A Control System for a Flexible Spine Belly Dancing Humanoid

Takanishi Laboratory
Humanoid Robotics Institute
Waseda University

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Mercurio Maurizio - 681054
Nava Alessandro - 681546
Recently, there has been a lot of interest in building anthropomorphic robots. Research on humanoid robotics has focused on the control of manipulators and walking machines. The contributions of the torso towards ordinary movements (such as walking, dancing, attracting mates, and maintaining balance) have been neglected by almost all humanoid robotic researchers.

We believe that the next generation of humanoid robots will incorporate a flexible spine in the torso. To meet the challenge of controlling this kind of high-degree-of-freedom robot, a new control architecture is necessary.

Inspired by the rhythmic movements commonly exhibited in lamprey locomotion as well as belly dancing, we designed a controller for a simulated belly-dancing robot using the lamprey central pattern generator.

Experimental results show that the proposed lamprey central pattern generator module could potentially generate plausible output patterns, which could be used for all the possible spine motions with minimized control parameters.
Central Pattern Generator (CPG)

Similar to snakelike robots and the tendon driven robots, the next generation of humanoid robots will incorporate a flexible spine as the torso. Given that such a robot will have a greater degree of freedom (DOF) than existing robots, it is necessary to find a simple control strategy to cope with the increased complexity.

Inspired by the rhythmic movements commonly seen in lamprey locomotion as well as belly dancing, we designed a controller for a simulated belly-dancing robot based on the lamprey Central Pattern Generator (CPG).

The lamprey belongs to the most primitive vertebrate group, the cyclostomes. It is considered by biologists to be a prototype vertebrate because its brain stem and spinal cord have all the basic vertebrate features, yet the neurons in each category are an order of magnitude fewer than in other vertebrates.

We believe that some of the principles found in the motor control of the lamprey can be applied to the design of a controller for a high-DOF humanoid robot. The reason is that the lamprey has 100 segments, each of which has at least four muscles (to allow yaw, pitch, and roll). By varying only the global and extra excitations from the brain stem, the lamprey is able to change its body shape.
Central Pattern Generator (CPG)

Such simplicity is ideal in a controller for a high-DOF, flexible spine humanoid robot. As a first step, we investigate the possibility of using a CPG-based controller and a minimized number of input parameters to control a high-DOF, flexible spine model humanoid.

Neural Model of the Lamprey CPG
The controller is composed of 100 interconnected segmental oscillators (only five segments are shown here). Each segment consists of eight neurons of four types:

- motoneurons (MN),
- excitatory interneurons (EIN),
- lateral inhibitory interneurons (LIN),
- contralateral inhibitory interneurons (CIN).

Connections with an arrow ending represent excitatory connections, while those with a dot ending represent inhibitory connections. Vertical lines indicate that there are intersegmental couplings among the neurons within the CPG. Due to the complexity of the couplings, the actual intersegmental connections are not shown here.

Note that in this implementation, the brain stem itself is considered as a neuron unit. Each neuron within the CPG receives the same amount of global excitation from this special neuron. Moreover, neurons near the head segments receive extra excitation.
To model a neuron unit, we used a leaky integrator with a saturating transfer function. The output $u$ (a $[0, 1]$) of the unit neuron is the mean firing frequency of the population it represents. It is calculated using the following set of formulas:

\[
\begin{align*}
\dot{\xi}_+ &= \frac{1}{\tau_D} \left( \sum_{i \in \Psi_+} u_i w_i - \xi_+ \right), \\
\dot{\xi}_- &= \frac{1}{\tau_D} \left( \sum_{i \in \Psi_-} u_i w_i - \xi_- \right), \\
\dot{\vartheta} &= \frac{1}{\tau_A} (\mu - \vartheta), \\
\mu &= \begin{cases} 
1 - \exp\{(\Theta - \xi_+)\Gamma\} - \xi_- - \mu \vartheta & (\mu > 0), \\
0 & (\mu \leq 0)
\end{cases}
\end{align*}
\]
• $\mathcal{W}_i$ represents the calibrated synaptic weights;

• $\Psi_+$ and $\Psi_-$ represent the groups of presynaptic excitatory and inhibitory neurons, respectively;

