Evaluating the Utility of Motor Primitives for Simplifying Neural Control of Multidirectional Human Gait

Abstract

Introduction: It has been hypothesized that the nervous system simplifies muscle coordination through modularity, using neural patterns to activate muscles in groups called synergies. Here we investigated how simple modular controllers based on invariant motor primitives (synergies or patterns) might generate muscle activity for multidirectional locomotion. Methods: We extracted motor primitives from unilateral electromyographic recordings of 25 lower-limb muscles during five locomotor tasks, walking forwards, backwards, leftwards, rightwards and stepping in place. Primitives were extracted from individual tasks, and also collectively from all five tasks in order to investigate shared primitives. We then assessed the ability of these primitives to reduce the dimensionality of control. To evaluate dimensionality we introduced the modular control ratio, which compared the minimum number of neural outputs needed to generate task-specific muscle activity to the number of muscles activated. Results: When considering each task individually we found that modularity had the potential to reduce dimensionality compared to independent muscle control, by as much as two-thirds. However, these benefits were degraded when motor primitives were shared amongst locomotor tasks. For instance, the total number of shared synergies required to generate muscle activity for five multidirectional gaits was nearly as high as the number of muscles activated during each task (Fig. 1A). Shared patterns also exhibited limitations in reducing dimensionality, specifically related to their ability to accommodate tasks involving more rapid muscle contractions or longer cycle durations. Discussion: These results suggest that the utility of shared motor primitives may depend on if they can be flexibly adapted for specific task demands, for instance, by multisensory feedback or by inclusion in a more complex sensorimotor control architecture. Thus, our findings motivate the need for more sophisticated (yet falsifiable) formulations of modular control or alternative motor control hypotheses to explain muscle coordination. One limitation to the methodological approach used here is that it attempts to infer neural control strategies from statistical analysis of muscle activity. Future research may, however, benefit from predictive models, for instance, integrating neuromotor control hypotheses with multi-muscle biomechanical simulations (Fig. 1B) to develop testable predictions about muscle coordination during locomotion.