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Detection thresholds for electrostimulation combined with robotic leg support in sub-acute stroke patients

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Abstract— **Stroke is one of the leading causes of disability in adults in the European Union. It often leads to motor impairments, such as a hemiparetic lower extremity. Research indicates that early task-specific and intensive training promotes neuroplasticity and leads to recovery and/or compensation. One way to provide intensive training early after a stroke is via robot-supported training. A rehabilitation robot was designed by Life Science Robotics (Aalborg, Denmark) that can provide continuous repetitive movements of the hip, knee, and/or ankle in e.g., a lying position. In order to emphasize active contribution by the patient, actively triggered electrical stimulation (via muscle activation) can be combined with robotic assistance. The current study aims to compare different threshold estimation methods for detection of movement intention from muscle activity for actively triggered electrical stimulation during robot-supported leg movement in stroke patients. Three sub-acute stroke patients were included for a single measurement session. They performed knee extension and/or ankle dorsal flexion with four different threshold estimation methods to assess the intention detection threshold to initiate electrostimulation. The thresholds were based on the resting level of muscle activity (of m. rectus femoris or m. tibialis anterior) plus two or three times the standard deviation of the average resting value, or the resting level plus 5% or 10% of the peak muscle activity during a maximal voluntary contraction. The results showed that the method based on the resting muscle activity plus two times the standard deviation was the most stable across the three included stroke patients. This method had a detection success rate of 86.7% and was experienced as moderately comfortable. In conclusion, performing knee extension and/or ankle dorsal flexion with electromyography triggered electrostimulation is feasible in sub-acute stroke patients. Muscle activity-triggered electrostimulation combined with robotic support based on a threshold of resting levels plus two times the standard deviation seems to detect movement initiation most consistently in this small sample of sub-acute stroke patients.**

Index terms - **Stroke, Electrostimulation, Robot, Rehabilitation**

I. Introduction

Stroke is one of the leading causes of disability in adults in the European Union (EU). Yearly, stroke affects more than 1 million inhabitants of the EU [1]. In the acute stroke phase, around 80% of the patients experience functional deficits in motor control, such as a hemiparetic lower extremity [2], [3]. The severity of the motor impairment depends on the area and size of the lesion in the brain affected by the stroke [4]. Early rehabilitation is important for the recovery of stroke patients. Studies have shown that initiation of rehabilitation within the first two weeks post-stroke has a beneficial effect on recovery. [5]–[7]

In the acute phase after stroke, patients are often unable to walk unassisted, which results in bedridden or wheelchair-dependent patients for a certain period [3]. Research suggests that stroke rehabilitation should contain early task-specific and intensive training to stimulate recovery [3]. Therefore, the rehabilitation program should consist of several hours of daily training, supervised by a physical therapist. These intensive rehabilitation programs result in a high burden in terms of labour for the therapist as well as health care costs [8]. Besides this, providing highly intensive training to patients in the early phases post-stroke, with severe impairments, is challenging.

To enable intensive training in the early phase after stroke, a bedside rehabilitation robot has recently been designed (ROBERT, Life Science Robotics, Denmark). It provides continuous passive and active repetitions of movements of the lower extremity, while the user is in seated, supine, prone or side lying position. The robot compensates for the gravity and can also support the movement of the leg from the start to the end position. ROBERT consists of a robot arm, that can be connected via a linkage to a fixture. The fixture can hold the foot and is strapped with textile sheets around the lower leg. Actively triggered electrical stimulation (ES) can be applied in combination with robotic support to stimulate a more active contribution by patients during training and promote motor relearning. In this situation, the robot can support the movements by compensating for gravity, while actively triggered ES stimulates the muscles to contract throughout the movement, after active initiation by the patient (ROBERT-SAS: Sensing And Stimulating).

