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Towards a Cybernetic Model of Human Movement

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Abstract

An elementary computational framework, as a first step to an eventual comprehensive model of human movement, is presented. Such a model in conjunction with anatomical, physiological and experimental studies should provide a means of verifying theoretical, experimental, and heuristic models of human movement. For this purpose, a three-dimensional three link humanoid model and a two-link planar arm model are presented to explore responses to simple external forces. Such models are useful for a variety of current applications in art, science, engineering, sports, and medicine. The models are subjected to kinesthetic, auditory, and visual inputs. Creating desired behavior is the goal. The models are flexible, modular, and expandable for inclusion of more segments, muscles, and sensory and central nervous system (CNS) processing. Three computer simulations are presented: rhythmic maneuvers of the three link model, in response to periodic motion of a platform, the planar arm producing visually observed alphabet-like characters in response to visual inputs, and processing of music to provide rhythms for a three-link dance.

Keywords: Three-dimensional dynamics, stability, coordination, rhythmic movement, auditory, visual and kinesthetic inputs, periodic and non-periodic response

1. Introduction

Norbert Wiener presented the concept of modeling the movement of living systems in *Cybernetics: Or Control and Communication in the Animal and the Machine* (Wiener, 1961). This book provided a foundation for research in complex systems of analysis and synthesis to represent the behavior and processing of living systems. The current research presented hereafter aims to apply this concept specifically to human movement and demonstrate a modular framework towards a cybernetic model.

Many anatomical (Gray, 1977), physiological (Henneman, 1980; McMahon, 1984), neuroscientific (Kandel, Schwartz, & Jessell, 2000; Ghez, 1991; Mergner, 2007), and neurobiological (Grillner, 1981; Shadmehr & Wise, 2005)studies deal with human movement. A computational framework can integrate and unify these separate studies and allow for large scale simulation of the human neuro-musculo-skeletal structures within the current state of knowledge or with more comprehensive systems of the future. In addition, such a framework will allow indirect testing of experimentally or heuristically derived hypotheses and principles about human movement. It also provides for non-invasive confirmation of measured parameters, paths and central nervous system (CNS) structures that perhaps will never become directly accessible for measurement. Further, such a framework is modularly expandable and one can replace its elements with more realistic and substantive information about human movement as more research results become available.

An elementary version of such a computational framework is presented here. The inputs to the frame are restricted to environmental and acoustical rhythmic signals because they are much easier to deal with a simple framework. More complex routine daily movements are more difficult to implement with the simple framework, and require a more realistic and substantial frame of neural, muscular and skeletal structures. Still more difficult movements are the internally motivated ones such as walking on a tight rope or other artistic and athletic movements.

Two subframes are presented in this paper. A three-dimensional three-link (Shadmehr & Wise, 2005; Shadmehr & Wise, 2005) humanoid model is presented for studying the response to kinesthetic and auditory inputs. A second two-segment planar arm has been presented elsewhere (Hemami & Dariush, 2010; Hemami & Dariush, 2012; Hemami, Clymer, & Hemami, 2012) to test models of the spinal circuits in force control (Hemami & Dariush, 2010), of spinal and motor circuits (Hemami & Dariush, 2012) and of central pattern generators and the basal ganglia (Hemami, Clymer, & Hemami, 2012; Hemami & Moussavi, 2014). This model is used here for reproducing alphabet symbols as seen by a vision system, and is also extended to three-link, three-dimensional arm models (Hemami, Clymer, & Hemami, 2012; Che, 2012) for the same purposes.

The dynamics, control, and stability of the three-link rigid body model are presented in Che (2012) and Hemami and Zheng (2012). The model is flexible and modular, and can be expanded to include more segments, actuators, sensory and CNS components for coordinated motion or in response to external auditory, visual and tactile commands.

Briefly, the first link represents the two legs held tightly together. The second link represents the two thighs held together. The third link represents the hip, the torso, the upper limbs, the neck and the head. Methods of deriving the equations of motion are discussed elsewhere (Hemami & Wyman, 2012; Hemami & Zheng, 2012). Rhythmic performance of the system, in response to periodic motion of a platform is digitally simulated. The same can be extended to audio induced motion provided that the system is supplemented by an ear-like device that imitates the human processing of music by the ear, and detects the rhythm. Subsequently central pattern generators follow the rhythms and are coupled to the muscular system of the body through the mechanisms of the spinal cord and above.

