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A patient-controlled functional electrical stimulation system for arm weight relief[☆]

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ABSTRACT

A patient-driven control strategy for Functional Electrical Stimulation (FES), which amplifies volitionally-initiated shoulder abductions, is proposed to improve stroke patients' rehabilitation. Based on the measured abduction angle, a FES-induced muscle recruitment is generated that yields a pre-specified percentage of this angle – yielding arm weight relief. To guarantee the correct recruitment also under fatigue and uncertain muscle activation we employ feedback control of the recruitment level determined by filtering the FES-evoked electromyogram. Filter parameters are user-optimized to obtain a linear relation between filter output and angle with a good signal-to-noise ratio. The auto-tuned recruitment controller (RC) was tested on five healthy subjects and compared to direct stimulation (DS) while muscle fatigue progressively occurred. Results showed a more linear relation between recruitment level and angle than between non-controlled stimulation intensity and angle ($R^2 = 0.93$ vs. $R^2 = 0.79$, angular range of 54°). After 6 min of stimulation, abduction decreased by 42% ± 14 for DS and by 0% ± 12 for RC, showing an effective compensation of fatigue. RC yielded significant smaller errors than DS in generating desired angles (0.23% ± 5.9 vs. 14.6% ± 9.7). When FES-induced arm weight support was provided, a mean reduction of the volitional effort (determined by Electromyography) of 78% was achieved compared to angular tracking without FES. First experiments with one acute stroke patient are also reported.

1. Introduction

Functional Electrical Stimulation (FES) is widely used for the rehabilitation or assistance of patients affected by neurological diseases [1]. It artificially activates paretic muscles during functional tasks by electrical stimulation of intact lower motor neurons. The increased afferent feedback provided by FES is known to modulate motor cortex function and excitability to enable recovery [2]. Recent studies [3,4] advocated the use of FES co-incidentally with the voluntary drive to enhance even more the plasticity of the central nervous system, so as to further improve its therapeutic effects [5].

One way to achieve synchronization between FES and volitional activity is to use myo-controlled neuroprostheses, in which the residual volitional EMG signal of the paretic muscle is used to control the timing and the intensity of the stimulation of the muscle itself [5]. Different strategies to control FES based on the residual EMG of the stimulated muscle were proposed in the literature. EMG-triggered controllers, which trigger the onset of a predetermined stimulation sequence applied in an open loop modality based on the volitional EMG, were firstly designed [6,7]. These systems are easy to implement and clinically feasible but do not actually assure the synchronization of FES and the intended voluntary movement after the trigger. This drawback is overcome by EMG-proportional controllers, which modulate the stimulation proportionally to the volitional EMG [8,9] and thus amplify weak residual muscle activity. However, this solution is less feasible on patients because it requires smooth muscle contractions to prevent oscillations caused by the closed-loop control system. An on/off non-linear control system was recently proposed [10]: it allows even patients with reduced muscle contractions to autonomously activate and deactivate the stimulation support exploiting their residual muscle activity, but it can lead to imprecise motor control.

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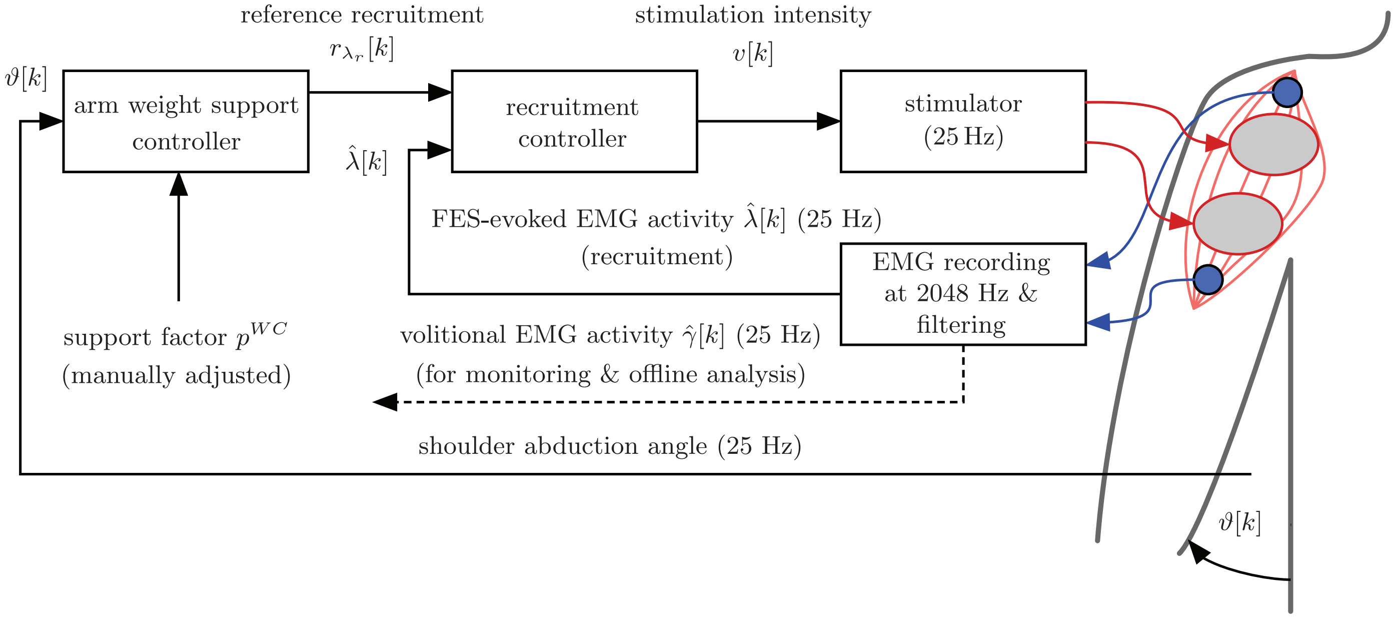