• $\xi_+$ and $\xi_-$ are the delayed reactions to excitatory and inhibitory inputs;

• $\Theta$ represents the frequency adaptation observed in real neurons

The parameters for each type of neuron are given in the table. The values of these parameters and those for the connection weights are set up in such a way that the simulation results from the model agree with physiological observations.
Mathematical Model of Neurons

<table>
<thead>
<tr>
<th>Neuron type</th>
<th>$\Theta$</th>
<th>$\Gamma$</th>
<th>$\tau_D$ (ms)</th>
<th>$\mu$</th>
<th>$\tau_A$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIN</td>
<td>-0.2</td>
<td>1.8</td>
<td>30</td>
<td>0.3</td>
<td>400</td>
</tr>
<tr>
<td>CIN</td>
<td>0.5</td>
<td>1.0</td>
<td>20</td>
<td>0.3</td>
<td>200</td>
</tr>
<tr>
<td>LIN</td>
<td>8.0</td>
<td>0.5</td>
<td>50</td>
<td>0.0</td>
<td>—</td>
</tr>
<tr>
<td>MN</td>
<td>0.1</td>
<td>0.3</td>
<td>20</td>
<td>0.0</td>
<td>—</td>
</tr>
</tbody>
</table>

- $\Theta$ is the threshold,
- $\Gamma$ the gain,
- $\tau_D$ the time constant of the dendritic sums,
- $\mu$ the coefficient of frequency adaptation,
- $\tau_A$ the time constant of frequency adaptation.

The neural activity of the entire swimming controller have been calculated by integrate Equations 1 to 4 using a fourth-order Runge-Kutta (RK4) method with a fixed time step of 1 ms.
Behavior of a Segmental Oscillator

The brain stem provides input signals to stimulate all the neurons. Only neurons that are actively inhibited stay inactive.

Suppose that initially the neurons on the left are slightly more active. The EINI neuron excites all the ipsilateral neurons, while the CINI neuron inhibits all the contralateral neurons. This prevents simultaneous activity on both sides.

Due to its higher threshold and time constant, the LINI neuron becomes active later in the cycle to act as a burst suppressor to the CINI neuron. This allows the neurons on the right to become active.

The CINr neuron on the right in turn inhibits all the neurons on the left. After a while, the activities of the neurons on the right are terminated by the LINr neuron, and the entire cycle starts again.

Using this mechanism, an alternating pattern of muscular activity on the right and left sides of a single body segment can be generated.
In order to determine how the segmental oscillator behaves under different excitations, has been tested a implementation of Ekeberg’s segmental oscillator with a brain stem excitation from 0.2 to 1.0 in steps of 0.1. At the end of each simulation (one for each excitation value), the amplitude and frequency from the outputs of the left motoneurons are calculated.

When the segmental oscillator with asymmetric initial conditions receives enough excitation from the brain stem, an alternating pattern of neural activity is generated.
Increasing the brain stem excitation from 0.2 to 1.0 increases the maximum amplitude as well as the frequency of oscillation of the motoneuron outputs.
Global excitation from the brain stem stimulates all neurons in the CPG; sufficient stimulation results in oscillations in each individual segment at a frequency that depends on the strength of this global excitation signal.

Extra excitation is supplied from the brain stem to the five most rostral segments of the CPG. The effect of this, interacting with intersegmental coupling, is to induce a roughly equal relative phase lag between successive segments in the CPG.

The global excitation controls the amplitude (mean firing frequency) of the motoneuron outputs as well as the frequency of oscillation of the CPG.

The extra excitation alters the intersegmental phase lag largely independently of the global excitation.
To determine how the entire CPG behaves under different excitation combinations, has been tested implementation of Ekeberg’s model under global excitation ranges from 0.2 to 1.0 (in steps of 0.1) and extra excitation ranges from 0% to 200% (in steps of 10%).

- At each excitation combination, a neural simulation is performed. The characteristics (such as amplitude, frequency, and phase lag) of the neural wave that result from the outputs of the left motoneuron in the middle of the CPG, say segment 50, are recorded. The results are shown in Figure.

