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A novel FES control paradigm based on muscle synergies for postural rehabilitation therapy with hybrid exoskeletons

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***Abstract*— Hybrid exoskeletons combine robotic orthoses and motor neuroprosthetic devices to compensate for motor disabilities and assist rehabilitation. The basic idea is to take benefits from the strength of each technology, primarily the power of robotic actuators and the clinical advantages of using patient's muscles, while compensating for the respective weaknesses: weight and autonomy for the former, fatigue and stability for the latter. While a wide repertory of solutions have been proposed in literature for the control of robotic orthoses and simple motor neuroprosthesis, the same problem on a complex hybrid architecture, involving a wide number of muscles distributed on multiple articulations, still waits for a practical solution. In this article we present a general algorithm for the control of the neuroprosthesis in the execution of functional coordinated movements. The method extracts muscle synergies as a mean to diagnose residual neuromotor capabilities, and adapts the rehabilitation exercise to patient requirements in a dynamic way. Fatigue effects and unexpected perturbations are compensated by monitoring functional state variables estimated from sensors in the robot. The proposed concept is applied to a case-study scenario, in which a postural balance rehabilitation therapy is presented.**

I. INTRODUCTION

Hybrid control emerges as a technique for the generation of controlled movements by means of functional electrical stimulation (FES) in combination with external (robotic) actuators. This approach allows overcoming the disadvantages of each single technique when taken separately. Hybrid exoskeletons look forward to tackling current technological limitations to promote a more integral rehabilitation paradigm (use of residual muscle activities, closer cognitive H-R interaction, etc.).

HYPER project intends to represent a breakthrough in the research of hybrid exoskeletons. It centers its activities on rehabilitation solutions for the particular case of Cerebrovascular Accident (CVA), Cerebral Palsy (CP) and Spinal Cord Injury (SCI), by focusing on rehabilitation exercises based on functional tasks. The main goal of the system is to deal with variability in the human neuromuscular structures, with dynamical adaptations according to the latent motor capabilities of the users.

This work proposes a new approach for controlling the FES module of a hybrid exoskeleton, aimed to overcome typical problems of this types of solutions such as muscle fatigue and selectivity. Control algorithm is driven by user-specific neuromotor and functional state variables, extracted from muscular, kinematic and kinetic activity of the subject during the execution of the movement. In the proposed approach, this information will be used to adapt muscle stimulation to the patient and to regulate the overall action of the hybrid exoskeleton. The core of the approach is based on the hypothesis that muscles are activated through a small ensemble of neural connections, called muscle synergies [2].

The control algorithm will be first applied to balance rehabilitation therapy, which is one of the functional task identified in HYPER. The rehabilitation consists in the execution of rhythmic movements in the sagittal plane.

In the following section, a brief review of the concepts and technologies behind FES and hybrid control will be presented. The limitations of actual implementations will be highlighted, with particular concern on clinical applications. In section III, the most relevant potentials of muscle synergies hypothesis related to hybrid control will be stated. The proposed feedback control paradigm for FES will be described in details in section IV. The following section V will present details of the application in a balance rehabilitation therapy. Next steps and future applications are discussed in the last section.

II. HYBRID EXOSKELETONS

Motor neuroprosthesis

Restoration of motor functions based on FES has been widely studied since the first developments by Krajl et al. [11]. Clinical application provides both therapeutic and functional benefits by retraining of atrophied muscles and upper-motor-neuron. Once trained, muscles can be used to generate functional movements. There is a growing evidence that FES can enhance functional movements such as gait and other physiological activities [14].

When it comes to control multiple articulations by stimulating a consistent number of muscles, as occurs when controlling advanced exoskeletons, the control system becomes more complex. The number of degrees of freedom (DoF) and the absence of reliable models for FES-generated muscle force make the control problem extremely complex.

Over the last years, the increasing interest in hybrid exoskeletons motivated the development of new electrostimulators. Advances in microelectronics and electrode materials enabled new FES systems capable of handling electrode

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arrays and to implement more complex control algorithms to generate synchronized and adaptive stimulation patterns, [4].

