On the Role of Postural Synergies for Grasp Force Generation and Upper Limb Motion Control

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***Abstract*— Although human movements are extremely complex, our nervous system is able to implement effective control strategies, leveraging on a generalized simplification approach. Several works described this behavior within the framework of synergies, which can be regarded as basis ingredients for motion generation through dimensionality reduction. Focusing on hand kinematics, this concept allowed to dramatically improve our understanding of the neuro-physiology of hand motor system, offering effective mathematical tools to identify pathological deviations from the physiological case. At the same time, these observations have found a fertile application field in robotics, suggesting simple yet effective manners to design and control artificial systems, with a reduced number of actuators or inputs. However, while much has been said about kinematic hand synergies and their implications for engineering, there are still open issues to tackle. Solving these issues could give better insights on the synergistic organization embedded within the human body, finally impacting the future development of robotic devices. In this paper, we will explicitly focus on the role that hand postural synergies play for grasp force control, and on preliminary observations on a synergy-based organization for upper limb motion generation. Applications of these neuroscientific findings for devising a principled simplification approach in assistive and rehabilitation robotics are finally discussed.**

I. INTRODUCTION

The human hand is an extremely complex system, composed by many joints, muscles and sensory receptors, which constitute a highly sophisticated and dexterous apparatus of our body. Several neuroscientific studies suggested that the human nervous system is able to cope with such complexity and organize it in a simple environment leveraging on a control space of reduced dimensionality [1], usually defined as synergistic control space.

For example, at the kinematic level, it is well-known that few combinations of the hand DoFs, e.g. described in terms of main principal components (PCs, i.e. postural synergies or eigenpostures) of hand joint angles recorded in grasping tasks, and organized in a geometrical basis, can take into account large part of hand pose variability [2]. This idea has then been successfully applied to robotics to devise simplified design and control guidelines for artificial systems [3].

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Although much has been said about synergies, there are still some important points that would deserve scientific attention. Indeed, the geometrical description of hand control offered by the eigenpostures in the kinematic space cannot be directly applied to explain force generation and distribution in grasping and manipulation tasks. To overcome this limitation, the concept of *soft synergies* has been introduced, where geometric synergies define a reference configuration towards which the real hand is attracted and at the same time repelled from, due to the interaction with the object and hand compliance. This model has been subsequently adapted for the development of soft and under-actuated hands [3].

Notwithstanding, the investigation of the role of postural synergies for the achievement of successful and robust grasp performance in terms of contact force distribution is still in its infancy. For these reasons, in the first part of this work, we will present our recent results on the incremental enrollment of postural synergies for the execution of successful grasping strategies, taking into account hand/object relative configuration. The second part of the paper will show our recent findings on modular and synergistic control of human upper limb kinematics, and their implication to robotics. Indeed, while a lot of works have been devoted to the study of hand synergies, much remains to be done to analyze whether and to which extent such a synergistic behavior is preserved in motion control of human upper limb.

II. POSTURAL SYNERGIES AND GRASP FORCE GENERATION

The mechanical compliance of the hand, as described in the soft synergy model [4] and in accordance with the Equilibrium Point Hypothesis [5], is the key enabling factor for a grasp to be successful. This characteristic has been then applied for the design of a novel generation of deformable robotic hands. These devices capitalize upon their intrinsic adaptability to purposefully exploit object and environmental constraints, thus multiplying their grasping capabilities, as humans actually do [6]. Such soft robotic devices often combine compliance and under-actuation, the latter can be achieved leveraging on soft-synergistic inspiration for dimensionality reduction [7].

Motivated by the interest that soft manipulation is gaining in robotics, and by the need of fully understanding and taking advantage from the neuroscientific concept of synergies - e.g. for device design, the foundations of a new framework for grasp analysis have been laid. The goal of this framework is to throw light on the role that kinematic eigenpostures play for grasping force generation.

In [8], authors numerically demonstrated that for a paradigmatic human hand the same postural synergies that are important for pose generation are also involved in the optimal distribution of contact forces during the grasp. Pushing further such an investigation, in [9] we discussed the characterization of grasp force distribution local minima, while varying the hand/object relative poses, and whether such minima are preserved while we incrementally enroll postural synergies for reference posture generation [4].

To reach this goal, we performed simulations with four different objects grasped through a 19 articular joints soft robotic hand, which we assumed to be fully actuated. The simulated grasps were used to evaluate - while increasing the number of synergies enrolled - the variations of optimal grasping force distribution (according to the optimality definition reported in [4]). We found - as expected - that, as the number of synergies available increases, the probability to successfully grasp an object with a given relative hand-object configuration increases as well. In addition, what is noticeable is that the increase of the number of postural synergies - which could be interpreted as an augmentation of hand dexterity capabilities - seems to preserve the local structure of the optimal force distribution functional. In other words, we noticed that the local minima for grasp force distribution are preserved, while the hand dexterity capabilities are increased.

III. Synergies in human Upper Limb kinematics

Most of human capabilities to interact with the environment rely on the architecture of human hands, whose positioning in space is crucial in everyday life task. The latter point has pushed our interest to investigate the rest of upper limb, and to verify if there are synergistic patterns underpinning human upper limb kinematic control. To achieve this goal, we performed experiments with thirty-three young healthy volunteers (Age: 26.6 ± 3.2, 17 female, all right handed) performing a set of 30 common actions - also called Activities of Daily Living (ADL), repeated three times. These actions were chosen so as to span the kinematic workspace of the human arm. Upper limb kinematics was recorded through a motion capture system, assuming a 7 DOF kinematic model, while an extended Kalman Filter-based identification tool was used to retrieve joint angles from the motion capture measures (for further details the interested reader could refer to [10], here omitted for the sake of space).

We applied Principal Component Analysis (PCA) to the whole dataset of movements, observing that there is no predominance of one Principal Component (PC) upon the others, which was, on the contrary, the case for hand kinematics [2], [11], [12], [13]. Indeed, for the upper limb, the first three PCs account for 32.15%, 24.77% and 16.03% of the total variance, respectively. Notwithstanding, the first three PCs together allow to explain more than 70% of the whole dataset variability, i.e. the upper limb kinematics. In other terms, the Euclidean space defined by the first three PCs represents a low dimensional control manifold, where most of the variability of upper limb movements is described. In addition, there is no dominance of specific DoFs among the synergy coefficients, but rather there is a mixed enrollment of all the DoFs.

IV. Conclusions and Applications to Robotics

The results presented in this paper further sustain the evidence of a low-dimensional synergistic control framework underpinning both grasp force and upper limb motion generation. While these outcomes have a neuroscientific value per se, they also open interesting scenarios for robotics and clinical assessment. The demonstration that the incrementality of postural hand synergy enrollment is also preserved for optimal force distribution can be indeed exploited for the development of soft synergy-inspired robotic hands, embedding additional synergies in their design for enhanced manipulation capabilities [14]. At the same time, the observations on a low-dimensional space for upper limb kinematics generation could be used to devise simplified control and design strategies for exoskeletons and artificial devices for assistive and rehabilitation robotics. Finally, such a synergistic description could be employed to quantitatively identify deviations from the physiological case, which can be ascribed to pathological conditions such as stroke.

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