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Reply to comment

Towards a synergy framework across neuroscience and robotics: Lessons learned and open questions. Reply to comments on: "Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands"

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We would like to thank all commentators for their insightful commentaries. Thanks to their diverse and complementary expertise in neuroscience and robotics, the commentators have provided us with the opportunity to further discuss state-of-the-art and gaps in the integration of neuroscience and robotics reviewed in our article. We organized our reply in two sections that capture the main points of all commentaries [1–9]: (1) Advantages and limitations of the synergy approach in neuroscience and robotics, and (2) Learning and role of sensory feedback in biological and robotics synergies.

1. Advantages and limitations of the synergy approach in neuroscience and robotics

As described by all commentators, the theoretical framework of synergies has inspired research on the nervous system's ability to control multiple degrees of freedom across a variety of contexts and experimental models. In the context of bio-inspired design of neuroprosthetic devices, Alessandro et al. [1], D'Avella [3], Lacquaniti et al. [5], Latash [6], Schieber [8], and Schwartz [9] point out that synergies have been a useful approach to study a wide range of motor behaviors besides hand control, including upper limb movements and locomotion, and describe some of the major findings of this research. Further, Schwartz [9] provided an insightful overview of the evolution of the concept of synergies, starting from pioneering work of Bernstein and Sherrington. All commentators concurred about the tremendous potential offered by leveraging the concept of synergy in robotics design for understanding neural control of movement. At the same time, they also raised important questions about how to best address such integration. Brock and Valero-Cuevas [2] make a point by noting that redundancy of degrees of freedom is counter to what one would expect to result from evolutionary process. According to the commentary by Lacquaniti and colleagues [5] (and as further reviewed in [10]), the acquisition of complex motor behavior in locomotion might rely on the sensorimotor system's ability to combine and acquire low-dimensional modular representations of motor commands, akin to motor synergies. Latash [6], who has performed extensive investigations on synergies, offers a thought-provoking alternative view of synergies as mechanisms whose functional role is leveraging, rather than reducing, the large number of dimensions of the sensorimotor system – which he defines as being *abundant*, rather than *redundant*. Latash [6] also commented that the central nervous system may specify spatial reference configurations for salient variables, which can be defined according to a hierarchical and hence synergistic organization. At the same time, performance variables (e.g. forces, displacements, and muscle activations) emerge with respect to external conditions. These Reference Configurations (RC) can be therefore mapped on a set of control variables through redundant, or abundant, transformations. For this reason, we agree with Latash [6] that to correctly define synergies from a biological perspective requires studying control variables involved in these transformations, which remains a challenging task.

However, from an engineering point of view, even a less far-reaching version of the RC concept in terms of spatial reference provides a very useful conceptual framework. We refer to this framework as "soft synergy" model, which can be profitably employed to drive the design of simple, but effective robotic hands. At the same time, it offers a valuable tool for robotic modeling, e.g., to explain the generation of performance variables (e.g. force distribution), which are related to external conditions and salient variable configurations (e.g. geometrical description of postural synergies). The Pisa/IIT SoftHand, whose design is inspired by such a soft synergy idea, represents a good example of the mutual inspiration between neuroscientific studies and robotics, and a first attempt to translate the neuroscientific considerations reported by the authors in technological applications.

Brock and Valero-Cuevas [2] made a distinction between prescriptive and descriptive synergies. Prescriptive synergies, and associated dimensionality reduction, are grounded in the biological system's neural and biomechanical architecture. In contrast, descriptive synergies are the measurable net outcome of the interaction between the operation of prescriptive synergies and the environment. These concepts appear not to be irreducibly different from the ideas postulated in the soft synergy model of a spatial RC living in the postural synergy manifold, and the actual configurations that the hand reaches at equilibrium under the attraction of the RC and the interaction with the environment. The main apparent difference is that the soft synergy model does not need a hierarchical description of the equilibrium manifold in terms of principal components or synergies. Although similarities and differences between these two sets of concepts certainly warrant further discussion and investigation, we will elaborate here on the hypothesis that a convergence is possible.

