SIMULTANEOUS AND PROPORTIONAL DECODING OF STIFFNESS AND POSITION INTENTIONS FROM TWO SEMG CHANNELS FOR UL PROSTHETICS

P. Capsi-Morales[1,2], C. Piazza[1], M. G. Catalano[2], A. Bicchi[1,2] and G. Grioli[2]

[1]*Centro "E. Piaggio" and Dipartimento di Ingegneria dell'Informazione, University of Pisa Largo Lucio Lazzarino 1, 56127 Pisa, Italy.*

[2]*Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy.*

ABSTRACT

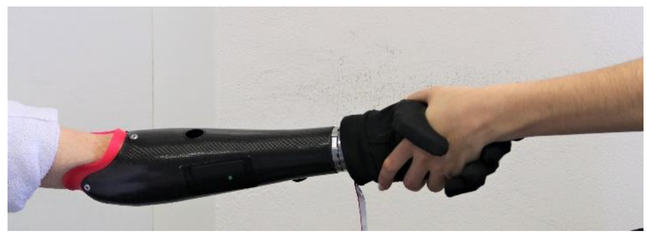

Figure 1: Physical social interaction between two subjects mediated by a soft robotic hand with variable stiffness control.

To physically interact with a rich variety of environments and situation-oriented requirements, humans continuously adapt both the stiffness and the force of their limbs through antagonistic muscle coactivation. Reflecting this behaviour in prostheses may promote control naturalness and intuitiveness and, consequently, their acceptance in everyday life. We propose a method capable of a simultaneous and proportional decoding of position and stiffness intentions from two surface electro-myographic sensors placed over a pair of antagonistic muscles. First, the algorithm is validated and compared to existing control modalities. Then, the algorithm is implemented in a soft under-actuated prosthetic hand (SoftHand Pro). We investigated the feasibility of our approach in a preliminary study involving one prosthetic user. Our future goal is to evaluate the usability of the proposed approach executing a variety of tasks including physical social interaction with other subjects (see Figure 1). Our hypothesis is that variable stiffness could be a compromise between firm control and safe interaction.

INTRODUCTION

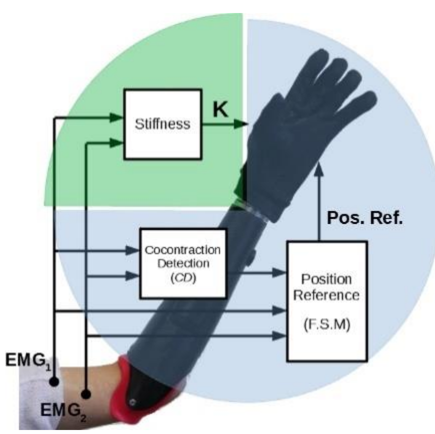

Figure 2: Block diagram of the proposed method: Three functional blocks decode stiffness (green colour) and position (blue colour) references from a pair of sEMG.

Artificial limbs are very valuable assets to restore some of the capabilities lost after an amputation. However, there is still a sharp separation between available functional devices and the real needs of prosthetic users [1]. Social interaction and safety are aspects that cannot be underestimated in prosthetics, especially in upper limb, due to the inherent interaction of the artificial hand with, not only the user, but also the rest of the world. Already in 1983, Hogan [2] suggested impedance control as the preferred paradigm for controlling prostheses, as it would provide the amputee with an essential component of the natural adaptative capability of humans, despite the severe sensory loss. Moreover, behavioural studies of postural limb control show that humans modulate joint stiffness to minimize the perturbing effects of external loads [3] and to improve limb stability and movement accuracy [4]. However, muscles stiffness regulation is not available in off-the-shelf prosthetic aids, neither its investigation is given, in literature, the space we believe it would deserve, both under the control [5] and mechatronics points of view.

We introduce a method for decoding an estimate of user's stiffness intention, based on cocontraction, which can be used simultaneously within a proportional velocity control framework, thanks to the inclusion of a custom Finite State Machine. The primary objective is to exploit cocontraction for a useful and intuitive increase of direct control robustness, a better decoding of patient's intentions and to enlarge prosthesis dexterity. The novel control was preliminary tested with one subject with limb loss, with encouraging results.

