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Neuro-fuzzy models for hand movements induced by functional electrical stimulation in able-bodied and hemiplegic subjects

Eukene Imatz-Ojanguren[a,*], Eloy Irigoyen[b], David Valencia-Blanco[a], Thierry Keller[a]

[a] TECNALIA Research & Innovation, Health Division, Mikeletegi Pasealekua 1-3, 20009 Donostia-San Sebastián, Spain
[b] UPV/EHU – University of the Basque Country, Intelligent Control Research Group, Alameda Urquijo 48013, Bilbao

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ABSTRACT

Functional Electrical Stimulation (FES) may be effective as a therapeutic treatment for improving functional reaching and grasping. Upper-limb FES models for predicting joint torques/angles from stimulation parameters can be useful to support the iterative design and development of neuroprostheses. Most such models focused on shoulder or elbow joints and were defined for fixed electrode configurations. This work proposes the use of a Recurrent Fuzzy Neural Network (RFNN) for modeling FES induced wrist, thumb, and finger movements based on surface multi-field electrodes and kinematic data from able-bodied and neurologically impaired subjects. Different combinations of structure parameters comprising fuzzy term numbers and feedback approaches were tested and analyzed in order to see their effect on the model performance for six subjects. The results showed mean success rates in the range from 60% to 99% and best success rates in the range from 78% to 100% on test data for all subjects. No common trend was found across subjects regarding structure parameters. The model showed the ability to successfully reproduce the response to FES for both able-bodied and hemiplegic subjects at least with one of the tested combinations.

1. Introduction

Functional Electrical Stimulation (FES) artificially activates motor nerves in order to elicit muscle contractions that lead to functional movements. This is achieved by means of an electrical stimulator and, at least, a pair of electrodes responsible for delivering electrical pulses to peripheral nerves [1]. FES has shown positive results in neurorehabilitation, where it has been used in a variety of therapeutic applications aimed at neurologically impaired patients [2–9]. It is known as neuroprosthesis when its aim is to assist functional movements by bridging the loss of central neuronal connectivity.

Surface electrodes are commonly used in therapeutic applications [9] for being non-invasive and easy to don/doff by placing them over the skin. Multi-field surface electrodes, consisting of an array of electrodes [10], allow increased target nerve selectivity compared to conventional surface electrodes [11,12]. This is essential in applications such as grasping, where precise activation of multiple muscles at different depths and positions over the forearm is required.

Modeling of FES has been addressed by many research groups over the last years. The classical FES model describes the relation of an electrical input or stimulation parameters to dynamic or kinematic outputs of the joints, which usually consists of a chain of sub-system models, such as skin models [13], nerve models [14,15], or musculoskeletal models [16,17].

Complete analytical upper-arm FES models include a shoulder model for 3 dimension force control, which was developed and validated with a SCI patient [18]; and a model of the elbow for predicting joint torques based on recursive adaptation and validated with both healthy and stroke subjects [19]. Regarding the hand, a thumb model for a force control application with surface FES electrodes was presented elsewhere [20]. Another work showed a simplified model of the fingers and wrist consisting of a 3-link rigid body system, where four fingers were considered as a single virtual finger, which was designed for an iterative learning control application [21]. Finally, another model based on multi-field FES surface electrodes was able to predict flexion forces of the four fingers from stimulation parameters [22].

Models that do not describe a chain of physical sub-systems but use bio-inspired approaches such as artificial neural networks (ANN) were used for a FES elbow extension controller for SCI subjects, where the model predicted FES parameters from remaining EMG activity signals [23]. Another approach included ANNs in feedforward and feedback parts to model the inverse dynamics

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[*] Corresponding author. Tel.: +34 619779568.
E-mail addresses: eukene.imatz@tecnalia.com, eukeneimatz@gmail.com (E. Imatz-Ojanguren), eloy.irigoyen@ehu.eus (E. Irigoyen), david.valencia@tecnalia.com (D. Valencia-Blanco), thierry.keller@tecnalia.com (T. Keller).

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Table 1
Information of participants.

