

UPPER-EXTREMITY FES SYSTEMS – CONTROL METHODS

Dejan Popović^{1,3} and Mirjana Popović^{1,2}

¹*Faculty of Electrical Engineering, 11000 Belgrade, Bulevar revolucije 73, Yugoslavia*

²*Institute for Medical Research, 11000 Belgrade, Dr Subotića 5, Yugoslavia,*

³*Center for SMI, Aalborg University, Frederik Bajers Vej 7, D-3, 9220 Aalborg, Denmark*

Abstract: Functional electrical stimulation (FES) is a tool to enhance daily living activities in humans with motor and sensory paralysis of the hand and arm. Implantable technology provides substantial advantages over the surface stimulation assistive systems for grasping and reaching, but over all performances must be much improved in order to allow community functioning. Most FES systems inherently rely on synergistic concepts of control; hence, the planning is based on the position of the most distal part, while the active control is at the most proximal part of the extremity. Applying synergies found in able-bodied humans while performing daily living activities is valuable because the biomechanics of the arm and hand remains more or less the same after the onset of disability. A hierarchical controller with logical, discrete upper level, and dynamical, sampled data feedback, lower level of control is suitable for implementing this concept. The controller needs at least two kinds of input: voluntary, for selecting the strategy of grasping (based on the visual information and knowledge), and the artificial sensory one, to replace diminished proprioception.

1. INTRODUCTION

In 1996 a workshop was organized to assess the state of the art in the field of grasping neuroprosthesis (NP). This meeting concluded [29] that grasping systems [24,25] have been developed to the stage of being approved by the very strict guidelines (FDA, USA). This review clearly states that there are still some issues to be resolved before these NPs are widely used. Recently, a growing interest can be noticed for quantifying functional deficits caused by central nervous system lesion [3,4,13,18,20,28,30]. These studies indicate that a standardized protocol must be developed for assessing of the functional level of disability in order to predict the outcome of the rehabilitation and use of a specific NP. Several studies focused to the following two directions: 1) improved control [e.g., 6,7,10,21,22]; and 2) integration of control of the wrist, elbow and shoulder [e.g., 2,8,11,14,29] with the grasping NP.

Evaluation of three different grasping and reaching systems provides some interesting data [15-17]. The functional independence measure (FIM), the quadriplegia index of function (QIF), upper extremity functioning test (UEFT), range of movements, and strength of grasping have been followed for at least six months. It was found that all three evaluated systems improve the functioning. FIM and QIF were increased for almost 100 percents in subjects who started with a low value, but only a little for subjects who retained some level of independence. UEFT scores improved for all functions tested, but the handling of small objects (e.g., finger food) remained a problem. Range of movements and the strength of grasp were greatly increased in all subjects. The changes started to be substantial about eight weeks after starting to use NPs. The final scores for all measures show that even with the system working properly, the independence remained limited. The frequency of using of NP, for all 27 subjects evaluated, shows variability, but in general implies to relatively short periods of its usage. An issue for assessing the relative importance of NP to the functioning is that only seven subjects continued to use it for daily activities once the study was terminated, even though the NPs were given at no cost. Four other subjects continued to use NP for therapy, 30 minutes in the morning, claiming reduced spasticity after being stimulated. Only one subject, from the eight, who participated in evaluation of the reaching system, continued to use it on a daily basis [17].

Stopping to use of a NP relates most probably to the substantial improvements of functioning without NP. Prolonged, daily, externally elicited activity of neuro-musculo-skeletal structures is responsible for those improvements [15-17]. This suggests that therapeutical effects of electrical stimulation of paralyzed muscles are substantial affecting both the peripheral system (e.g., stronger muscles, increased range of movements, decreased spasticity) and the functional organization of CNS.

2. NATURAL CONTROL OF GOAL-DIRECTED MOVEMENTS

The difficulties in using NPs are: 1) command interface is not intuitive enough, and it requires conscious actions; and 2) control is not flexible and adaptive. Eliminating the said problems was the main motivation for improving control, the bottleneck for better NPs.

