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Inter-individual variability of forces and modular muscle coordination in cycling: A study on untrained subjects

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A B S T R A C T

The aim of this study was to investigate the muscle coordination underlying pedaling in untrained subjects by using the muscle synergies paradigm, and to connect it with the inter-individual variability of EMG patterns and applied forces. Nine subjects performed a pedaling exercise on a cycle-simulator. Applied forces were recorded by means of instrumented pedals able to measure two force components. EMG signals were recorded from eight muscles of the dominant leg, and Nonnegative Matrix Factorization was applied to extract muscle synergy vectors *W* and time-varying activation coefficients *H*. Inter-individual variability was assessed for EMG patterns, force profiles, and *H*. Four modules were sufficient to reconstruct the muscle activation repertoire for all the subjects (variance accounted for >90% for each muscle). These modules were found to be highly similar between subjects in terms of *W* (mean $r = .89$), while most of the variability in force profiles and EMG patterns was reflected, in the muscle synergy structure, in the variability of *H*. These four modules have a functional interpretation when related to force distribution along the pedaling cycle, and the structure of *W* is shared with that present in human walking, suggesting the existence of a modular motor control in humans.

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1. Introduction

In our everyday life we easily perform many different movements and coordinate them in a harmonic, smooth fashion. One of the oldest issues in the study of human motor control is how the central nervous system (CNS) is able to organize and coordinate the large number of degrees of freedom, together with the abundance of actuators of the musculo-skeletal system (Bernstein, 1967). The management of this redundancy, i.e., the large number of muscles acting across a reduced number of degrees of freedom, suggests the existence of complex neurophysiological mechanisms acting at the level of the CNS for the generation of the neural commands able to control and stabilize movement (Guigon, Baraduc, & Desmurget, 2007). Nevertheless, simplifying explanations have risen from the scientific community in order to understand the role of the CNS in a simplified fashion (Macpherson, 1991).

The concept of synergy is a recurrent one in computational motor control, and it has been traditionally defined as a set of functional elements acting together either to achieve a desired motor behavior or to stabilize a performance variable (Latash, 2010; Scholz & Schöner, 1999). The existence of neural modules at the level of the spinal cord (Bizzi, Mussa-Ivaldi, & Giszter, 1991) has been extended to the concept of muscle synergies, i.e., low dimensional modules representing the neural control of movement from the peripheral nervous system (d'Avella, Saltiel, & Bizzi, 2003). Surface ElectroMyoGraphy (sEMG) has been widely used for the assessment of muscle coordination, in order to investigate the coordinative mechanisms and the neural strategies used by the CNS during the execution of movement (Farina, Merletti, & Enoka, 2004; Hug, 2011). By using innovative computational methods, sEMG signals recorded from several muscles involved in the execution of a motor task can be decomposed into a small number of muscle synergies, modules characterized by a group of muscles activated in synchrony and whose activity is modulated by amplitude-scaling and time-shifting mechanisms. In humans, muscle synergies have been investigated for different motor tasks, such as reaching movements of the upper limb (d'Avella, Fernandez, Portone, & Lacquaniti, 2008; Muceli, Boye, d'Avella, & Farina, 2010), maintaining of upright stance (Krishnamoorthy, Goodman, Zatsiorsky, & Latash, 2003; Torres-Oviedo, Macpherson, & Ting, 2006; Torres-Oviedo & Ting, 2007) and walking both in normal and pathological conditions (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006; Clark, Ting, Zajac, Neptune, & Kautz, 2010; Gizzi, Nielsen, Felici, Ivanenko, & Farina, 2011; Ivanenko, Poppele, & Lacquaniti, 2004; Monaco, Ghionzoli, & Micera, 2010). All these studies support the existence of a modular organization of the CNS (Tresch & Jarc, 2009).

Muscle synergies have been recently investigated also to describe sport motor tasks like pedaling and rowing, thus providing further evidence on the existence of simplifying neural control strategies based on muscle synergies (Hug & Dorel, 2009; Hug, Turpin, Couturier, & Dorel, 2011; Turpin, Guével, Durand, & Hug, 2011). When compared to tasks like walking or upper limb reaching, cycling can be considered as a simpler and quasi-constrained exercise, with low variable kinematics and with controllable experimental conditions. Recent studies by Hug, Drouet, Champoux, Couturier, and Dorel (2008) and Hug and Dorel (2009) investigated the muscle coordination underlying the execution of pedaling in a population of trained cyclists, showing that a high inter-individual variability of the sEMG patterns is not reflected in central coordination mechanisms, since the same small number of motor modules is robust and shared across subjects. Moreover, this inter-individual variability has been shown not to be reflected at the level of the pedal force profiles (Hug, Drouet, Champoux, Couturier, & Dorel, 2008). Nevertheless, up to now it is not clear if this behavior appears as a consequence of training.

In this study, in order to describe the task from a biomechanical point of view, sEMG will be recorded together with the forces applied at the shoe-pedal interface, with the aim of establishing whether or not the inter-individual variability shown in the management of the forces acting on the pedal is reflected in the variability of the muscle activation patterns. To this aim, by using the muscle synergies framework, we investigate the neural strategies used by untrained subjects during the