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A Novel sEMG triggered FES-Hybrid Robotic Lower Limb Rehabilitation System for Stroke Patients

Inga Lypunova Petersen, Weronika Nowakowska, Christian Ulrich, Lotte N. S. Andreasen Struijk

***Abstract* — Stroke is a leading cause of acquired disability among adults. Current rehabilitation programs result in only partial recovery of motor ability for the patients, which has resulted in an ongoing search for methods to improve the rehabilitation approaches. Therefore, this study presents a novel method for early onset of active rehabilitation by combining an end effector robot with surface electromyography (sEMG) triggered functional electrical stimulation (FES) of rectus femoris and tibialis anterior muscles. This rehabilitation system was demonstrated in 10 able-bodied experimental participants. Defining a successful exercise repetition as a fully completed exercise, from start point to end point followed by a return to start point, when FES onset is triggered by the EMG threshold, the results showed that 97% of the exercise repetitions were successful for a leg press exercise and 100% for a dorsiflexion exercise. Furthermore, an FES stimulation current amplitude of 20-53 mA was required for the leg press exercise and 10-30 mA for the dorsiflexion exercise. The resulting generated force was in the range of 43.0-141.2 [N] for the leg press exercise and 5.4-17.6 [N] for dorsiflexion.**

***Index Terms*— Stroke, neuroplasticity, rehabilitation robot, neurorehabilitation, functional electrical stimulation**

I. Introduction

According to the report from the Stroke Alliance for Europe, the incidence of stroke in the European Union in 2015 was equal to 613,148 events, which is expected to increase by 34% to 819,771 in 2035 [1]. Furthermore, stroke is a leading cause of acquired disability among adults, affecting 17 million people worldwide each year [2]. The most common impairment among more than half of all acute stroke patients is functional deficits in motor control [3] - [6], such as hemiplegia [7] and hemiparesis [8]. Just as stroke is occurring more frequently, so is the stroke-related burden of recovery and rehabilitation [3], [4]. There is a widespread agreement that rehabilitation of a bedridden post-stroke patient should begin as soon as possible after the stroke [3]. Physiotherapists provide therapy, which includes a combination of exercises aimed at restoring the functionality of the damaged neural tissue and increasing reorganization of neural pathways to relearn functions that were lost [3] - [5]. Task training, which relies on repeating practice during a single training session with the aim of a clear functional objective of an active motor sequence, has proven to be beneficial [3], [9].

As the standard training method requires involvement of the physical therapist, these sessions rarely consist of active training and can take up to a few hours daily per patient [3], [4], [6], [10], [11]. This results in high burdens in terms of health care costs as well as in terms of labor [10], [11]. Use of mobilization techniques together with the worldwide increase in the prevalence of overweight and obesity [12] associated with risk factors for stroke [13] have led to an increased prevalence of work-related musculoskeletal disorders (WMSDs) for therapists [14]. By aiding the therapist with an adjuvant therapy, labor-saving [15] and cost-effective robot-assistant technology (RT) [16], the therapists' emotional distress may be alleviated and the work-related burden will be relieved [15], [16]. For such robot rehabilitation technology to be optimal, it should provide active rehabilitation where the patients muscles are activated (In this study "active rehabilitation" means that the muscles of the patient are contracting during the exercise either voluntarily or through FES).

Among the wide range of therapeutic rehabilitation methods, which have been developed to improve motor recovery after stroke, active therapy can be obtained through Functional Electrical Stimulation (FES), which enables neuroplasticity in post-stroke patients [5], [17]. A number of studies have provided evidence of sEMG-triggered FES benefits on motor recovery of upper and lower limb function in patients after stroke, such as muscle strengthening, reduction of spasticity and reorganization of neural circuits after stroke [18] - [20].
The underlying principle behind FES assistance is that alternative motor pathways can be recruited and activated by stimuli to assist the stroke-damaged efferent pathways [20]. In order to enable and control simultaneous stimulation of muscle contraction by FES, surface electromyography (sEMG) can be used as a monitoring and control tool to identify intended muscle contractions. sEMG will reflect voluntary muscle activity, which can then be utilized to trigger FES. [19]

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There is a growing evidence that sEMG-triggered FES is more effective than non-triggered electrical stimulation in terms of muscle strengthening, voluntary muscle contraction [2], [21] and promoting more brain plasticity [22].

sEMG-triggered FES can be integrated in RT to directly activate the target muscles using sEMG from partly recruited muscles and assisting the attempted motion through FES, subsequently significantly increasing the effect of the rehabilitation [21].

