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The neural origin of muscle synergies

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Muscle synergies are neural coordinative structures that function to alleviate the computational burden associated with the control of movement and posture. In this commentary, we address two critical questions: the explicit encoding of muscle synergies in the nervous system, and how muscle synergies simplify movement production. We argue that shared and task-specific muscle synergies are neurophysiological entities whose combination, orchestrated by the motor cortical areas and the afferent systems, facilitates motor control and motor learning.

Keywords: motor primitive, spinal interneuron, motor module, non-negative matrix factorization, motor cortex

When the central nervous system (CNS) generates voluntary movement, many muscles, each comprising thousands of motor units, are simultaneously activated and coordinated. Computationally, this is a daunting task, and investigators since Bernstein (1967) have strived to understand whether and how the CNS’s burden is reduced to a much smaller set of variables. In the last few years we and our collaborators have searched for physiological evidence of simplifying strategies by exploring whether the motor system makes use of low-level discrete elements, or motor modules, to construct a large set of movement. In this brief communication, we argue that there is convincing evidence that the discrete elements for such simplification are muscle synergies, neurophysiological entities whose combination is orchestrated by the motor cortical areas and the afferent systems.

EXPLICIT ENCODING OF MUSCLE SYNERGIES IN THE NERVOUS SYSTEM

The core argument for the neural origin of motor modules rests on studies of the spinal cord in several vertebral species, conducted using a variety of techniques such as microstimulation (Bizzi et al., 1991; Güster et al., 1993), N-methyl-D-aspartate (NMDA) iontophoresis (Saltiel et al., 2001, 2005), and cutaneous stimulation (Tresch et al., 1999). With these approaches, we and others were able to provide the experimental basis for a modular organization of the spinal cord circuitry in the frog (with the studies cited above), rat (Tresch and Bizzi, 1999), and cat (Lemay and Grill, 2004). A spinal module is a functional unit of spinal interneurons that generates a specific motor output by imposing a specific pattern of muscle activation. The output of an activated module can be characterized as a force field, or the collection of isometric muscle forces generated at the limb’s endpoint over different locations of the workspace. In the spinal frog and rat, different groups of force field were activated as the stimulating electrode was moved to different loci of the lumbar spinal cord in the rostro-caudal and medio-lateral directions. Following the initial description of the force field, Mussa-Ivaldi and others found that co-stimulation of two spinal sites led to vector summation of the forces generated at each site separately. When the pattern of forces resulting from co-stimulation were compared with those computed by linear summation of the two individual fields, the co-stimulation fields and the summation fields were found to be equivalent in 83% of the cases (Mussa-Ivaldi et al., 1994). Similar results were also obtained by Hogan and colleagues (Lemay et al., 2001), Tresch and Bizzi (1999), and Kargo and Güster (2000). Vector summation of force fields led to the hypothesis that generation of movement and posture may be based on the combination of a few discrete motor primitives. A subsequent simulation study showed that the combinations of frog hind-limb muscles that produced stable force fields were similar to the muscle groups observed to co-activate in spinal microstimulation studies (Goebl et al., 2000). These results together argue that the experimentally derived force fields are generated by discrete groups of muscles activated as individual units, or muscle synergies, from whose linear combination a vast repertoire of movement and posture could be generated.

Most voluntary movements are the result of the simultaneous activation of a few muscle synergies via descending or afferent pathways which produces a complex electromyographic (EMG) pattern in the limb’s muscles. To retrieve the structures of muscle synergies from the variability of muscle activations, we and others have utilized a computational procedure, the non-negative matrix factorization algorithm (NMF), originally proposed by Lee and Seung (1999, 2001). The synergies identified by NMF are time invariant non-negative vectors whose linear combination is found, through an iterative update rule, to minimize the error of EMG...
reconstruction, with the additional assumption that this error follows a Gaussian distribution (Cheung and Tresch, 2005). The extracted synergies thus reflect spatially fixed regularities (Kargo and Giunter, 2008; Safavysnia and Ting, 2012) embedded within diverse muscle patterns. In addition to NMF, there exist other linear factorization algorithms, such as independent component analysis (Bell and Sejnowski, 1995) and independent factor analysis (Attias, 1999). For all of these algorithms, because each synergy can have components across any subset of muscles, any one muscle may belong to multiple synergies; this aspect makes the extracted synergies different from other formulations in which each muscle belongs to a single synergy. As Tresch et al. (2006) have shown, most of the algorithms, with the exception of principal component analysis (Julike, 2002), perform comparably in simulated and experimental data sets. This observation suggests the extracted muscle synergies are likely not an artifact contingent upon the particular assumptions employed by the algorithm for separating the activations of the synergies, but reflect basic aspects of muscle activations.

