In silico Spinal cord model shows the viability of targeting segmental foci along rostrocaudal axis for eliciting a variety of movement types

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Key points

3D model of lumbosacral spinal cord with sensory-motor circuitry and anatomical structures to carry out In silico stimulation experiments

Integration of neuronal models with OpenSim based musculoskeletal models, enabling study of spinal control and regulation of various movement types

In silico stimulation experiments reveal distribution of loci facilitating different movement types along rostrocaudal lumbosacral spinal cord; Antagonistic movement types are well separated along rostrocaudal axis; strongly antagonistic movement types even more so.

Closure of sensory motor loop, maintains these patterns along with a mild activation of antagonistic movement types, which could aid in movement stability and smoothness

Background

The modular organization of spinal circuits is an efficient strategy by which the spinal cord handles the complex descending motor commands and executes the final desired movement. Although the current computational models capture the modular organization of spinal cord, models that factor in the anatomical placement of functional circuits are not common. Especially, studies that aim to understand the effect of local spinal cord stimulation on movement will need an anatomically relevant setup. In order to build such models, we have combined a large amounts of information on spinal cord anatomy, physiology and musculoskeletal mechanics in our NEURO integration and Design – NEUROiD platform[7]. The current study introduces few early insights from a multi disciplinary and multiscale lumbosacral model built in NEUROiD.

Materials and Methods

- The multi disciplinary, multi scale lumbosacral spinal cord model generated using NEUROiD[7] **See Figure 3**
- Anatomy of various cross section are obtained from Paxinos [8]
- The neurons are placed in appropriate Rexed laminae; motor columns are distributed in 3D Segmental map as per Sharrard[5]
- The spinal circuitry comprising motoneurons, interneurons, dorsal root ganglion is generated based on joint-level muscle synergy based algorithm of NEUROiD[7][3][4]. **See Figure 2, Figure 4, Figure 5**
- The motoneurons are modeled as spiking neurons with Na^+, K^+, Ca^{+2}, K-Ca gated ion channels [6]
- The dorsal root ganglions are modelled as NetStim events and interneurons are modelled as Integrate and fire neurons[6]
- The cumulative motoneuron activity of the muscles involved in a movement type is plotted against stimulation site
- Motoneuron output is fed to a musculoskeletal model of lower limbs[2]. Afferents from muscles are fed back to spinal cord **See Figure 2**
- Neuronal simulations are run on **NEURON 7.4**[1] and musculoskeletal on **OpenSim 4.0**

Figures and Results

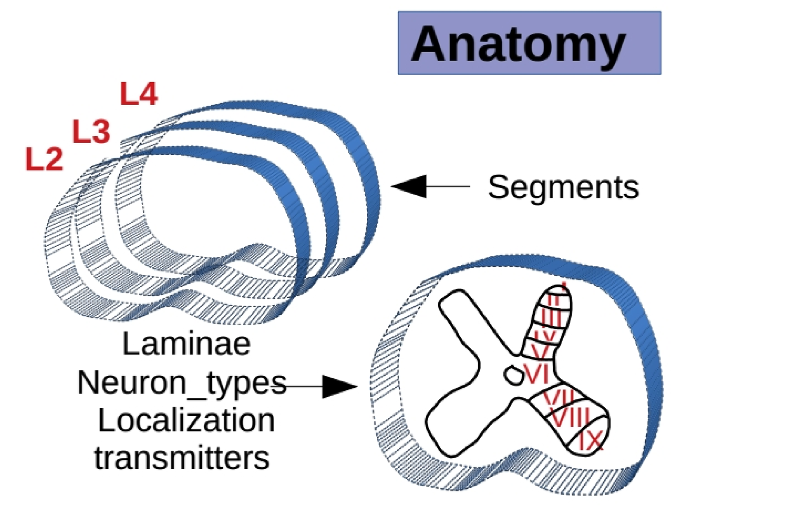

Figure 1. Schematic of Spinal cord information obtained from literature for building model