A prototype of the ROBERT-SAS combination was tested by Petersen et al. (2020) with ten healthy participants. Petersen et al. (2020) tested the support of knee extension and ankle dorsal flexion. ES was applied to the m. rectus femoris and the m. tibialis anterior respectively. In the study, two different thresholds to detect the movement intention from muscle activation were evaluated. The participants were instructed to rapidly contract the muscle after an auditory stimulus, followed by relaxation of the muscle. The completion rate of the exercises and the time between stimulus and ES onset were measured. The results showed high comple-

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tion rates for both thresholds and no significant difference in reaction time between stimulus and ES onset was found between the thresholds. However, whether these threshold methods work for stroke patients is questionable. Petersen et al. (2020) therefore concluded that the threshold method to detect muscle activation should be further evaluated in stroke patients. [9]

To further develop the robot combined with ES and test it with stroke survivors, a lab-based evaluation was planned. Similar threshold detection methods for actively triggered ES with stroke patients were tested. This evaluation focused on the feasibility of detecting movement initiation via muscle activity as a trigger for ES during leg movements combined with mechanical support by the robot. Therefore, the current study aimed to compare different threshold estimation methods for the detection of movement intention from muscle activity for actively triggered ES during robot-supported leg movements in sub-acute stroke patients. The performance of different threshold estimations was compared in terms of success rate and user experience.

II. Method

A. Participants

Sub-acute hemiparetic stroke patients were recruited from the local rehabilitation centre. Selection criteria were that they (1) have had a sub-acute ischemic or haemorrhagic stroke (>6 months after stroke), (2) aged 18 years and above, and (3) had a score on the Motricity Index (MI) between 0-25 (for knee and/or ankle). They were excluded if they (1) had a premorbid disability of the lower extremity, (2) had severe cognitive impairments as determined by the involved physician, (3) had a contraindication for mobilization of the lower extremity, like a bone fracture, (4) were pregnant or (5) had a pacemaker. This study was approved by the medical ethical review committee (under registration number NL76919.091.21) and all participants provided written informed consent before participating.

B. Threshold detection methods

In the current study, four different threshold estimation methods based on muscle activity as measured via surface electromyography (sEMG) were evaluated for their suitability as trigger for ES. Two methods were based on previous research with healthy volunteers [9]. Early prototype testing showed that the thresholds used by Petersen et al. (2020) were too sensitive in combination with a newer version of the robot, resulting in premature and persistent triggering of the stimulation. Therefore, the existing methods were adapted slightly to become more robust. Beside the two methods tested previously, two additional estimation methods based on a percentage of the maximum voluntary contraction (MVC) were evaluated in preliminary lab tests on healthy volunteers. Little differences were found between low percentages of the MVC. Furthermore, stroke patients were considered weaker than the tested healthy volunteers, which means that the MVC value will be lower and therefore the difference between low percentages of the MVC will be small. In conclusion, we chose two different percentages of the peak MVC based on the preliminary lab tests. The currently used threshold estimation methods were: (1) rest EMG plus 2 times the standard deviation of the average rest EMG value [SDx2]; (2) rest EMG plus 3 times the standard deviation of the average rest EMG value [SDx3]; (3) rest EMG plus 5% of the peak amplitude of the maximum voluntary contraction [MVC005] and (4) rest EMG plus 10% of the peak amplitude of the maximum voluntary contraction [MVC010].

$$SDx2 = mEMG + SD \cdot 2 \tag{1}$$

$$SDx3 = mEMG + SD \cdot 3 \tag{2}$$

$$MVC005 = mEMG + pMVC \cdot 0.05 \tag{3}$$

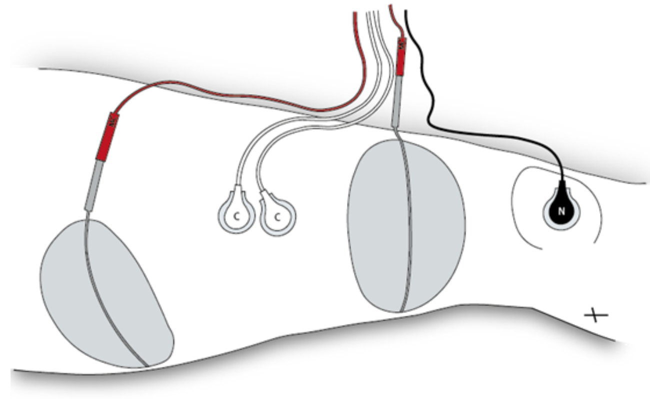
$$MVC010 = mEMG + pMVC \cdot 0.10 \tag{4}$$