DECODING OF STIFFNESS & POSITION

It is well known that the position of a joint is defined by the equilibrium of the various muscles acting on it, together with external forces. However, the multiple action of antagonistic muscles, i.e. coactivation, defines the mechanical properties of the joint as well. In order to benefit from the intrinsic muscle stiffness regulation that humans have, we propose an algorithm capable to decode both position and stiffness intentions from two sEMG channels with the inclusion of coactivation.

A common method to estimate the level of coactivation of a pair of muscles is to correlate it to the weighted average of the level of activation of the two antagonistic muscles (e.g. as in [6]), as

$$K = C_1EMG_1, C_2EMG_2 \ . \qquad (1)$$

Stiffness K can either increase due to involuntary reaction to external disturbances, voluntary cocontraction, or reciprocal muscle activation. Unfortunately, combining this estimate with traditional velocity control schemes, would have the inconvenience that pure cocontraction phenomena, unless perfectly symmetrical and synchronized (which never happens in practice), would be interpreted as either open or close commands, depending on which of the two EMG signals is observed overcoming its threshold first.

To prevent this issue, we observe that usually the level of the extensor muscle contraction is almost zero when closing, and the opposite happens when opening. Therefore, we can define an additional variable used for binary (true/false) detection of pure cocontraction, *CD*, as in

$$CD = \begin{cases} 0, & if\ min(C_1EMG_1, C_2EMG_2) < Th_{CD} \\ 1, & otherwise \end{cases} \qquad (2)$$

where Th_{CD} is a suitable threshold value. Consequently, *CD* will be one only when cocontraction is intended, as both sEMG have a high level of activation, and null when only one of the two sEMG is above the threshold, indicating a motion intention.

Note that the calculation of *CD* and *K* are simultaneous and independent, thus the algorithm keeps generating commands of velocity and stiffness simultaneously. It is possible to observe that there is some correlation between motion commands and stiffness, since when the user contracts one muscle, e.g. to close the hand, it will always command a minimum level of stiffness, proportional to the minimum level of activation needed for the active muscle to overcome its threshold (see Figure 3), but this reflects the natural behaviour of muscles, being a desired and welcome effect.

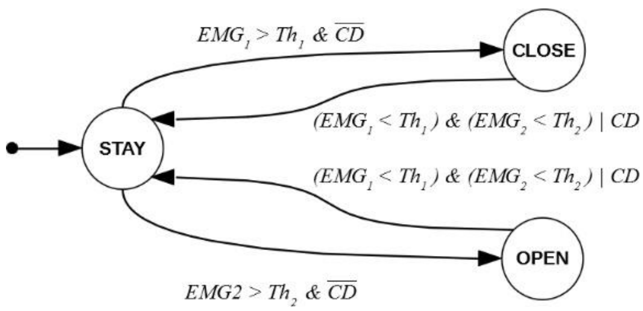

Figure 3: Finite States Machine used to refine the speed of the hand. Hand states are defined by circles, while guard conditions are written directly nearby the arrow connecting pre and post states. The starting state is STAY. *Th1* and *Th2* are the activation threshold for each channel to detect intention of movement.

Figure 3 shows the Finite State Machine that is ultimately used to discriminate the user's intention to modify the reference configuration (*RC*) - opening or closing the hand - or to hold it still. The definition of the hand *RC*, in analogy with typical velocity control frameworks, is updated as

$$\dot{RC} = \begin{cases} C_1EMG_1, & if\ CLOSE \\ 0, & if\ STAY \\ C_2EMG_2, & if\ OPEN \end{cases} \ . \qquad (2)$$

ALGORITHM VALIDATION

We present an example of the behaviour of the proposed algorithm, and compare it to existing methods, highlighting the different interpretation of the user's intentions. Two EMG signals were collected and read into MATLAB Simulink (Mathworks, Inc) from a healthy subject (female, age 26). Two commercial sEMG sensors were used to get the signals (13E200=60, OttobockGmbH, Germany). The various control algorithms were run in Simulink.

