Computational motor control framework based on muscle synergy. Perspectives from dynamics and control engineering

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INTRODUCTION

The human musculoskeletal system is an overly redundant and highly nonlinear dynamic system, with time delays and motor noise. Such a system is a nightmare for control engineers. Yet, the central nervous system (CNS) manages to control the body movements precisely, efficiently, and even in the presence of external disturbances and other uncertainties. How the CNS does that is still unanswered. Different theories have been suggested to describe the mechanisms by which the CNS controls the motion. Among them are the theories of Equilibrium Point [1], Muscle Synergy [2], and Minimal Intervention [3]. There are numerous studies supporting each of them, but no general theory has yet to provide a comprehensive answer.

METHODS

Muscle synergy has been proposed as a way to simplify the control signals descending from the CNS. According to this theory, the CNS activates the muscles by combining bundles of activation, where each bundle contains a number of muscles with fixed relative activations. In our research, we provide computational tools to investigate the requirements and validity of muscle synergy theory, from an engineering point of view. We argue that mechanical constraints (in the environment and within the body) as well as the nature of the task play an important role during efficient control of movements. More specifically, we argue that the CNS has learned multiple sets of muscle synergies, each of which is employed during execution of a certain type of task.

We suggest that different tasks are distinguished by the task space variables that need to be controlled. For instance, if the intended task is elbow flexion, the task space is the elbow rotation, and the actively controlled variable is the elbow joint angle. In this case, the CNS is probably not concerned with the position of the hand. However, during the task of hand reaching to mouth, the variable that is actively controlled by the CNS is the hand position, for which a three-dimensional task space must be defined. Although similar sets of muscles are activated to perform the two tasks, the mechanical requirements of the task are different, which may imply different control strategies (and hence muscle synergies).

We propose a motor control model with a hierarchical structure (Figure 1(A)): the high-level controller deals with trajectory planning at the task space, and decides on the task space acceleration (a_{ref}) required to perform the action. The low level controller translates this reference task space acceleration into muscle activations using the associated muscle synergies. Each muscle synergy produces an acceleration vector in the task space, and all these vectors form a basis set that spans the task space. Therefore, any desired acceleration vector can be decomposed into the basis set. The corresponding coefficients can be used to combine the synergies to generate the desired task space acceleration. In other words, this method replaces the computationally heavy nonlinear optimization with a fast vector decomposition to solve the muscle force-sharing problem.

RESULTS

In Figure 1(B) we have provided simulation results of motion control musculoskeletal arm, when the hand moves 20 cm upwards from a resting position. The model has three degrees of freedom in the task space (3D position of hand), and one extra degree of freedom (elbow motion) which is left uncontrolled. The synergy-based framework produces near-optimal results, with 90-95% reduction in computation time.

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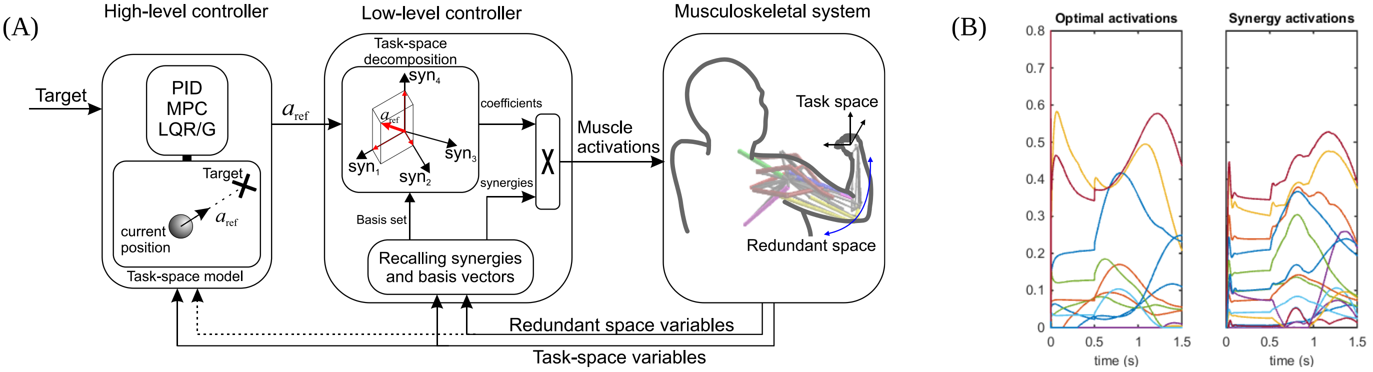

Figure 1. (A) The synergy-based framework for motion control. (B) The simulation results. The hand starts to move upwards at t=0.5 s.