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Smart control for functional electrical stimulation with optimal pulse intensity

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Abstract: Transcutaneous electrical stimulation is a common treatment option for patients suffering from spinal cord injury or stroke. Two major difficulties arise when employing electrical stimulation in patients: Accurate stimulation electrode placement and configuration of optimal stimulation parameters. Optimizing the stimulation parameters has the advantage to reduce muscle fatigue after repetitive stimulation. Here we present a newly developed system which is able to automatically find the optimal individual stimulation intensity by varying the pulse length. The effectiveness is measured with flex sensors. By adapting the stimulation parameters, the effect of muscle fatigue can be compensated, allowing for a more stable movement upon stimulation over time.

Keywords: algorithm; efficient stimulation; functional electrical stimulation; muscle fatigue reduction; optimal stimulation; stroke; transcutaneous electrical stimulation.

1 Introduction

Functional electrical stimulation (FES) has been used to help patients who suffer from stroke or spinal cord injury for many years now [1]. FES is able to support patients in activities of daily living, like walking or grasping [2]. Performing electrical stimulation in most cases arises

two core questions: Where the optimal placement of the stimulation electrodes is and which stimulation intensity should be applied [3]. Addressing the former question, prior studies have investigated the optimal electrode placement by using electrode arrays [4]. Addressing the latter is an equivalently complex question, as parameters vary from patient to patient. Providing neither too strong, nor too weak stimulation intensity is crucial, as too weak stimulation leads to an insufficiently opened hand or incorrect step while walking. Too strong stimulation exhausts the muscles quickly without any further benefit, leading to muscle fatigue [5].

Here we present a newly developed system which is able to increase the intensity of stimulation in a stepwise manner until the optimal point is reached. We demonstrate its use in a chronic stroke patient with hand paresis, focusing the opening of the hand. In order to cancel out fatigue, we regulate the intensity, allowing a stable opening of the affected hand.

2 System design

Figure 1 shows the typical stimulation sequence for the hand opening. At first stimulation is too weak and causes no reaction. After the intensity is increased, the hand starts to open and soon the maximal extension is reached. Increasing the intensity even more would lead to an inefficient stimulation, as the hand is not opened significantly further, so lowering the intensity, leading back to the point of optimal stimulation, has to be done. The stimulation intensity is then kept constant until the user decides to stop the stimulation or the hand starts closing due to fatigue. To keep the hand open at a constant level, the intensity has to be increased.

The whole system is divided into three parts. The first part consists of the implementation of a program on the stimulator (here Motionstim8), controlling stimulation intensity. The second part comprises the feedback system to analyze stimulation response and measure the efficiency of the stimulation applied. The third part covers

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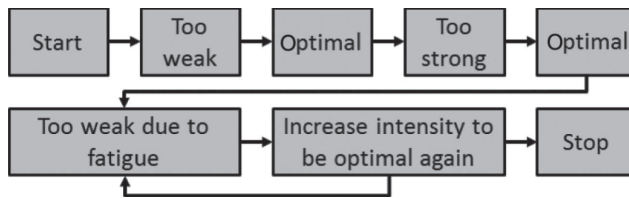


Figure 1: Flow diagram of stimulation status during a typical grasping motion.

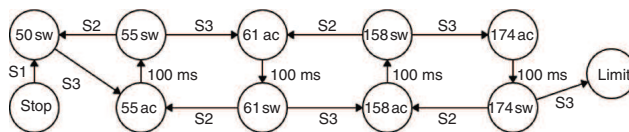


Figure 2: State Machine of Motionstim8 implementation.

the software implementation of the overall control system on the used micro-controller board.

2.1 Stimulator program

We used the commercially available stimulator Motionstim8 (Medel GmbH, Hamburg, Germany). The advantage of the Motionstim8 is the accessibility of four digital inputs, which can be used to control the stimulator to a certain degree. As the amplitude is fixed and can only be changed manually, the pulse length was used to control the intensity of the stimulation. The available Motionsoft software was used to program the course of stimulation. It is able to handle four inputs and up to 30 state machine states. Figure 2 shows the implementation of the state machine for the controllable stimulation intensity program.

The secure start point, which is needed to prevent unwanted stimulation, is program stage *00-stop*, where the stimulation is deactivated. The following state can only be arrived as long as a low signal is applied to input 1, therefore acting as a security switch for interruption or lost connection. The state *01-50-switch* activates continuous stimulation with a pulse width of 50 μs and is also ready to switch to a higher intensity state if necessary, which can be controlled with input 3, letting the state machine move to the next state, *02-55-active*.

