Control of redundant musculoskeletal systems using muscle synergies

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Humans can perform a task in multiple ways (kinematic redundancy), and for each motion, there are an infinite number of solutions for muscle activations (dynamic redundancy). Muscle synergy theory has been proposed to address the challenge of dynamic redundancy [1]; however, its usefulness in motion control and its relation with kinematic redundancy has not been thoroughly investigated. We have proposed a comprehensive synergy-based framework for the control of musculoskeletal systems that simultaneously handles the kinematic and dynamic redundancies. It allows for fast calculation of muscle activations to perform a task, without the need to solve an optimization problem.

The proposed framework is shown in Fig 1(A). In this hierarchical structure, the feedback control occurs in the *task space*. This high-level controller specifies the corrective signal (the needed accelerations in the task space, a_{ref}), using robust, optimal or even error-driven (e.g. PID) control logics. In the low-level controller, the acceleration signal is translated into muscle activations using muscle synergies. This framework is based on the fact that each synergy has a known effect in the task space, and we assume that the nervous system knows the acceleration vector that each synergy produces. The set of all the synergy-produced acceleration vectors form a basis set for the task space. An arbitrary task space acceleration can be decomposed onto this basis set with little computational effort. We can then combine the synergies with the calculated coefficients to find the muscle activations that produce the desired task space acceleration.

In the proposed framework, the control of task-related degrees of freedom is separated from the redundant ones (defined by Uncontrolled Manifold). We have considered two types of synergies: the ones that only produce task space accelerations, and the ones that only affect the motion in the redundant space. Therefore, the high-level controller may only deal with the task space variables using the task-related synergies, and neglect the control of the redundant variables. One important assumption in this framework is the dependence of the synergies on the desired task space. For example, the synergies for a 3-dimensional reaching task would be different from a 1-dimensional elbow flexion, because of the difference in the task space. We hypothesize that for efficient control of motion, the nervous system knows multiple sets of synergies to use in different tasks.

In Fig 1(B) we have provided simulation results for motion control of a musculoskeletal arm, when the hand moves 20 cm up 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.

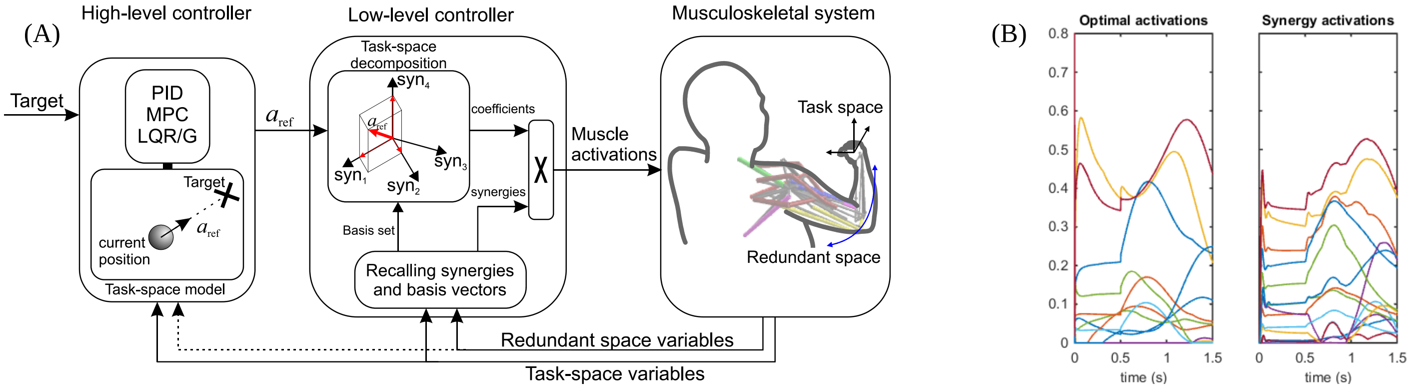

Fig 1. (A) The synergy-based framework for motion control. (B) The simulation results. The hand starts to move upward at t=0.5 s.

References

[1] Bizzi, E., Cheung, V. C. K., D'Avella, A., Saltiel, P., & Tresch, M. C. (2008). Combining modules for movement. Brain Research Reviews, 57(1), 125–33.