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Investigation of the roles of spinal pathways in human upper limb movements using neuromechanical simulation

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1 Motivation

Human movements emerge from complex interactions between the musculoskeletal system, the neural system and the external environment. The control of such movements is realised through a hierarchical neural system composed of various brain regions and the spinal cord (SC). Motor planning is mainly conducted in higher brain regions, whilst the SC acts as brain-muscle gateway and implements its own motor control centre with fast reflexes. Spinal circuits are indeed very old from an evolutionary point of view, they were present in the first vertebrates about 500 million years ago and fully allowed basic locomotion [1]. Nevertheless, the role of spinal pathways in the control of upper limb movements is not clear. Previous models have studied this question, but they considered with and without SC scenarios only, without accounting for various spinal reflex strength scenarios [2, 3]. This exploratory study aims at identifying the role of various spinal pathways in upper limb motor control.

2 Methods

To do so, we use a model integrating a step command to emulate brain command, a modular SC model and a musculoskeletal upper limb model. This musculoskeletal model includes 1 degree of freedom (DoF) at the elbow and 1 DoF at the shoulder actuated by 7 muscles; deltoid anterior, biceps long and short, triceps long, lateral and medial, and brachialis, simulated with OpenSim software [4]. To control these muscles, the modular SC model includes for each muscle the following pathways depicted on Fig. 1A [5]:

- Ia stretch reflex: monosynaptic excitatory pathway from muscle stretch feedback conveyed by Ia fiber
- Reciprocal Ia inhibition (RI) between antagonists: disynaptic inhibitory pathway from antagonist stretch feedback conveyed by antagonist Ia fiber
- II static stretch reflex: disynaptic excitatory pathway from static stretch feedback conveyed by II fiber
- Ib autogenic inhibition: disynaptic inhibitory pathway from muscle tension feedback conveyed by Ib fiber

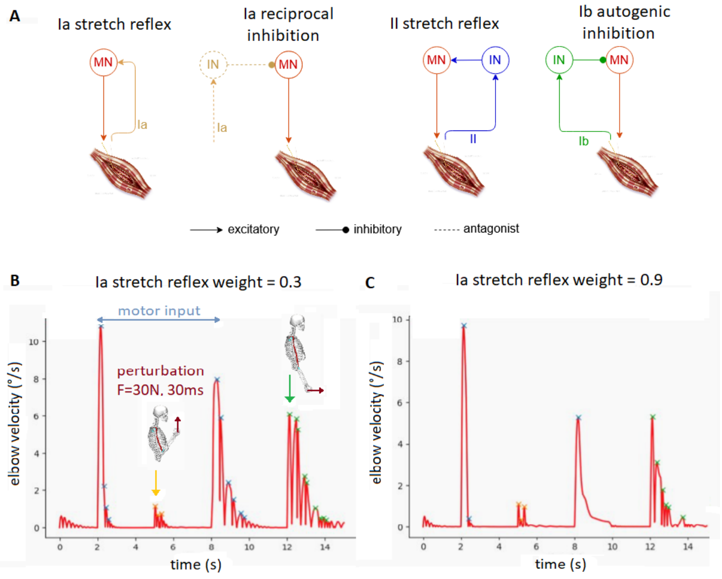

Figure 1: Spinal pathway models and simulated trajectory examples: A) Schematic of the four studied spinal pathways, with MN and IN standing for motoneuron and interneuron. B) Simulated trajectory for Ia stretch pathway with a synaptic strength of 0.3: a brain step command of 6 seconds is input to the flexor muscles, and two perturbations of 30 newtons and 30 milliseconds each are applied at the hand, one at flexed position and one at extended position. C) Same scenario with a synaptic strength of 0.9.

These pathways are modeled with leaky dynamics for each neuron:

$$\tau \dot{r}(t) = -r(t) + \sigma(\sum_i w_i r_i(t - \tau_i)), \qquad (1)$$

where r stands for the neuron firing rate, $\tau = 1$ms is the activation time constant (we consider fast-response large neurons); σ is a steep sigmoid function with an offset of 0.5 and a scaling factor of 10 emulating the on-off behaviour of neurons; i describes the neuron input signals; w_i is the synaptic weight of the input connection, tested from 0 to 1 for each pathways; r_i is the input activity; and $\tau_i = 30$ms stands for the stretch reflex response delay in upper limbs. The sensory signals from the Ia, II and Ib fibers are modeled using Prochazka's fiber rate models [6].

