# An integrated neuro-mechanical model of the mouse to study neural control of locomotion

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## 1 Introduction

Locomotion is a result of the complex interplay between the neural system, biomechanics, somatosensory feedback and the environment. With the advent of modern molecular-genetic tools, significant progress has been achieved in identifying specific neuron types in the spinal cord and brainstem involved in different aspects of locomotion, especially in rodent [1]. However, how somatosensory feedback interacts with the spinal circuits to control locomotion remains poorly understood. Here, we present the neuro-mechanical model of mouse locomotion and use it to explore interactions between the spinal circuits and somatosensory feedback and the role of the feedback in the control of locomotion (Fig 1).

Investigating the role of somatosensory feedback is challenging even in a simulated environment and requires developing and integrating the models of neural system, biomechanics, somatosensory feedback, and physical environment. In this work, we will progressively move from an abstract model to a more complex system combining the neural models from [2] and the biomechanics from [3]. This will allow us to systematically study sensory-motor integration in the spinal circuitry.

## 2 Methods

The closed-loop neuro-mechanical interactions were simulated in a 3D physics environment MuJoCo [4] under FARMS [5] simulation framework.

### 2.1 Neuro-mechanical model

We adapted our previously developed mouse musculoskeletal model [3] to simulate hindlimb locomotion with a reduced set of muscles.

The spinal circuitry for locomotion was modeled as a two layered neuronal network initially proposed by McCrea and Rybak [6]. It included rhythm generators [7], each controlling one limb, that defined the locomotor frequency and flexor-extensor alternation. The rhythm generators projected their activity to the pattern formation circuits which generated muscle synergies and created muscle-specific activation patterns, which was used to drive muscles of the musculoskeletal model.

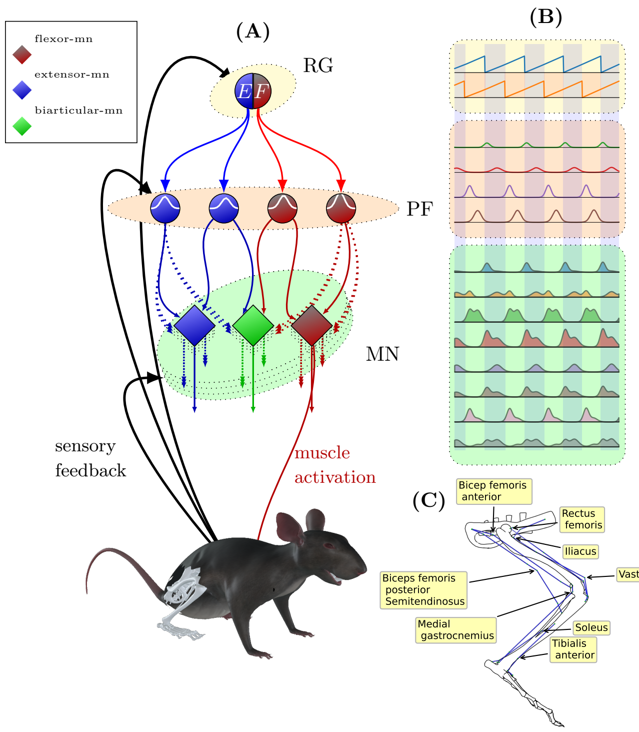


**Figure 1:** Components of the closed-loop neuro-mechanical mouse locomotion. (*A*) The spinal circuit model controlling single hind limb and comprising the rhythm generator (RG), pattern formation (PF) and motornerons (MN) producing specific activation of different muscles and receiving proprioceptive feedback that forms a closed-loop control of locomotor limb movement. (*B*) Activity of RG, PF and MN over a few step cycles. (*C*) Hindlimb muscles simulated.

Proprioceptive (spindle Ia and II, and Golgi tendon Ib) and exteroceptive feedback signals provided sensory feedback to the spinal circuit model. Spindle group II stretch feedback from tibialis anterior and iliopsoas and Golgi tendon Ib feedbacks from medial gastrocnemius and soleus were connected to the rhythm generators (affecting timing of phase-transitions). Basic Ia and Ib reflexes were organized at the motoneuron level. Proprioceptive feedback signals were modeled as described in Markin et al. [8].