Hybrid exoskeletons

The motivation behind hybrid exoskeletons is that muscle stimulation can be assumed as a source of joint power, which gives a reduction on the robotic power demand, reducing the weight of both actuator and power source. Working together with FES, mechanical structure of the robot allows for joint stabilization during stand phases of gait. This hybrid approach is considered as a potential solution for current robotic actuator limitations, and is accepted as a more natural solution [12]. A comprehensive review on hybrid exoskeletons can be found in [8].

The objective of a hybrid controller is to regulate passively or actively the net power delivered to the joints to achieve a functional and safe desired movement. There have been several theoretical developments of hybrid controllers, but the lack of adequate muscle models and advanced FES systems did not allow implementing those controllers in real conditions with pathologic subjects. The few hybrid controllers tested with pathologic subjects have assumed the FES as an unregulated and intermittent source of joint power. With this approach, the robotic exoskeleton is used to regulate net joint power and therefore to control the joint trajectory. In this regard, main issues that must be solved include: i) defining more accurate muscle models to control the joint torque produced by FES, ii) developing novel controllers that can deal with redundant characteristics of the musculoskeletal system, iii) improving physical and cognitive interaction between the user and the system, allowing the detection of abnormal patterns of movement, iv) implementing better control strategies that optimize task-dependent control functions, v) improving energy efficiency, to lower the weight of actuators and batteries.

III. MUSCLE SYNERGIES

Biomechanically, human body is a multi DoF and over-actuated system. The efficient and robust control achieved by the central nervous system has not been sufficiently understood and generates intense debate in neuroscience and bio-inspired robotics. Recent neurological research hypothesizes that in the peripheral areas of our nervous system we incorporate a distributed library of motor modules also known as muscle synergies, modulated with variable activation patterns triggered from the central system [2]. Thus, during the execution of a task the brain can focus on the execution of the plan from an high level perspective, while delegating the responsibility for the coordination of the activity of each muscle to the periphery, reducing the complexity of the motor control scheme.

Muscle synergies have three interesting properties. First, they can decompose the high dimensional EMG into a very low-dimensional ensemble of variables, i.e. the time-varying activation signals and the weighting coefficients, namely synergies. Second, they are strictly correlated to functional performance [13] and their modulation spans user space [7]. Third, synergies are consistent across healthy subjects [10].

These basic properties can bring substantial improvements to traditional FES control approach, in particular for: i) stimulating precise groups of muscles instead of activating single muscles independently, ii) establishing ad-hoc compensatory strategies, i.e. deciding which muscle groups to stimulate in order to provoke a desired functional effect on the specific subject, and iii) detecting abnormal neuromotor strategies of the patient, by comparing his/her specific weights (synergies) and activations with the healthy ones.

IV. MUSCLE SYNERGIES-BASED CONTROL

The proposed FES control algorithm, depicted in figure 1, fuses four sources of information to generate the compensative action: i) a set of healthy references constituted by synergies and activations observed on healthy subjects performing a similar task, ii) the residual neuromuscular activity of the subject, iii) a set of functional state variables, and iv) the interaction forces between the human and the robot.

The residual neuromuscular activity, is extracted in a preliminary diagnostic phase, and is used to anticipate the spontaneous muscle activity of the subject. Local (joint velocity and torque) and global (kinematics of CoM) state variables are monitored to verify the correct execution of the movement. Interaction forces are used to estimate the performance of the patient and for safety reasons.

Robotic actuators complement the action of FES by driving limbs kinematics to a prescribed trajectory, defined in the therapy. The control of the robot should follow classical assist-as-needed paradigm [9] and is beyond the scope of the paper. The control algorithm is composed of three main blocks, described in the following paragraphs.