The equations for these four different threshold methods can be found in eq. 1-4, in which mEMG stands for the mean resting EMG, pMVC for the peak of the MVC and SD for the standard deviation of the resting EMG. The rest EMG and standard deviation were determined by measuring the sEMG for a two-second interval in which the patient was instructed to relax the muscle. The MVC was determined with the resistance of the robot set to its highest value. The participants were instructed to try to execute one movement with as much force as they could.

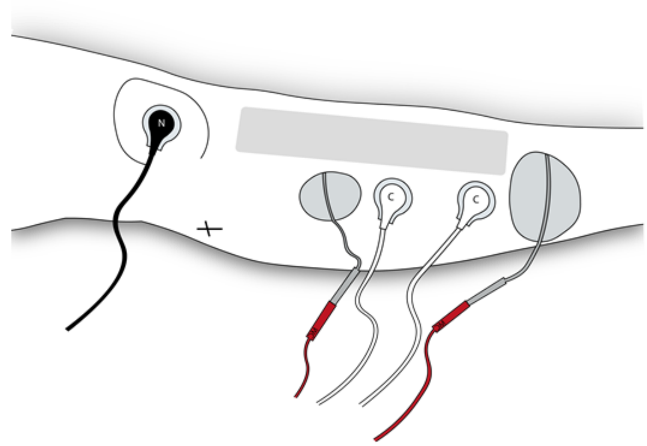
C. Study design and instruments

This was a cross-sectional observational study with a single measurement session. Sets of robot-supported knee extension and/or ankle dorsal flexion movements were performed with different threshold estimations for detection of movement initiation from muscle activity as trigger for ES. The Fugl-Meyer Assessment (FMA) (lower extremity module), MI (lower extremity module), and the Functional Ambulation Categories (FAC) were determined to quantify the ability to walk and the motor function of the lower extremities. In addition, participant characteristics, such as age, gender, time since stroke and affected side were noted as well.

To trigger ES for knee extension, we collected EMG of the m. rectus femoris and for ankle dorsal flexion we collected EMG of the m. tibialis anterior. The mean of the collected EMG was compared against the value calculated with one of the threshold estimation methods. We used a RehaIngest EMG recorder (Hasomed, Magdeburg, Germany) and surface EMG electrodes with a diameter of 10mm. Per movement, a dual-channel electrical stimulator, RehaMove3 (Hasomed, Magdeburg, Germany) was used for the ES. Oval stimulation electrodes with a size of 8 x 13 cm were attached to the leg for the m. rectus femoris and one round electrode with



(a) Overview of the electrode placement for Knee extension. M. rectus femoris is used for stimulation.



(b) Overview of the electrode placement for ankle dorsal flexion. M. tibialis anterior is used for stimulation.

Fig. 1: Overview of the electrode placement for sEMG recording and electrical stimulation. The grey pads (round/oval) were used for stimulation, the white electrode (c) for measuring sEMG of muscles and the black electrodes (n) was used as reference.

diameter 3.2cm and one oval electrode 4 x 6cm for the m. tibialis anterior. An overview of ES electrodes and sEMG electrodes for knee extension can be found in Fig. 1a and for ankle dorsal flexion in Fig. 1b

D. *Study protocol*

Participants were lying supine on a bench, with their trunk slightly raised and a pillow under their head. Before the measurements started the leg was connected to the robot and the target movement was set by the researcher by moving the leg through the desired trajectory, which was recorded by the robot. The amplitude of ES was determined in a participant- and movement-specific way. The amplitude of ES was increased in steps until the target movement was reproduced using ES, while still being comfortable for the participant. As a safety precaution, the ES could be stopped by either the researcher and/or participant by pressing a stop button to turn off the stimulation. After the setup was done, a maximum of eight different conditions were executed per participant. These conditions consisted of evaluating the four different threshold detection methods for the two movements. The number of executed conditions was dependent on the ability and load capacity of the participant. The participant was asked to try to perform the movement, every attempt to trigger ES and/or initiate the movement by the participant was noted. During every attempt, surface EMG was measured and compared to the threshold. If the threshold was reached, ES was initiated to stimulate knee extension or ankle dorsal flexion. When the target movement was completed, the leg was returned to the start position by mechanical assistance from the robot. Per condition, 10-15 attempts were performed.

