Simulated reaching driven by amplitude-controlled single-actuator versus rate-coded multi-motor-unit muscles

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Summary

Human muscles are divided into multiple motor units (MUs) which are controlled via rate-coded excitation impulses, but these features are rarely included in musculoskeletal models. We investigate how this omission impacts simulated reaching movements by comparing a model powered by single-actuator amplitude-controlled muscles with one powered by multi-MU muscles controlled via impulse trains. While comparable overall final accuracy was achieved with both models, the trajectories of the MU pool model were less straight, suggesting single-MU amplitude-coded control may be better for trajectory tracking but not necessarily for accuracy.

Introduction

Human muscles comprise multiple motor units, each recruited to contribute to force production through variation of the timing and frequency of its firing rate (i.e. rate coding). While models representing muscle MU pools (e.g. [1]) exist, these two inherent complexities (multiple MUs and rate coding) are often omitted in musculoskeletal models, where muscles tend to be represented by single actuators whose excitation or activation amplitude is varied continuously (i.e. amplitude coded). To investigate the functional consequences of including these muscle characteristics, we compare simulated reaching performance when the movements are driven by amplitude-coded single-actuator muscles versus rate-coded MU pool muscles.

Methods

We used a conceptual upper limb model with three d.o.f.s and three pairs of antagonistic monoarticular muscles [2]. Planar horizontal reaching movements towards four targets (Figure 1 insert) were implemented using a PD controller tracking a straight trajectory with a bell-shaped velocity profile.

Two muscle models are compared: In the baseline model, each muscle is a single actuator and the desired forces from the controller are amplitude coded to produce excitation signals [2]. In the rate-coded MU pool model, each muscle is represented by a pool of 100 parallel MUs with identical length, contraction speed and moment arm. MU strengths and recruitment thresholds are exponentially distributed [1]. The desired controller force is used as a neural drive signal for the MU pool, converted into instantaneous firing rates for each MU using a rate function derived from a leaky-integrate-and-fire model [3], and the firing rates are then converted online into excitations via comparison with time elapsed since the last excitation impulse.

The PD parameters are optimized for each model separately by minimizing the average error in the final position over the four target locations.

Results and Discussion

Both models performed the reaches successfully, with both final position and tracking accuracy within 1 mm for all targets (Figure 1). Controller optimization for each model resulted in task-wise differences in the final accuracy: the MU pool model was more accurate for three of the targets but notably worse for target 2 (contra-lateral target). The main difference in the models' performances was in the straightness of the trajectory, as captured by the tracking error. For targets 2 and 3, introducing rate-coding and multi-MU structure into the muscles resulted in small but visible deviations from the planned trajectory.

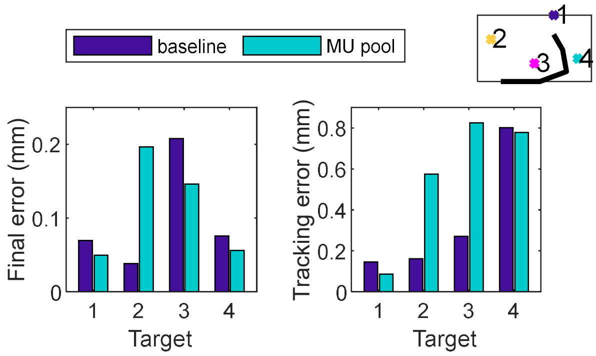

Figure 1: Final and tracking errors for the baseline single-MU amplitude-coded model and the rate-coded MU pool model across four targets. Top right insert shows target locations relative to the initial arm position.

Conclusions

We compared reaching simulations powered by single-actuator amplitude-controlled muscles with those powered by multi-MU muscles controlled via rate-coded excitations. While comparable final reaching accuracy could be achieved with both models, the MU pool model showed reduced trajectory straightness. Our results suggest that the division of a muscle into multiple MUs with rate-coded control may enhance final accuracy, but the effect is task-specific and may come at the cost of reduced trajectory accuracy.

Acknowledgments

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References

[1] Fuglevand AJ et al. (1993) *J Neurophysiol,* **70**: 2470–2488.
[2] Murtola T and Richards R (2023) *R Soc Open Sci,* **10**: 221453.
[3] Caillet et al. (2022) *PLOS Comp Biol*, **18**: e1010556.