Some common principles of motor control organization in organisms [1,9] may serve as a useful guideline for the design of control algorithms. The fact that goal-directed movements are reproducible for a given task in different living species implies that optimization of some sort is taking place during learning of such motions. This optimization is inherent to the self-organization.

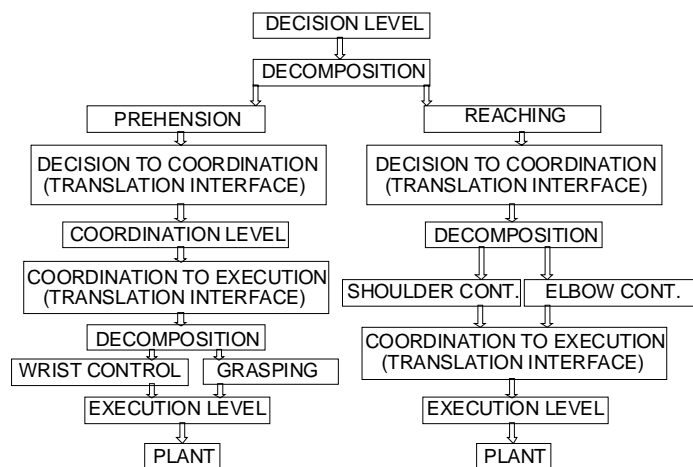
When activated to perform a self-paced, non-constrained functional motion, the neuro-muscular system prefers some trajectories from other. The constraint imposed by the task determines the trajectory (e.g., straight line movements are adequate for fast pointing movements; starting the movement with the proximal joints and adjusting the position of the hand while moving distal segments is effective for precise positioning, etc.).

Skill acquisition processes are optimized in such a way that the open loop control is preferred to the closed-loop control as long as it does not affect the performance of a functional motion. Invariant of functional motions, motor patterns, automatic movements and reflexes are the means by which the use of the open-loop control mode is extended in the execution of motor acts. Open-loop control sets free the vision system and the conscious level to monitor the environment and prepare the organism for new activities. The execution of skilled movements is organized that the flow of control information from the higher levels is minimized. Lower control level dispose, thus, with maximum autonomy while performing a skilled motor act [23].

3. ARTIFICIAL CONTROL OF GOAL-DIRECTED MOVEMENTS

The control proposed for NP is based on the above stated principles. We originally synthesized control of reaching by using nonanalytical, hierarchical controller for the elbow joint movements in humans with CNS lesion [15]. The implemented strategy uses the principle of synergy found in able-bodied subjects, which allows persons with disability to plan the movement in terms of the most distal segment, and actually volitionally move the most proximal segment [1,5,9]. When reaching, the movement is planned in the external reference frame based only on the visual information of the initial position of the hand and the position of the target [5,26,27]. The visual information is automatically transferred to the universal, that is, user non-specific constraint between the shoulder and elbow joints [26]. Hence, when a person moves volitionally his/her upperarm, the elbow joint angular velocity profile is constrained. An approximation of this constraint is so called scaling law [14,16]. The final step is the usage of the mapping at the lowest, actuator level. The actuator for assisting the elbow extension is m. Triceps Brachii, and its mapping connects the joint angular velocity with the parameters of electrical stimulation. The principle of this operation follows the original ideas of extended physiological proprioception [23].

An appealing version of the controller, which can be used for the control of goal-directed movements, has been suggested [12]. The control that we are developing (Fig. 1) for goal directed movements is presented.



The algorithm at the top includes a decision level (Fig. 1). At this level the user selects the task and voluntarily triggers the appropriate interface. Two activities will be activated simultaneously; one (prehension) ensuring that the hand is properly oriented for the selected task [1,9], and the second to bring the hand to the appropriate position (reaching). The reaching control will rely on synergistic behavior of neighboring joints, while the prehension has to be an open-loop type activity. At this point the prehension allows only lateral and palmar grasps.

The coordination level is a sampled data, discrete feedback system. In this system a rule-based structure is to be implemented. Machine learning can generate rules, that is the knowledge base. Once the control signals are generated, they are translated to the lower execution level. The execution level must include customized model, because of the nonlinearities and time variations of the neuro-musculo-skeletal system. These models are not existing in a ready to use form, but there are some valuable developments on the way.

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