ALTERNATIVE MYOELECTRIC CONTROL THROUGH NEURAL SYNERGISTIC INFORMATION

Patricia Capsi-Morales[1,2], Deren Barsakcioglu[3], Manuel G. Catalano[1], Giorgio Grioli[1], Antonio Bicchi[1,2] and Dario Farina[3]

[1]Istituto Italiano di Tecnologia - SoftRobotics Lab for Human Cooperation and Rehabilitation, [2]University of Pisa - Research Center E.Piaggio, [3]Imperial College of London - Department of Bioengineering

ABSTRACT

This work combines for the first time structural and computational synergies defined by neuronal information. The main idea is to investigate the existence of motor neuron synergies and their potential as sources for myoelectric control. First, we developed a new version of the soft hand with 2 degrees of actuation (DoA) for prosthetic applications. Then, we used HD-sEMG to study the behaviour of motor units in different manipulation tasks and to identify motor modules or neural synergies. Based on this dimensionality reduction in both the mechanical prosthetic design and the neural control, we propose a method to map the neural information into prosthesis control. With this approach, we first show that neural synergies have greater dimensionality than classic muscle synergies. This property and a greater degree of independence determine the possibility of a natural, robust and simultaneous control of several DoA by neural synergies. The proposed method can be implemented into an available framework of online decomposition (i.e. online extraction of motor units) in order to create a platform to study different myoelectric control methods and compare their performance in a virtual environment, and in the real-time control of the SoftHand Pro-2. The creation of this platform permits further developments on the existence of modules in upper-limb motor control, the relation between different synergistic levels and its use for assistive and rehabilitative robotics with different type of patients.

INTRODUCTION

Modularity is present in both structural and computational components of a control architecture, and it has a functional purpose. It is commonly assumed that the remarkable versatility and adaptability in motor control is the result of employing modularity as the key organizational principle of the central nervous system [1]. Research on synergistic control has focused on developing analytical techniques to reveal the existence and the origin of the reduction in the dimensionality of the hand control space. The framework proposed in [2] suggests that the spinal circuits could explain many experimental observations about synergies revealed by studies of hand kinematics, kinetics, and EMG signals. Compared to animals and humans, state-of-the-art robotic hands still show limited and inflexible motor skills. Nonetheless, advances in robot technology allow researchers to explore and develop into how the motor, sensory, and cognitive functions might be integrated into meaningful architectures. The creation of artificial systems embedding synergies represents a benchmark to explore different concepts of modularity and to experimentally investigate possible interactions between motor and cognitive processes, which are fundamental for human understanding.

Postural synergies are considered to guide and simplify the design of hands, while allowing a high level of dexterity in the coordination of multiple joints. We developed a prosthetic version of a multi-synergistic hand (i.e. the SoftHand Pro-2) that presents two synergies, capable of reproducing continuous movement of all fingers in opposite directions. Improving upon the traditional advanced robotic hands, multi-synergistic permit the continuous mapping of different grasp patterns and their transitions. Moreover, multi-synergistic robotic hands could theoretically yield in-hand manipulation of objects. Note that to implement in-hand manipulation in fully actuated robotic hands, sophisticated algorithms and sensing strategies are generally required. The SoftHand Pro-2 could manipulate objects of different shapes with just two synergistic behaviors and requires a simpler control strategy. However, because of its synergistic nature, the control modality must match this concept and be also synergistic in order to create a proper mapping. Individual fingers movements, which are needed for simultaneous and proportional control during in-hand manipulation, are extremely hard to decode from sEMG sensors on extrinsic muscles (the common condition for transradial amputee subjects). To overcome peripheral coupling when a task requires independent finger actions [3] or for several coordinated multi-digit actions [4], finer modulation of neuromuscular activity might be necessary. This work proposes an alternative myoelectric control strategy based on the functional organization of motor units (MU) and neuronal synergistic information. We hypothesize that this methodology presents higher dimensionality and better specificity than other alternatives, such as muscle synergies. Moreover, this control method may not only be adequate to command a synergistic prosthetic hand, but the integration of both structural and computational synergies contributes to the creation of a framework to further develop on the existence of modules in upper-limb motion control and its application for assistive and rehabilitative robotics.