Recall that global excitation is the excitation that the brain stem applies to all the neurons in the CPG, and extra excitation is the excitation applied only to the neurons located in the five segments closest to the head. The extra excitation is a percentage of the global excitation.
The fundamental moves can be broken down into three types of motions: rhythmic oscillations, circular motions, and alternate contraction of muscles in two different body segments on the same plane. To mimic these movements, our proposed behavioral controller consists of three modules.
The first module of the controller involves a simulated lamprey central pattern generator. It generates motions that involve rhythmic oscillations (such as bending the body back and forth) as well as propagation of traveling waves along the body (as in the camel and snake arms). To generate rhythmic spine motions using the lamprey CPG, we set the global and extra excitations from the brain stem as well as the plane of motions. Since the four basic spine motions (flexion, hyperextension, lateral flexion, and twisting) as well as body undulations are planar motions, all the 3-DOF joints along the spine rotate about the same axis, and the other DOF are fixed. Thus, we only need one parameter to switch the connections between CPG outputs and motors. As a result, a total of three input parameters are adequate to control these motions. After the neural simulation is performed, the outputs from the motor neurons are then saved into a data file for the calculation of joint angles in MATLAB. Once the plane of motions is specified, the result is used to control a simulated humanoid in Poser 5 through a script program written in PoserPython.
The second module of the behavioral controller is a posture database, which stores rotational joint angles required for specific postures. By sequencing these postures, dance modules such as the hip circle, vertical hip circle, hip release, hip shimmy, and shoulder shimmy can be made. Through a combination of these modules, more advanced dance moves can be achieved.

Finally, in the third module, one needs to specify the amounts of rotation and the common plane of motions of two chosen joints. It is then possible to step through the body joints in opposite directions to generate circular motions.
A belly-dancing humanoid has been simulated in Poser 5 (Curious Labs), using the 3D human skeleton model developed by DAZ Productions. The reason for choosing this model is its similarity to a real skeleton: each of the individual vertebrae has a 3-DOF joint, which allows rotations along the yaw, pitch, and roll axes. To rotate a joint about a specific axis, one can use the dials in the parameters palette or data from an external file. Another advantage of using the skeleton model is that it is easier to show body movements without clothing.

Note that the four basic spine motions and body undulations are planar motions. Once the plane of motions is specified, all the vertebrae turn about the same axis and the other degrees of freedom are fixed.

Dermatomes are arranged in a highly ordered way on the body surface. It has been possible to map the distribution along the body surface of the dermatomes for all of the spinal segments by studying the sensibility and responsiveness that remain after injury to dorsal roots . . . dermatomal maps provide an important diagnostic tool for localizing levels of injury to the spinal cord and dorsal roots.

A dermatome is a restricted peripheral region of the skin. It is innervated by a single dorsal root, which contains sensory neurons that enter the spinal cord from the body.
Guided by the dermatomal maps, we coupled the motoneuron outputs from the lamprey CPG to the model spine. Given that each motoneuron output is between 0 and 1, the difference between the left and right motoneuron outputs at each segment is amplified 20 times. After this amplification, the spinal movements become observable and realistic. Each calibrated value is then used as the rotational angle (along a specific axis of rotation) for the corresponding vertebra.

The dermatomes of each spinal segment are located on particular regions of the body: C, cervical; T, thoracic; L, lumbar; S, sacral.
The human spine is an arched vertebral column. It consists of seven cervical vertebrae, twelve thoracic vertebrae, five lumbar vertebrae, the coccyx, and the sacrum. Between each neighboring pair of vertebrae there is an intervertebral disk, which acts as a shock-absorbing cushion.

The main functions of the spine are to protect the spinal cord and to act as a support to the upper body weight. In addition, it provides both stability and mobility in our daily activities.
Anatomy of the spine

The actions that are possible in the three spinal regions (cervical, thoracic, and lumbar) on the sagittal, frontal, and transverse planes depend on the different sizes, shapes, and articulations of the bones. According to kinesiologists such as Fitt, the possible actions achieved by the human spine are:

1. Flexion and hyperextension on the sagittal plane.
2. Lateral flexion to either side of the body on the frontal plane.
3. Rotation to the left and right on the transverse plane. This is mainly achieved in the thoracic region.

The last two functions are very important for flexible spine humanoid robots.
Neural wave generated by the lamprey CPG with global excitation 0.7 and no extra excitation. Solid lines represent the outputs from the left motoneurons, and dashed lines those from the right motoneurons.