The need for separating the description of the RC/prescriptive synergy manifold and the equilibrium/descriptive manifold, which was brought up also in the commentaries by Alessandro et al. [1] and d'Avella [3], was indeed at the origin of the experimental design originally used by Santello and colleagues [11], who extracted RC/prescriptive hand postural synergies by asking subjects to grasp imagined, rather than real, objects. Interestingly, our recent study based on kinematic synergies revealed that a synergy-based model could encode grasping virtual objects in human motor cortical areas significantly better than somatotopic or muscle-based models [12]. The demonstration that synergies are both topographically arranged in human motor areas across individuals, and correspond to meaningful motor primitives that group together multiple joints, support the idea that the nervous system specifically exploits synergies "as a control mechanism" [3,9]. In particular, these observations revealed that human motor cortical areas represent hand postures by combining few elementary synergy-based module, thus indicating how descriptive synergies – at least in part – overlaps with prescriptive synergies. Indeed, kinematic synergies account only for a portion of the brain activity, thus implying that other performance variables, which are required to grasp or to manipulate an object and have to be continuously monitored to allow for online corrections (e.g. contact forces, muscle activity, temporal patterns of movements, action goals, etc.) [6] might also be encoded in primary motor cortex (e.g., [13]). However, despite recent findings reported in [12], the role of cortical motor areas – i.e., whether they actually contain information on synergy modules or simply act as a mere selector of motor primitives that are encoded at different levels – still remains open.

Robotics researchers have leveraged RC/prescriptive synergies observed in humans to simplify control [14] and design [15] of artificial hands, but work in "The Hand Embodied" went a step further by combining these concepts with a soft robotic implementation, thus instantiating the soft synergy paradigm by conferring the compliance needed to adapt to the environment [16]. This approach significantly increases the versatility of the hand: as the artificial hand can attain configurations outside the simplified RC synergy manifold, the user can exploit environmental constraints to shape the hand across a much richer variety of postures [17,18]. By doing so, softness effectively acts as a multiplier of prescriptive synergies onto a higher dimensional equilibrium manifold, where a wider repertoire of behaviors can be achieved.

Laumond [7] pointed out limitations of applications of the concept of synergies to robotics [7], and in particular the issue of limiting the range of dexterous behaviors when taking inspiration from biological synergies to design robotic hands. Similarly, Schieber [8] commented that synergies have limitations in biological artificial systems: the reproduction of biological motor behaviors by robots would require a very large number of synergies. As [7] and [8] also pointed out, there are limitations due to the fact that synergies are intrinsically task dependent [19]. For example, playing piano requires different and more complex action-driven movements. However, there is evidence suggesting that complex actions, such as haptic exploration, can be described through synergies, which can be used to reconstruct "simpler" postures (e.g. grasps). This points to the existence of commonalities of digit movement coordination patterns across these tasks [20]. All of these comments on functional limitations of synergies are perfectly justified for the case where reference synergies are used prescriptively, i.e. rigidly. However, these limitations can be mitigated by experimental evidence showing that humans can use a hand designed with a single reference synergy to perform complex tasks (see e.g., [21]), by exploiting the interaction of the environment constraints and the hand softness. In general, however, it is clear that to achieve better dexterity, e.g. for doing in-hand manipulation tasks, the number of independently controllable reference synergies has to be increased.

These considerations also offer significant insights on the mechanisms underlying learning of novel synergies, and how task requirements may shape them. Specifically, and as pointed out by Ficuciello and Siciliano [4], the intrinsic limitation in the range of tasks that robotic synergies can perform could be addressed by leveraging upon machine learning techniques for posture generalization [22,23]. A non-mutually exclusive approach is to increase the functional capabilities of artificial hands by leveraging additional degrees of actuation, or to implement hands based on different RC synergy sets for different sets of tasks. A robotic hand implementing two independent soft synergies has been recently demonstrated [24]. This hand can rotate grasped objects even without recurring to help from environmental constraints. There is an obvious trade-off between having a more dexterous robot hand and the corresponding increase in cost, fragility, and complexity of control. It should be pointed out that building a complex hand (for example, with all joints independently controlled) may be much easier, from a research perspective, than conceiving one where the same degrees of freedom are organized according to a principled simplification scheme. The real research challenge could thus be posed as to design the simplest hand that can perform a given task or set of tasks, and to investigate the conjecture that the "minimalistic" hand that can perform all tasks humans can perform is the human hand itself.

