Spinal Reflexes with Constant Feedback Gains can Produce Stable Bipedal Walking and Running

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I. Introduction

Spinal reflexes are known to be important for legged locomotion, but their exact contribution and relation to other spinal circuits are poorly understood. Neuromusculoskeletal simulations are useful for unraveling these underlying mechanisms, enabling fine-grained, well-defined studies that are virtually impossible in real-world experimentation [1], [2].

However, studies that use spinal feedback predominantly rely on *Finite State Machines* to select feedback pathways and gains based on the active phase of the gait cycle (swing, stance, etc.). This is problematic, since there is no direct neurological evidence for such systems, while states and transitions are hand-crafted based on domain-specific knowledge.

In search of a better alternative, we assessed to what extend proprioceptive reflexes could still produce locomotion when all feedback gains are set to constant values – relying fully on the process of *reciprocal innervation* for producing flexion and extension patterns. To our surprise, this approach turned out to be sufficient for generating a variety of stable gaits.

II. Methods

We use a planar 9 degree-of-freedom, 7 segment musculoskeletal model (torso, femur, tibia, foot) with 14 hill-type musculotendon units (7 per leg) [2]. Each muscle i is excited by u_i solely through constant-gain delayed feedback:

$$u_i = \left[\mathrm{c_i} + \sum_{j \in \mathcal{J}_i} \left[\kappa_{ij}^L L_j^{\Delta T} + \kappa_{ij}^F F_j^{\Delta T} \right] + \kappa_i^V V^{\Delta T} \right]^+, \quad (1)$$

where $\mathrm{c_i}$ is a constant offset, $\mathcal{J}_i$ is the set of muscles that includes both i and antagonists of i, κ_{ij}^L and κ_{ij}^F are feedback gains for muscle length $L_j^{\Delta T}$ and muscle tension $F_j^{\Delta T}$, κ_i^V is a feedback gain for $V^{\Delta T} = \phi^{\Delta T} + \kappa^d \dot{\phi}^{\Delta T}$, which represents vestibular feedback based on torso orientation ϕ and improves stability over multiple strides. $[]^+$ is the rectifier or ramp function. Neural delays ΔT are based on experimental data: 35ms for ankle muscles, 20ms for knees, 10ms for hips, and 100ms for $V^{\Delta T}$. Note that these delays are significantly longer than those used in previous studies.

The crux is in finding the right values for $\mathrm{c_i}$, κ_{ij}^L, κ_{ij}^F, κ_{ij}^V, and κ^d. After discovering appropriate initial values and pruning feedback paths with minor contributions, we used SCONE [3] to optimize the remaining set of 35 parameters for cost-of-transport, penalizing excessive ground reaction force.

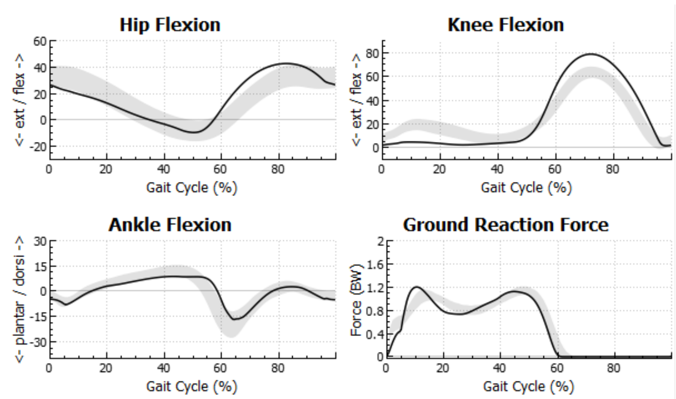

Fig. 1. Simulation results of walking with constant feedback gains

III. Results

The results of our – perhaps somewhat naive – approach far exceeded our expectations. We ended up requiring only 27 reflex pathways per leg (13 force, 9 length and 5 vestibular) to produce stable gait that matches real-world data remarkably well (see Fig. 1 and the supplementary video). The controller could also produce a running gait after adding a target velocity term, as well as adapt to slopes and perturbations. Preliminary efforts to extend this strategy to 3D models are promising.

Our results demonstrate proprioceptive reflexes to be a remarkably powerful control primitive. Even though we know other circuits, such as central pattern generators, play an important role in gait [4], we might need to re-evaluate their relation and dependencies. Our work will be released as open-source after publication.

References

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