis of the IMU in sensor coordinates is given by $\mathbf{y}_S = [0 1 0]^T$. The reference frame coordinates of this vector are obtained by

$$\begin{bmatrix} 0 \\ \mathbf{y}_S \end{bmatrix} = \mathbf{S} \mathbf{q}(k) \otimes \begin{bmatrix} 0 \\ \mathbf{y}_E \end{bmatrix} \otimes \mathbf{q}^{-1}(k),$$

where $\otimes$ denotes quaternion multiplication. Likewise, the measured angular rate $\mathbf{\omega}_S$ can be expressed in reference coordinates by

$$\begin{bmatrix} 0 \\ \mathbf{\omega}_S \end{bmatrix} = \mathbf{S} \mathbf{q}(k) \otimes \begin{bmatrix} 0 \\ \mathbf{\omega}_E \end{bmatrix} \otimes \mathbf{q}^{-1}(k).$$

The angle between the $y$-axis of the IMU and the vertical $z$-axis $\mathbf{y}_E$ of the reference frame is equal to the trunk roll angle plus 90°/s. Hence, using only the $z$-component of $\mathbf{\omega}_S$, we can determine the trunk roll angle by

$$\phi(k) = \arccos(\frac{\mathbf{\omega}_S[k]_z}{2} - \frac{\pi}{2}).$$

Likewise, the time derivative of the trunk angle is obtained by projecting the angular rate $\mathbf{\omega}_S$ onto the roll axis of the trunk, which is perpendicular to $\mathbf{y}_S$ and $\mathbf{z}$:

$$\dot{\phi}(k) = \mathbf{\omega}_S \cdot \left( \frac{\mathbf{z} \times \mathbf{y}_S}{\|\mathbf{z}\|_2 \|\mathbf{y}_S\|_2} \right),$$

According to Sanders et al. (2017) and Deschodt et al. (1999), the leg kick in front crawl swimming plays a major role for keeping the body in a streamline position. The type of synchronization depends on the skill level of the swimmer since expert swimmers execute several flutter kicks during one arm movement. For our subjects, we assume a slow swimming movement and synchronize the knee extension of each side to the forward movement of the contralateral arm. To realize the roll angle-triggered stimulation, we designed a state machine based on the sensor information (cf. Fig. 6) which starts a stimulation phase of 0.4 s as soon as the trunk roll angle exceeds 15° at an angular velocity of more than 40°/s. All thresholds and stimulation durations are so far only first guesses and need to be adjusted for paraplegic swimmers individually.

5. PRELIMINARY EXPERIMENTAL RESULTS

With this state machine, we performed an experiment with a healthy subject on a padded platform where the trunk extends beyond the table to allow free shoulder movements. The IMU sensor was attached with a Velcro strap
Fig. 6. State machine implemented in Stateflow® where entry defines a singular action when the state is entered and during defines a periodic action for each time index $k$, where $\text{cur\_left}$ and $\text{cur\_right}$ describe the scale of the output current for the left and right leg, $\text{dphi}$ describes the roll angle velocity and $\text{after}$ indicates in the Stateflow syntax that the state machine should leave the state after exact 0.4 s.

The swim sessions were always accompanied by a trained pool guard. Furthermore, all recruited subjects are able to swim without stimulation.

At the current state, two subjects completed the FES land training and the first swimming training and assessment sessions. Both subjects are ASIA impairment scale A with lesion level T5/6. The training was done at 16 m pool and one subject used a snorkel. In Fig. 8, the averaged results of the elapsed time for the swimming trials are shown. For both subjects, a clear training effect can be observed. The difference between swimming speed with and without FES is $\approx$5%. The difference between swimming speed with and without FES in combination with TCS is $\approx$15%. Additionally both subjects reported
individually that swimming with tSCS reduced spasticity in the lower extremities for up to 4 hours.

6. DISCUSSION AND CONCLUSION

A new concept for FES assisted-swimming in paraplegics was proposed which uses a waterproof stimulator and electrodes to produce a swimming movement of the paralyzed legs. During underwater experiments, a periodic FES-induced extension of the knee was achieved, which lead to a propulsion movement. To synchronize the leg movements with the upper body movement, an inertial sensor can be attached to the trunk, and the roll angle of the trunk can be used to trigger the stimulation in future. As trigger criterion, a combination of the absolute roll angle of the trunk and the angular velocity is proposed. So far we only tested the new method on a healthy subject, and we were able to trigger the stimulation of the contralateral side. This new method shall be tested with paraplegic subjects in the SWIMSTIM study in future.

The ongoing study will include validation of the results in a larger number of paraplegic patients. 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 established. In addition, the stimulation could also be used recreationally by paraplegics for swimming and 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 (Tamburella et al., 2013; Stevens et al., 2015).

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