In the second stimulation intensity state the applied pulse width is 55 μs . After a delay of 100 ms to prevent unintended fast switching, the stimulator moves over to the third stage *03-55-switch*, which acts accordingly to *03-55-switch*, also allowing to switch to a lower intensity state with input 2.

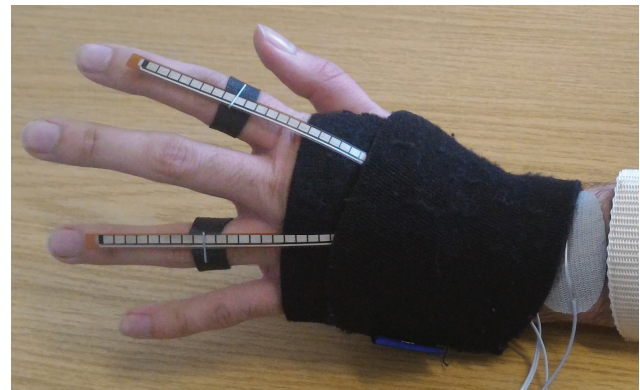


Figure 3: flex sensors with wristband and attachment rings for hand movement characterization of a stroke patient.

Each following stimulation intensity is implemented the same way as the intensity with a pulse width of 55 μs , containing an active state and a switching state. For N stimulation intensities this leads to a total number of $2 \cdot (N - 1) + 3$ states. As the Motionstim8 is able to handle up to 30 states, a total of 14 different pulse widths, 50 μs to 174 μs in steps of 10% each, have been implemented.

Reaching a pulse width of 174 μs and trying to increase again leads the stimulator into a warning state and gives the user feedback that the maximum intensity is reached. Stimulation is then deactivated and the stimulation amplitude has to be increased manually to maintain correct control.

2.2 Feedback system

To control the efficiency of the electrical stimulation, it is necessary to measure the degree of hand opening during the stimulation. For this reason, hand movement was measured using flex sensors. They were attached to a wristband and kept close to the fingers with ring attachments as seen in Figure 3. The system has two sensors that are monitored, one for the index finger and one for the ring finger.

2.3 Micro-controller implementation

To decide whether or not a stimulation is efficient, an Arduino Uno micro-controller board was used to calculate the efficiency and filter the sensor values using a median filter. The flex sensors were connected, using a voltage divider, to the analog input pins of the Arduino, thus

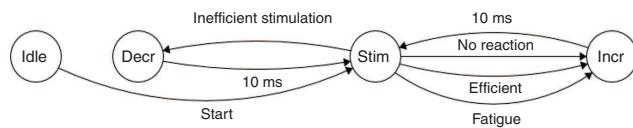


Figure 4: Arduino state machine for stimulation control.

enabling the Arduino to characterize the hand opening of the stimulated hand.

The Arduino implementation is loop based. Each loops duration is 10 ms in total and has the same order of instructions, as described in the following:

1. Check current sensor values
2. Transmit detailed data via USB
3. Check control state machine (see Figure 4)
4. Wait until total time of 10 ms has passed

The code for checking the sensor values as well as recording and sending the data were placed outside of the state machine, hence allowing better timing control. In addition the device can also be used as a pure monitoring device without using the control algorithm.

As shown in Figure 4, the state machine for stimulation control is divided into four main states *Idle*, *Stimulation*, *Increase* and *Decrease*.

Idle – In *Idle* state, the stimulation is disabled, setting output 1 to high, therefore keeping the Motionstim8 in *OO-stop*. In addition, the system determines the current sensor level. This is done to be able to determine an adapting starting point in order to calculate the degree of hand opening. *Idle* state is left when a stimulation shall be started as triggered by the user.

Stimulation – The state *Stimulation* handles the continuous stimulation of the hand and checks whether the intensity has to be increased or decreased. As seen in Figure 4, there are three reasons to increase stimulation intensity and one reason to decrease stimulation intensity. They correspond to the three increments of stimulation intensity shown in Figure 1. Increase intensity until there is either a reaction, until stimulation becomes inefficient or to cancel out fatigue.

Firstly, if the stimulation intensity is too weak and no reaction occurred, the intensity has to be increased, leaving the state and moving over to *Increase*. This usually happens in the first stages of stimulation intensity, prior to reaching the threshold of successful stimulation. The second reason for increasing the intensity occurs as soon as the hand starts too open and the movement is strong enough to be determined as effective, respectively a dramatic change of sensor values. This is true if the degree of hand opening exceeds approximately 10% of the

maximum hand opening degree. Thirdly, when the hand starts to close due to muscle fatigue, the intensity has to be increased again. This decision is based on a comparison between the degree of hand opening during the optimal stimulation point and the current sensor level.

