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Comment

Transferring synergies from neuroscience to robotics ☆ Comment on "Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands" by M. Santello et al.

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1. Introduction

Our understanding of how organisms control their limbs, i.e. systems with multiple muscles and joints, has had a profound and transformative impact on grasping and manipulation in robotics. Roboticists have struggled for a long time (and still do) with the algorithmic complexities that arise from the combinatorial explosion associated with the similarly high-dimensional problem of controlling robotic limbs. In the context of hands, this means that there are many muscular and kinematic degrees of freedom that need to be controlled to produce a desired manipulation behavior. Generating such control commands is provably difficult (e.g., as per the curse of dimensionality) even for very simple systems [6]. It is therefore critical to understand how organisms produce physical behavior using their complex anatomical limbs.

A compact characterization of relevant, low-dimensional control subspaces promises to greatly facilitate the replication of human manual capabilities in robotic hands. Several lines of research in neuroscience provided evidence that organisms indeed learn to identify and use such low-dimensional subspaces for neural control of limb motions and forces. Early work identified low-dimensional motor primitives in the spinal cord of vertebrates [17,18]. Other

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work discovered a low-dimensional organization of human movements [10,16,23,33]. These experimental descriptions of dimensionality reduction of behavioral variables require only few basis functions, called synergies, that can be combined to explain the majority of the observed data.

But the last few decades have also seen heated debates about the nature of synergies. We say concepts in the plural because there are multiple definitions and interpretations of synergies. In the particular case of the neural control of limb and hand function, it remains debatable whether or not the nervous system implements synergies for the purpose of simplifying the dimensionality of the control problem [1,24,25,37,38]. Moreover, we have challenged the concept of muscle redundancy itself—which then challenges the need for simplification of the control problem and the need for synergies. The concept of muscle redundancy (having too many muscles or kinematic degrees of freedom) is indeed paradoxical with evolutionary biology and clinical reality. Why would an evolutionary process encode, grow, repair, control, etc., more muscles or joints than are strictly necessary? If the musculoskeletal system is redundant, why does disability arise even from mild neurological or orthopedic conditions? The fact that limbs are driven by musculotendons whose lengths are overdetermined (the rotation of a few joints sets the lengths and reflex responses of all muscles) also holds clues about this. This raises the possibility that organisms have evolved to have only enough degrees of freedom to be versatile while meeting the multiple spatio-temporal constraints of behavior in the real world given the structure and capabilities of the neuromuscular system, as discussed in detail in [21,24,38].

2. Descriptive versus prescriptive synergies

The ongoing debates about synergies in the realm of neuroscience must not hamper roboticists in their efforts to transfer and exploit the associated concepts in their field. But the challenges to the practicing roboticist include the lack of absolute certainty inherent to the deductive nature of neuroscience research [39], and the breadth of the neuroscience literature. Thus there is need to bring these different fields together in a way that helps both sides [38]. To facilitate this transfer in the context of synergies, it is important to distinguish between two possible interpretations of the dimensionality reduction in behavior: synergies could either be *descriptive* or *prescriptive* [21,38].

The subspace (i.e., manifold) of feasible motor actions is defined by the combination of the mechanical capabilities of the limb, the abilities and strategies of the controller, and the constraints (i.e., requirements) defining the task. Any successful execution of a task must by definition inhabit that subspace. Conversely, it is obvious that a motor command generated randomly will only by rare coincidence accomplish a desired task because it would need to have the good luck of being part of that lower-dimensional manifold, which may or may not be linear. Moreover, adding more task constraints defines a more particular control strategy as it further reduces the dimensionality of the subspace of all possible control commands [21].

Descriptive synergies are derived from experimental data. They capture the observed lower-dimensional structure of the subspace of feasible motor actions for a given task. Therefore, if we analyze behavioral variables (e.g. EMGs, kinematic variables, etc.), it is to be expected that we will detect that, as a consequence of meeting the constraints of the task, those variables will inhabit a low-dimensional manifold that *describe* the successful executions of the tasks.

By contrast, a prescriptive synergy is implemented by the controller to produce the task. It is an inherent property of the control law, and the controller is only able to execute control commands obtained from the combination of available synergies. A good example of this is the successful use of dynamic movement primitives for complex behavior in robots [31].

It is difficult—if not impossible—for statistical inference and deductive reasoning to uniquely identify the strategy used by a hidden controller (be it biological or robotic). Witness for example the challenges facing model-based estimation, machine learning, and optimal control when identifying the cost functions used by organisms [39]. Descriptive synergies are easily observed in experimental research. But proving the existence of prescriptive synergies of neural origins is much more difficult [25,37]—although there continue to be some recent efforts in that direction [2,20].

When exploring the distinction between descriptive and prescriptive synergies, one must bear in mind data suggesting that the nervous system may not have absolute, independent control over all muscles because of both anatomical and neural constraints [32,40]. Importantly, the role of perception on motor control, and even independence of muscle actions, is an important one that also requires further understanding [1,3,4,17,21,22,26,29,30,35].