The first panel of Fig. 5 shows the EMG activations, while the three remaining panels present the system responding to the following control modalities:

- PPC-PS: Proportional Position (used e.g. in [6]) with Proportional Stiffness;
- PVC-HS: Proportional Velocity (FSM 1) with High constant Stiffness;
- PVC-LS: Proportional Velocity (FSM 1) with Low constant Stiffness;
- PVC-PS: Proportional Velocity (FSM 2) with Proportional Stiffness.

where FSM 2 refers to the machine previously detailed (figure 3), while the FSM 1 does not consider CD as an input of its conditions.

The differences between the two variables related to muscle coactivation used in this work (*K* and *CD*) are observable in figure 4. *K* is presented in the second and fourth panel, proportional to muscle activation. *K* tends to rise both in the case of cocontraction and of pure contraction, making the detection of pure cocontraction phenomena hard. This leads to the introduction of *CD*, which is defined by the variable *cdet* represented by the grey area of the first panel. Comparing *cdet* to a simple threshold (the dashed black line), there is a clear categorization between cocontraction and other types of muscle activation.

Concerning position reference, in the case of proportional position control (second panel), based on the difference between EMG_1-EMG_2, we observe how cocontraction is interpreted in opposition to as intended, reducing the level of activation. This results in motion of the hand in a direction opposed to the desired one. In addition, although PPC is more reactive to muscle variations, the subject must keep the muscle active during all the time in order to maintain the hand closed. This is tiring both from a physical and mental point of view. Regarding the performance of the two FSM for PVC, FSM 1 already solves the problem of the tiredness, but is not able to understand pure cocontraction as an extra user's intention. As seen in the third panel, the FSM states does not correspond with the real intentions, not just closing the hand when cocontracting, but also not opening the hand in the first part, as no relaxing phase (STAY state) occurs before the opening intention (around t = 5s). On the contrary, FSM 2 understands correctly subject's intentions, closing and opening just when the proper muscle is active, and remaining in STAY state when nothing occurs or if the user cocontracts to increase the stiffness but not intend to change hand position. Although it is noticeable some very fast oscillations of the FSM 2 close to cocontractions, when just one of the EMG is active (e.g. shortly after 14s and before 22s), in practice these oscillations do not affect *RC* sensibly.

GRASP COMPLIANCE

The proposed method was implemented on a soft underactuated hand device, the SoftHand Pro [7]. To the best knowledge of the authors, this is the first experimental validation of impedance control in prosthetics hands performed by an amputee, indeed, previous works as [8] and [9] used healthy subjects only. We validate the feasibility of the control algorithm used by a prosthetic user with informed consent. The subject (female, age 37) has a congenital malformation at the trans-radial level in the left arm. She typically uses a cosmetic prosthesis but is well trained in control of standard myoelectric prostheses. We study the response of the system with regards to an external perturbation while using the four control algorithms presented in the algorithm validation section.

CONCLUSIONS

In order to achieve different desired behaviours in upper limb prosthetics for Activities of Daily Living and for social interactions, an alternative solution to the classical sEMG based control is explored. The proposed method includes stiffness modulation of the hand, proportional to muscle coactivation with a proportional velocity control of the hand configuration with the use of a Finite State Machine. The algorithm is preliminarily validated with a prosthetic user, comparing it with other conventional control modalities implemented in the SHP. Eventually, this concept could be implemented in other rigid prosthetic hands, where differences between modalities could be even more visible/useful, as their only compliance can be given by the motor impedance.

Preliminary results evidence a better understanding of user's intentions through the inclusion of cocontraction on the control algorithm. Different performances are observed among control strategies studied, which could influence subjects' perception. For the moment, the user underlined the lack of confidence and difficulties to command the hand when using the Low constant Stiffness control (LS), because of the lack of reactivity, and Proportional Position Control (PPC), because of the amount of cognitive load required.

Our objective is to explore the perceived function of variable stiffness control compared to strategies with a constant stiffness value. User's preferences will be assessed by the System Usability Scale (SUS) [10] after performing a set of tasks without having any information about the control implemented in the prosthetic hand. Among these tasks, one- and two-handed object manipulation are included together with self-interaction and social interaction with 12 able-bodied volunteers. Volunteers reactions will be also collected and analysed.