Neuromotor Estimator

The Neuromotor Estimator analyzes muscular activity from superficial EMGs to assess the residual neuromotor abilities of the subject. Muscle synergies and time-varying activations signals are estimated from EMG through NNMF algorithm. Time-varying activations return information on the timing of muscular activations. Muscle synergies give an indication of the groups of muscles that are activated synchronously. It is important to know that single muscle activation is not generated by one single module, but is the result of the combined activity of many modules, each with different timings. This overlapped activity of different neural sources is not visible from traditional EMG analysis approach. The novelty of the proposed approach resides in decoding this neural organization, and then activating muscles according to the deciphered control architecture.

Task-level Observer

The Task-level Observer is a state machine that identifies the system state based on robot sensors. It alerts other components when the state changes. Sensory data are fused to generate functional state variables needed to calculate the compensative action.

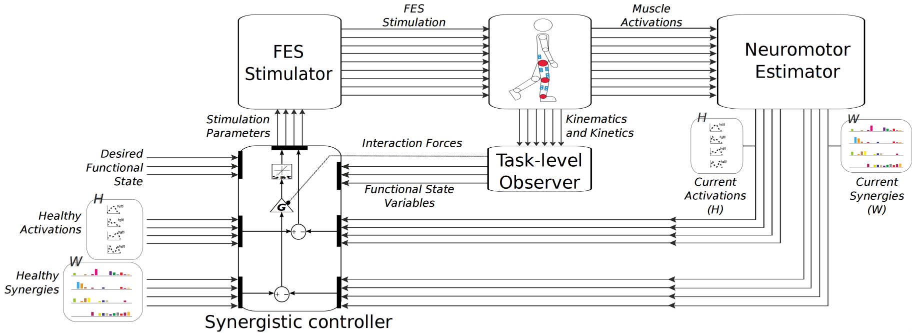

Fig. 1. Control scheme based on muscle synergies

Synergistic Controller

The Synergistic Controller closes the control loop by integrating clinical informations (synergies and activations from patient and healthy reference), functional state variables and interaction forces. It provides the FES stimulator with the appropriate set of stimulating parameters. The global amplitude of the stimulation is controlled from a gain factor adjusted accordingly to interaction forces. Choice of channels will directly result from the analysis of synergies. In fact, each synergy specifies which muscles have to be activated at the same time. Relative amplitude between active muscles is a function of synergies, since synergies also define all the weighting coefficients between neural activations and muscles. Timing is chosen from the analysis of activations, which represent the time-varying envelope of neural commands. Stimulation frequency is set with typical value according to the desired evoked movements.

V. BALANCE REHABILITATION THERAPY

The control scheme will be first applied to a balance rehabilitation therapy for CVA and specific SCI patients, consisting in the execution of anterioposterior and mediolateral sway at different frequencies, reaching the limit of stability in both directions. The rationale for applying healthy muscle activation patterns with FES during the execution of functional tasks is that the appropriate proprioceptive feedback provided in coordination with the executed movement and thus voluntary execution of the task, provides positive feedback loop that promotes neurorehabilitation [1] [5]. Balance control appears to be driven by time-modulated and spatially fixed muscle synergies [15], whose activations are correlated with the direction of the center of mass (CoM). We choose CoM kinematics as functional control variable, because there is evidence that it is the same feedback variable used for postural control of balance in humans,[15]. A synergy-based biological scheme of control has been proposed by Ting et al. for balance control [16]. In this implementation, the neuromotor control is modeled as a multi layered system with synergies activations modulated on the higher level controller, based on the kinematics of the CoM. From a practical point of view, CoM positions are calculated from joints kinematics, while CoM acceleration from GRFs.

Hardware setup

The requirements for the robot are to control lower limb articulations (pelvis, hip, ankle and knee) and measure joint angles, GRFs and interaction forces between human and robot. The requirements for the motor neuroprosthetic counterpart are to measure and control muscle activity on lower limbs. The hardware consists in i) a 6 DOF lower limb exoskeleton for ankle, hip and knee, with a potentiometer on every joint to measure articular angles, ii) a multi-anode multi-cathode FES system including 32 independent channels with variable current pulse shapes (biphasic, load compensated), amplitudes (0.5-100 mA, 200V) and frequencies (1-10kHz) [4], iii) a force platform (NEUROCOM) for GRF sensing, and iv) 16 EMG electrodes per leg for the extraction of muscle synergies.

