Passive Reach and Grasp with Functional Electrical Stimulation and Robotic Arm Support

Ard J. Westerveld, Alfred C. Schouten, Peter H. Veltink, and Herman van der Kooij

Abstract— **Rehabilitation of arm and hand function is crucial to increase functional independence of stroke subjects. Here, we investigate the technical feasibility of an integrated training system combining robotics and functional electrical stimulation (FES) to support reach and grasp during functional manipulation of objects. To support grasp and release, FES controlled the thumb and fingers using Model Predictive Control (MPC), while a novel 3D robotic manipulator provided reach support. The system's performance was assessed in both stroke and blindfolded healthy subjects, where the subject's passive arm and hand made functional reach, grasp, move and release movements while manipulating objects. The success rate of complete grasp, move and release tasks with different objects ranged from 33% to 87% in healthy subjects. In severe chronic stroke subjects especially the hand opening had a low success rate (<25%) and no complete movements could be made. We demonstrated that our developed integrated training system can move the passive arm and hand for functional pick and place movements. In the current setup, the positioning accuracy of the robot with respect to the object position was critical for the overall performance. The use of a higher virtual stiffness and including feedback of object position in the robot control would likely improve the relative position accuracy. The system has potential for post-stroke rehabilitation, where support could be reduced based on patient performance which is needed to aid motor relearning of reach, grasp and release.**

I. INTRODUCTION

Stroke survivors often have a diminished arm and hand function, which reduces their ability to interact with objects, like drinking or opening a door. Rehabilitation of arm and hand function is important to increase functional independence of stroke subjects. To assist the rehabilitation process, a single rehabilitation solution, which combines reach support with grasp and release training is desirable.

In the past decades robotic technology has emerged to aid stroke rehabilitation. Robots are particularly useful to train highly repetitive tasks, which do not require the continuous presence of a therapist. Many robotic systems capable of supporting or training the arm during reach are available [1]. Some robotic systems to support the hand have been developed [2]. However, hand robotics require complex mechanisms and is therefor not attractive for integrated hand and arm training, especially not in a home environment.

Besides therapeutic robotics also functional electrical stimulation (FES) can restore hand function in stroke survivors. FES of finger and thumb muscles can be beneficial for stroke subjects in relearning functional grasp and release movements [3]. However, current commercially available systems use an open loop approach, which limits performance and requires continuous user input [4]. To increase training independence, an approach for training without the need for a therapist being continuously present is preferred. Recently, we have developed a Model Predictive Control (MPC) approach to selectively control fingers and thumb for grasp and release with FES [5]. The strength of this approach is the use of a personalized model relating the stimulation level to the resulting movement to overcome the high variability between subjects [6]. In addition, this method has potential for application in an automated system allowing for therapist-independent training.

The overall goal is to develop an integrated post-stroke training environment for home use by combining robotic arm support and FES support for grasp and release. For relearning after stroke a high level of patient involvement is required [7], therefore a training system should focus on adapting support to the ability of the individual patient [8,9]. However, as a first step, we will focus on full support of movement (in which the subject is passive) in healthy subjects and chronic stroke subjects. The aim of this paper is to demonstrate the feasibility of a combined robotics-FES rehabilitation system for full support of functional object manipulation tasks. Full support will be the most challenging from a technical point of view and is therefore considered here.

II. METHODS

A. Subjects

Two stroke subjects (S1-S2) and two healthy subjects (H1-H2) participated, see Table I. The affected side for the stroke subjects and the dominant side for the healthy subjects was supported. The study was approved by the local ethics committee and all subjects gave written informed consent.

TABLE I. CHARACTERISTICS OF THE PARTICIPATING SUBJECTS

	S1	**S2**	**H1**	**H2**
Age	62	67	25	28
Gender	M	M	M	M
Hand	R	R	R	R
ARAT	3	11	n.a.	n.a.
Months +stroke	160	112	n.a.	n.a.

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A.J. Westerveld, A.C. Schouten, P.H. Veltink and H. van der Kooij are with the MIRA Institute for Biomedical Engineering and Technical Medicine, University of Twente, 7500 AE Enschede, The Netherlands (e-mail: a.c.schouten@tudelft.nl).

A.C. Schouten and H. van der Kooij are also with the Department of Biomechanical Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands.