1.1 Applications of the Model

There are several applications of the model in various fields and disciplines. In dance, two or more people engage in coordinated movements that are performed under distributed control. In solo danc-ing, the interaction is primarily with a stationary environment (Jalics, Hemami, & Clymer, 1997; Jalics, Hemami, Clymer, & Groff, 1997). Interaction of humans with inanimate stationary or moving objects merit separate treat-ment (Narendra, 1978; Vidyasagar, 1993). In surfing, both the human and the environment are moving. In drawing figures, the arm moves but the environment is stationery. The presentation here emphasizes an integrated point of view of all three (Youcef-Toumi, 1996). This integrated point of view is useful in formulating the dynamics, in computer simulation and animation (Hodgins & Raibert, 1990; Lee & Shin, 1999; Hodgins, 1996) of natural and artificial systems, and in modeling humanoid, robotic and marionette systems (Hodgins, 1996) that are comprised of systems of connected rigid bodies. Other applications in assistive devices (Snyder & Kazerooni, 1996) and crash simulation systems can be cited. Another important application of this approach is in the realm of miniaturized elec-tromechanical systems where mechanical components, electrical drives, instrumentation, computational units and interfaces are densely packaged in small spaces. As robots, manipulators, and probes become smaller (Tanimoto, Arai, Fukuda, & Negoro, 1999; Arai, Sugiyama, Fukuda, Iwata, & Itoigawa, 1999) and more self-contained, the need for this kind of physical and mathematical integration increases. Application in sport activities involve jump-ing (Hemami & Utkin, 2002; Hemami & Wyman, 2012), landing (Zheng & Hemami, 1984), collision, and contact with the environment (Hemami & Wyman, 979). Medical applications are used for articulating structure, function and comparative studies (Iqbal & Roy, 2009; Humphrey, Hemami, Barin, & Krishnamurthy, 2010; Humphrey & Hemami, 2010). They also allow quantitative study of sensory and processing deficits in stability and balance both for healthy and injured humans. Postural adjustments are used to keep balance ranging from a pure ankle strategy to a pure hip strategy (Nashner & McCollum, 1985; Horak & Nashner, 1986; Shupert, Horak, & Black, 1994). It is often necessary to measure movement of the center of gravity and the center of pressure (Pai & Patton, 1997; Jian, Winter, Ishac, & Gilchrist, 1993). Diagnostic applications of such tests are reported (Mauritz, Dichgans, & Huf-schmidt, 1979; Mauritz, Dietz, & Haller, 1980). Postural adjustments in voluntary limb movements are discussed in (Nashner & Cordo, 1981; Friedli, Hallett, & Simon, 1984). Application to patients with vestibular deficits is cited in Nashner, Black, and Wall (1982).

Regarding behavior of the healthy and the injured on a platform, the interaction can be represented exactly in the equations of motion. The three-dimensional three-link system subject to horizontal platform disturbance, formulated in this paper, can be used for such purposes. A procedure is applied for stability of such systems in the absence of any disturbance. In its simplest form, this system can be used for testing and implementation of conjectures and hypotheses regarding the workings of the CNS in dealing with such disturbances. This means digital computer simulations can be undertaken with this system to emulate and imitate human postural maneuvers under platform disturbance. In order to make the formulation, and the computer simulations more relevant, one may additionally impose joint structure and constraints to limit the range of certain angles, i.e., some states. One may have to include sufficient stiffness and vary it in order to prevent the system from unacceptable behavior. One objective may be to assess the effect of the disturbance, both analytically and computationally at all the joints, and see the effect of joint structure on the postural strategy selected in balance maintenance.

The input to the arm system is the recording of the motion via a vision system, for example (Dariush et al., 2009). The output of the system is a similar or duplicate motion by the end point of the arm in the sagittal plane. More complex cases would be a human or robot imitating an observed human movement.

The processing is intended to ultimately imitate neural processing and transmission in the CNS or those of standard artificial neural network design methods such as presented in Behera, Gopal, and Chaudhury (1996). When signals with a large dynamic range are involved, either of two options are available:

1. The signals are normalized to maximum amplitude of unity, and a gain factor is attached to the signal as a tag or associate memory.
2. The signal is transformed to a pulse frequency modulated signal where a larger amplitude can be represented by a higher frequency. A special case involves storage and transmission of gains that may have a large dynamic range.