E. *Outcome measures*

The primary outcome of the current study is the success rate of the intention detection. The intention detection can be seen as the threshold that is successfully reached, which results in the activation of the ES to execute the movement. Furthermore, after every set of attempts, the Visual Analogue Scale (VAS) was used to determine the comfort level of the participant during the condition.

F. *Data analysis*

The success rate of the intention detection was expressed as the percentage of times the ES threshold was reached in relation to the total amount of attempts. VAS scores were noted per condition on a scale from zero to ten, with zero representing no discomfort and a score of ten most imaginable discomfort. Descriptive statistics were used to describe the participant characteristics (such as age, gender, affected side and time since stroke), the intention detection success rate, and VAS scores.

III. Results

Three sub-acute stroke patients were enrolled in the study. Tab. I shows an overview of the general characteristics of the three participants. They had a mean age of 49.3 years; one was male and two were female. The average time post-stroke was 15 weeks (sd: 6.2 weeks) and they all had a Functional Ambulation Categories (FAC) score of 4, indicating that they were able to walk independently without assistance and supervision of a therapist on a flat surface. Two of the participants performed ankle dorsal flexion and one performed knee extension as part of the training with the ROBERT-SAS. Participant 1 (P1) performed ten repetitions per condition and the other two (P2 and P3) performed fifteen repetitions per condition. These inequalities occurred through limited time and load capacity of the patients.

Regarding the results of the primary outcome measure, Tab. II shows the success rate of the intention detection method for the stimulation of ankle dorsal flexion or knee extension. In general, the results show that the success rate of the two methods that were based on the rest EMG plus a proportion of the standard deviation (SDx2 and SDx3) was

TABLE I: General characteristics of the participants

	P1	P2	P3
Age (years)	71	31	46
Time post-stroke (weeks)	21.7	9.4	13.7
Affected side	Left	Right	Left
Gender	Male	Female	Female
Amplitude ES (mA)	26-27	47	34
Motricity Index:			
- knee	25	19	25
- ankle	0	14	25
FMA	11	30	14
FAC	4	4	4
Movement	ankle DF	Ankle DF	Knee extension

DF: Dorsal flexion; FAC: Functional Ambulation Catagories; FMA: Fugl-Meyer Assessment; ES: Electrical stimulation

TABLE II: Success rate per detection threshold in % for each participant and averaged across participants

Method	P1	P2	P3	Average
SDx2	70%	100%	90%	86.7%
SDx3	50%	100%	NE	75%
MVC 005	40%	6.67%	60%	35.6%
MVC 010	60%	0%	NE	30%

SD: standard deviation; MVC: Maximum Voluntary Contraction; NE: Not executed

the highest, with respectively an average of 86.7% and 75% of successfully performed repetitions. The methods based on the rest EMG plus a percentage of the MVC scored lower and were on average 35.6% and 30% for respectively 5% and 10% of the MVC peak.

Tab. III shows the results of the VAS score per participant per condition. In general, the stimulation was experienced as moderately comfortable. Differences in comfort levels between thresholds varied across participants. P1 reported no difference between methods, P2 reported ES to be more comfortable during the MVC-based thresholds, whereas P3 reported higher discomfort during ES with MVC-based thresholds.