One key component of the system is the FES systems. This FES system, called TEREFES, can be programmed to stimulate muscle groups (serveral electrodes per group) in flexible manner. The TEREFES includes Simulink (Mathworks Inc.) models that can be used to control the device, creating complex and overlapping stimulation patterns. Thus, TEREFES can simulate muscle activation driven by bioinspired muscle synergies.

Protocol workflow

To calculate the compensative action, the control uses online data from sensors and offline data from both a preliminary study on healthy people and a diagnosis of the patient, as described below.

1) Preliminary study: In the preliminary study, a library of healthy references is generated. These references are described in terms of synergies, activations and functional variables (kinematics of limbs and CoM). During the study, healthy subjects are asked to perform rhythmic sinusoidal movements in the sagittal plane while wearing the robot. The exoskeleton is controlled in zero-impedance mode, to minimize interaction forces. Muscle synergies, activations and functional variables are recorded and shared muscle synergies extracted [6]. FES is not needed for the preliminary study.

2) Diagnosis: The diagnosis phase is needed to estimate the residual neuromotor capabilities of the patient and to adapt the therapy. Muscle synergies and activations are used as an indicator of the evaluated neuromotor function[3]. To perform the extraction, the robot applies to these joints reference trajectories pre-defined in the preliminary study. The patient is asked to follow the movements. The objective of this procedure is to estimate synergies and activations that the patient would generate during the therapy. We expect that the robot will consistently alter muscle activity. However, one possible solution would be to control the robot in the same way than during therapy phase. In this phase, FES is also not used.

3) Therapy: During therapy, FES is finally applied for functional compensation. To calculate the amplitude of current pulses required by each muscle, healthy muscle synergies and activations are compared to the ones extracted from the patient in the diagnosis. Since muscle can only be driven with a positive current, muscle weight is set to 0 when a muscle is overexcited in the patient comparing to the reference. The following equation describes the assessment of the muscular activity:

$$H_{assist} = max(H_{healthy} - H_{residual}, 0) \tag{1}$$

and

$$W_{assist} = max(W_{healthy} - W_{residual}, 0), f \tag{2}$$

where H are the activations and W the synergies of reference ($healthy$) and patient ($residual$). The amplitude of the electrical stimulation provided by FES, I, is limited by patient's tolerance, and it is calculated with a reconstruction function that ensembles previously calculated assistive activations and synergies. This calculation is made following the equation

$$I_{assist} = max(G * W_{assist} * H_{assist}, 0), \tag{3}$$

where the product $W_{assist} * H_{assist}$ calculates a balance between the current required for each muscle, and G represents a gain that increases when a degradation of the performance of the patient occurs.

The estimation of this performance comes from the level of interaction force between the human and the robot, measured by the exoskeleton during the exercise. Forces, and therefore G, can take positive or negative values when opposing or anticipating the movement. For this reason, when forces equals zero or becomes negative, the stimulation level is set to 0.

VI. CONCLUSIONS

An innovative control algorithm for the FES module of an hybrid exoskeleton was presented. Electrical stimulation is dynamically balanced using feedback informations from functional variables measured by the robot. The analisys of muscle synergies in the patient allows to adapt the compensative action to the specific patient and task. A balance rehabilitation therapy was proposed for a first validation of the controller.

Preliminary studies on healthy and pathologic subjects to realize reference and validation libraries are being performed [17]. Future directions of the studies will be the extension of balance rehabilitation therapy to multiple directions and different tasks, like rehabilitation of sit to stand function or compensation of external perturbations. To rehabilitate more dynamic functions, like walking, the limited portability of the system needs to be improved. The integration of with force sensors in the soles can resolve this limitation. Finally, an interesting approach that will be considered to foster the effects of rehabilitation will include the application of FES for the stimulation of propriocepive feedback.

