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A hybrid tool for reaching and grasping rehabilitation: the ArmeoFES

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***Abstract*— Many research groups are currently working with robotic devices for hand grasp rehabilitation and restoration. A common problem in this area is the fact that existing and commercially available robotic exoskeletons are able to provide gravity compensation of the shoulder and elbow but do not provide any support for the grasping and releasing movements of the hand. The lack of a flexible support technology for the hand reduces the possible ways in which clinicians can deal with the issue of a personalized, effective rehabilitation. This paper presents new software that allows FES assisted grasping to integrate with the ArmeoSpring (Hocoma AG). The system uses a Man-In-The-Loop control approach, whereby surface EMG signals from proximal muscles are used to trigger and modulate multichannel FES applied to distal muscles, thus allowing patient induced and strength adapted movement control of the hand. Combining volitionally controlled FES with arm-weight-compensation allows early adoption of FES assisted therapy for patients, augmenting their functionalities and extending training capabilities with the ArmeoSpring.**

I. INTRODUCTION

Functional Electrical Stimulation (FES) has shown promise as a means of improving hand grasp functionality and thus quality of life of individuals with Spinal Cord Injury. When used on such individuals, FES actively involves them in therapy and supports and facilitates recovery of activities of daily living [1]. FES therapy has also revealed significant benefits over conventional therapy showing: reduced disability, improved voluntary grasping and increased independence of spinal cord injured (SCI) individuals with tetraplegia [2], [3]. Devices such as the ArmeoSpring (Hocoma AG) have shown to be a useful complement to conventional therapy techniques with Stroke patients [4], and are supposed improve upper limb function in cervical SCI patients.

ElectroMyoGraphic (EMG) signals have been used to control FES systems for some years [5], [6], [7]. This control approach makes use of remaining voluntary muscular function, using the user's movement intention to extract information on the desired level of stimulation.

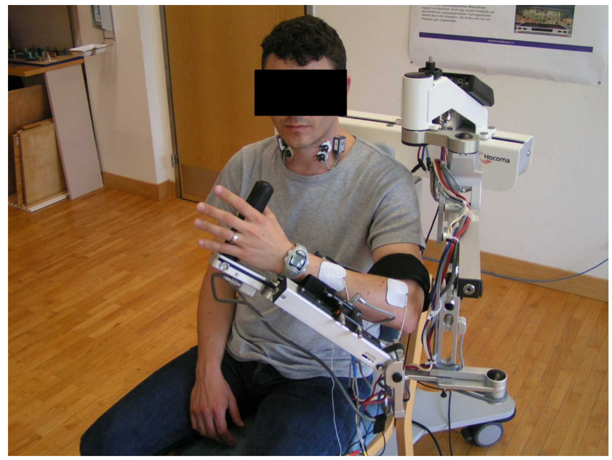

Fig. 1. A healthy subject seated in the ArmeoSpring, with TeleMyo DTS sensors over the sternocleidomastoid muscles.

As indicated by Micera et al. [8] a surface EMG-based control system can be reliably used in a clinical context if 1) the system is robust and accurate in extracting user intent; 2) the mapping of the controls is direct, hiding complexity from the user; 3) the response time of the system is negligible. From a user's perspective this translates to providing the sensation that the neuroprosthesis is acting transparently, giving confidence in its behavior.

EMG control strategies based on proportional or threshold algorithms and finite state machines provide simple and accurate methods to control artificial devices [8]. Such methods are well suited to real-time applications due to their simplicity.

Despite FES being a historically well-known technology, its diffusion in rehabilitation is still limited by several factors and thus FES treatment is only received by a small number of patients who could potentially benefit [1]. Some major problems in applying FES therapy, as outlined by Donovan-Hall et al. [1], are a lack of resources, such as equipment and staff training, and the view that some FES devices are unreliable or lack the necessary integration to be easily usable and understandable by clinicians.

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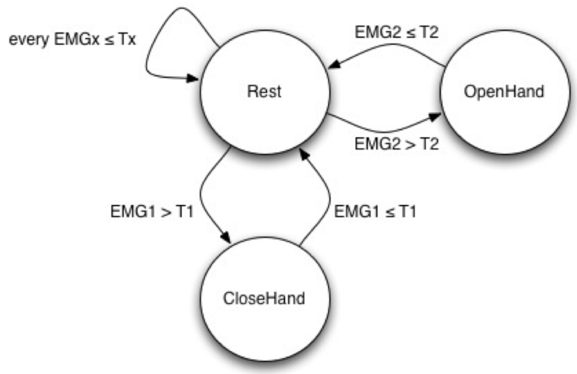

Fig. 2. Transitions between the three finite states, dependent on the activity of the two EMG channels, above or below their respective threshold levels (T).