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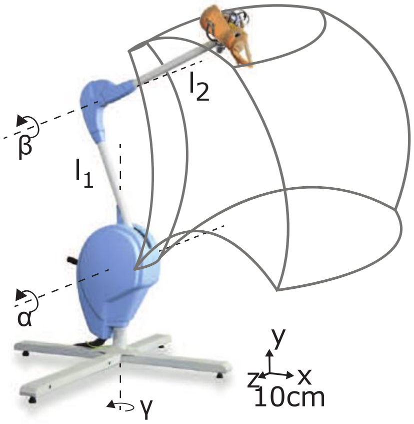

Figure 1. Robotic device used to position the arm in space [10]. The active rotational axes are indicated with the dotted lines. The subject's arm is supported at the lower arm using an arm cuff; the device provides adjustable gravity support and guidance in the preferred movement direction. The range of motion is indicated by the grey lines.

B. .Experimental setup

1) Robotic device for reach support

A custom-built robotic device was recently developed (Demcon, Enschede, The Netherlands) [10]. This device (see Fig. 1) is a 3D end effector, which compensates gravitational forces passively and provides active guidance with damper based drive trains. These two key features make the device inherently safe by the use of low power motors and decoupling of the motors and the load. In addition, the device is compact, has low weight and allows for fast donning and doffing.

The device can apply forces to the subject's arm using three active and three passive degrees of freedom. An adjustable spring, mounted parallel to the actuator of the β axis, passively compensates for the weight of the subject's arm. The rotation of links l_1 and l_2 are actuated with two additional actuators mounted in the base. At the end point a passive gimbal is mounted between the linkage and the arm cuff, which allows for arm rotations relative to the linkage. A six degrees of freedom force sensor mounted at the end of the linkage measures the interaction forces between the arm and the linkage. With the encoders on the active axes and potentiometers on the passive gimbal the arm and hand positions are obtained. The robot's embedded computer (Bachmann electronic GmbH, Feldkirch, Austria) received reference force setpoints from an xPC target computer (The Mathworks, Natick, USA).

2) MPC and FES to support grasp and release

We recently developed a model predictive controller (MPC) for electrical stimulation of finger muscles to facilitate grasp and release [5]. The same method was applied in the current study to control opening and closing of the hand. The obtained system model was used by the MPC [11] to calculate the optimal stimulation amplitudes in order to reach the reference finger angles.

Two custom-built electric stimulators (TIC Medizin, Dorsten, Germany), each having three independent stimulation channels, stimulated the finger and thumb muscles. In total nine electrodes were placed. Three stimulator channels were used for targeting thumb muscles (abductor pollicis longus, opponens pollicis and flexor pollicis brevis), the other three channels were used through a multiplexer for targeting both the flexor digitorum superficialis muscle (three electrodes) and the extensor digitorum communis electrodes muscle (three electrodes). During grasp tasks the flexor electrodes were activated and during release tasks the extensor electrodes were activated. The electrodes were placed at positions evoking selective movement of individual fingers to allow for more selective finger control, see Fig. 2. As the ring and little finger were less selective and often respond simultaneously, they were targeted with a single electrode.

A VisualEyez (Phoenix Technologies, Burnaby, Canada) motion capture system was used to track positions of active LED markers on hand and fingers. Three markers were based on the back of the hand to represent the hand coordinate frame. In addition, two markers were placed on the proximal phalanges of each finger. From these markers metacarpophalangeal (MCP) joint angles were calculated. For the thumb angles in the plane of the coordinate frame (flexion/extension) and perpendicular to the coordinate frame (abduction/adduction) were calculated.

The measured marker motions were sent to the xPC target computer. The MPC system was implemented on this computer using the marker motions to calculate finger angles and control the fingers towards reference angles. Together with the generation of set point forces for the robotic manipulator, the xPC target computer thereby provided synchronous control of reach, grasp and release.

C. Experimental protocol

Initially, the electrodes were placed on the target muscles, based on visual inspection of the evoked responses. In addition, maximum stimulation amplitudes were determined for all electrodes. The maximum was determined by occurrence of one of the following three events: subject discomfort, crosstalk to other muscles or saturation of the response, which was in general the first event to occur. When all electrode positions were determined, the arm was fixed in the cuff of the robotic manipulator and the passive weight compensation was adjusted for the subject's arm weight.