Fig. 1. Control scheme to achieve arm weight support by stimulation of the medial deltoid muscle.

A different approach to use FES co-incidentally with the voluntary drive, is to measure the desired target posture and to derive by means of an inverse mechanical model the joint moments required to achieve and to maintain that posture [11]. Then, partial or full support can be obtained by producing these moments partially or fully by means of FES. Compared to EMG-proportional stimulation, less precise muscular control is demanded from the patient. However, this approach requires precise neuro-musculoskeletal models to determine the desired stimulation intensities. Such models are difficult to obtain in clinical practice.

For repetitive tasks within a tightly controlled environment, Iterative Learning Control (ILC) can be applied to find the correct FES support in presence of residual muscle activity [12]. From trial to trial, ILC adjusts the stimulation intensity in order to improve the performance based on the measured joint angles from the previous trial.

The majority of FES-controlled systems use the stimulation intensity as control signal and solely observe the stimulation effect by measuring joint angles. Such control systems are slower than physiological movement control where forces and velocities are internally sensed by Golgi tendon organs and muscle spindles, respectively. In addition, when multichannel FES is delivered to obtain complex movements, the measure of the resulting angles is a global measure that is not able to sense the condition, e.g. muscle fatigue, of the stimulated muscles. Moreover, by solely using joint angles to measure the movement induced co-incidentally by FES and the patient it is not possible to distinguish between the volitional effort and the contribution provided by FES.

In a previous work [13], we proposed the use of FES-evoked EMG to assess the level of FES-induced muscle recruitment and to incorporate feedback control of it into FES systems. In our recent work [14], we could demonstrate in a case study on one healthy subject that such recruitment control enables the precise delivery of a desired movement support also in presence of muscular fatigue up to the maximal possible stimulation intensity that is adjusted by the controller. The desired support could be administrated synchronously to the voluntary muscle contractions in a repetitive tracking task and was modulated depending on the tracking performance and the observed volitional EMG activity. Additionally expected advantages of the recruitment control are the linearization of the of nonlinear muscle dynamics and the reduction of hysteresis effects in the muscle activation [13].

In this contribution, we propose a patient-driven control strategy, similar to that reported by Riener and Fuhr [11], which amplifies weak voluntary initiated shoulder abductions by providing an adjustable virtual arm weight support. Based on the measured abduction angle, a FES-induced muscle recruitment is generated that yields a pre-specified percentage of this angle. The use of recruitment control deliberates from obtaining complex muscle models as previously required [11]. A fast auto-tuning procedure for the EMG filter, applied on FES-evoked EMG, and for the recruitment controller is introduced. The performance of the employed underlying recruitment control is investigated in a study with healthy subjects with respect to the linearization of the system behavior and to the long-term generation of desired movement support also when muscle fatigue occurs. The maximal achievable arm weight support is determined by observing the reduction of volitional EMG activity during a user-controlled angle tracking task. In contrast to our previous work and ILC, the proposed approach is not restricted to repetitive tasks which renders its use more versatile. The feasibility of the proposed control strategy was finally demonstrated in a case study with one acute stroke patient.

2. Methods

2.1. System overview

The proposed control scheme, shown in Fig. 1, is intended to support patients with a weakness in shoulder abduction. FES is applied to the medial part of the deltoid muscle using a current-controlled stimulator (Rehastim, Hasomed GmbH, Germany) and self-adhesive electrodes (ValuTrode® CF4090 (4 × 9 cm), Axelgaard Manufacturing Co., USA). A stimulation frequency of 25 Hz was used and corresponded to the sampling frequency of the control system (sampling index k). The control signal $v[k] \in [0, 1]$ is