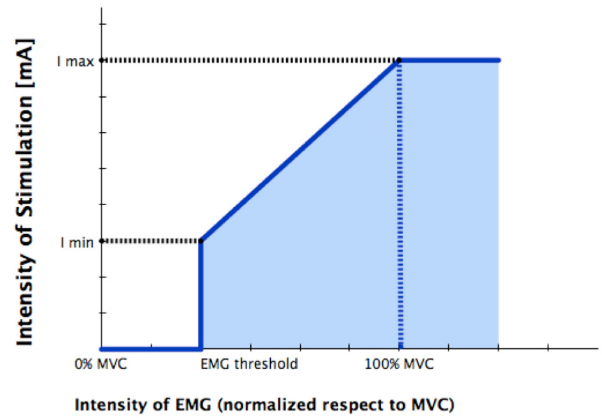

Fig. 3. The relationship between EMG amplitude level and stimulation current.

The EMG controlled FES system aims to address these issues by providing a stable, user-friendly interface which complements the ArmeoSpring therapy approach. This will provide ease of use for the clinicians, making FES assisted therapy more accessible to SCI individuals. The gravity compensation environment will provide a platform allowing SCI patients to train with this non-invasive end effector neuroprosthesis.

II. Materials and Methods

A. *Hardware*

The hybrid system (Figure 1) consists of a passive upper arm exoskeleton with gravity compensation (ArmeoSpring, Hocoma AG), a 4-channel constant current stimulator (Compex Motion), and a wireless surface EMG system (TeleMyo™ DTS, Noraxon). Bipolar electrodes (Dual Electrodes, Noraxon) are used for surface EMG recording and 2”x2” electrode pads (Pals® Clinical, Axelgaard) are used for stimulation.

B. *Setup*

In order to set up the system, the motor points for hand opening and closing are detected empirically with the stimulation system. Motor points are defined as the most appropriate electrode positioning areas on the skin, causing the best possible contraction of the related muscle or muscle group to be stimulated.

During this process the following current levels are defined: minimum current required for contraction (I_{min}), the maximum current after which no increase in contraction intensity is observed (I_{max}), and the stimulation current which causes pain (I_{pain}). The system is said to be comfortable if $I_{max} < I_{pain}$.

C. *EMG control of FES*

EMG signals are recorded from two independent muscles that retain a degree of voluntary control, i.e. voluntary contraction ability over and above their normal activity levels during therapy tasks. An example would be the left and right sternocleidomastoid muscles of the neck. As active EMG blanking is not implemented, the EMG electrodes must be placed proximally to the elbow.

The maximum voluntary contraction (MVC) is defined for each of the muscles as the maximum EMG amplitude during a 5 second recording. During operation EMG signals are filtered (3rd order butterworth, high-pass, 50Hz) to remove ECG artefacts. The filtered signals are fed into a finite state machine with 3 states, where transitions are controlled by activity of each EMG signal, as shown in Figure 2. For comfort and safety reasons the transition between states is limited such that a state changes has to pass through the rest state.

In each state, stimulation is delivered in such a way as to achieve the desired action of the hand, with an intensity that is proportional to the EMG control signal, i.e. proportional control. For flexibility, the responsible therapist can predefine the actions during the setup phase. The I_{min}, I_{max}, MVC and threshold levels define the stimulation intensity – EMG amplitude relationship, shown in Figure 3.

D. *Software*

The ArmeoSpring is used in conjunction with Armeocontrol software, providing various games and exercises that can be used for patient assessment, training, and performance tracking. This software also allows for recording of all arm kinematics including the position of the end effector in a 3D workspace. This time-stamped kinematics information is dumped into a single file which can be synchronized offline with the recorded EMG signals.