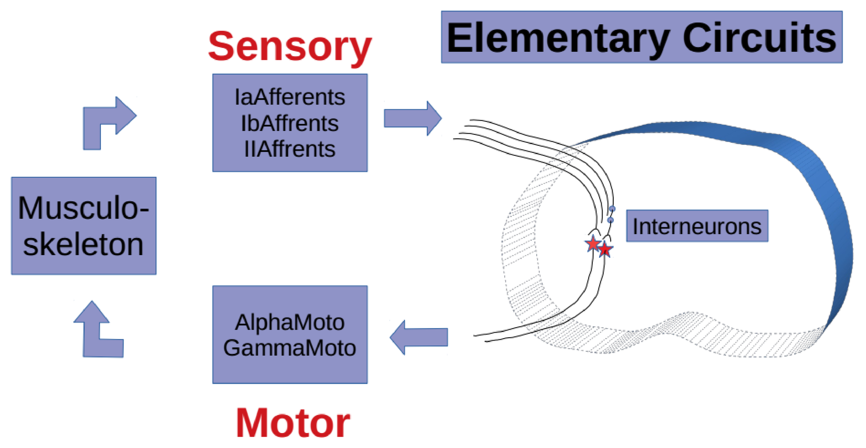

Figure 2. Schematic of Spinal elementary Circuitry interacting with musculoskeletal model

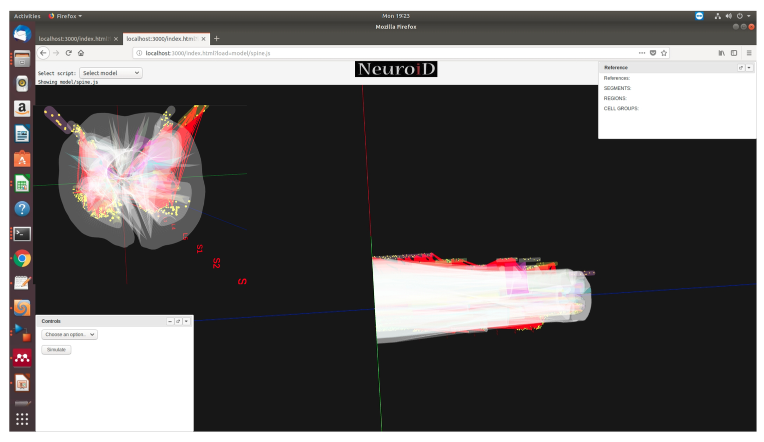

Figure 3. 3D lumbosacral spinal cord model model with circuitry(Crossectional view in inlet)