Schieber [8] also discusses the impact of the interplay between neuroscience and robotics on the development of neuroprostheses, as well as on advancing our understanding of brain function. As an example of a relevant application, we mention here the prosthetic version of the Pisa/IIT SoftHand, which has been preliminarily tested on individuals with upper limb loss and successfully used to perform activities of daily living, e.g., playing cards and picking up a coin from a table surface [25]. The commentaries of Laumond [7] and Schieber [8] share the underlying notion that caution should be observed when applying biological principles to robotics, and biological synergies are no exception. We agree with this point. Robotics has often taken inspiration from evolution, and awareness of how biological systems work is a powerful tool for researchers. However, bio-aware robotics should not be reduced to merely trying to imitate Nature. This is not really an option, given that the physics of materials available to engineers is totally different from biological materials, which also implies differences in the type of intelligence that is embodied in biological structures. Rather, what bio-aware robotics tries to do is to describe neuroscientific observations and understanding into a language that can be translated into artificial systems to inform a more effective design. This language is by necessity mathematical, and geometry appears to be the most effective abstraction to describe actions and interaction of natural and artificial systems.

2. Learning and role of sensory feedback in biological and robotics synergies

One of the major questions regarding synergies is the extent to which their organization may be fixed or flexible with regard to their ability to adapt to different task conditions, and be reconfigured as a function of learning processes. Understanding these fundamental phenomena could lead to insight into the design of more versatile robotic devices. This was pointed out by Ficuciello and Siciliano [4], who also suggested the potential benefits of investigating learning algorithms in conjunction with synergies. These investigations would aim at combining a low-dimensional control space with the system's ability to adapt to a wide variety of task condition. We welcome this suggestion and agree that it would be particularly useful for robotic designs that combine synergy-based dimensionality reduction with soft robotics [16–18]. This would enable to naturally multiply the degrees of freedom of these systems, which can deform and adapt to the external environment, and thus be capable to perform a wide range of actions. At the same time, such an ability could be profitably employed to reproduce tasks with dynamically changing constraints, leveraging upon environment exploration, e.g. within the general framework of Reinforcement Learning or Iterative Learning Control [22,26]. If such an integration of learning algorithms and synergies could be optimized, performance of heavily under-actuated devices should significantly improve without having to compromise the complexity of their mechanical design. Related to generalization and learning of synergies in humans, two important points are brought up by Lacquaniti et al. [5]: the limited extent to which synergies can generalize to task performed under different conditions, and the role of modular synergies as 'building blocks' whose integration allows for the acquisition of more complex motor behaviors. Within this framework, different synergies might therefore result from combining existing ones as required by the task. Examples of implementation of this concept to robotics in the form of dynamic motion primitives are described by d'Avella [3], who also suggests that a better understanding of the role of synergies in biological sensorimotor learning could have a significant impact on robotics.

The above considerations bring up a complementary dimension to motor execution through synergies, i.e. sensory feedback and how this may play a role in assembling new synergies or drive new combinations of pre-existing synergies to create new ones [27]. Alessandro et al. [1] commented on the concept of sensory synergies proposed in our article, how these may differ from motor synergies, and elaborated on open questions in the synergy literature. Both definitions of motor and sensory synergies rely on the concept of dimensionality reduction. Specifically, while in the motor domain the human brain needs to face the problem of coordinating many degrees of freedom, in the sensory domain the objective is to generate meaningful perceptual representations from the high dimensional space of sensory inputs. Thus, motor and sensory synergies can be considered as two mirror processes within the same sensorimotor loop: An analytic process from an intended action to multiple muscle activation and a synthetic process from multiple sensory inputs towards a unique, meaningful percept.