The first task is recording the observed motion, and specifying the desired end point trajectories in the external inertial space. In turn, these trajectories should be processed to derive the desired angular trajectories of the arm and forearm. For an elbow application for prosthesis, see Haj and Hogan (1990).

One may consider two separate central mechanisms for producing the desired angular input trajectories (Hemami & Dariush, 2010) to this system.

1. Recall of some normalized trajectories from memory, and processing them to accommodate the size and speed of movement i.e., speeding or slowing these trajectories in time to fit the desired speed and size of motion (Brooks, 1986, Chapter 7).
2. Producing the desired trajectories in a pattern generator, Wang and Alkon (1993) from a set of parameters that are associated with the maneuver of interest.

The first method involves learning methods of the CNS (Kandel, 1967) and will be the subject of a separate study. One main reason is that, according to Kandel (1967), learning is not accomplished by specifying new connections in the brain, but, instead, is implemented by increasing or decreasing the functional efficacy of previously existing connections. It is also worthwhile to direct attention to Fig. 19 of the same article where several mechanisms for information storage in the CNS are proposed, and by which, functional efficacy is demonstrated in several different ways. A simple interpretation of Kandel's observation is to equate functional efficacy with gain.

Only the second method is considered here, namely, that the trajectories of a planar maneuver are visually observed, recorded in memory and used for controlling the end point of the two-link system to produce the same trajectory - the main differences being the speed of motion and the size of the maneuver in comparison with the recorded movement. Specifically we shall consider the letter 'P' from the alphabet. Only the trajectory of motion is of interest.

We assume that we can extract the trajectory of motion as two independent functions of time in an inertial $x - y$ plane as two functions of time $x(t)$ and $y(t)$. These signals are scaled down (i.e., normalized) to a sufficiently low level so that the maximum values of both coordinates are less than unity.It follows that there are four scaling problems (Brooks, 1986, chapter 7) involved here.

1. The scaling for the observed signals so that regardless of the size of the observed trajectory, the neural signals are limited in amplitude to satisfy the magnitude constraint of the neural signal. This means the plane in the striate cortex where these signals are stored is a square such that the coordinates of all neurons in the square have amplitudes between zero and one.
2. The time scaling that involves speeding up the stored motion or slowing it down to fit the requirement of the abilities of the two- link system in order to be able to execute the movement with ease (Georgopoulos, Kalaska, & Massey, 1981).

3. The constraint of the size of the executed maneuver. If the maneuver is very small, and it is to be executed by the hand only a finger could be involved. If the maneuver is larger, the wrist and possibly the elbow could be involved. For a still larger maneuver, the shoulder and possibly trunk movement could also be involved. This aspect of the dynamics of the maneuver merits separate and independent investigation along the lines of Evart's contributions in the area of selective attention (Evarts, Shinoda, & Wise, 1984). This subject is not pursued further here.

4. The present design does not limit the range of any gains.

There are four notable advantages of the method espoused here. First, larger modules of systems of rigid bodies can be constructed from the dynamics of smaller sub modules (Hemami & Zheng, 2012; Hemami & Wyman, 2012). Second, forces of constraint, contact, and connection can be left in the dynamics and computed or eliminated (Hemami, Clymer, & Hemami, 2012; Hemami & Utkin, 2015). Third, passive structures (such as ligaments, cartilages and cups in living systems) that can maintain connection constraints can be included (Hemami & Hemami, 2014). Finally, the interface of the system with higher centers of communication and control is relatively easy to implement (Hemami & Moussavi, 2014; Hemami & Dariush, 2012; Li, Hemami, & Che, 2013; Hemami & Utkin, 2015).

There is another dimension of complexity that will not be considered here, namely, contact of all sort with the environment such as pushing on an external object while the the motion takes place (Evarts, Shinoda, & Wise, 1984, Chapter 3) and rubbing a surface (Laroussi, Hemami, & Goddard, 1988; Hemami, Wongchaisuwat, & Brinker, 1987; Buchner, Hines, & Hemami, 1988). In this class of problems, the end effector moves on a pre-specified trajectory and the forces of contact have to be simultaneously controlled.

