Analyzing the performance of two-layer CPG in different sets of neural parameters and inputs

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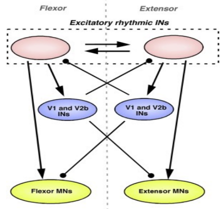
Abstract

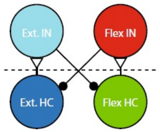
This work explores the effect of descending drive and feedback stimuli on oscillation frequency control and phase response of a two-layer central pattern generator (CPG). Many models of locomotion utilize this, or a similar model, as the driving rhythm generator of movement. However, the neuron parameters in those models are determined by a combination of optimization and hand-tuning. The role of different parameter choices remains unknown. Specifically, we explore how **weak mutual excitation** between oscillators and different descending drive strengths impacts these behaviors of the CPG. We also explore how the rhythm generator controls and influences the pattern formation layer under various stimuli/inputs. **This analysis will benefit the design and implementation of future models investigating locomotion control.**

Background

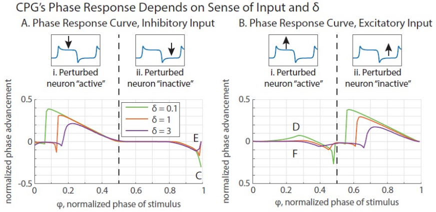
The weak mutual excitation between oscillators in the rhythm generator is hypothesized from the observation of synchronous rhythmic excitation of flexor and extensor motor neurons when V1 and V2b inhibition is absent.



(Zhang et al., 2014)



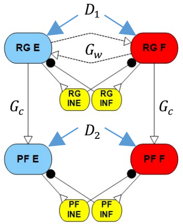
Several studies have used dynamic analysis to explain the behavior of the half-centers. Szczecinski's work has shown how to predict oscillation frequency, and determine phase response sensitivity to different parameters.



The stimulus is either +/- 5 nA applied to the inhibitory interneuron, in a square pulse with a duration of 5% of the oscillation period. $\delta = V_{\infty,inh} - E_{lo}$. A larger delta results in faster, more robust oscillations.

(Szczecinski et al., 2017)

Model Description



For all neurons: $C_m = 5\ nF$, $G_m = 1\ uS$, $E_r = -60\ mV$.

Oscillators (OC): $G_{Na} = 1.5\ uS$, $E_{Na} = 50\ mV$,

$A_h = 0.5$, $S_h = -0.6$, $E_h = -60\ mV$, $\tau_h = 350\ ms$,

$A_m = 1$, $S_m = 0.2$, $E_m = -40\ mV$, $\tau_m = 2\ ms$.

Interneurons (INs): $G_{Na} = 0\ uS$.

For all synapses: $E_{lo} = -60\ mV$, $E_{hi} = -40\ mV$.

OC->IN: $g_{syn} = 2\ uS$, $E_s = -40\ mV$.

IN->OC: $g_{syn} = 2\ uS$, $E_s = -70\ mV$

Between RG: $g_{syn} = G_w$, $E_s = -40\ mV$

RG->PF: $g_{syn} = G_c$, $E_s = -40\ mV$

$$C_m\frac{dV}{dt} = G_m\cdot(E_r - V) + \sum G_{syn,i}\cdot(E_{s,i} - V) + G_{Na}\cdot(E_{Na} - V)\cdot m\cdot h + I_{app}$$

$$G_{syn,i} = \begin{cases} 0, if\ \ V_{pre} < E_{lo} \\ g_{syn,i}\cdot\dfrac{V_{pre} - E_{lo}}{E_{hi} - E_{lo}}, if\ \ E_{lo} < V_{pre} < E_{hi} \\ g_{s,i}, if\ \ E_{hi} < V_{pre} \end{cases}$$

$$\frac{dm}{dt} = \frac{m_\infty(V) - m}{\tau_m(V)}, \qquad \frac{dh}{dt} = \frac{h_\infty(V) - h}{\tau_h(V)}$$

As τ_m is small and $\tau_m << \tau_h$, $m = m_\infty(V)$

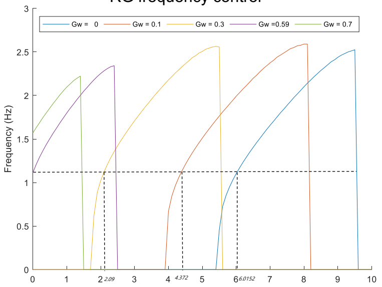
$$z_\infty = \frac{1}{1 + A_z\cdot\exp(-S_z\,(V - E_z))}$$

z represents either m or h

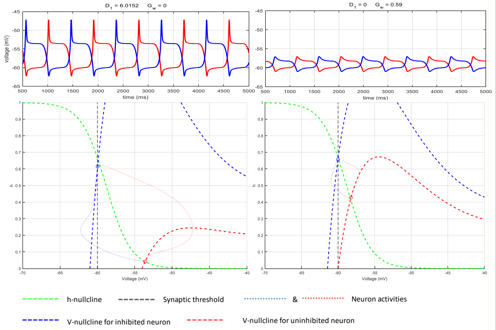
$$\tau_h(V) = \tau_h\cdot h_\infty(V)\cdot\sqrt{A_h\cdot\exp(-S_h\,(V - E_h))}$$

Results

RG frequency control



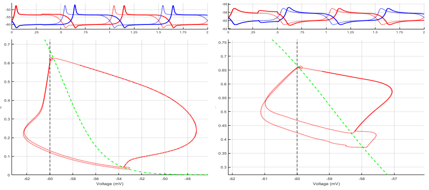
If we want a desired frequency of 1.1136 Hz, there are infinite solutions found by varying Gw and D1 Stimulus. For example, possible solutions are [Gw D1] = [0 6.0152]; [0.1 4.372]; [0.3 2.09]; [0.59 0]. However, the performance for different conductances is not the same, **as shown below**.



These two rhythm generators have different parameters and oscillate at the same frequency. Notice that the weak mutual excitation between the oscillator half-centers changes the magnitude of neuron activation and the shape of the oscillation curve by shrinking the size of the phase orbit. The **self-oscillation** case (D1=0) has a very small phase orbit.

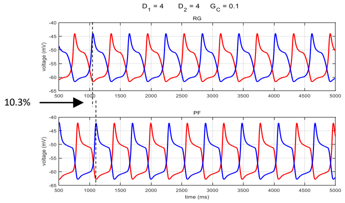
RG phase response due to perturbation

The perturbation response when an excitation stimulus of 5 *nA* is injected into the extensor neuron of the rhythm generator during 0.3-0.5 of the normalized phase duration.

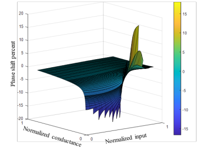


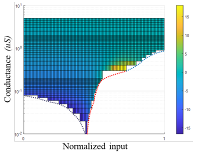
The stimulus prolonged the active phase of extensor neuron for both cases. It shifts the phase for pure drive case by 10% and self-oscillation case by 7%.

Phase shift between the PF and RG layers when different drives are applied



The frequency of the rhythm generator layer and the pattern formation layer are the same at 1.6813 Hz. But there is a 10% phase delay when comparing the two layers.





References

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