REFERENCES

[1] Juan-Manuel Belda-Lois, Silvia Mena-Del Horno, Ignacio Bermejo-Bosch, Juan C Moreno, Jose L Pons, Dario Farina, Marco Iosa, Marco Molinari, Federica Tamburella, Ander Ramos, Andrea Caria, Teodoro Solis-Escalante, Clemens Brunner, and Massimiliano Rea. Rehabilitation of gait after stroke: a review towards a top-down approach. Journal of neuroengineering and rehabilitation, 8(1):66, January 2011.

[2] E Bizzi, V C K Cheung, A D'Avella, P Saltiel, and M Tresch. Combining modules for movement. Brain research reviews, 57(1):125–33, January 2008.

[3] M G Bowden, D J Clark, and S A Kautz. Evaluation of abnormal synergy patterns poststroke: Relationship of the fugl-meyer assessment to hemiparetic locomotion. Neurorehabilitation and Neural Repair, 24(4):328–337, 2010.

[4] F Brunetti, a Garay, J C Moreno, and J L Pons. Enhancing functional electrical stimulation for emerging rehabilitation robotics in the framework of hyper project. IEEE ... International Conference on Rehabilitation Robotics : [proceedings], 2011:1–6, June 2011.

[5] John Chae, Lynne Sheffler, and Jayme Knutson. Neuromuscular electrical stimulation for motor restoration in hemiplegia. Topics in Stroke Rehabilitation, 15(5):412–426, 2008.

[6] S A Chvatal, Torres-Oviedo, S A G. Safavynia, and L H Ting. Common muscle synergies for control of center of mass and force in non-stepping and stepping postural behaviors. Journal of Neurophysiology, 106(2):999–1015, 2011.

[7] Andrea D'Avella, Alessandro Portone, Laure Fernandez, and Francesco Lacquaniti. Control of fast-reaching movements by muscle synergy combinations. The Journal of neuroscience : the official journal of the Society for Neuroscience, 26(30):7791–810, July 2006.

[8] A. J. del Ama, A. D. Koutsou, J. C. Moreno, A. de-los Reyes, A. Gil-Agudo, and J. L. Pons. Review of hybrid exoskeletons to restore gait following spinal cord injury. Journal of Rehabilitation Research and Development, (IN PRESS).

[9] V Reggie Edgerton and Roland R Roy. Robotic training and spinal cord plasticity. Brain research bulletin, 78(1):4–12, January 2009.

[10] Y P Ivanenko, R E Poppele, and F Lacquaniti. Five basic muscle activation patterns account for muscle activity during human locomotion. Journal of Physiology, 556(1):267–282, 2004.

[11] A Kralj, T Bajd, and R Turk. Gait restoration in paraplegic patients: a feasibility demonstration using multichannel surface electrode FES. Journal of rehabilitation . . . , 1983.

[12] Juan C Moreno, Antonio J Del Ama, Ana de Los Reyes-Guzmán, Angel Gil-Agudo, Ramón Ceres, and José L Pons. Neurorobotic and hybrid management of lower limb motor disorders: a review. Medical & biological engineering & computing, August 2011.

[13] R R Neptune, D J Clark, and S A Kautz. Modular control of human walking: A simulation study. Journal of Biomechanics, 42(9):1282–1287, 2009.

[14] EJ Nightingale and J Raymond. Benefits of FES gait in a spinal cord injured population. Spinal Cord, 2007.

[15] S A Safavynia and L H Ting. Task-level feedback can explain temporal recruitment of spatially-fixed muscle synergies throughout postural perturbations. Journal of Neurophysiology, 107(3):159–177, 2012.

[16] LH Ting. Dimensional reduction in sensorimotor systems: a framework for understanding muscle coordination of posture. Progress in brain research, 2007.

[17] D Torricelli, M Aleixandre, I M Alguacil Diego, R Cano De La Cuerda, F Molina Rueda, Carratalá Tejada, S Piazza, and J L Pons. Modular control of mediolateral postural sway. EMBC, 2012.