A computational model predicts muscle spindle firing in passive and active conditions.

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Summary

Muscle spindles are sensory organs located in skeletal muscles with independent control through gamma motor neurons. Both gamma motor activation and muscle spindle Ia sensory output show task-dependent modulation. However, technological limitations prevent direct testing of this modulation's purpose during diverse behaviors. We developed a computational model to simulate Ia output based on intrafusal muscle fiber dynamics. To understand the role of Ia output in behavior, we simulated spindle responses to sinusoidal length changes, representing tasks like postural sway or locomotion. By adjusting model activations according to literature, we are the first to reproduce Ia output in locomotor conditions using a single model. We further demonstrate how through independent tuning of two gamma activation types (static and dynamic), Ia output can encode differences between expected and actual extrafusal muscle stretch. These findings support theories that muscle spindle sensory responses can distinguish between externally generated and self-generated movement.

Introduction

Proprioceptive information from muscle spindle sensory afferents plays a critical role in sensorimotor control, yet how this information is shaped by gamma motor drive during behaviour is unclear. Muscle spindles are innervated by two types of motor neurons—gamma static and gamma dynamic. Few direct measurements in animal experiments have found independent gamma static, gamma dynamic, and alpha motor activity[1]. However, technological limitations prevent empirical investigation into how such independent motor activity influences muscle spindle firing in awake, behaving animals. Here, we use a computational muscle spindle model with biophysical intrafusal muscle fibers to investigate how gamma activation modulates spindle sensory afferent output.

Methods

The model includes two types of intrafusal fibers—bag 1 and chain—modelled as half sarcomeres, whose force output are determined by rate equations governing cross-bridge attachment and detachment[2,3]. Bag 1 fiber receives gamma dynamic activation while chain fiber receives gamma static activation. The extrafusal fiber modelled parallel to the intrafusal fibers is governed by different rate equations and receives alpha activation. These are combined with a phenomenological receptor potential model. Final Ia afferent response is validated against empirical data under passive and active conditions, including various gamma motor activation profiles[1]. We simulate afferent response to sinusoidal length changes, representing tasks like postural sway or locomotion.

Results and Discussion

By modulating only the activations to this model according to literature, we reproduced Ia output observed during both passive and active conditions (Figure 1). Using the same rhythmic muscle movements (Figure 1, row 1), we show that Ia output increases with muscle stretch and goes quiet during shortening (Figure 1, row 5, grey). In contrast, gamma activity, as observed during decerebrate cat locomotion results in increasing Ia output even during shortening, with the peak occurring at stretch onset (Figure 1, column 1). Our model predicts a qualitatively similar Ia output from similar modulation of gamma activity alone (Figure 1, column 2). Furthermore, through independent tuning of the two types of gamma motor activations (gamma static and gamma dynamic), the muscle spindle Ia afferent response can encode information about the difference between the expected and actual extrafusal muscle stretch (not shown).

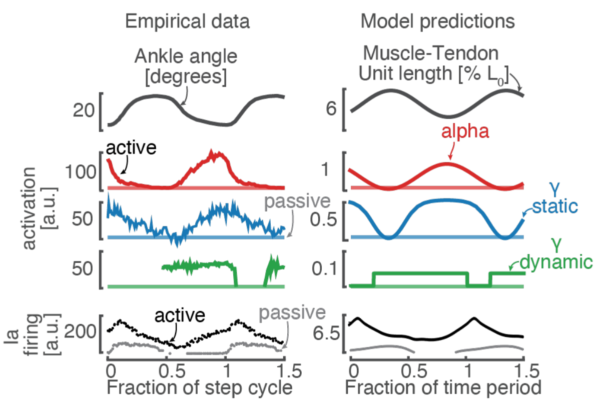

Figure 1: Passive vs. active Ia afferent firing (row 5, grey vs black) qualitatively explained by activations (rows 2, 3, 4, light vs dark).

Conclusions

These results support existing hypotheses in the field that muscle spindle sensory signaling distinguishes externally generated movement from self-generated movement. Biophysical modeling of muscle spindles is essential for understanding their sensory role in behavior, as empirical data is mostly limited to passive conditions.

Acknowledgments

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References

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