Some RT applications include different methods for neurorehabilitation among which is sEMG-triggered FES [18], [19]. However, most RTs aim at rehabilitation of the upper extremities [2], [20], [23] or can be used later in the rehabilitation process as they require that the patients have some ability to walk or cycle [2], [17], [20], [21], [23], which may not be the case in the early post-stroke phase.

Studies suggest that a time window may exist where the process of neuroplasticity is more effective. Biernaskie et al. found evidence that a 5-week period of rehabilitation which began 30 days after stroke was far less effective in improving functional outcome and in promoting growth of cortical dendrites than the same neurorehabilitation therapy started 5 days after an infarct [24] which indicates the importance of early rehabilitation. Thus, there is a need for active RT solutions in the eraly post stroke phase where the patients are often bedridden.

At present, the rehabilitation robot ROBERT®, developed by Life Science Robotics [25], assists in active and passive mobilization of the lower extremities, to engage post-stroke patients in early rehabilitation, as it supports therapy for bedridden patients, but it does not support activation of paralyzed muscles in the post stroke phase. The above-mentioned advantages of sEMG-triggered FES in neurorehabilitation suggest that combining sEMG-triggered FES with ROBERT® could be beneficial for post-stroke rehabilitation, as it will engage weakened or paralyzed muscles; thus, achieving early active post-stroke therapy of the lower limbs. Therefore, this study implemented and tested a novel hybrid robotic rehabilitation system based on sEMG-triggered FES support of lower limb rehabilitation with the robot ROBERT®.

II. METHODS

A. System architecture

The overall system consisted of a control system, an sEMG acquisition device, an FES device, the rehabilitation robot ROBERT®, the system operator and the experimental participant as described below (Fig. 1).

1) Operator: The operator's responsibility was to operate the control system, running on a laptop, and record the exercise trajectory with the rehabilitation robot ROBERT®.

2) Control System: In order to enable the control and interaction between the sEMG acquisition device, the FES device, the rehabilitation robot ROBERT® and an experimental participant, the control system was implemented in MATLAB©, running on a laptop (Fig. 2). The control system enabled data acquisition sessions via NI USB-6221 (National Instruments, USA), which included sEMG acquisition (1,000 Hz sampling rate), sending pulses generated in MATLAB© to the FES device (10,000 Hz sampling rate) and sending commands to and receiving messages from the robot ROBERT® via UDP and TCP protocols. Furthermore, a sound stimulus notifying the experimental participant to start the exercise, was implemented in the control system.

3) sEMG acquisition: sEMG was used for real-time monitoring in order to trigger FES when the recorded sEMG exceeded a certain threshold value. The sEMG analogue amplifier used in this study was a CED1902 amplifier (Cambridge Electronic Design Limited). The sEMG was high pass filtered with a cutoff frequency of 20 Hz and low pass filtered with a cutoff frequency of 1,000 Hz and additionally filtered with a notch filter for the 50 Hz power line noise. The gain was set to 1,000. The energy of the sEMG signal was concentrated below 300 Hz and the sampling frequency was set to 1,000 Hz, based on the analysis of sEMG signals recorded in a pilot study. Then the sEMG was bandpass filtered between 20 Hz and 300 Hz in the control system and passed through another notch filter for the 50 Hz power line noise. Based on the literature [26], [27] and a pilot study, two sEMG thresholds (th1 and th2) were defined as shown in equations 1 and 2. At the beginning of each exercise session, the sEMG threshold was estimated by measuring the resting sEMG for two seconds from rectus femoris and tibialis anterior, respectively. This was done by calculating the mean of the rectified full wave EMG for a 2 second interval of the resting sEMG. During the exercise, a mean of the rectified full wave EMG was found for 100 sample sequences and compared to the threshold.

$$\mathrm{th1} = \mathrm{mean}(|\text{resting sEMG}|) + \frac{\mathrm{SD}(|\text{resting sEMG}|)}{2} \tag{1}$$

$$\mathrm{th2} = \mathrm{mean}(|\text{resting sEMG}|) + \frac{\mathrm{SD}(|\text{resting sEMG}|)}{3} \tag{2}$$

For recording of sEMG signals from rectus femoris and tibialis anterior, two active electrodes (Ambu® Neuroline 720 electrodes) were applied in a bipolar configuration for each muscle (Fig. 3).

4) *FES:* For the generation of electrical stimulation pulses, a STMISOLA stimulator (Biopac Systems, Inc.) was used. The electrical stimulation was applied to the rectus femoris and the tibialis anterior, respectively (Fig. 3). Based on the literature [28], [29], [30], [31] and the evaluation of FES parameters for lower extremities in a pilot study, a unipolar square pulse with a pulse width of 200 µs per phase with a pulse frequency of 50 Hz and a current amplitude varying from 10 mA to 53 mA was applied.

