A Simple Network of Proprioceptive Reflexes Can Produce a Variety of Bipedal Gaits

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Summary

In this work, we explore the control capabilities of a simple reflex controller that consists of only monosynaptic and antagonistic length and force feedback pathways with constant gains. Despite its simplicity, we found our control framework capable of producing a wide variety of natural gaits – without requiring any rhythmic inputs or high-level state machines modulating the feedback gains. Our work highlights the important role and flexibility of proprioceptive reflexes and suggests a necessary re-evaluation of their role in locomotion.

Introduction

It is known that human motor control relies heavily on sensory information, yet the role of proprioceptive reflexes in legged locomotion is still poorly understood [1, 2]. While previous simulation studies have shown great potential for reflex-based control strategies [2, 3], these controllers are typically catered to specific gaits, using hand-crafted feedback pathways that are active in specific gait phases. In this work, we explore the control capabilities of a basic spinal controller, which consists of only monosynaptic and antagonistic length and force feedback pathways with constant gains.

Methods

We use a planar, 6 DOF model actuated by 18 Hill-type muscles (HFL, GLU, HAM, VAS, GAS, TA, SOL, BFSH, RF) in SCONE [4] and Hyfydy [5]. Each muscle is excited using delayed length and force feedback with constant gains:

$$u_i(t) = c_i + \sum_{j \in \mathcal{R}_i} [\kappa_{ij}^L \tilde{L}_j(t - \Delta t) + \kappa_{ij}^F \tilde{F}_j(t - \Delta t)] \quad (1)$$

with delays Δt of $\{10, 20, 35\}$ and $\mathcal{R}_i$ mimicking all monosynaptic connections as well as connections between antagonistic muscles (see Figure 1). These reflexes are active throughout the gait. The reflex gains k_{ij} and offsets c_i are optimized using CMA-ES [6] to minimize cost function J based on target velocity and effort minimization. We tune the initial state of the model to fit the targeted movement and optimize the parameters for five gaits: walking and hopping, forwards and backwards, as well as running.

Results and Discussion

Despite its simplicity, our control network could generate stable movements for all five targeted gaits (see Figure 2). We compared the forward walking kinematics and muscular activation to human experimental data and find good agreement. The controller can also be used to find gaits at various speeds. We obtain walking at our target speed of $1.2\,\mathrm{m/s}$, the maximum running speed we obtain is at $3.42\,\mathrm{m/s}$.

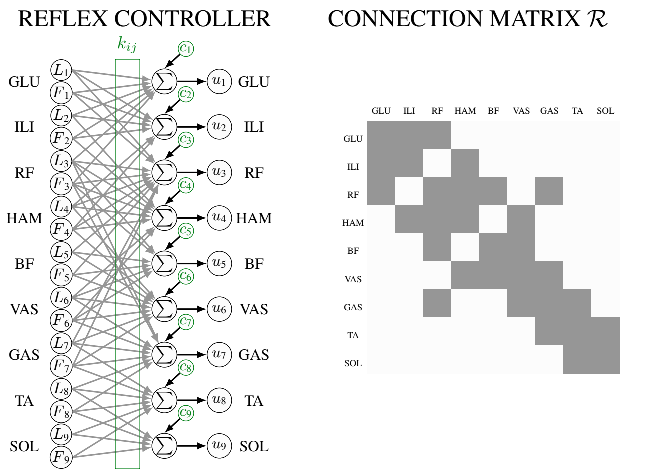

Figure 1: Our reflex controller calculates stimulation based on delayed force $\tilde{F}$ and length $\tilde{L}$ and a constant offset c_i. Feedback gains and offsets (highlighted in green) are optimized based on high-level objectives. Implemented pathways $\mathcal{R}_i$ include homonymous and antagonistic pathways for length and force.

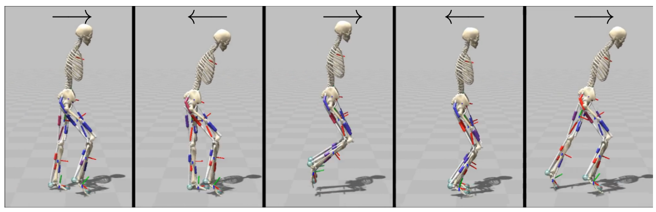

Figure 2: Our control network can produce forwards walking, backwards walking, forwards hopping, backwards hopping, and running (left to right).

Conclusions

We show that a simple spinal reflex controller can generate rhythmic behavior and produces a wide range of different movements. The reflexes are unmodulated and active in all gait phases, challenging the view of CPGs or finite state machines being necessary to generate stable locomotion. This work thus demonstrates that proprioceptive reflexes are a remarkably powerful control primitive and provides a simple and versatile framework which lays the foundation for more complex control structures.

References

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