However, the concept of sensory synergies implies that central nervous system preferentially encodes some aspects of the environment that are important for task accomplishment, and that such aspects can be characterized in terms of high-level features. In [28,29] was hypothesized the existence of a synergistic organization of the somatosensory system, where the higher order variables that have to be stabilized are percepts, whereas the lower-level degrees of freedom are provided by the huge amount of sensory inputs from different body locations. Configurations of the afferent signals that are consistent with synergies would occur more likely than those associated with afferent signals that are not consistent with synergies. This would act to stabilize the perceptual systems towards specific synergistic postures. Sensory synergies would thus represent attractors towards natural hand postures.

Alessandro et al. [1] also pointed out that, besides the above general definition of synergies, motor synergies offer a model on how such a reduction could be obtained, whereas such a model is more difficult to conceptualize in the sensory domain. In the motor domain, two different strategies could be involved in the synergy-based control of artificial and biological systems: (1) identification of the subspace of control commands necessary to achieve task goals, and then development of a basis set of synergies spanning the workspace; or (2) choice of a small set of synergies and their use for task accomplishment. When searching for similar strategies in the sensory domain, an example of how dimensionality reduction could be attained is the sparse coding of tactile information in cuneate neurons, which seems to be apt at segregating haptic features [30]. Such segregation of tactile input features in the cuneate nuclei provides an example of a synthetic (or synergistic) representation of the fundamental stimulus features in the somatosensory system. However, what is still unclear is how to generalize this concept and use it to explain the generation of complex perceptions. The concept of multi-sensory integration might answer this question [28]. Here we describe an example of how such integration might lead to discrimination of softness. When humans probe a given material for softness, this leads to force and displacement sensing, and also creates patterns of cutaneous strain-stress distributions. Although such kinesthetic and tactile stimulations lead to different sensory representations, both are important for softness discrimination during the interaction with compliant non-deformable objects [31]. Specifically, kinesthetic and cutaneous cues or, more specifically, the associated higher order variables based on varying contributions from lower-level sensors (e.g. mechanoreceptors, muscle spindles, etc.), are fused into a coherent perceptual representation. This can be described as the combination of a large number of sensory synergies to generate reliable perception of physical stimuli. Additional psychophysical evidence supports the hypothesis that sensory and motor inputs can cooperate to provide a unique perceptual representation, as observed in [32] for the fusion of touch and proprioception in hand kinematics perception. Here, a mapping between the strain pattern on the skin and the coordinated motor activity can be observed, which is consistent with the definition of sensory-motor synergies [33]. Nevertheless, how the recruitment of sensory synergies operates and at what level of the sensory system it occurs remain open questions.

Schwartz [9] emphasizes that correlational structures identified at different levels of biological systems, ranging from groups of neurons to muscles or fingers, might represent one aspect of a more fundamental defining property of brain function. Here the challenge is again separating what Schwartz [9] calls the ‘neural drivers’ of identifiable correlations in motor output from correlations in behavioral variables arising from biomechanical constraints (non-neural drivers), i.e., multi-joint tendons causing torques at multiple joints in response to the action of one muscle acting on its tendon. Schwartz [9] further proposes that the functional role of synergies at the highest hierarchical levels of the neural control system might be to reduce the information load by controlling groups of neurons, thereby significantly reducing the dimensionality of the control space. A critical point is that the correlational structure in the descending commands to muscles should be flexible in order to effectively fulfill the above-described functional role. It follows that correlational structures in the motor output should not be interpreted as the by-product of fixed modules in the nervous system. To this aim, even if it was shown that the functional neuroanatomy of kinematic synergies was embedded in motor cortical areas and that sensorimotor areas encode different combinations of synergies [12], other functions such as continuous monitoring for on-line adaptation and motor corrections are also likely encoded in the brain to integrate the flexibility and adaptability of modular control.

3. Summary

The review article and the commentaries highlight important advances in our understanding of biological synergies and how this has inspired novel approaches in robotics design. Although further work is needed to elucidate the interplay between correlational structures across different levels of biological systems, the integration of neuroscience and robotics has proven to be an effective way to generate novel insights, theories, and practical applications, and thus yields tremendous potential for advancing the mission of both fields.

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