The electrodes used for FES were Dura-Stick Premium 50x90 mm for rectus femoris and Dura-Stick Premium 32 mm for tibialis anterior. Prior to the exercise session, the current amplitude was adjusted individually for each participant. The maximum current amplitude which was not painful yet activating the rectus femoris and tibialis anterior muscles to produce the expected muscle movement, was then chosen [31].

5) *Rehabilitation robot ROBERT®:* A rehabilitation robot developed by the Danish company Life Science Robotics ApS was employed in this study [25]. The robot was classified as an

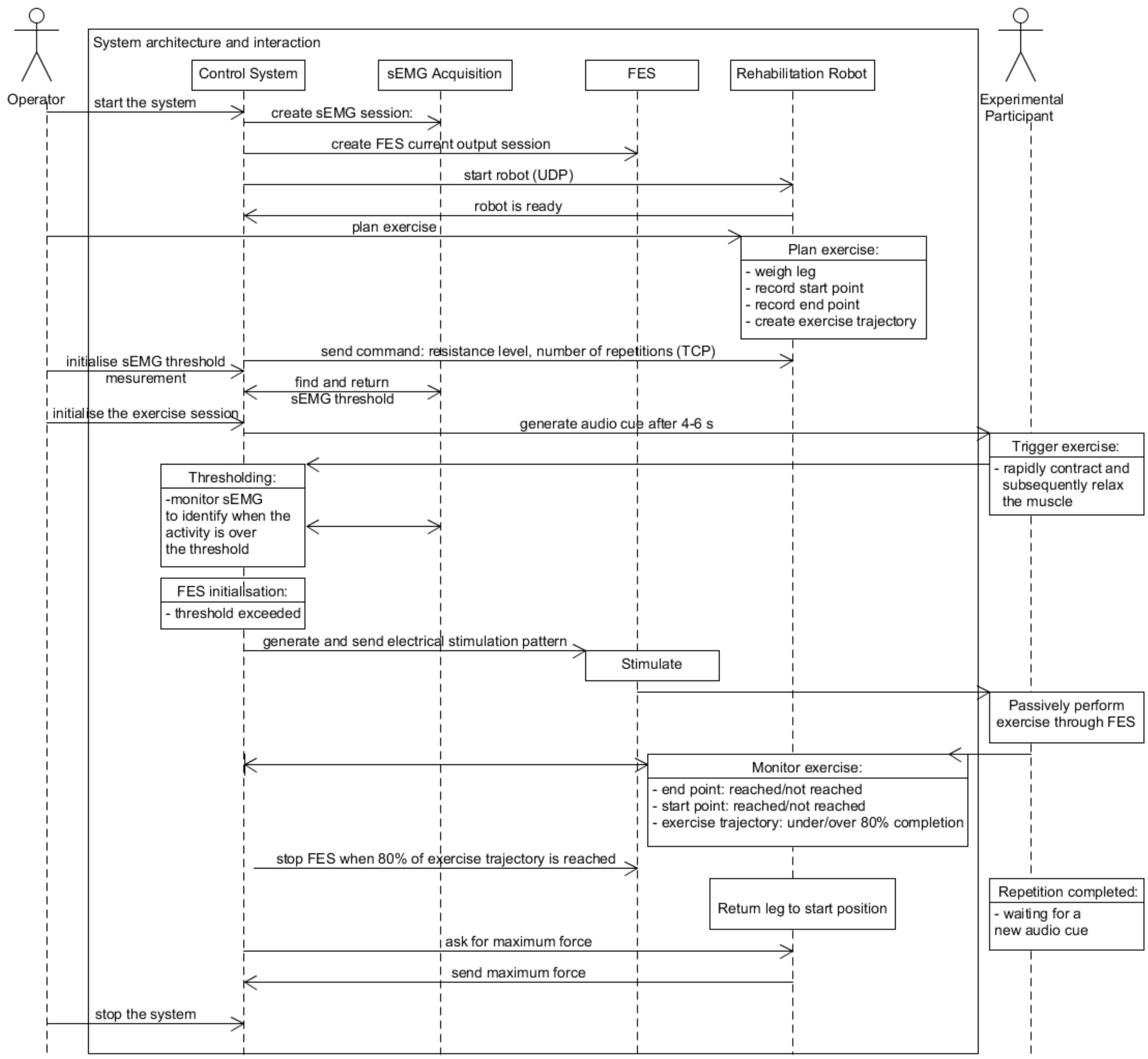

Fig. 1. The successful scenario for one exercise session which is identical for upper as well as lower leg training and where the interaction between the system components sEMG acquisition device, FES device, the rehabilitation robot and the experimental participant is controlled by the control system. The top row shows the system components.

