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On theory of motor synergies

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ABSTRACT

Recently Latash, Scholz, and Schöner (2007) proposed a new view of motor synergies which stresses the idea that the nervous system does not seek a unique solution to eliminate redundant degrees of freedom but rather uses redundant sets of elemental variables that each correct for errors in the other to achieve a performance goal. This is an attractive concept because the resulting flexibility in the synergy also provides for performance stability. But although Latash et al. construe this concept as the consequence of a "neural organization" they do not say what that may be, nor how it comes about. Adaptive model theory (AMT) is a computational theory developed in our laboratory to account for observed sensory-motor behavior. It gives a detailed account, in terms of biologically feasible neural adaptive filters, of the formation of motor synergies and control of synergistic movements. This account is amplified here to show specifically how the processes within the AMT computational framework lead directly to the flexibility/stability ratios of Latash et al. (2007). Accordingly, we show that quantitative analyses of experimental data, based on the uncontrolled manifold method, do not and indeed cannot refute the possibility that the nervous system tries to find a unique (optimal) solution to eliminate redundant degrees of freedom. We show that the desirable interplay between flexibility and stability demonstrated by uncontrolled manifold analysis can be equally well achieved by a system that forms and deploys optimized motor synergies, as in AMT.

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1. Introduction

Adaptive model theory (AMT) is a computational theory about information processing performed by the nervous system in control of movement (for review see Neilson & Neilson, 2005a). It is so named because of its key proposal that the nervous system includes adaptive neural circuitry able to form *adaptive models* of dynamical relationships between neural signals. The mathematical theory of adaptive modeling is well described (Haykin, 1986; Marmarelis, 2004; Westwick & Kearney, 2003; Widrow & Stearns, 1985) and technological applications are numerous. Most of the adaptive control techniques that we employ in AMT have been implemented in technological control systems and are well recognized in the engineering literature (Goodwin & Sin, 1984; Isidori, 1995; Kuo, 2005; Widrow & Wallach, 1996).

A substantial body of work supports the view that the cerebellum functions as an adaptive control system (for review see Barlow, 2002). Consistent with this literature we suggest that the adaptive models proposed in AMT are located in cortico–subcortical–cortical loops through parts of the basal ganglia and cerebellum. In previous publications reviewed in Neilson and Neilson (2005a) we have shown how adaptive models of sensory/sensory, motor/motor, and sensory/motor relationships account for many aspects of motor behavior. We focus here on adaptive formation of task-dependent motor synergies. We will describe below how adaptive models of relationships between joint angles and muscle lengths can be used to fine-tune the connectivity of descending motor pathways to form energy efficient motor maps. These motor maps not only overcome redundancy in the musculo-skeletal-reflex system, but also activate muscles in appropriate proportions to achieve required movements with a minimum demand by the muscles for metabolic energy. For a detailed account of theory and review of experimental background see Neilson and Neilson (2005b).

Recently, Latash et al. (2007) published a paper titled "Toward a new theory of motor synergies". Based on the observation that, across trial-to-trial repetitions of a movement, there is often less variability in joint-angle space in directions that influence performance variables than in directions that do not, they propose that the nervous system does not try to find a unique (optimal) solution to a task by eliminating redundant degrees of freedom (DOF). Rather, they contend that the nervous system uses the redundant sets of elemental movements to ensure more accurate (less variable) performance. Such a proposal is contrary to the one in AMT outlined above.

As described below, the key experimental measure on which Latash et al. base their view can be expressed in terms of flexibility/stability ratios that are typically found to be greater than one. While we do not dispute these findings, we argue that they provide neither a necessary nor sufficient condition to conclude that the nervous system does not seek a unique (optimal) solution to overcome redundant DOF. We will show that, despite using optimization and feature extraction to overcome redundancy, the adaptive controller proposed in AMT generates flexibility/stability ratios greater than one.

2. Concepts of synergy

2.1. Definitions

As discussed by Latash et al. (2007), Bernstein (1947/1967) studied the kinematics of striking a chisel with a hammer by highly skilled blacksmiths. He found that variability in the position of the head of the hammer across a series of strikes was less than the variability of joint-angle trajectories of the arm swinging the hammer. He concluded that the joints were not acting independently but were correcting each other's errors. Similar observations have been made for hammering movements by craftsmen with high levels of skill for stone knapping (Biryukova & Bril, 2008). The kinematic pattern observed in these craftsmen was found to be strongly individual and the highest level of skill was characterized by the highest flexibility of movement kinetics.

Latash et al. (2007) and Latash (2008, 2009) interpret such observations as showing that the nervous system does not seek a unique (optimal) set of constraining relations between joint angles. Consistent with this they define *synergy* as a neural organization of a multi-joint system that (i) organizes