In section , the three-link and the two-link systems are presented. Kinetic input in the form of platform motion and the response to the platform motion are considered in section . Visual input and the arm response are considered in section . Auditory input exciting coordinated rhythmic motion is considered in section . Discussion and conclusions are presented in section . Appendix, and references follow.

2. The Dynamics and Control

2.1 The Three-Link System

The dynamics of the three-link rigid body system, shown in Figure 1, is presented in Hemami and Zheng (2012); Hemami and Wyman (2012). More detailed information information about the dynamics of three-dimensional systems is presented in Hemami (2002); Hemami, Dariush, and Barin (2005).

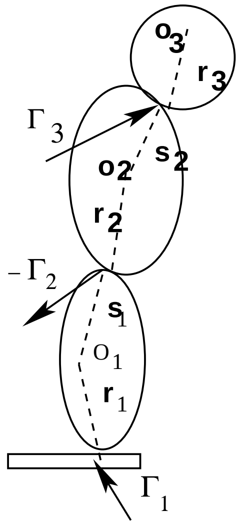

Figure 1. The Three-link humanoid on a mobile platform

Stability is achieved by the simultaneous co-activation of agonist - antagonist pairs of muscles at least by three pairs at every joint (Hogan, 1984). In the sagittal plane, five pair of actuators are proposed corresponding to the action of three pairs at the joints and two pairs of bi-articulate pairs across the leg and across the thigh. This activation results in the 9×9 positive definite matrices of position and velocity control. These matrices have been approximated from the muscular levels of excitation in the sagittal plane, and Hooke's law. For simplicity, the feedback structures are taken to be the same for the frontal and medial planes. From the stability point of view, these gain matrices can be derived by pole assignment (Hemami, Barin, & Pai, 2006). One may also use Lyapunov stability to estimate the region of stability (Hemami, 2002; Hemami & Utkin, 2002).

The humanoid could interact dynamically with a stationary environment, such as in running, walking or pushing on a surface (Hemami & Dariush, 2010; Mergner, 2010). A two-humanoid dance, similar to human dancing would entail activity with distributed control between the two systems. Interactions with a surf board, or platform would entail coupling of two systems but the control would be limited to the humanoid. Alternatively, the platform could be moving by forces and actuators that are not under control of the humanoid, and his control strategies may or may not be effective or adequate for certain platform or surf board maneuvers. We consider the latter case here in more detail, when the platform is subjected to deliberate periodic motion. We further assume that the size of the platform is large enough so that the motion of the platform is independent of what the humanoid does. This implies that the platform motion can be a priori and independently defined. Thus, the dynamics of the platform and the humanoid can be reduced to the dynamics of the humanoid and the kinematics of the platform. Therefore the acceleration vector of the point of contact of the humanoid with the platform is the input to the humanoid system to which the humanoid would respond.

A more general case of the above argument is to specify the acceleration of the platform, and integrate it twice with respect to time to arrive at its velocity and position.

The derivation of the forces of support follows the well-established procedure of Hemami and Wyman (1979, 1980) except that the kinematics of the platform motion replace its dynamics, and the position, velocity, and acceleration of the platform enter the equations of motion. We only consider horizontal translational acceleration in the sagittal plane. Further, we assume that the contact of the foot with the platform is maintained, i.e., the humanoid does not slip or leave the surface of the platform.

2.2 The Two-link Planar System

The planar system is considered in detail in Golliday Jr and Hemami (1976). The two-link sagittal limb that represents the arm-forearm system is shown in Figure 2. It is attached to a fixed inertial reference frame (ics). The state variables of this system are the vector Θ of the angular positions of the links with respect to the vertical line, and the angular velocity vector $\dot{\Theta}$. The inputs to the system are the two torques (or couples) applied at the shoulder and elbow joints of the arm.

$$\Theta = [\theta_1, \theta_2]'; \tag{1}$$

and let the input vector U be

$$U = [u_1, u_2]^T. \tag{2}$$

$$J(\Theta)\ddot{\Theta} + B(\Theta), \dot{\Theta}) + G(\Theta) = EU, \tag{3}$$

The robot arm is actuated with two torque generators at the joints (Golliday Jr & Hemami, 1976). The physical parameters of the robot are given in the Appendix. The robot can draw circles, semi-circles and a straight lines (Hemami & Dariush, 2010). The central control problem has been formulated with pattern generators (Wang & Alkon, 1993; Bay & Hemami, 1987; Wang, 2003). We will not consider issues of scaling for the amplitudes and the speed of motion here. The speeding up of the writing or slowing the motion down can be implemented by contraction or expansion of the trajectories of motion in time. The magnitude scaling is a more complex issue in natural systems and may involve attention sets (Evarts, 1975) and other issues (Brooks, 1986).