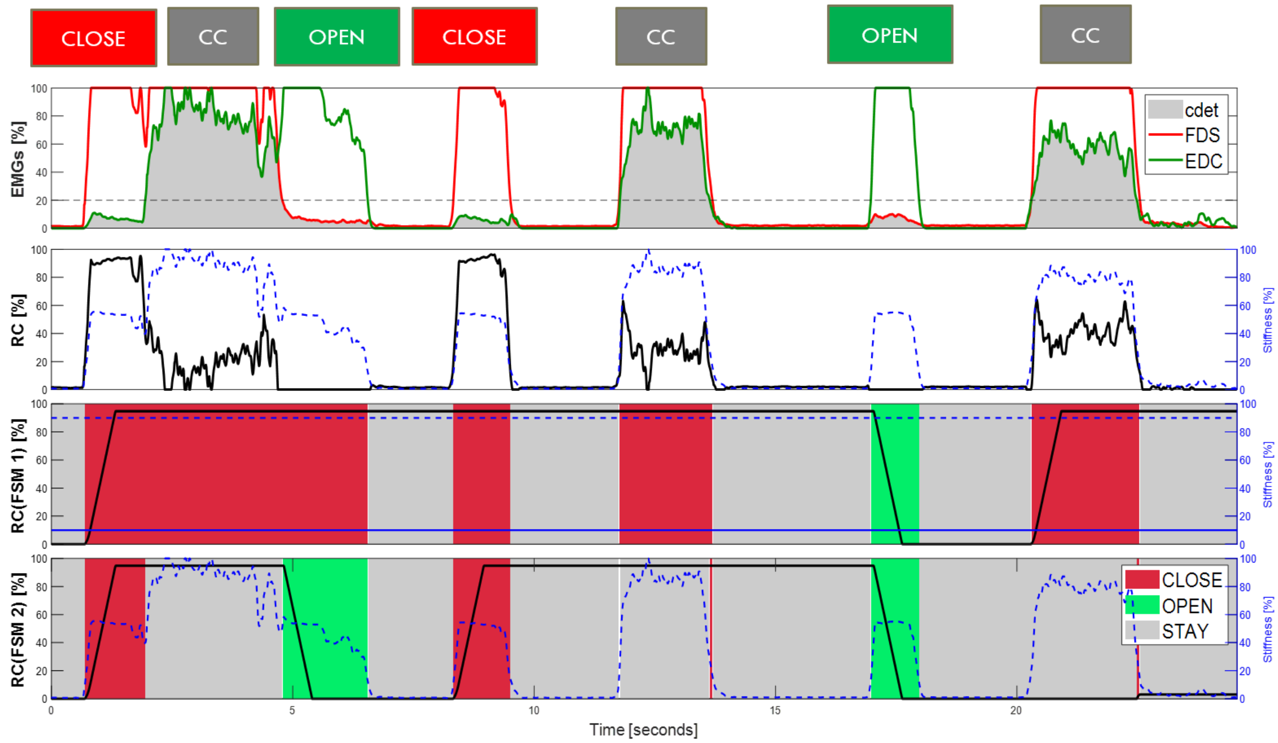

Figure 4: Experimental comparison of different control strategies responding to the same muscle activation. The first panel presents the muscle activation from a healthy subject performing a series of intentions described in coloured boxes in the upper part of the graph. The variable $cdet = min(C_1 EMG_1, C_2 EMG_2)$ defines *CD* for the FSM 2. Second panel shows the outputs of PPC-PS, third panel the overlapped outputs of PVC-LS and PVC-HS, while fourth panel reports the outputs of PVC-PS. Black line (left y-axis) reports RC while blue line (right y-axis) reports stiffness reference. In the third panel, both high and low constant stiffness are represented, HS is outlined with a blue dashed line, while LS with a blue continuous line. All quantities are normalized. In the bottom two cases, where FSM are employed, colours are used to represent the state (detected intention of the user) in each moment. Red areas correspond to when closing is understood by the algorithm, green when opening, and grey when the hand keeps the previous position.

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