IV. Discussion

The current study aimed to compare different threshold estimation methods for the detection of movement intention from muscle activity for actively triggered ES during robot-supported knee extension and ankle dorsal flexion in sub-acute stroke patients. The results from three initial sub-acute

TABLE III: Visual Analoque Scale per particpant per condition

Method	P1	P2	P3
SDx2	5	4	3
SDx3	5	4	NE
MVC 005	5	0	5
MVC 010	5	0	NE

SD: standard deviation; MVC: Maximal voluntary contraction; NE: Not executed

stroke patients showed that methods based on rest EMG plus a proportion of the standard deviation have a considerably higher success rate, of at least 75 percent, compared to the MVC-based method. All three participants perceived ES as relatively comfortable and could be endured well throughout the session. This indicates that it is feasible to reproduce the target movement using EMG-triggered ES, using person-specific ES amplitudes, in combination with robotic support.

A previous study into the threshold value for initiating movement in a robot combined with ES used two threshold calculation methods in healthy volunteers. Both methods were based on the resting EMG plus a proportion of the standard deviation. They found high completion rates for both thresholds and more successful system performance for a threshold of 0.5 times the standard deviation. However, they also found that this threshold was also more sensitive to noise, in terms of the percentage of the stimulation that was triggered prematurely. This can be caused by not relaxing after a repetition as the muscle activity will stay above the threshold. The results found in the study of Petersen et al. 2020 are in agreement with what was found in the current study. This means that the threshold based on the resting EMG plus a proportion of the standard deviation of the rest EMG can be used in both healthy persons and stroke patients.

Other studies that investigated EMG-triggered electrostimulation after stroke mainly focused on upper extremity [10], [11]. They all successfully used threshold values that were based on mean resting muscle activity plus a proportion of the standard deviation, which is in accordance with the current study. Dipietro et al. (2005) showed that EMG-triggered electrostimulation also worked in one case of a severely affected stroke patient [10]. This suggests that the results found in the current study may be translated to more severely affected stroke patients.

There were several limitations to this study that affect the interpretation of our findings. First of all, although informative, the sample size was very small, as this was a first exploratory study towards proof-of-concept. Furthermore, in all participants the lower extremity was only moderately affected by the stroke in terms of functional gait ability and time post-stroke was at least 2 months. It is not known whether the current results can be translated directly to more severely affected stroke patients. Nevertheless, as this study did involve patients in their sub-acute phase, comparable outcomes are expected in patients earlier post-stroke. Also, it should be noted that two of the three participants did show severe limitations in terms of motor function when looking at FMA scores.

In addition, some issues were experienced that provided valuable input for further development of the combined robot-ES system. Those lessons learned related mostly to the robustness of the combination of robotic device and electrostimulator (e.g., ES module and robot sometimes lost connection) and usability issues that became apparent with intensive use (e.g., desire to have real-time visual feedback about muscle activity during movement initiation when setting up ES, instances when ES alone didn't result in movement completion and ES continued without the leg moving until ES turned off after 8 seconds by the system or manually turned off by the participant or tester).

After considering those lessons learned, adjustments to the system were made to improve robustness, add a real-time display of EMG, etc. In addition, based on the results of the initial three participants, the developers designed a more sophisticated Assist-As-Needed (AAN) approach to provide patient-specific support from either robot, ES, both, or none, that can be adjusted from one repetition to the next. This enables rapid changes of type or amount of support with increasing fatigue, co-activation, etc. within and between exercise sessions. Furthermore, the AAN approach enables providing support by robot and/or ES only when needed, emphasizing active contribution by each patient. As a next step, the updated version of the robot + ES system is currently undergoing testing in our lab, aimed at assessing the performance of the combination of AAN robotic support and ES in sub-acute stroke patients.

V. Conclusion

This research aimed to compare different intention detection estimation methods for EMG-triggered ES of the lower extremity of sub-acute stroke patients. The results showed that the method based on the rest EMG plus 2 times the standard deviation had the highest success rate in all three participants and was tolerated relatively well. Although based on a very small sample size, the present findings indicate that using a detection threshold based on resting EMG values as trigger for ES during robot-supported knee extension and ankle dorsal flexion is promising. In addition, this suggests that EMG-triggered ES combined with robotic support is feasible in sub-acute stroke patients with moderate impairments.

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