This work represents a unique opportunity that combines the expertise in neural interfacing (ICL, London) and in soft-synergistic robotics and prosthetic hands (IIT, Italy). Although this investigation presents several applications, its major potential applies to the field of prosthetics, where robotic devices become part of subject's missing body parts. We hypothesize that the lack of modularity as a principal direction in the design of artificial arm mechanics and control algorithms burdens the acceptance of prostheses and a natural bionic integration. This study attempts for the first time to match neural synergistic information with kinematic synergies. We decoded the activity of motor neurons innervating the hand while 9 participants exerted isometric forces during different wrist and hand movements related to the corresponding kinematics of the prosthetic arm. We then identified components explaining the variance of the motor neuron outputs, named motor neuron synergies (MNS, firstly introduced in [5]). For a better understanding of the functional role of MNS, and observe their applicability in myoelectric control, we compared them with synergies extracted from EMG amplitudes, i.e., muscle synergies. This work provides insights into the organization of neural inputs to spinal motor neurons from an offline analysis and proposes the first myoelectric control that uses neural synergistic information to control robotic hands which, to date, has been inferred through analysis of muscle synergies. We plan to apply this myoelectric control to the physical prosthetic hand, designed with postural synergies, and test its feasibility in online experiments.

This work stems from a collaboration within the ERC Synergy Project Natural BionicS, which is an international and multidisciplinary collaboration of European researchers to create fully integrated, symbiotic replacements for human limbs. The consideration of computational synergies introduces a completely fresh perspective for myoelectric control and appear especially interesting for multi-synergistic robotic devices. Furthermore, this collaboration aims at providing a foundation for merging neuroscientific and robotic principles. Promoting the combination of both concepts (motor neuron and kinematic synergies), we expect to provide prosthesis users with dexterous robotic systems with more intuitive and natural control.

DEVELOPMENT OF MULTI-SYNERGISTIC HANDS

The selection of appropriate prescriptive synergies in robotic devices is a difficult task as the observed behavior in humans (descriptive synergies) does not necessarily reveal the required control used by the nervous system (prescriptive neural synergies). Defining task-relevant prescriptive synergies is further complicated as their performance depends on the specific parameters and context of the task. The earlier developed SoftHand Pro is able to realize a vast range of grasps, and provides improved adaptability due to ts physical compliance and its synergistic actuation (i.e. by an designed tendon-driven differential mechanism) for improved adaptability. Despite its effectiveness in many practical conditions, this artificial hand presented some limitations in terms of dexterity when compared to a natural hand. The use of a single degree-of-actuation (DoA)prevents the execution of more complex tasks, like fine pre-shaping of fingers and in-hand manipulation. As a consequence, the SoftHand Pro-2 has been developed for prosthetic applications and for taking advantage of recent advances in the concept of neural synergies.. This is an under-actuated soft prosthetic hand with two synergistic behaviours. The combination of multiple soft kinematic synergies provides a continuous workspace that, in theory, is able to reproduce several hand postures and in-hand manipulation with a natural approach. The aim is to generate additional motions with minimal changes in the original mechanics of the SoftHand Pro, which has been already tested in clinical environments and real conditions with positive outcomes [6]. This framework turns transmission friction from a disturbance into a design feature, as suggested in [7], doubling the DoAs with little additional complexity. The vision of associating this mechatronic design to specific neural structures is different from any other current approach to prosthesis design.

Mechanical design

The SoftHand Pro-2 exhibits a total of 15 joints mostly embedding the flexion/extension of its fingers (see Figure 1). One revolute joint is present at the thumb, accounting for its abduction for a better opposition. The remaining 14 joints embedded in fingers are compliant rolling-contact element (CORE) joints. Elasticity is introduced in each joint. A single tendon moves from the palm base, connecting all the fingers, and two motors actuate the tendon, pulling it from its two sides. If the motors move in the opposite direction, the tendon length is shortened, and the SoftHand Pro-2 closes exhibiting a power grasp. If instead, only one motors moves, the tendon pulls from the corresponding side, partly closing the hand and generating a non-power grasp, but a rotation of the fingers from side to side, which can generate pinch to index point postures.