A graphical user interface (GUI) was developed in LabVIEW (National Instruments) to allow the clinician to define the parameters required by the state machine, record EMG signals and to implement the real-time EMG control of FES. The GUI (Figure 4) also allows the following parameters to be adjusted for therapy optimization:

1) efficacy of stimulation – *current intensity for each state*
2) triggering threshold – *level of EMG activity which will trigger stimulation*
3) responsiveness – *speed at which the system reacts to*

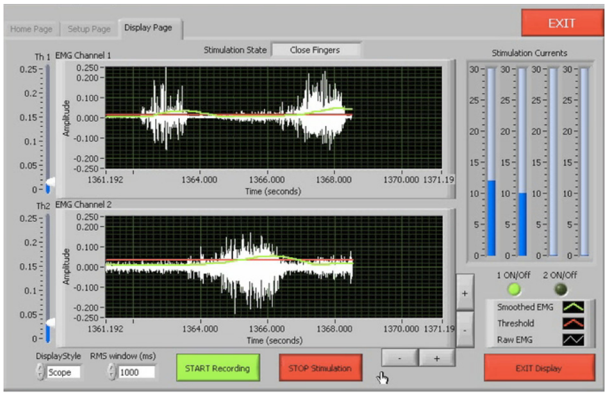

Fig. 4. A screenshot of the GUI, developed in LabVIEW, while implementing EMG control of FES. The EMG activity on the top EMG channel can be seen eliciting stimulation of the first two FES channels, shown by the vertical blue bars on the right.

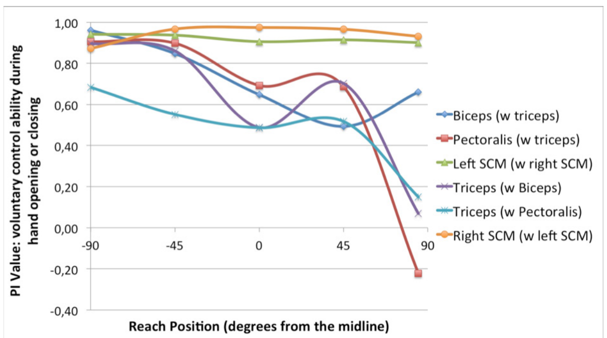

Fig. 5. Performance Index (PI) of a single subject during the reach and grasp tasks over the five reach positions.

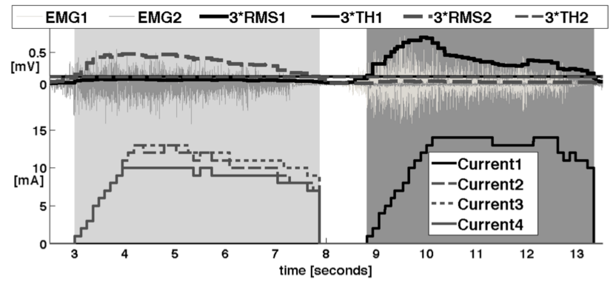

Fig. 6. Light gray background: hand closing; dark grey background: hand opening. The top graph shows how the two RMS signals (amplified by 3) are used to enter either the closed or open state, and the bottom shows how these RMS amplitudes above the corresponding thresholds modulate the amplitude of the stimulation currents.

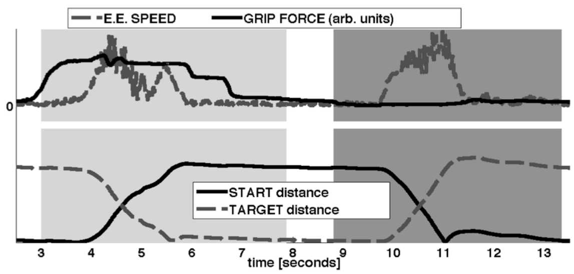

Fig. 7. Light gray background: hand closing; dark gray background: hand opening. The top graph shows the grip force and movement speed of the ARMEO end effector, while the bottom shows the displacement from start and target positions during the grasp and reach test.

changes in EMG activity

4) smoothness of stimulation current change – *a current change rate limiter with saturation*

E. Preliminary Tests

Preliminary investigations into the proximal muscles have been carried out on two healthy subjects to obtain an indication of which muscles are applicable to proportional EMG control of FES for hand opening and closing. EMG signals were recorded over the biceps brachii, triceps brachii (long head), pectoralis major and the left and right sternocleidomastoid (SCM) muscles. Subjects were required to perform the following tasks:

1) reach out to a predefined position (-90°, 45°, 0°, 45°, and 85° from the midline),

2) contract one of the muscles used to control FES opening of the hand (triceps, or left SCM) at MVC level,

3) contract one of the muscles used to control FES closing of the hand (biceps, triceps, or right SCM) at MVC,

4) move to a location directly in front of their torso

5) contract one of the muscles used to control FES opening of the hand at MVC.

A Performance Index (PI) was then defined as:

$$PI = 1 - EMG_{passive}/EMG_{active}$$

Where EMG_{active} is the EMG activity level (mean rectified) when MVC level contraction is intended and $EMG_{passive}$ is the level of EMG activity resulting from contraction of the other muscle. This PI gives an indication of the amount of voluntary control a person has over the muscle, over and above normal activity, during reach and grasp tasks.