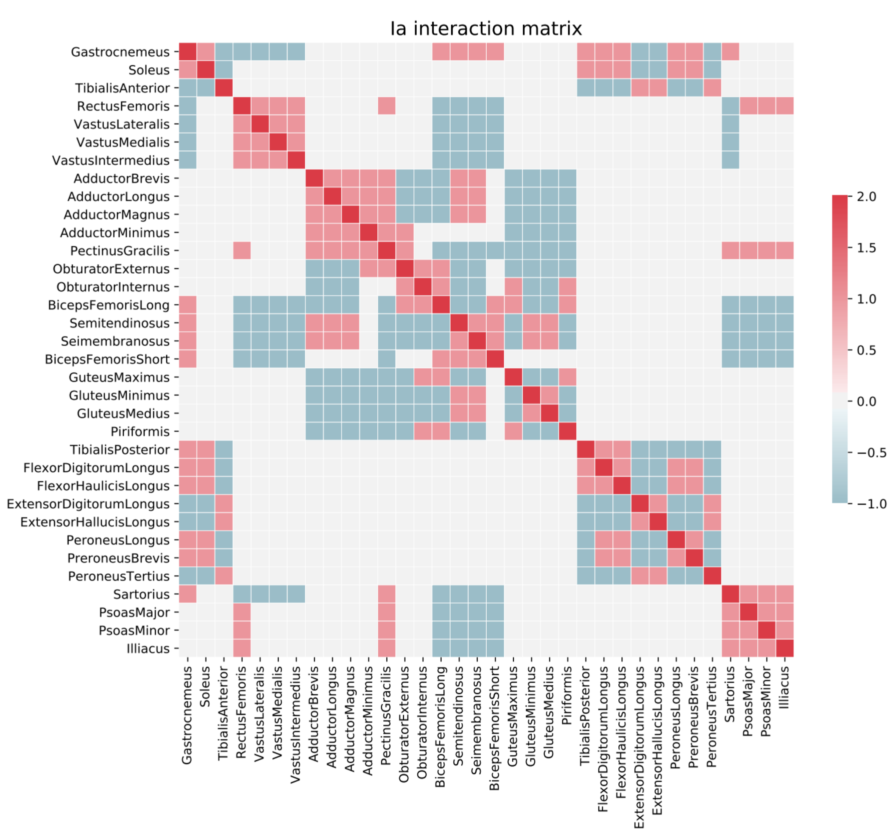

Figure 4. Ia Synergy

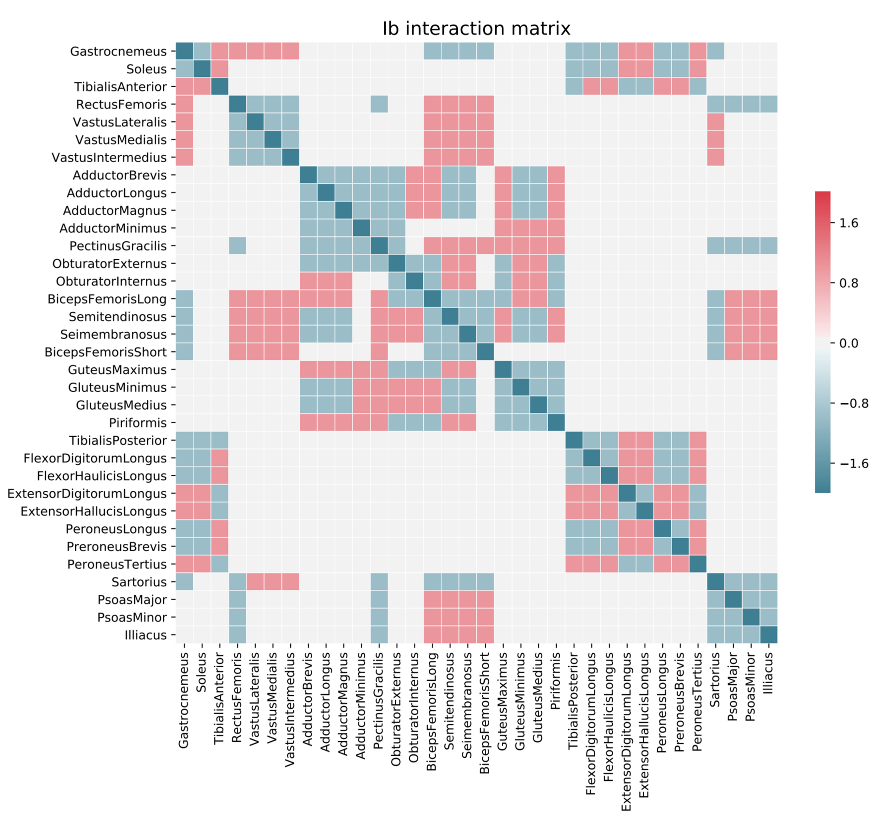

Figure 5. Ib Synergy

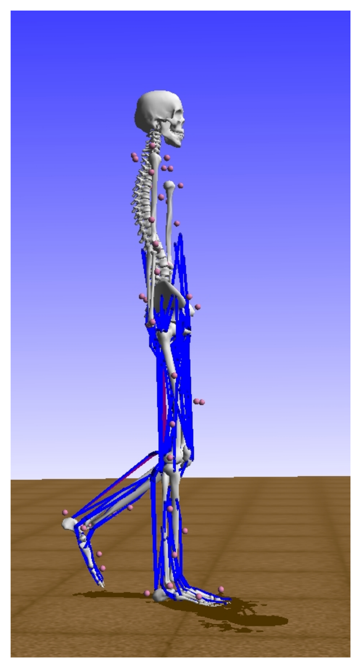

Figure 6. knee_flexion on OpenSim model

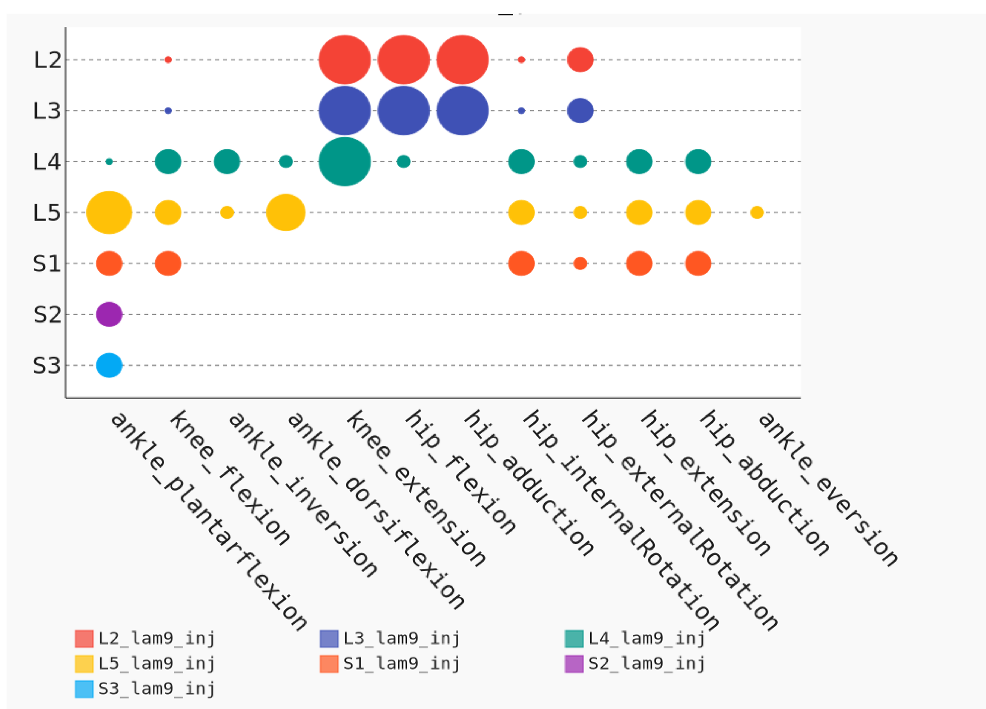

Figure 7. The Segmental activation of Lamina IX vs Movement types

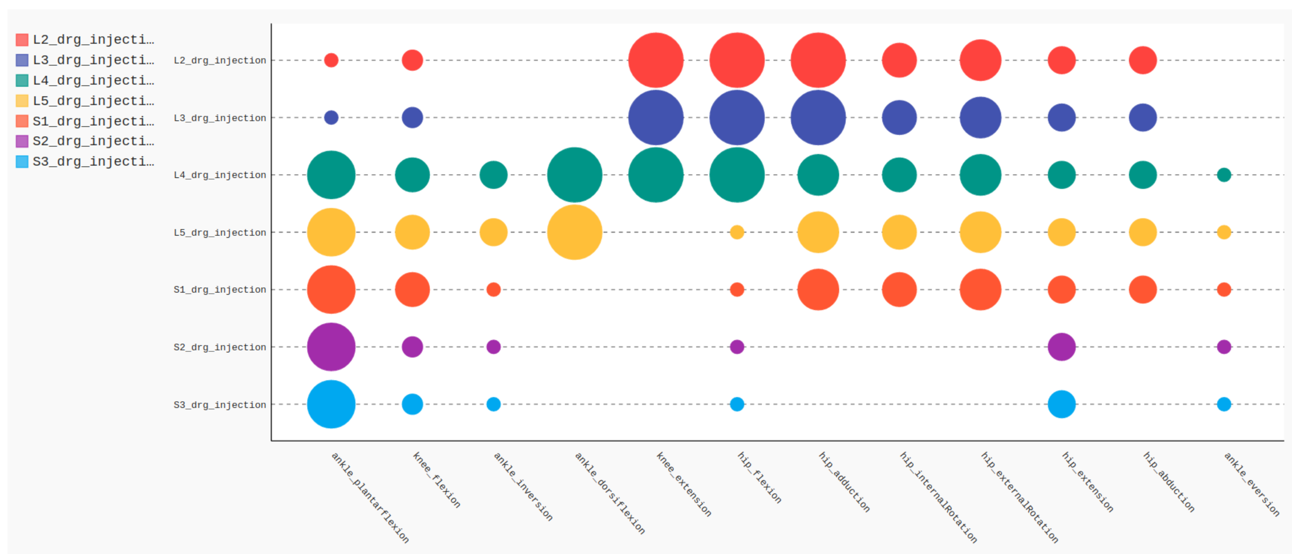

Figure 8. The Segmental activation of Dorsal Root Ganglions vs Movement types

Discussion

- The major emphasis of the current study is to investigate the effect of stimulation at various loci in a 3D composite spinal cord-musculoskeletal model
- Identifying the relation between stimulation sites and the movement types mediated are challenging
- This study has implications to design of stimulation protocols
- The Laminae IX and Dorsal Root Ganglions are accessible sites for the electrical stimulation in animal studies and the same has been chosen as In silico Stimulation sites
- Stimulation at Laminae IX shows varies movement types. **See Figure 7**
- The movements that are strongly opposed or are major antagonists are found to be separated along the rostro-caudal axis. **See Figure 7**
- The current model combines an anatomically relevant neuronal circuit model of spinal cord with musculoskeletal system and such a setup could be helpful in the assessment of degree of Spinal Cord Injury, study of spinal lesions and design of therapeutic stimulation protocols

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