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A Neural Pattern Generator that Exhibits Arousal-Dependent Human Gait Transitions

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Abstract

A neural pattern generator based upon a non-linear cooperative-competitive feedback neural network is presented. It can generate the two standard human gaits: the walk and the run. A scalar arousal or GO signal causes a bifurcation from one gait to the next. Although these two gaits are qualitatively different, they both have the same limb order and may exhibit oscillation frequencies that overlap. The model simulates the walk and the run via qualitatively different waveform shapes. The fraction of cycle that activity is above threshold distinguishes the two gaits, much as the duty cycles of the feet are longer in the walk than in the run.

1 A Neural Pattern Generator for Human Gait Timing

In various quadruped gaits, different relative order of limb oscillations distinguish between various gaits. However, the human walk and run gaits cannot be distinguished on the basis of limb order, since both gaits have the same relative limb order. Nor can they be distinguished on the basis of frequency of oscillation, since each gait may exhibit the same frequency: The limbs may oscillate at the same frequency during fast walk as they do in a slow run. The neural pattern generator described below is an Elias–Grossberg oscillator [2]. It exhibits two distinct oscillatory regimes that can be quantitatively distinguished on the basis of qualitatively different waveform shapes. Let

\[ x_i = -Ax_i + (B - x_i)\left[f(x_i) + I_i\right] - (C + x_i)\left[\sum D_{ij}g(y_j)\right] \] (1)

\[ y_i = E\left[(1 - y_i)[x_i]^+ - y_i\right], \] (2)

where

\[ [\omega]^+ = \max(\omega, 0) \] (3)

\[ f(\omega) = \frac{F_1([\omega]^+)^2}{F_2 + ([\omega]^+)^2}, \quad g(\omega) = \frac{G_1([\omega]^+)^2}{G_2 + ([\omega]^+)^2}, \] (4)

and \( i = \{1, 2, 3, 4\} \). Here \( x_i \) is the activity, or potential of a fast excitatory neuron or population, and \( y_i \) is the activity of a slow inhibitory interneuron or population; see Figure 1A. The excitatory and inhibitory activities obey a shunting equation [3]. A single arousal source controls a scalar GO signal, \( I_i \), to each \( x_i \). Although each \( x_i \) receives the same GO signal, symmetry is broken in the oscillator by allowing changes in arousal to arrive at each \( x_i \) at slightly different times. The

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Figure 1: (A): Each channel of the oscillator is an \((x,y)\) pair. Each activity \(x\) receives the an arousal or \(GO\) signal and is self-excitatory. Oscillations are generated by a feedback from a slow inhibitory interneuron with activity \(y\). (B): Inhibition in the neural pattern generator; each arrow represents an inhibitory connection from one channel’s \(y\) to another channel’s \(x\). See text for inhibitory coefficient labels, \(D_0, D_1, D_2,\) and \(D_3\). Note that there is no \(D_2\) leg→arm or \(D_3\) arm→leg inhibition.

Simulations Results

Muybridge [4] observed that humans use a limb timing pattern similar to the quadruped walk. The human does not have in-phase synchronization of the contralateral arm and leg, as would be the case if human limb timing was analogous to a trot. Our simulations demonstrate a bifurcation from one state in which no limb is in-phase with any other into another state in which no limb is in-phase with another (although all limbs are 1:1 phase locked). Although this paper addresses the biologically observed case, it is worth noting that the two channel version of the oscillator [1] is capable of two qualitatively distinct 180° anti-phase oscillatory regimes, and could be used to control a walk and a run were there in-phase synchronization of the contralateral arm and leg.
Figure 2: A switch from a walk, $I = 0.1$, to a run, $I = 0.15$. Note that the relative phase stays the same, but the shape of the waveform changes dramatically. $A = 1.0$, $B = 1.1$, $C = 2.5$, $D0 = 0.8$, $D1 = 0.185$, $D2 = 0.15$, $D3 = 0.15$, $E = 1.5$, $T1 = 9.8$, $G1 = 3.9$, $F3 = 0.5$, $G2 = 0.5$. $\text{cordlag} = 0.0025$, $\text{sidelag} = 0.001$, $t_{\text{max}} = 60.0$. The arousal increment occurred at $t = 30$ and only the arousal was changed.

Figure 3: A plot of the thresholded output, the white parts of the bar indicate suprathreshold activity (signal to lift limb) and the black parts indicate subthreshold activity. Note the clean initiation of the walk and the clean transition to the run. The output threshold was .33. Other parameters are as in Figure 2.

The four-channel system reported herein exhibits two oscillatory regimes that exhibit qualitatively different waveform shapes while maintaining the same relative order of $x_i$ activity. We interpret the regime occurring at lower arousal levels as the walk and the regime at higher arousal levels as the run. Examples of the two different waveforms are shown in Figure 2. The walk oscillations (on the left of the figure) are characterized by sharp peaks that take up a smaller fraction of the cycle than do the more plateau-like oscillations that characterize the run (on the right side of the figure). In the model, all that is necessary to switch between the walk and the run is a fixed small parametric shift in the arousal level. The same data shown in Figure 2 has been thresholded to generate the plot in Figure 3.

Figures 2 and 3 clarify how it can be that different human gaits cannot be distinguished by relative limb order. The frequency plot for the model walk and run in Figure 4A shows that the oscillator can generate overlapping frequency regions, so frequency alone also cannot be used to distinguish between its gaits. A quantitative metric that can distinguish the gaits is shown in
Figure 4: (A): The frequencies of the walk and the run. Notice that the walk and the run can the same frequency at different arousal levels, hence frequency cannot be used to discriminate between the gaits. The frequencies were sampled at arousal increments of .01 and the initial conditions were reset to zero for each sample. Other parameters are as in Figure 2. (B): The walk and the run can be distinguished quantitatively by the fraction of the cycle that each \( x_i \) has suprathreshold activity.

Figure 4B, namely the fraction of the cycle in which an \( x_i \) is above threshold: walks show fractions of cycle above threshold of less than .23, whereas runs are above .31. This property suggests how a limb may have a longer duty cycle, i.e. may remain on the ground a larger fraction of the time, during a walk than a run.

References