active therapeutic equipment of class IIa according to EN 60601-1. ROBERT® was used to enable the leg press and the dorsiflexion exercises for each experimental participant and provided five levels of spring like resistance. The values of resistance levels were found using Hooke's law (Equation 3) where F represents the force [N], k is a spring constant [N/m] and x is the displacement [m].

$$F = -kx \text{ [N]} \quad (3)$$

The resistance levels increase with the spring constant, k, increasing from level to level. The robot had six degrees of freedom and corresponding spring constants (Fig. 4). As both the leg press and the dorsiflexion exercises were performed in the YZ-plane, the spring constants, k, used in this study were for level one and were 50 and 300 [N/m], respectively (Fig. 4). The displacement was different for each experimental participant as it depends on the anatomical differences.

The exercise trajectory was defined by manually moving the leg with the robot arm from a start point to an end point for the leg press and the dorsiflexion, respectively (Fig. 5). The start point for the leg press exercise was defined as the position, in which the experimental participants were lying in a Semi-Fowler's position at 30 degrees with the knees and hips bent 90 degrees (Fig. 3 b). The end point was defined as the position in which the leg was fully extended, and the knees and hips were at almost 0 degrees, without hyperextending the knee (Fig. 3 b). Start point for the dorsiflexion exercise was defined as the position, in which the experimental participants were lying in the Semi-Fowler's position with the leg fully extended, knees

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and hips placed at 0 degrees and the foot in neutral position. The end point was defined as the position 10-20 degrees anterior to neutral position, as a natural range for dorsiflexion

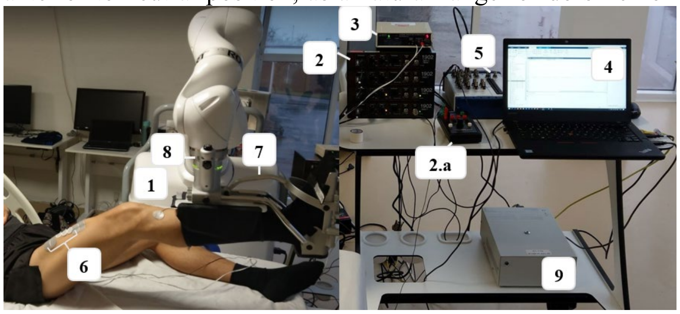

Fig. 2. The system components: the rehabilitation robot ROBERT® (1), the sEMG acquisition device (2 and 2.a) and the FES device (3) were controlled via the control system implemented in MATLAB, running on a laptop (4). Communication between the control system and the system components was enabled through NI USB-6221 (5). FES and sEMG electrodes (6) were placed according to SENIAM recommendations for tibialis anterior and rectus femoris. The fixture (7) was placed and adjusted to the size of the lower leg and foot and prepared to be attached to the robot's arm coupling (8). The isolated power supply (9) was used to ensure safety for the participant in the experimental setup.

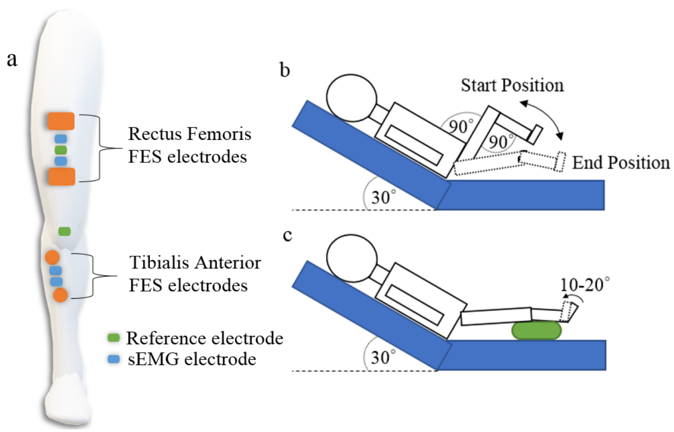

Fig. 3. a: FES electrodes, bipolar sEMG electrodes and reference electrodes for the sEMG-signal acquisition and stimulation were placed on tibialis anterior and rectus femoris. b: Definition of the start and end points of the trajectory for the leg press exercise. c: Definition of the start and end points of the trajectory for the dorsiflexion exercise. The green oval represents a pillow, which was placed under the experimental participant's lower leg to enable free movement of the foot.

motion (Fig. 3 c) [32].

In the rehabilitation robot's program, the end point was defined as at least 80% of the planned exercise trajectory as described above and with no movement for 500 ms for both leg press and dorsiflexion exercise. These parameters were chosen to ensure the completion of the exercise repetition.