Subj	Gender	Age	Brain injury cause	Time from injury	Wrist PROM flex.(°)/ext.(°)	Wrist AROM flex.(°)/ext.(°)
1	Female	27	n.a. (healthy)	n.a. (healthy)	69.2/78.5	69.2/74.9
2	Male	29	n.a. (healthy)	n.a. (healthy)	71.5/71.9	71.5/67.23
3	Male	38	n.a. (healthy)	n.a. (healthy)	70.4/72.2	70.4/70.2
4	Male	53	Trauma	4 years	42.1/35.3	42/7.6
5	Female	65	Stroke	4 years	51.2/32.6	51.1/0
6	Female	61	Stroke	10 years	51.5/54.1	51.5/45.4

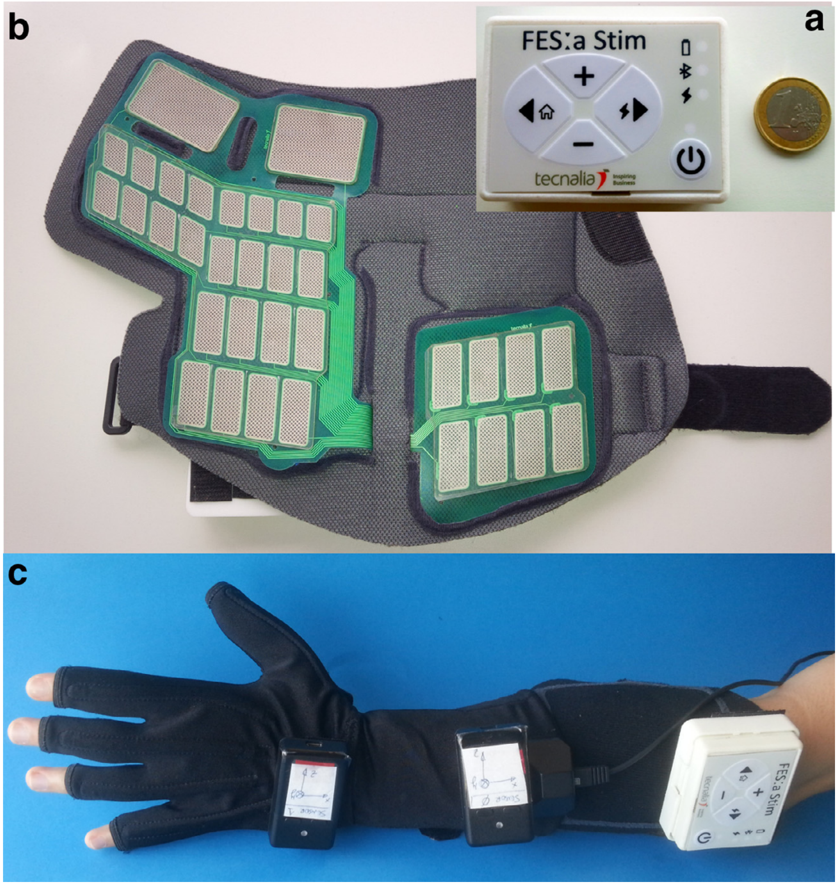

Fig. 1. a) *FES:a stimulator*, b) *FES:a electrodes* embedded in a garment, c) sensorized glove.

of the arm [24]. Expert systems based on fuzzy logic have been presented for other lower-limb FES applications such as rowing [25] or cycling [26, 27]. Finally, hybrid neuro-fuzzy approaches have shown successful results in lower-limb FES control applications, such as rowing, where the system was tested in SCI subjects and was able to adapt to fatigue [28].

Most of the described upper-limb FES models focused on elbow and shoulder joints, they were simplified for control purposes and they were based on a fixed electrode configuration. However, electrode position affects significantly the elicited hand movements due to high inter-subject variability and high musculoskeletal complexity of the forearm and the hand [29–32]. Thus, models involving application sites as inputs could help the design of advanced selective surface neuroprostheses for grasping.

Therefore, in this work we present a recurrent fuzzy neural network (RFNN) approach for modeling wrist, thumb and fingers kinematics induced by a forearm surface multi-field FES system, in which electrical stimulation application sites on the forearm are taken into account. This approach has been tested on data collected from three healthy and three chronic brain injured hemiplegic subjects. Since neurophysiological characteristics of healthy compared to hemiplegic subjects are very different [29–32], an analysis has been carried out to find out how different structure approaches affect the performance of the model across subjects.

2. Methods

2.1. Subjects

Data from three healthy subjects and three chronic acquired brain injury subjects suffering from left hemiparesis were collected. Details are provided in Table 1. Passive range of motion (PROM) and active range of motion (AROM) of the wrist for each subject are provided to indicate the functional impairment of the hemiplegic subjects. All the participants were familiar with FES as each of them had received at least 60 h of electrical stimulation (above motor threshold) during a month prior to the data collection session. Approval for the data acquisition sessions was obtained at ADACEN (Acquired Brain Injury Association of Navarra) and all subjects signed an informed consent before participating in the study.