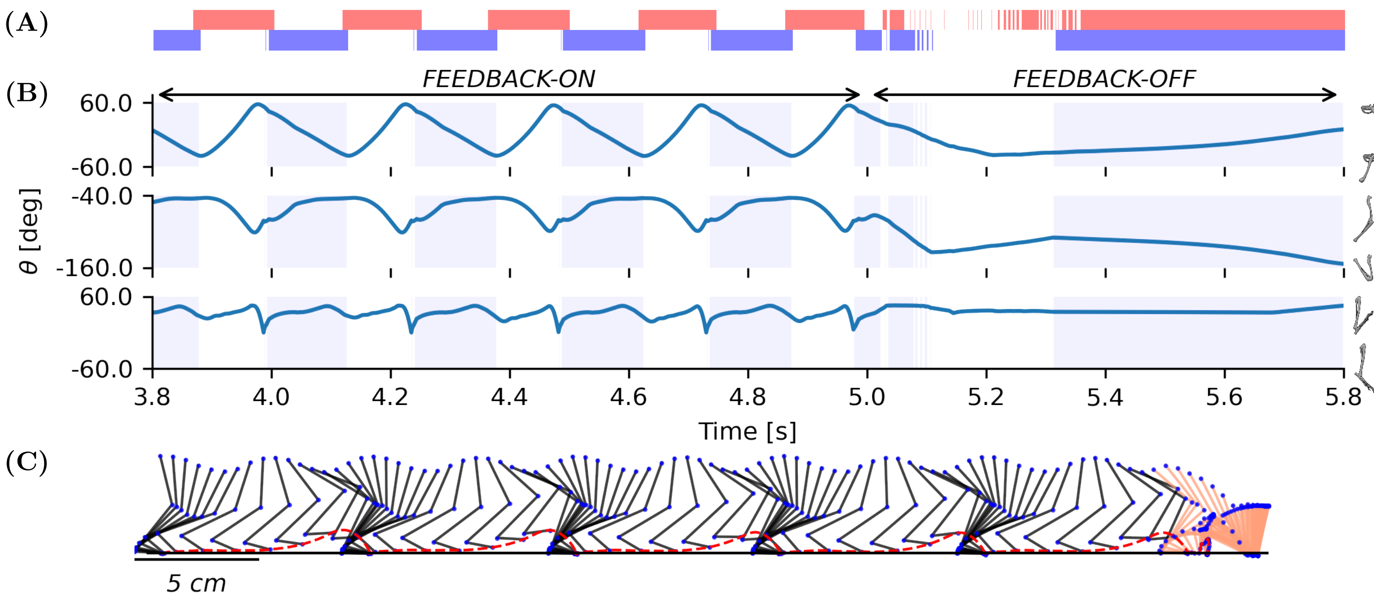


**Figure 2:** Over-ground locomotion after parameter optimization with sensory feedback ($t < 5.0[s]$) and later perturbed by removing sensory feedback ($t > 5.0[s]$). ($A$) Footfall patterns of the left and right hindlimb feet. ($B$) Hindlimb hip, knee and ankle flexion-extension joint angles (blue shaded area indicates stance phase). ($C$) Stick diagram showing stable step cycles with sensory feedback and model failing when sensory feedback was removed.

### 2.2 Optimization

We used covariance matrix adaptation-evolution strategy (CMA-ES) [9–11] to identify model parameters (descending drives, muscle synergy weights, and feedback weights) that lead to stable locomotion. The objective was to have the model walking over a flat ground with a minimum desired average speed (0.3 m/s) with the account of additional constraints such as maintaining a minimum pelvis height, minimizing joint ligament forces and muscle activation.

## 3 Results and Discussion

The closed loop mouse neuro-mechanical model was able to successfully locomote with feedback signals controlling only the rhythm generators and low-level reflex loops (Fig 2). Sensory feedback was essential for locomotion; when feedback connection weights were set to 0, the model immediately fell.

The current model represents a proof-of-concept and will be used as a setup for our upcoming studies on sensorimotor integration in the spinal circuits. In the future, we will study feedback pathways to the pattern formation circuits (affecting muscle synergies), commissural and long propriospinal interneurons. We will then use this model to explore the relative roles of different sensory feedback loops in realizing locomotion. We will also extend our model to simulate control of full 3D-quadrupedal locomotion with the aim to provide an open-source model that can be used as a test-bed to explore different hypotheses on the interactions between spinal circuits and sensory feedback.

## 4 Acknowledgements

This study was supported in part by NIH grants R01NS112304, R01NS115900, R01NS100928, and R01NS110550; NSF CRCNS/DARE grant 2113069; and ERC Salamandra project grant 951477.

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