B. Experimental participants

This study was approved by the North Denmark Region Committee on Health Research Ethics. Ten able-bodied experimental participants (five male and five female, 23-58 years old) participated in the study after giving written informed consent. The inclusion criteria were: 18 years old or older, outside of BMI Obesity class III, able to fully extend the knee of the dominant leg, able to fully perform a dorsiflexion of the

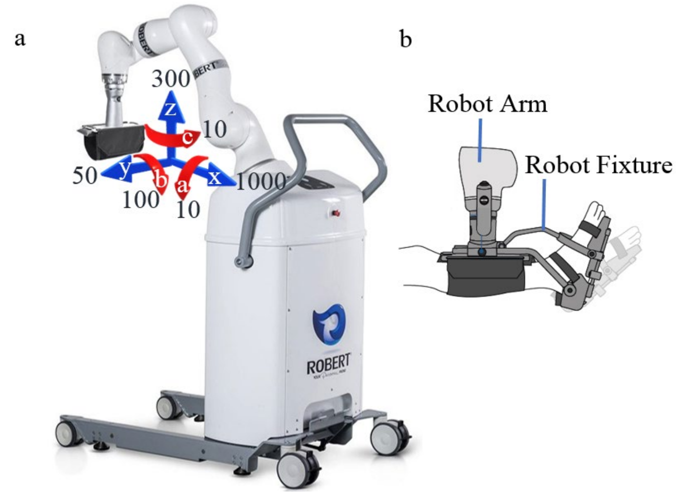

Fig. 4. a: The axis (x,y,z) of the robots arm and the corresponding spring constants of ROBERT® of the resistance level 1. b: The robot arm and the robot fixture.

foot of the dominant leg, able to cooperate, communicate and understand instructions, able to tolerate electrical stimulation.

The exclusion criteria were neurological or musculoskeletal illnesses affecting the motor function in the lower limbs, skin infection or irritation at the placement site of the FES and sEMG electrodes, pacemaker, pregnancy, mental diseases, and lack of ability to cooperate.

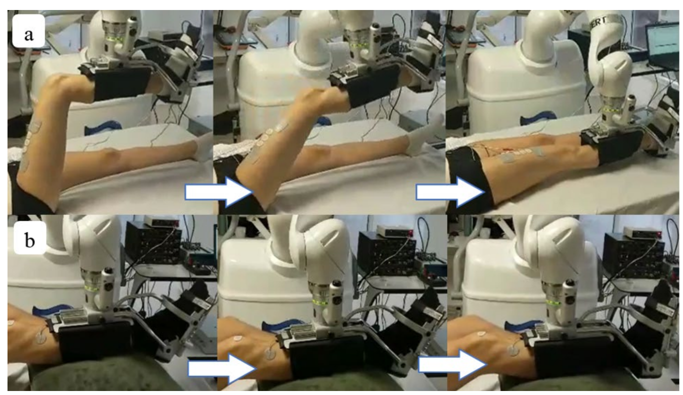

Fig. 5. a: The exercise trajectory for the leg press exercise. b: The exercise trajectory for the dorsiflexion exercise.

C. Experimental procedure

The skin surface of the experimental participants was prepared prior to the attachment of the electrodes according to the SENIAM guidelines for skin preparation [33]. The SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) was developed by the Biomedical Health and Research Program (BIOMED II) of the European Union, which resulted in recommendations for the procedure of sensor placement and signal processing methods for sEMG [34]. The sEMG electrodes were placed parallel to the muscle fibers over the muscle belly of rectus femoris and tibialis anterior, as recommended in the SENIAM guidelines [33]. FES electrodes were placed based on the knowledge of anatomy and supported by the Altastim guidelines [34]. The active FES electrode for the rectus femoris was placed proximally and towards the lateral side of the muscle. The indifferent electrode was placed at the midline and centered in the rectus femoris belly. For the

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tibialis anterior, the active FES electrode was placed at the beginning of the muscle belly, distally from the fibular head. By following the muscle belly, the indifferent electrode was placed close to the tibia, about 2/3 of the way further down the shin. Positioning and orientation of the FES and sEMG sensors were preceded by palpation of muscles when the muscles were slightly contracted (Fig. 3). Each experimental participant was to complete 40 repetitions with the same resistance (level 1). Each exercise session consisted of 10 repetitions of either a leg press (Fig. 5 a) or dorsiflexion (Fig. 5 b) exercise, with the sEMG threshold 1 (th1) and 10 repetitions with the sEMG threshold 2 (th2).