EMG signals, recorded during a test, and the resulting stimulation currents can be seen in Figure 6. The RMS of the EMG signals has been amplified by 3 for clarity. Speed and movement of the end effector and the grip force on its handle, during the same test, are shown in Figure 7. These demonstrate real-time operation of the system. As the ARMEO outputs force in arbitrary units, the precise grasp force at the end-effector cannot be measured, however a trend can be observed in the grip force during hand closing.

III. Results and Discussion

The PI values over the range of reach positions, for all muscles investigated is shown in Figure 5. From this, it can be seen that the SCM muscles of the neck are the only muscles with stable performance (PI > 0.85) over all the investigated reach positions.

At the time of writing three healthy subjects had used the system and were able to synchronously control grasping and reaching, as can be seen in Figure 7. During grasp and reach task (light grey region in Figures 6 and 7) the voluntary EMG activity elicited stimulation currents, which in turn caused contraction of the hand and increased the grip force on the end effector. While there was movement of the end effector during

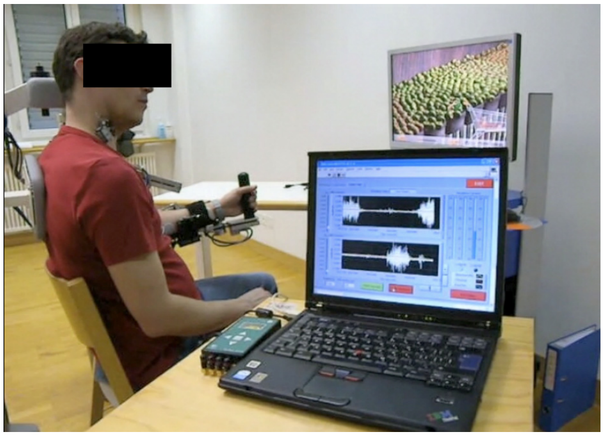

Fig. 8. One of the healthy subjects playing an Armeo game requiring picking of apples by grasping the handle, moving to a shopping cart while grasping, and releasing the handle to drop the apple into the cart. Grasp and release was achieved through EMG controlled FES.

reach (Figure 7), the grip force remained at a relatively stable level. The change in grip force was smoother for grasping of the end effector than for its release.

The system allowed subjects to comfortably use several of the Armeo games, as illustrated in Figure 8, achieving grasp and release tasks required for the games solely by means of FES.

The simple control criterions used by this software are expected to allow quick evaluation of ArmeoFES's applicability to patients. This software can be used as a flexible training tool for hand grasp assistance, providing augmented training where active intervention of the patient is required. Since voluntary control of the proximal muscles is necessary, some patients may require training during the first sessions to learn how to efficiently activate these muscles. Visual feedback is implemented which allows patients to understand the simple control logics, while for patients with auditory preference different tunes could be used as a feedback signal in the near future.

Flexibility in defining the EMG thresholds, used to trigger the state change, is provided by control bars, always visible to the therapist, which allow easy tweaking of the system.

Responsiveness of the EMG detection algorithm can be easily adapted by changing the length of an integration window, with values in the range of 150-1000 ms. Shorter windows will result in quicker response times, but more noise effects. Longer windows will provide a slower but more stable response.

Since FES is provided using commercially available electrodes, special patient needs in terms of stimulation comfort and selectivity can be considered by the therapist. As a safety measure the current amplitude is limited to supposedly safe levels, in order to prevent potentially dangerous stimulation. Rapid changes of the modulated current intensity are smoothed by an adaptable slew rate limiter, in order to improve the stimulation comfort.

IV. CONCLUSION

We integrated a portable wireless EMG amplifier with a pc-controlled FES system to be used for FES induced grasp therapy. This tool will be tested in combination with a robotic gravity compensation exoskeleton on SCI patients using FES assisted hand grasp tasks. The modularity of the system gives the experimenter freedom to easily tune the control scheme according to the specific patient's training needs. Feasibility tests are expected to provide preliminary results with healthy subjects and SCI patients during the next months.

As a result we may expect that in reach-grasp training tasks the ArmeoFES may have an advantage, over the ArmeoSpring alone, due to the ability to induce EMG mediated grasp in patients completely unable to control the hand and to adapt the levels of the maximal current intensity on patients with partial control thus reducing the assistance as needed.

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