Recent electrophysiological experiments in the lower vertebrates, cat, and monkey have provided evidence that the temporal activations of muscle synergies identified by computational algorithms are expressions of neural activities. In the frog, discharging neurons in the intermediate zone of the spinal cord were found to be significantly related to activations of muscle synergies rather than activities of individual muscles (Hart and Giszter, 2010). In the cat, activities of distinct groups of neurons in the forelimb motor cortex recorded during reaching coincided with activations of muscle synergies identified by a cluster analysis (Yakovenko et al., 2011). In the monkey, intra-cortical microstimulation of an area of the motor cortex with descending connections to the spinal interneurons evoked EMG patterns decomposable into muscle synergies that, remarkably, matched the ones observed during natural reach-and-grasp behaviors (Overduin et al., 2012). This finding directly supports the idea that the expression of voluntary movement relies on a complex pathway connecting the motor cortex and the spinal interneurons; through this circuitry, the cortex selects and combines the appropriate spinal interneuronal modules, and supplies the modules with temporal patterns of activation appropriate for the behavior being executed.

There is emerging evidence suggesting that the above conclusions may also underlie production of voluntary movement in humans. In a group of mildly to moderately impaired stroke survivors with lesions in the motor cortical areas, we observed that the muscle synergies extracted from the stroke-affected arm were similar to those of the unaffected arm despite marked differences in motor performance between the arms (Cheung et al., 2009b). This observation is compatible with the proposal that muscle synergies are structured in the brain stem or spinal cord, and after a stroke, altered descending commands from the supraspinal areas generate abnormal motor behavior through faulty activation of the spinal modules. Similar results for the lower limb have also been presented (Clark et al., 2010). It is of course entirely possible that in humans who have developed highly skilled movements, like pianists (Gentner et al., 2010) or professional athletes (Fière and Hug, 2012), the motor cortex may also encode muscle synergies (Gentner and Classen, 2006; Rathelot and Strick, 2006). How the

DO MUSCLE SYNERGIES HAVE A NON-NEURAL ORIGIN?

Kutch and Valero-Cuevas (2012) have recently proposed that the muscle synergies extracted from EMGs using factorization algorithms could have a non-neural origin. Through cadaveric experiments and computational models, these authors showed that constraints arising from the selected task and/or limb biomechanics could produce apparent couplings among muscles even when each muscle in the model is assumed to be independently controlled. This point of view that emphasizes non-neural constraints represents an important contribution to the ongoing debate on the provenance of the previously observed low-dimensionality of muscle activations (Tresch and Jarc, 2009), and offers important complementary insights. There are, however, a number of developmental and clinical studies that place the view of Kutch and Valero-Cuevas in a different light.

For instance, in a recent developmental study on human locomotor primitives, Lacquaniti and his colleagues (Dominici et al., 2011; Lacquaniti et al., 2012) demonstrated that the development of motor patterns from the neonatal to the toddler stages is primarily a result of the addition of new patterns to the few basic patterns present at birth. The precise temporal activations of all primitives are shaped gradually, over many years, as the individual grows from being a toddler to a preschooler, and finally to an adult. This progressive addition and fine-tuning of motor primitives could reflect how an infant, on his or her way to bipedal locomotion, “learns” new muscle synergies, presumably through mechanisms of associative learning and/or supervised learning, or one analogous to the mechanism responsible for the formation of ocular dominance columns in the developing visual cortex (Hubel and Wiesel, 1959). While the precise roles of genetic control in motor development remains to be established, it is conceivable that sensory feedback from muscles and tendons triggers adaptive changes in the spinal interneuronal circuitry to tune or create modules specifically tailored to the limb biomechanics of the individual, and informs other areas of the CNS of these modifications. At the termination of these developmental processes, the biomechanical properties of the limb are fully incorporated into the architecture of the motor modules, thus resulting in a match between the plant and its neural controllers that allows high-caliber motor performance. Since the limb biomechanics of different individuals are at least slightly different, it is not surprising that the precise structures of some muscle synergies are subject-specific (Fière-Ovondo and Ting, 2010). Thus, our argument that muscle synergies could have a neural origin is not incompatible with the idea that the precise structuring of each muscle synergy incorporates knowledge of both the musculo-skeletal dynamics (Bernáker et al., 2009) and other biomechanical properties of the limb.

