Artificial representation of spinal sensorimotor circuits: a path to study motor learning
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Introduction
Rehabilitation approaches taking advantage of spinal circuitry abilities are being developed, giving hope for functional outcomes for patients suffering from severe spinal cord injuries (SCI) [1]. In parallel, experiments on animal models have shown a potential difficulty: task-specific recovery (TSR). Animals trained on one task got better at it but simultaneously got worse at untrained tasks [2]. Wolpaw formulated the Negotiated Equilibrium Hypothesis (NEH), which could explain TSR: all motor behaviors in an individual’s repertoire compete for their usage of their common spinal circuits. A supraspinal supervisor arbitrates, in order to reach a negotiated equilibrium [3]. This experimental protocol involves spinal circuits that have been modeled [4]. It first integrates a task into the motor behaviors repertoire of rats (bipedal walk on a treadmill). This task is then perturbed by the acquisition of a new behavior (operant conditioning of the soleus H-reflex). In healthy rats, the quadriceps H-reflex undergoes compensatory changes.

This work is the first step towards a comprehensive framework for the study of plasticity and learning mechanisms in the spinal cord. The chosen approach is to reproduce Wolpaw’s experiment. This could allow to validate the model against experimental observations. Here we focused on modeling a spinal reflex circuit controlling two antagonist muscles, which allows for capturing the alternative and repetitive nature of locomotion.

Methods
An artificial neural network (ANN) was implemented to model the locomotor spinal circuit. Its structure was based on a realistic model [4]. The ANN learned motoneuron (MN) outputs from muscle stretch. Once trained, the monosynaptic weights of the direct connection between first hidden layer and output layer were linearly increased to model operant conditioning of the H-reflex.

To measure the similarity between neurons of the first hidden layer and muscle spindles sensory neurons, we fitted their simulated firing rates to an empirically validated model [4]:

\[ S(t) = a + b \text{stretch}(t) + c \text{velocity}(t) + d \text{EMG}(t) \]

Networks

The output neurons receive contributions from three neuronal populations: the first hidden layer neurons, and the inhibitory and excitatory second layer neurons

Network used as basis for ANN. Muscle spindles output group-Ia and –II afferents. Group-Ia connect monosynaptically to motoneurons.

References

Results
The ANN could reproduce alternated stretch-driven motoneuronal activity, as previously obtained with a realistic neuro-biomechanical model. However, contributions of the three populations connected to the output were qualitatively different from their counterparts in the realistic network. Modifying the monosynaptic weights successfully mimicked the operant conditioning in most but not all trials. The variability in the obtained weights distributions was likely due to the high number of DOF of the ANN.

In reality, sensory afferents are of multiple types. While the fitting of the firing rates of the first hidden layer neurons was appreciable good (\( r^2 = 0.79 \)), it did not allow to split these neurons into group-ia (most sensitive to contraction velocity) and group-ii (sensitive to stretch) clusters.

Potentiation of the monosynaptic response

For all trials, increasing the monosynaptic weights led to increased muscle activity in the active phase. For some trials the rest phase was also affected (behavior 2), which was not the case in behavior 1 nor in experimental results.

Conclusions
ANN can be used to build natural-like networks and are able to describe experimental behaviors with quite some precision. They can also be used to study modifications to the networks that occur during plasticity, training, and possibly injury in the future. Subsequent work could focus on:

- What function does the brain optimize? Wolpaw showed that some kinematic features of the walking gait are preserved after operant conditioning [5]. Inclusion of a biomechanical model in closed-loop with our ANN would be necessary to conduct such analysis.
- Which sensory signal is used to assess if the motor objective is reached? Experimental evidence was found in favor of dorsal ascending tracts [6], which contain sensory afferents. However, the first hidden layer of the ANN does not behave exactly like those fibers, and this might prevent modeling of this phenomenon.

How is the supervisor acting on the spinal circuitry? Primary afferent depolarization (PAD) causes presynaptic inhibition of afferent fibers, and there is evidence that PAD could be mediated by descending commands [6]. This could be a way for the supervisor to influence network weights. PAD could be modeled by a multiplicative factor in front of each artificial network weight, which the supervisor would control.

Contributions of the 3 populations to ANN output. During the rest phase of the muscle, strong excitation is compensated by strong inhibition. In the realistic model however, excitation is weak and inhibition strong.