The simulated trajectory is finally composed of a brain step command of 6 seconds input to the flexor muscles, and two perturbations of 30 newtons and 30 milliseconds each applied at the hand, one at flexed position and one at extended position as depicted on Fig. 1B.

We then compare the resulting simulated trajectories for each pathway with various synaptic weight (w) in terms of movement smoothness and robustness against perturbation. More precisely, we computed the number of elbow velocity peaks during movement ($N_{p,mov}$), the damping of these peaks ($D_{p,mov}$), and spectral arc length (SAL, negative metrics, closer to 0 for smoother movements) for the first characteristic [7], and the number and maximal amplitude of elbow velocity peaks due to perturbation ($N_{p,pert}, A_{p,pert}$), and the damping of these peaks ($D_{p,pert}$) for the second.

3 Results

Fig 1B and C show the resulting simulated elbow kinematics for the Ia stretch pathway with a synaptic strength of 0.3 and 0.9 respectively. We can observe that the elbow velocity profile is smoother with a higher synaptic strength.

Fig. 2 shows the resulting movement smoothness (SAL) and response to perturbation ($N_{p,pert}$) for all the spinal pathways with various synaptic strengths. The Ia stretch pathway is the most sensitive to weights variation, with both metrics monotonically varying with increased synaptic weights. The SAL increases, while the number of peaks due to perturbation decreases, revealing smoother and more robust movements with increasing synaptic weights.

The other pathways present a less characterised behavior along with weight variations. The II stretch pathway still shows more robust movements and the Ib inhibitory pathway less smooth movements with increasing synaptic weights.

4 Discussion

The present model reveals that the Ia stretch reflex is the most sensitive spinal reflex to synaptic weights variation, increasing movement smoothness and robustness against perturbation with increasing synaptic weight. Thus, our results assign to the spinal stretch pathways a pivotal role in providing robustness against perturbation, whereas previous models have pointed a key role of muscle passive elasticity [3, 8] of Ib autogenic pathway [2] in handling perturbations.We aim at furthering this study by considering kinematics and muscle activity recorded data to compare and validate the model.

The present exploratory approach is deemed of great interest as it allows the investigation of the effect of various spinal pathways. Such studies could be done to investigate the effect of other reflex characteristics like reflex delay [3, 8], and further model pathological conditions involving various neural impairments.

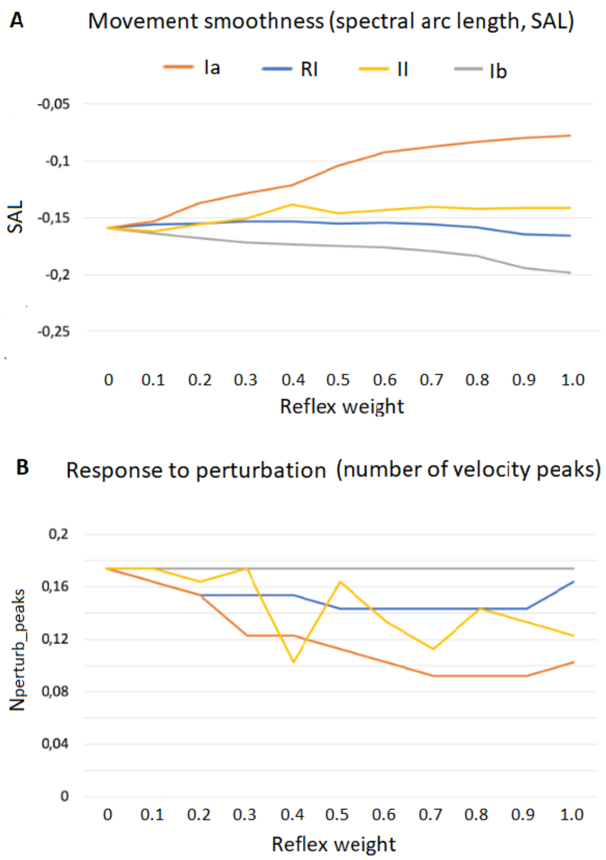

Figure 2: Results: A) Movement smoothness and B) Robustness against perturbation for various weighted spinal reflexes, with Ia, RI, II and Ib standing for Ia stretch reflex, reciprocal Ia inhibition, II static stretch reflex, and Ib autogenic inhibition.

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