Ideally, a strong case supporting the neural origin of the muscle synergies extracted from the EMG is should come from a comparison between the number of experimentally derived synergies and
Muscle synergies may be conceived as representing elementary building blocks whose superposition allows the expression of a vast number of movements and postures. Similar concepts have been advanced by a number of laboratories with a variety of species ranging from Aplysia (Ting et al., 2004), to the frog (D’Aquila et al., 2003; Hart and Giszter, 2004), rat (Tesch and Bizzi, 1999), cat (Ting and Macpherson, 2005; Elbrier et al., 2006; Krouchev et al., 2006), monkey (Overduin et al., 2008), and humans (Kram and Cavanagh, 2000; Tresch and Bizzi, 1999; Lüdtke et al., 2005). Each motor behavior results from a combination of both synergies shared between behaviors, and synergies specific to each or a few behaviors. While we do not know the maximum number of in-born and learned motor tasks each species may produce, it is conceivable that in any individual, the numbers of all task-specific and shared synergies combined may exceed the number of relevant muscles, in which case the EMGs recorded over all possible behaviors are not expected to exhibit a low dimensionality. This theoretical possibility raises the question of how muscle synergies of neural origin simplify movement control. We think muscle synergies simplify the production of posture and movement in the following senses. First, for tasks that can be executed by many possible trajectories or muscle activation patterns, a set of pre-existing muscle synergies can serve as a preferred channel through which the motor commands are specified. Muscle synergies thus effectively remove any musculoskeletal redundancy at the levels of posture (Santello et al., 1998; Weiss and Flanagan, 2004; Bicchi et al., 2011), kinematics (Flash and Hochner, 2005), and muscle activation, by constraining how the muscles can be activated (Bernstein, 1967; Full and Koditschek, 1999; McKay and Ting, 2008).

Another related set of findings has come from studies of muscle synergies in human stroke patients. Briefly, using the NMF algorithm and a non-negative least-squares technique, we characterized post-stroke alterations of muscle synergies in the stroke-affected arm as reflecting either a merging or a fractionation of the unaffected-arm muscle synergies (Cheung et al., 2005) persisted even after complete hind-limb deafferentation.

DO MUSCLE SYNERGIES SIMPLIFY MOVEMENT PRODUCTION BY DECREASING THE NUMBER OF DEGREES OF FREEDOM?

Motor cortical damage, the degree of synergy fractionation varied with the temporal distance from stroke onset (which reflects how long the motor system had been influenced by post-stroke plasticity). Given that these two patterns of synergy change correlate with variables related to the state of the nervous system, and that the biomechanical structures of the stroke-affected and unaffected arms are expected to be similar, it is likely that neural constraint is a major contributor to the structures of the observed muscle synergies in the affected arm. Alterations and merging of both upper- and lower-limb muscle synergies in stroke survivors have similarly been reported in several other recent studies (Clark et al., 2010; Giuzi et al., 2011; Roh et al., 2013).


Domingos, N., Ivanenko, Y. P., Cappellini, G., d’Avella, A., Monlau, V., and others (2009). Can motor outputs be generated only by combining a handful of spatially fixed muscle synergies? Monosynaptic stretch reflex, for instance, clearly contributes to the activities of each individual muscle. Also, at least for humans, with sufficient training even individual motor units of a single muscle could be voluntarily controlled (Bursac, 1963). These and other additional mechanisms of motor-output generation further augment the flexibility of the motor system, and could conceivably play a role during the acquisition of motor skills (Kargo and Nitz, 2005).

One fruitful direction of future research is to determine precisely how the CNS integrates non-synergy-based mechanisms with the existing muscle synergies for the execution of a wide range of movements. In the higher primates and humans, there are two subdivisions of the primary motor cortex: a rostral, phylogenetically older region that contains descending effects destined to the spinal interneurons, and a caudal, phylogenetically newer region that contains cortico-motoneuronal (CM) cells with monosynaptic innervations to the motoneurons of individual shoulder, elbow, and finger muscles (Bardot and Strick, 2009). It is plausible that while the “old” motor cortex contributes to motor output by providing activation drives for the spinal modules, the “new” motor cortex further sculpts the activations of specific muscles by bypassing the spinal mechanisms through the CM cells. Controlling movement by combining muscle synergies and other proposals based on independently controlled muscles (Kuch et al., 2005; Valero-Cuevas et al., 2009) are not necessarily mutually exclusive.

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Conflicts of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.