The experimental participants were instructed to rapidly contract the muscles and subsequently relax the muscle, every time a sound stimulus was heard, in order to initialize the FES. The sound stimulus was generated randomly after 4 to 6 seconds following each completed exercise repetition. Once the sEMG signal exceeded the threshold, the FES started in order to complete the repetition. Once the end point of the exercise trajectory was reached, the FES was stopped, and the leg was returned to the start position by the rehabilitation robot. The experimental participant then waited for the next sound stimulus. The exercise session was completed once 10 repetitions had been conducted and a 5 min break was held after each completed exercise session.

D. Statistics

The statistical data analysis was performed in IBM SPSS® Statistics (IBM Corporation, USA). The number of repetitions triggered by the experimental participants was analyzed using Wilcoxon Sign-Rank Test with a 5% level of significance. The average time from the sound stimulus to the muscle stimulation initialization (FES onset), was investigated using a paired samples t-test. A Pearson product-moment correlation and a linear regression were applied to analyze the correlation between the current amplitude for recruitment of the rectus femoris and the tibialis anterior muscles across all the experimental participants. A Spearman rank-order correlation test was applied to evaluate the correlation between the current amplitude level and the maximum force generated by the stimulated muscle. The correlation between sex and current amplitude level, the correlation between sex and the maximum generated force, and the correlation between sex and sEMG threshold for the leg press and the dorsiflexion, respectively, were evaluated using a one-way ANOVA. The choice of statistical tests was based on the type of data and an evaluation of the normality distribution.

III. RESULTS

The hybrid sEMG-triggered and FES-supported robotic rehabilitation system in this study performed with exercise completion rates of 99% for both the leg press exercise and the dorsiflexion exercise excluding one outlier, P8, who could not tolerate the required stimulation current amplitude.

For the leg press exercise, 97% and 100% of the exercise repetitions were completed for th1 and th2, respectively (Table II). The remaining 3% of the leg press exercise with th1 (two repetitions for P9 and one repetition for P10) were visually assessed as not fully completed because the experimental participants P9 and P10 did not receive the specified current stimulation due to a suspected issue with the FES module.

For the dorsiflexion exercise, 100% of the exercise repetitions were completed with both th1 and th2 (Table II).

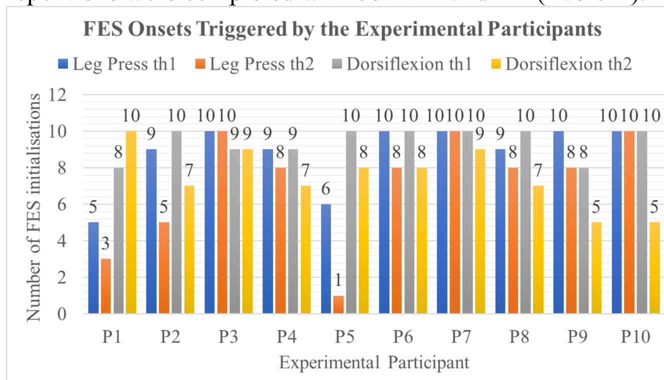

Fig. 6. Each bar individually represents the number of FES onsets, triggered by each experimental participant, for each exercise and sEMG threshold (th1 and th2). All the prematurely triggered repetitions (by noise) were excluded from the data in the figure.

This result was obtained with the exclusion of experimental participant P8 who was an outlier, as the current amplitude level became too painful whilst it was still insufficient for the completion of the leg press exercise (20 mA) and of the dorsiflexion exercise (10 mA). Therefore, a complete exercise was impossible to conduct for P8 with the resistance yielded by the robot. For the leg press exercise, FES onsets were triggered in 88% and 71% of the attempts for th1 and th2, respectively (Fig. 6 and Table II).

TABLE I
AVERAGE TIME FROM THE SOUND STIMULUS TO THE FES ONSET FOR THE TH1 AND TH2 DURING THE LEG PRESS AND DORSIFLEXION EXERCISE FOR EACH EXPERIMENTAL PARTICIPANT. LP: LEG PRESS, DF: DORSIFLEXION

Threshold	Mean ± Standard Deviation [s]	
	LP	DF
Th1	0.16±0.03	0.15±0.01
Th2	0.16±0.02	0.15±0.02
Total (Th1 and Th2)	0.16±0.24	0.15±0.03

TABLE II
AVERAGE NUMBER OF REPETITIONS COMPLETED, FES ONSETS AND CURRENT AMPLITUDE FOR THE LEG PRESS AND THE DORSIFLEXION EXERCISE

	Leg Press		Dorsiflexion	
	th1	th2	th1	th2
Repetitions Completed	97%	100%	100%	100%
FES Onsets (not premature)	88%	71%	94%	75%
Current Amplitude [mA] (Mean ± SD)	36.6 ± 10.1		20.0 ± 10.0	