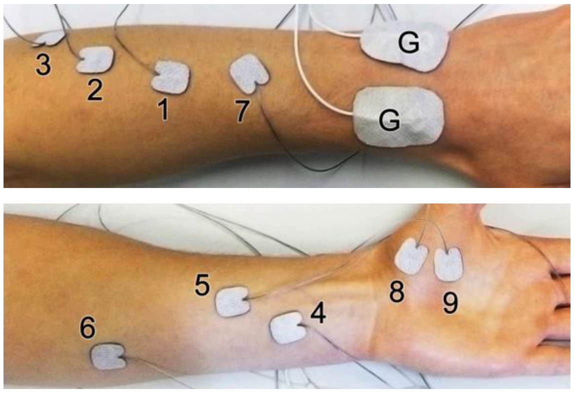

Figure 2. Overview of electrode placement on the dorsal (a) and palmar side (b) of the arm and hand. Electrodes are placed above the finger extensors (1..3), finger flexors (4..6), abductor pollicis longus (7), opponens pollicis (8) and the flexor pollicis brevis (9). Two ground electrodes (G) were used for each of the two stimulator device.

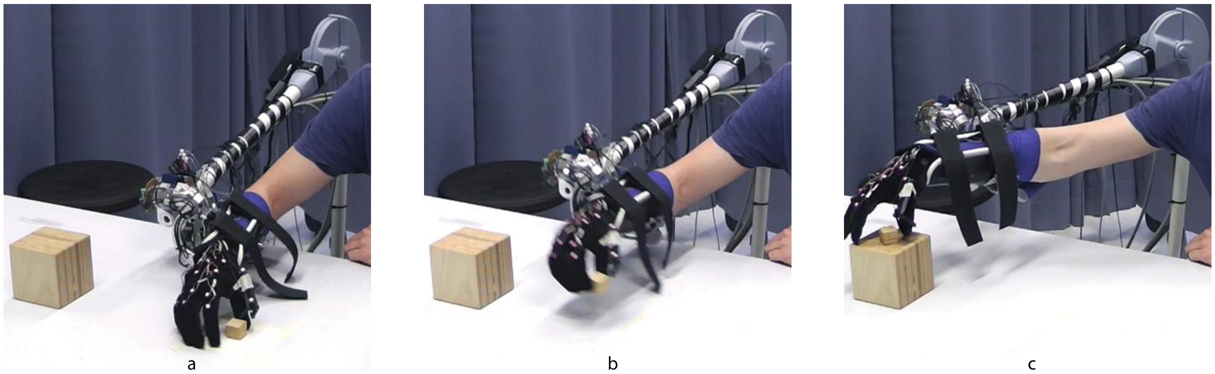

Figure 3. Example of the controlled movement in a healthy subject: a) reach to grasp, b) grasp and move and c) objects release.

Subsequently, an initialization procedure was started to obtain a subject specific model relating the input stimulation amplitude to the resulting finger movement. During this procedure each electrode was activated with random stimulation amplitudes up to the determined maximum while the subject was relaxed. The robot was in a fixed position slightly above the table in front of the subject. This position was later used as a starting position for the movements.

The Action Research Arm Test (ARAT) [12] was used as a test bed for passive grasp and release movements. Four objects of the ARAT (the wooden ball (Ø 7.5 cm) and three cubes: 2.5 cm, 5 cm and 7.5 cm) were selected to evaluate the system with objects of different weight, size and shape. The respective weights of the objects were 0.14 kg, 0.01 kg, 0.09 kg and 0.3 kg, for the ball and the cubes ordered by increasing size. Coordinates representing three positions were pre-programmed into the robot: A) a starting position, B) a position were the ARAT objects were initially placed (on the table in front of the subject), and C) a target position were the objects had to be moved to.

The reference trajectories followed a minimum jerk profile to move between two defined positions with a predefined duration. A fixed virtual stiffness of 100 N/m was implemented to let the force controlled robot guide the arm towards the reference trajectory based on the measured position.

1) *Task specification*

During all tasks the subjects were asked to relax. The healthy subjects were blindfolded to prevent voluntary interference. Tasks were repeated five times for each object for both fast movement (5.5 seconds in total) and slow movement (24 seconds in total). The movement was divided in six subtasks:

1. move from the start position to the object
2. open the hand for grasp
3. close the hand while holding the robot in position
4. move and hold the object
5. position the hand for release, and
6. release the object.

First the robot was set to keep the arm in the starting position. Next, the robot and MPC were set to follow reference trajectories according to the described subtasks. Subtasks 1 and 2 overlapped in time to increase smoothness of movement. After object release the hand was moved back to the starting position to be ready for the next trial. When the object was grasped successfully and released at the target position, the trial was marked successful. Otherwise, the subtask on which the movement failed was logged. When the robot had returned to the starting position, the operator replaced the object for the next object.