The decrement of stimulation intensity is used to get back from overshooting the optimal stimulation point as shown in Figure 1. This happens as soon as a stimulation is marked as inefficient. In practice this means that the hand is already open and an increasing intensity cannot open the hand even more, therefore wasting energy and stressing the patient. The state is then changed to *Decrease*.

Increase – In order to deliver a low output signal on output 3 that can be detected by the Motionstim8, the *Increase* state keeps the output at a constant low level for 10 ms. This is extremely important for reliable operation, as both systems, Arduino and Motionstim8, are not synchronized. After the delay the state switches back to *Stimulation*. During *Increase* the output of the stimulator is still active, stimulation and control are not interrupted by short pauses.

Decrease – This state behaves in the same way as *Increase*. In *Decrease* output 2 is set to low instead of output 3, compared to *Increase*.

It should be noted that the Motionstim8 prioritizes lower number inputs, e.g. input 1 has a higher priority than input 2. Therefore stopping the stimulation before decreasing the intensity is prioritized and the increase of intensity is treated with the lowest priority.

3 System demonstration

The developed system was tested on ten healthy subjects and one stroke patient. Two different test scenarios were performed. The first test characterizes a single hand opening and keeps the hand open for two minutes straight. This reflects the case of a closing hand due to fatigue and forces the control system to increase the intensity. As shown in Figure 5, the initial increasing intensity is performed until the optimal stage is reached, surpassed by one stage to ensure that the optimum is really reached and then lowered back to the optimal level. In addition to that a decrease of hand opening due to fatigue triggers another increment of the intensity, as intended.

The second test scenario consists of several opening and closing motions of the hand in a short interval, mimicking grasping motions. As shown in Figure 6, six adjacent grasping motions were successfully performed.

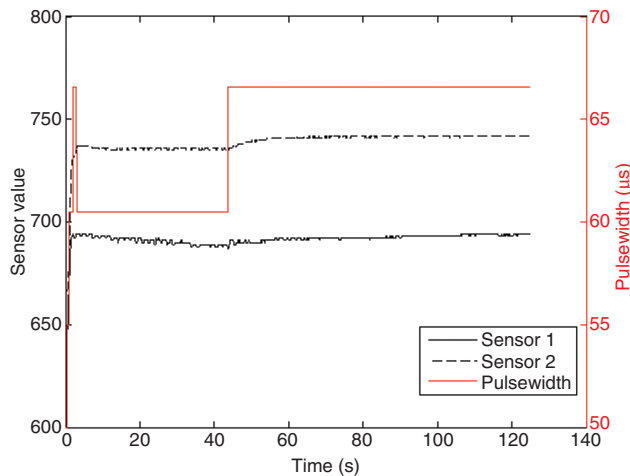


Figure 5: Continuous stimulation with initial intensity ramping and correction due to fatigue cancellation of one test subject.

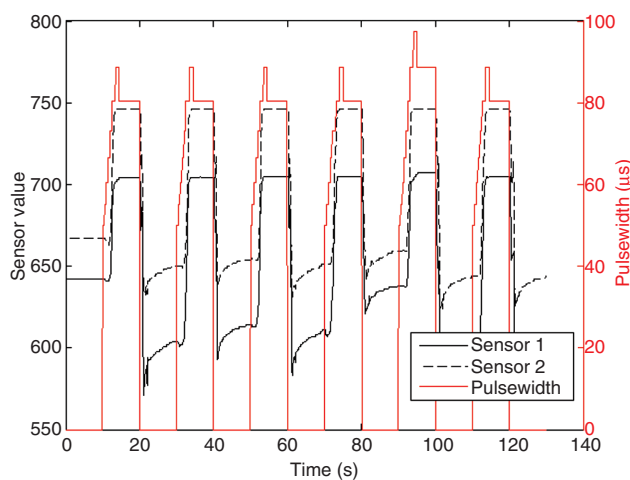


Figure 6: Repeating grasping motions with varying needed intensities and approximately same hand opening of one test subject.

Even though they vary in intensity, each single motion is approximately equal, with the same degree of hand opening.

4 Discussion and conclusion

The developed system is able to open the hand as intended, thereby reacting to different influences like

changing starting point, fatigue or different intensities needed. As the system is currently only evaluating one of the flex sensors, one future improvement would be to include the second sensor value into the threshold comparison.

Another improvement would be to use the end value of a prior hand-opening sequence in order to determine more accurate thresholds and decrease ramp up time to the needed intensity. Hence prior values could be used as an approximate target for every new stimulation. In addition, the threshold values for optimal stimulation could then be adjusted, as current values are now solely based on experience and an approximation of 10% of an opened hand.

Author's Statement

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