An FES onset occurring less than 168 ms after the sound stimulus for the leg press exercise and less than 190 ms for the dorsiflexion exercise was assessed as premature as the average reaction time from an audio stimulus to the EMG onset for able-bodied individuals is 208 ± 39.6 for the rectus femoris muscle [35] and 220 ± 30 for the tibialis anterior muscle [36]. For the dorsiflexion exercise, 94% and 75% of the of the FES onsets, triggered by the experimental participant, were completed with th1 and th2, respectively (Fig. 6 and Table II). The remaining

6% for th1 and 25% for th2 were triggered prematurely. Wilcoxon Sign-Rank Test elicited a statistically significant difference between th1 and th2 FES onsets for both the leg press ($p = 0.017$) and the dorsiflexion ($p = 0.023$) exercise. The statistical analysis of the time from the sound stimulus to the FES onset, was performed only on the successfully completed FES onsets. The average time from the sound stimulus to the FES onset did not significantly depend on the sEMG threshold for the leg press exercise ($p = 0.333$) (Fig. 7 top). On average, the time from the sound stimulus to the FES onset was 0.97 s for th1 and 1.05 s when th2 was applied. This dependency of the time, from the sound stimulus to the FES onset, on the sEMG thresholds was not significant for the dorsiflexion exercise ($p = 0.131$), as the average time was 1.08 s and 0.96 s for th1 and th2, respectively (Fig. 7 bottom).

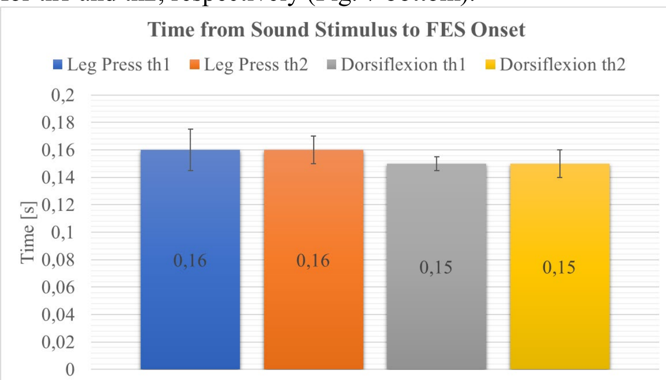

Fig. 7. Each bar represents mean and standard deviations of the time from the sound stimulus to the FES onset with th1 and th2, respectively.

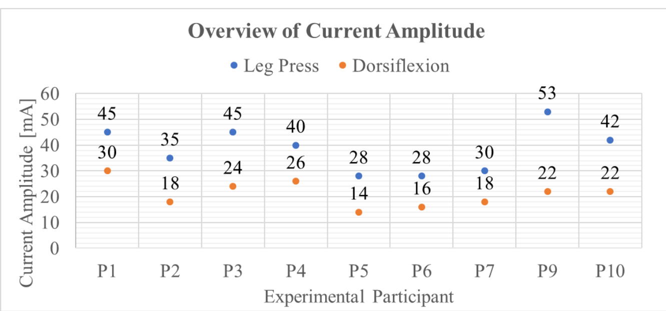

Fig. 8. Current amplitude values required to perform the leg press and the dorsiflexion exercise for each experimental participant.

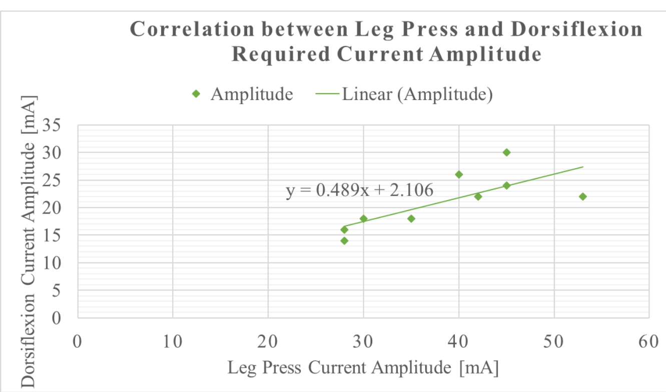

Fig. 9. Correlation between required current amplitudes for the leg press and dorsiflexion exercises and the regression equation;, x represents leg press current amplitude and y represents dorsiflexion current amplitude. Each point in the plot represents a particular participant.

The average current amplitude required to perform the leg press exercise was found to be 36.6 ± 10.1 mA and 20.0 ± 6.0 mA for the dorsiflexion exercise (Fig. 8 and Table II)).

A strong, positive correlation appeared within the individual experimental participants between the required current amplitude for performing the leg press exercise and the required current amplitude for performing the dorsiflexion exercise, which was statistically significant ($r = 0.741$, $n = 9$, $p = 0.022$, Fig. 9).