D. *Recordings and data analysis*

The primary outcome measure was the success of the functional object manipulation task for the selected ARAT objects: wooden ball (Ø 7.5cm), small cube (2.5cm), middle sized cube (5 cm) and large cube (7.5 cm). Success rates for the different objects were logged for all subjects. In addition the success rates for the subtasks were logged. Trials were aborted when a subtask failed; therefore the number of evaluated trials per subtask depends on the success of all preceding subtasks.

Interaction kinetics was a secondary outcome measure. Kinetic data obtained from the robot's force sensor was used to estimate voluntary interference by the subject. In addition, kinematic patterns of hand position were obtained from the robot's sensors and finger joint angles were obtained from the motion capture data. The performance in tracking the hand and finger reference trajectories was evaluated.

III. RESULTS

Examples of the different hand states (hand open, object grasp and object release) controlled with MPC are shown in Fig. 3

A. *Success rates*

In Table II the success rates of the full reach, grasp, move and release movement sequences with the different objects are shown. The successes and failures of all trials in healthy subjects and stroke subjects distributed over the different subtasks are presented in Fig. 4. In the healthy subjects the majority of trails was finished successfully. In healthy and stroke subjects positioning of the robot had high failure rates. In the stroke subjects, hand opening was only successful in a few trials and none of the objects was successfully grasped. For the stroke subjects, no data was available for moving the object, positioning the hand for release and releasing the object, since all trials had failed before object movement could occur.

TABLE II. SUCCESS RATES OF COMPLETE OBJECT MANIPULATION TASKS

	S1	S2	H1	H2
Age	62	67	25	28
Gender	M	M	M	M
Hand	R	R	R	R
ARAT	3	11	n.a.	n.a.
Months +stroke	160	112	n.a.	n.a.

In S1 the electrical stimulation was successful outside the robot, however when the arm was placed in the arm cuff of the robot, the finger flexors did not respond to the stimulation anymore, likely due to skin/electrode movement with respect to the muscle. Therefore when this observation was made the other objects were not evaluated to save time as this would not provide new information. In S2 the stimulation of grasp and release was relatively successful, however the middle finger had high tonus and did not extend sufficiently which caused pushing away of the larger objects. Therefore evaluation of the largest cube was omitted. For the small cube, reach was mainly successful but the grip was not firm enough to prevent slippage of the object.

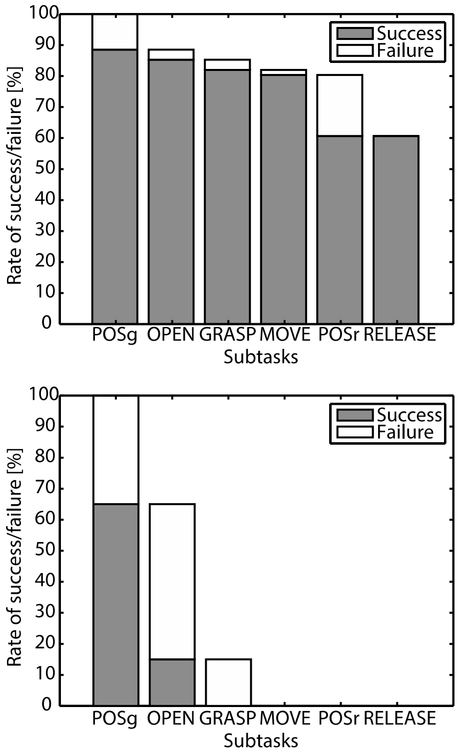

Figure 4. Causes of failure in healthy subjects (a) and stroke subjects (b). Bars indicate occurrences of successful trials (gray) and failures (white) for each of the following subtasks: positioning hand for grasping (POSg), opening hand for grasping (OPEN), grasping the object (GRASP), hold and move the object (HOLD), position the hand for object release at the target position (POSr) and release the object at the target position (RELEASE).

B. *Tracking performance*

Fig. 5 shows time series of arm/hand movement and finger movement during multiple trials in subject H1. The performance of tracking the reference positions was evaluated separately for arm movement and finger movement. The arm position tracking RMS errors averaged over all trials was 69.6 ± 17.5*mm* and 145.1 ± 27.8*mm* for healthy subjects and stroke subjects respectively. Thus the positioning errors in stroke patients were about twice as large as in the healthy subjects. Steady state errors for opening the hand for grasp in healthy subjects were 14.6 ± 11.0°, 18.8 ± 16.2° and 19.1 ± 11.6° for index, middle and ring finger respectively and 18.5 ± 12.6° and 21.4 ± 14.4° for thumb abduction and extension respectively. In the stroke subjects hand opening steady state errors were 32.5 ± 9.1°, 25.5 ± 7.7° and 11.2 ± 6.3° for index, middle and ring finger respectively and 8.2 ± 6.3° and 6.9 ± 3.6° for thumb abduction and extension respectively. Angular errors of ~20° will lead to a displacement of ~3*cm* at the fingertips, depending on the finger length.