Figure 1: Final design of the novel prosthetic hand, the SoftHand Pro-2.

Hand capabilities

This hand is able to perform both precision (i.e. pinch or tripod) and power grasps, as well as to manipulate objects while maintaining a stable grasp through the embedded intelligence in its autonomous finger contact forces. The hand demonstrates that a larger variety of grasping and manipulation tasks can be theoretically performed by combining only two DoAs with softness and synergistic behaviors. The capability of in-hand manipulation, such as for the pouring of a liquid may be also executed by exploring the two synergies at different intensity levels without any compensation at the wrist level (usually related to wrist abduction/adduction). Because of the exploration of friction, sequential control inputs, may result also in different hand configurations, which is considered a feature to be explored, especially if a patient uses proportional velocity control (PVC). Even though the problem of manipulation modelling is solved for fully actuated hands (i.e. when the hand kinematics are injective), this is more complex for synergy-based hands. However, prosthesis users would most of the time have visual feedback of the manipulated object. Therefore, with a more natural control of the prescriptive synergies of the artificial hand, the additional feature of in-hand manipulation may become a feasible capacity. This feature is explored in this work through the use of motor neuron synergies.

MOTOR NEURON SYNERGIES

One motor neuron can receive inputs from several corticospinal inputs, mediated by premotor interneurons. A motor neuron synergy (MNS, termed in [5]) corresponds to a stable pattern of muscle activation (dynamic system), observable already at the premotor neurons level. Contrarily, the extraction of muscle synergies considers the spatiotemporal organization only from individual muscles. The concept of MNS is compatible with the existence of motor primitives, which could correspond to a set of synergies that are simultaneously activated for the coordinated control of a more complex system. In practice, to extract neural synergistic organization, we factorized the output spike trains of motor neurons innervating the extrinsic hand muscles found at the upper forearm level (common area to place EMG sensors in transradial amputated subjects). In addition, it has been suggested that the descending motor commands may control the dynamics of a system by modulating the shape of its synergies. The theoretical framework in [8] incorporates the notion of variable time shifts for individual synergies, that could permit the quantification of the degree of flexibility of a synergy related to the width of its valley when activated. The inclusion of fixed and flexible synergies in the control loop are of interest for the precise control of prostheses and perturbation avoidance. Here, we recorded data from different able-bodied subjects while performing isometric contractions during different manipulation tasks. Then, we concatenate all EMG signals recorded through HD-sEMG sensors to extract common features among hand positions. The methodology proposed combines EMG signal decomposition for the extraction of MU, and the application of non-negative matrix factorization (NMF) to observe neural synergistic information. Then, we propose a mathematical relation among upper-limb movements included (which are feasible to replicate with the hardware) and the extracted MNS. Doing so, we define the motor inputs or control commands necessary for the use of the prosthesis and an appropriate mapping of the subject intentions into robotic postures. Figure 2 shows an example of the recorded data from a pilot subject and the offline analysis of their MNS. The matrix W is the time-invariant weights of the synergies observed in 63 MU. The matrix H shows the time-variant activation of the defined synergies and their morphology according to the recorded tasks, visible at the bottom of Figure 2. Results show the repetitive use of MU in different hand postures, and accordingly, how this is translated into common neural synergies for different hand configurations.

