

Can modular control coordinate different modes of locomotion while maintaining low dimensionality?

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Introduction

It has been hypothesized that the central nervous system simplifies locomotor control by using a modular architecture -- using neural activation patterns to excite groups of synergistic muscles. In order for this neural strategy to accommodate different modes of locomotion (e.g., forward walking, backward walking, sideways walking) it requires flexible control of either the temporal patterns, or the muscle synergies, or both. One extreme version of this control approach, the temporally-fixed strategy, would use invariant temporal patterns while modulating muscle synergies to perform different tasks. The other extreme, the spatially-fixed strategy, would use invariant muscle synergies while controlling the neural activation patterns. In either case, the fixed patterns or synergies could be separated into specific (task-dependent) libraries, or alternatively could be part of a shared (task-independent) library. In this study we asked: which of these modular control architectures can coordinate muscle activations for different modes of locomotion while also simplifying motor control by reducing the dimensionality of neural outputs?

Methods

We recorded muscle activation patterns from 8 healthy subjects during five different locomotor tasks in order to explore modularity as a way to reduce the dimensionality of neural control. We extracted fixed muscle synergies and patterns from unilateral EMG recordings of 27 muscles using non-negative matrix factorization, assuming first a shared library of synergies or patterns, and next assuming multiple task-specific libraries. For each formulation of modular control we then computed the minimum number of fixed synergies or patterns needed to reconstruct the EMGs from each task. Then the number of synergies or patterns needed was compared to the number of muscles activated during each task in order to investigate the degree to which these modular strategies reduce the dimensionality of motor control. Additional complementary analyses were performed to estimate the reduction in neural activation dimensionality and to ensure that the results were independent of methodological choices.

Results & Discussion

We found that only a modular control strategy using task-specific libraries was adequate to reconstruct muscle activations and retain low dimensionality of neural activation patterns. Architectures using a single shared (task-independent) library could reconstruct EMG patterns, but this organization required that a large set of synergies or patterns, on average more than 10, be recruited in order to perform a task such as walking. At best a shared library of fixed muscle synergies would reduce the dimensionality of motor control by about 30%. However, this is almost certainly an overestimate of the benefit and we would expect it to be lower if additional tasks were studied. A task-dependent architecture, on the other hand, allowed for fewer temporal activation patterns (i.e., the neural outputs). On average this reduced the number of neural outputs by over 60%, compared to controlling each muscle individually. The trade-off is that the total number of modules (synergies or patterns) contained throughout the collection of task-dependent libraries was very large, scaling roughly linearly with the number of tasks. In conclusion, we found that when it comes to reducing the dimensionality of neural outputs across different modes of locomotion, not all modular architectures are created equal. If the body does simplify motor control by using a modular strategy, it likely does so by using task-specific, not shared, modules.