IV. DISCUSSION

In this study we showed the technical feasibility of using a system combining robotics and functional electrical stimulation for functional tasks in which the subject was passive. The high success rates in healthy subjects, together with the fact that the failure rate in stroke subjects was partially influenced by technical limitations, indicate the potential of the system for application in post stroke rehabilitation.

A. *Technical limitations*

Two technical limitations can be identified after evaluation of the current system: 1) a possible mismatch in programmed object locations and actual object locations and 2) interference of the robotic arm cuff with the electrical stimulation outcome.

Currently the object location was pre-programmed in the robot controller and the applied virtual stiffness was relatively low. As the subjects are passive, already small

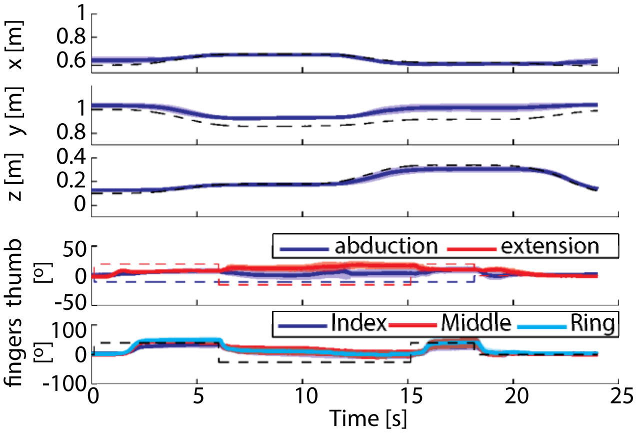

Figure 5. Measured arm/hand positions and finger angles (solid) compared to reference positions and angles (dashed) for trials with a 5cm cube for subjects H1 (top). Thumb and finger angles are reported relative to the subject's neutral position. Angles were defined zero when the subject relaxed his hand and stimulation was off

positioning deviations can result in a failure. However, for future systems we suggest to incorporate active user involvement (also desired for rehabilitation) in combination with intention detection, which improves the positioning accuracy and reduces the number of failures, as the user can then actively steer the system to the desired position.In subject S1, the arm connection of the robot might have influenced the electrical stimulation responses. Currently, the cuff of the robot is attached over the middle of the forearm and thus placed over the electrodes. A redesign of the arm connection is suggested to remove this interference problem.

B. *Clinical implications*

Fully supporting the reach, grasp and release movements will be a first step towards an integrated system for rehabilitation after stroke. To apply this system in the clinic or in a home environment, two important modifications are required before the system can have clinical merit: 1) donning and doffing time should be reduced, including a more mobile finger measurement system, 2) support should be tailored to the ability of the individual patient instead of full support.

To reduce donning time, array electrodes [14] could be included to automatically search for the best electrode positions. To reduce MPC initialization time, intelligent solutions are needed, like a form of initial automated electrode testing [14] and recursive model estimation (e.g. [15]). In addition, models obtained from previous sessions might be used as a starting point. For clinical application also a more compact and more plug and play solution is needed to measure finger motion. Measurement gloves [16] or commercially available devices like Microsoft Kinect [17] or LEAP motion [18] might be used as a more portable solution for feedback of finger angles.

For rehabilitation purposes, it is desired that the patient can control the movement [13]. To promote motor relearning, the amount of support should be based on patient performance such that the patient is maximally active and still able to complete the task [9]. Therefore iterative learning control [8] or other assist-as-needed approaches (e.g. [9]) are necessary to use the current system successfully for rehabilitation.

V. CONCLUSION

A combination of Model Predictive Control of FES and robotic arm support can be successful in supporting functional tasks. With the mentioned further improvements, the current system has great potential for support of movement during post-stroke functional training. Due to the compactness of the system, future versions might also become applicable in a home environment, allowing for intensive therapy. For therapy after stroke, the current approach should be extended towards an assist-as-needed approach with user intention detection to maximize patient involvement. Benefits and feasibility of such an approach should be further investigated. However, since passive movement has been shown technically feasible, we are confident that reducing the support to engage the patients will be also feasible with the current system.

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