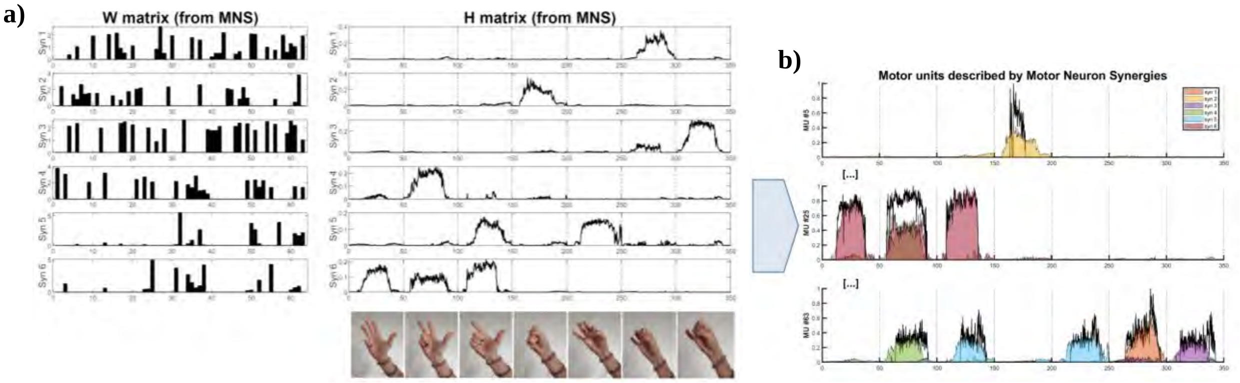

Figure 2: Example of motor neuron synergies from a pilot study. **a)** show the resulting matrices from NMF applied to motor units (MU), **b)** the reconstructed MU from the defined MNS. The vertical dashed lines in a) H matrix and b) represent the concatenation of the different manipulation tasks recorded and combined.

CONCLUSIONS

Preliminary results validate the potential of the proposed vision and the use of neural synergies for the control of postural synergies embedded in a prosthetic hand as an alternative myoelectric control that could permit more advanced manipulative skills with a natural approach. The methodology proposed can be implemented in a computationally efficient real-time interface based on the decoding of the activity of spinal motor neurons from wearable HD-sEMG sensors [9], which would permit the real-time testing of the control method while actively controlling the prosthesis with different subjects. Future work aims at the use of the resulting platform in the Medical University of Vienna with different types of patients (e.g. congenital, amputated subjects or patients with certain surgical conditions such as TMR), that will allow the investigation of how neuronal information varies across users. This framework permits future studies on the effect of modularity in the reduction of cognitive load in patients.

REFERENCES

[1] A. d'Avella, M. Giese, Y. P Ivanenko, T. Schack, and T. Flash. "Modularity in motor control: from muscle synergies to cognitive action representation," *Frontiers in computational neuroscience*, vol. 9, pp. 126, 2015.

[2] M. Santello, G. Baud-Bovy, and H. Jorntell. "Neural bases of hand synergies," *Frontiers in computational neuroscience*, vol 7, pp. 23, 2013.

[3] M. Santello, M. Flanders, and J. F Soechting. "Postural hand synergies for tool use," *Journal of neuroscience*, vol 18(23), pp. 10105–10115, 1998.

[4] M. H Schieber and M. Santello. "Hand function: peripheral and central constraints on performance," *Journal of applied physiology*, vol 96(6), pp. 2293–2300, 2004.

[5] S. Tanzarella, S. Muceli, M. Santello, and D. Farina. "Synergistic organization of neural inputs from spinal motor neurons to extrinsic and intrinsic hand muscles," *Journal of Neuroscience*, vol 41(32), pp. 6878–6891, 2021.

[6] P. Capsi-Morales, C. Piazza, M. G. Catalano, G. Grioli, L. Schiavon, E. Fiaschi, and A. Bicchi. "Comparison between rigid and soft poly-articulated prosthetic hands in non-expert myo-electric users shows advantages of soft robotics," *Scientific reports*, vol *11*(1), pp. 1-15, 2021.

[7] C. Della Santina, C. Piazza, G. Grioli, M. G Catalano, and A. Bicchi. "Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit softhand 2." *IEEE Transactions on Robotics*, vol (99), pp. 1–16, 2018.

[8] Mark L Latash, Vijaya Krishnamoorthy, John P Scholz, and Vladimir M Zatsiorsky. "Postural synergies and their development," *Neural plasticity*, vol 12(2-3), pp. 119–130, 2005.

[9] D. Y Barsakcioglu, M. Bracklein, A. Holobar, and D. Farina. "Control of spinal motoneurons by feedback from a non-invasive real-time interface," *IEEE Transactions on Biomedical Engineering*, vol 68(3), pp. 926–935, 2020.