Using this neural wave, the humanoid is able to achieve hyperextension.
Basic moves

flexion / hyperextension  lateral flexion  rotation

Those are planar movements, i.e. they are achievable by rotating all the vertebrae on the same axis.
In this experiment we try to mimic the camel move. This is another planar movement.

We set the global and extra excitations from the brain stem to 0.3 and 120% respectively. The extra excitation and intersegmental couplings cause a phase lag of 1% between successive segments along the CPG. Using the motoneuron outputs from the fifth to the sixth second to control the joint angles at each frame, a traveling wave can be made to propagate along the spine.
The camel
The beauty of belly dancing is that the body motions are rhythmic and well defined. Most of the seemingly complex dance moves emerge from a combination of sliding, circulating, twisting, and wavelike moves of the torso and arms.

In a typical course on belly dancing, the students learn a set of basic body postures, which forms the vocabulary of the dance. As the course progresses, more advanced dance movements can be accomplished by sequencing and/or superposing the basic postures. These postures are analogous to the motor primitives commonly described in literature on imitation learning.

Through computer animations and immediate feedback from a professional dance teacher, we developed a database of belly dance movements. It contains a set of fundamental dance postures.
Posture Database

Neutral (side)  Pelvis tilt  Pelvis tuck  Chest lift  Chest drop

Chest slide (left)  Chest slide (right)  Hip slide (left)  Hip slide (right)  Kick (right)

Head slide (left)  Hands up  Head slide (right)  Shoulder punch (left)  Shoulder punch (right)
Using three control variables (global excitation, extra excitation, and plane of motions) for the CPG model, we are able to reproduce the four basic spine movements defined by kinesiologists as well as body undulations commonly seen in belly dancing. The CPG is particularly good at controlling rhythmic motions.

From the experiments, our control system seems to be flexible. It would be interesting to apply the same controller to a different platform (such as a real robot with fewer spine segments) in order to demonstrate the adaptivity of the proposed control architecture.

When we reproduced the four basic motions of the human spine, we used the motoneuron outputs from the lamprey CPG to control every other vertebra of the simulated spine. The reason for this is that even at a global excitation of 0.3 (out of 1), the total amount of rotation from all 21 synchronized vertebrae becomes close to 200 deg. Given that the vertebrae are interconnected and that it is less important to differentiate the action of adjacent joints in these movements, this CPG-vertebrae mapping is acceptable to generate the motions for our model humanoid.

For the control of all spinal vertebrae using a wider range of control signals (the global and extra excitations), one can reduce the amplification factor involved in the calculation of joint angles.
At present, our CPG-to-vertebrae mapping scheme allows the switching of connections between CPG outputs to motors about any of the three DOF axes. For nonuniform spine motions, the CPG module can easily be modified to allow specifications of this variable for each individual vertebra.

Note that since some of the possible actions of the human spine are restricted by the articulation and shape of the bony landmarks, 3-DOF motions at each joint are not necessary.

Contrary to common belief, most of the movements in belly dancing are achieved through motions from the spine and/or the pelvis. Only the belly roll requires solely movements from the muscles.

Due to limited resources, we used our controller to control a weightless skeleton figure in 3D animation without taking into consideration body dynamics or other physical constraints (derived from the embodiment of the human skeleton model).

To implement the controller in a real humanoid robot, factors such as gravity, weight, balancing, collisions, inertia, and elasticity need to be considered.

**It would be interesting to model the human skeleton and abdominal muscles using a realistic physical simulator such as the MathEngine.**
Conclusion

This work demonstrates that by applying the control principles observed in the prototype vertebrate lamprey, it is possible to control the spine of a simulated humanoid robot.

By varying the global and extra excitations from the brain stem as well as the plane of movements, the proposed lamprey CPG module could potentially generate plausible output patterns, which could be used for all the possible motions of the human spine.

Furthermore, by incorporating the lamprey CPG and a posture database into described control system, the simulated humanoid robot is able to mimic the fundamental moves in belly dancing.

This work suggests that the proposed controller can potentially be applied to the control of a high-degree-of-freedom, flexible spine humanoid robot.
References


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Thank you for your attention