Spinal Reflexes can Produce Natural Bipedal Walking and Running Gaits

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I. Background

The way in which spinal circuitries contribute to human locomotion is a long-standing open research question. Neuro-musculoskeletal simulations can be useful for unraveling these underlying mechanisms, as they allow systems-level studies with fine-grained control. However, existing simulation studies typically use a finite state machine to select feedback pathways and gains based on the active phase of the gait cycle (swing, stance, etc.) [1]. This is problematic, since there is no direct neurological evidence for such systems, while the hand-crafted states and transitions are domain-specific and do not generalize to other behaviors.

We developed a neuromuscular controller that solely mimics established spinal reflex pathways [2], and optimized its parameters for high-level gait objectives. Surprisingly, our simple network was able to produce a variety of walking and running gaits, and generalized to 3D models.

II. Methods

A. Neuromuscular control network

The input to our spinal control network consists of group Ia afferents from spindle sensors (modeled as a weighted combination of muscle length and velocity), group Ib afferents from Golgi tendon organs (muscle tendon force), and vestibular afferents that represent relative head position and velocity. Ia afferents connect directly to homonymous motoneurons (MN) and Ia inhibitory interneurons (IaIN), which reciprocally inhibit antagonist MNs. Ib afferents connect to Ib interneurons (IbIN), which connect either inhibitory or faciliatory to MN and other IbINs. Renshaw cells (RC) recurrently inhibit MNs and IaINs (see Figure 1, left). Neural excitation is modeled as a rectified weighted (kij) sum of base bi and its inputs { X1, …, Xn }:

$$I_i(t) = \max(0, b_i + \sum[k_{ij} X_j(t - \Delta t_{ij})])$$

Neural delays Δt_ij are proportional to the length of the pathway, based on experimental data. Two-way connection delays for hip, knee and ankle muscles are 10ms, 20ms and 35ms respectively. One-way vestibular delay is 100ms.

B. Optimization

The crux is in finding the right weights k_{ij} and biases b_i. After finding suitable initial values, we optimized the parameters using single shooting in SCONE [3], based on target velocity, energy expenditure and joint load.

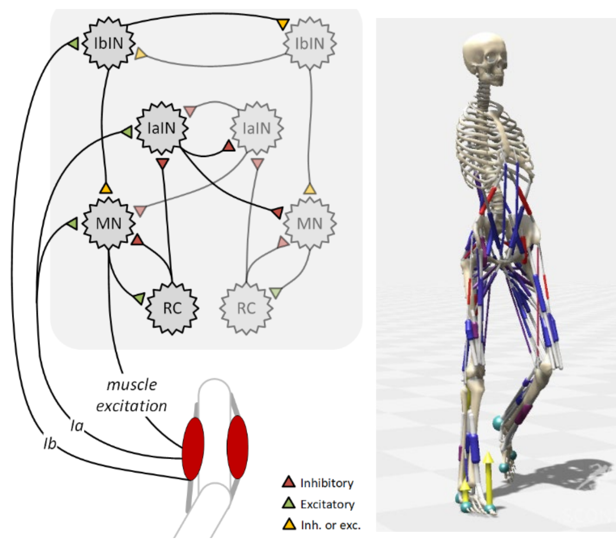

Fig. 1. left: spinal control circuits, right: 3D simulation model

III. Results & Discussion

After optimization, our neuromuscular controller could produce walking and running gaits that match real-world data. Results were on-par or better than control schemes with much more elaborate control, yet our control strategy generalizes better to running gaits, as well as 3D models. This enables a range of clinical applications and could help in the development of assistive devices. Our controller can potentially be augmented with additional interneurons and afferents to further increase its capabilities.

IV. Conclusions

Our results demonstrate proprioceptive reflexes to be a remarkably powerful musculoskeletal control primitive. Even though we know other circuits, such as central pattern generators, play an important role in gait, we might need to re-evaluate their relation and dependencies.

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References

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