No statistical significance was found for the correlation between sex and the current amplitude level for neither the leg press exercise ($p = 0.231$) nor for the dorsiflexion exercise ($p = 0.222$).

Furthermore, no statistical significance was found for the correlation between sex and sEMG threshold values for the leg press exercise ($p = 0.258$) and the dorsiflexion exercise ($p = 0.467$).

The generated force was in the range of 43.0-141.2 [N] for the leg press exercise and 5.4-17.6 [N] for the dorsiflexion exercise.

IV. DISCUSSION

The current study investigated a method for robot-based rehabilitation using sEMG-triggered FES proposed as a solution for early rehabilitation of bedridden stroke patients. The effect of using two different thresholds for the sEMG-triggered signal was investigated. For the leg press exercises, 97% of the exercises were completed while applying th1. The reason for the remaining 3% not being completed may be explained by an insufficient stimulation current amplitude, rather than the choice of the sEMG threshold as this was reported by the experimental participants P9 and P10. However, the percentage of prematurely triggered FES onsets depended on the choice of threshold. As shown in the study, th1 was less sensitive to noise triggering and unintentional FES triggering by the experimental participants. The evaluation of the FES onsets indicates that the choice of threshold is an important factor to consider in the implementation of sEMG-triggered FES, as a statistical significance was found between the system performance with th1 and th2 for both exercises. Even though the system performance with th1 was more successful than with th2, with an 86% success rate for the FES onsets for the leg press exercise and 95% for the dorsiflexion exercise, threshold th1 was not suitable for all the experimental participants due to premature FES onsets. This indicates that further investigation of this parameter could be useful to achieve that 100% of the FES onsets are triggered by the experimental participants. Still, for a stroke patient it may in some cases be difficult to exceed th1. The time, from the sound stimulus to the time when the sEMG triggered threshold was exceeded, was also investigated in this study. A short duration between an intent of motion and an actual motion is important for facilitation of neuroplasticity and thus for the rehabilitation outcome [5]. The results for the leg press exercise show that the shortest time, from the audio cue to the sEMG triggered threshold was exceeded, was 0.41 s (for experimental participant, P5, Fig. 6). This time includes the perception of the sound stimulus, the generation of an intent to move, sending the signal from the brain to the upper leg, recruitment of sufficient fibers to exceed the sEMG threshold and the processing of the sEMG during thresholding. For the dorsiflexion exercise, the shortest time from the sound stimulus until the sEMG triggered threshold was exceeded was 0.65 s (for experimental participant P4, Fig. 6).

The reason that this time was longer than for the leg press exercise could be that the participants found it harder to contract the tibialis anterior muscle, and consequently exceed the sEMG threshold without performing any movement when compared with contracting the rectus femoris muscle. Further, the neural signals have to travel for a longer time to reach the tibialis anterior muscle than to reach the rectus femoris. The variation in-between the experimental participants of the time from the sound stimulus to the sEMG triggered threshold was exceeded, may partly be explained by the differences in the ability to react to the sound stimulus among the experimental participants due to, e.g. concentration. There was no correlation between the generated maximum force and the current amplitude level for either of the exercises. This may partly be due to the anatomical differences between the individual experimental participants as the maximum generated force depended on the length of the trajectory of the performed motion, which was adapted to each experimental participant individually. The results of this study paves the way for a crucial early post-stroke onset of active rehabilitation of the lower limbs while the patients is still bedridden and the end-effector based robotic arm with the 6 degrees of freedom used in this study allows for a wide range of personalized exercises. The method may be used to prepare a patient for a later robotic gait rehabilitation therapy [37].

V. CONCLUSION

This study described the implementation and test of a novel hybrid robot - FES based rehabilitation system with sEMG-triggering. The proposed system allows for active training by FES activation of leg muscles to facilitate exercising against a spring-like opposing force provided by the robot. The system consisted of a control system, an sEMG acquisition device, an FES device and a rehabilitation robot, ROBERT®. The system was tested with 10 able bodied experimental participants and the results showed that 97% and the 100% of the exercise repetitions were successful for the leg press exercise and the dorsiflexion exercise, respectively. The choice of sEMG triggered threshold was an important factor in achieving a high success rate. The FES stimulation current amplitudes were in the range of 20-53 mA for the leg press exercise and 10- 30 mA for the dorsiflexion exercise, and the resulting generated force was in the range of 43.0-141.2 [N] for the leg press exercise and 5.4-17.6 [N] for the dorsiflexion exercise. Future work will address the induced effect of this system on neuroplasticity and on the functionality of individuals with stroke.

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