The block diagram of the system is shown in Figure 2. We consider a very primitive binocular vision system that maps the planar maneuver onto a planar sheet of neurons on the striate cortex where the local 's' type of neurons detect local motion of the cell in a particular direction (Zeki, 1976; Poggio, 1980). Suppose all the neurons that fire due to the maneuver of the object are registered by reading their coordinates along two orthogonal axes x and y as time progresses, and these 'normalized' coordinate values are registered in two storage media similar to "last - in - first - out" stacks. We assume the size of the maneuver is separately observed by recording the up and down and right and left angles of the excursion of the eyeballs (Messing & Durgin, 2005). The size information is separately associated with the object and its maneuver in an associate memory.

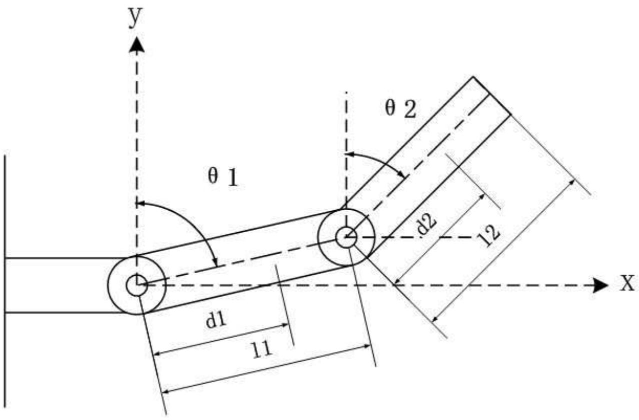

Figure 2. The two link system

This information is transferred to the pre-striate cortex where it can be tapped for the execution of the maneuver. There are two steps necessary to transform these normalized trajectories. The first step is to select the “set” based on the size of the intended movement. Once the set is selected, the desired angular trajectories of all the limbs involved in the movement should be computed. With each normalized desired angle signal, an additional gain parameter is attached that represents the constant gain number for that signal. Alternatively, the signals must be represented by pulse modulated signals where the instantaneous frequency, perhaps ranging from 1 to 100, will represent a corresponding dynamic range.

Once all the angular trajectories are defined, the second step is to scale the latter signals for the speed of movement; a slower than the recorded rate of storage of these signals will stretch the trajectories in time and slow down the movement. A faster reading out of these signals from the sequential storage will speed up the execution of the movement. These time - scalings do not affect the amplitudes of these angular signals that are limited to the range of zero and one.

The next step is to code these signals for transmission from, perhaps the basal ganglia, to the motor neurons. The gain and the normalized signal are input to a modulator that converts the absolute instantaneous strength of the signal to a frequency that is transmitted to the motor neurons. This is one rational for “repetitive firing. At the motor neuron, a short time integrator, with respect to time, converts the instantaneous frequency to amplitudes. Alternatively, a second stage of modulation may be needed to carry the frequency modulated signals to the muscles where the frequency will be converted to amplitude intensity.

3. Response to Platform Motion

We assume the humanoid is standing on a horizontal platform in a somewhat relaxed state:

$$\Theta = [0, 0.1, 0, 0, -0.1, 0, 0, 0.1, 0]^T \tag{4}$$

The superscript ^{T} means transpose, and this vector of angles implies a slightly forward leg, a slightly backward thigh and a slightly forward torso. The platform is moved back and forth a distance of about 10 centimeters repeatedly in a periodic fashion. The acceleration, velocity and position of the base of support are shown in Figure 3.

It is assumed that the main objective of the humanoid is to not lose balance. The strategy is to use a forward torso motion and backward leg and thigh motion to keep the center of gravity under the point of contact. If the humanoid had feet, the strategy would be to keep the center of gravity under the foot, or, alternatively said, within the base of support. Therefore centrally generated desired sagittal angles of the leg, thigh, and torso are input to the musculo-skeletal dynamics.

The thigh angle remains at zero in this particular case. The one period central sagittal angles are shown in Figure 4. The periodic sequence of these angles by a central pattern generator are shown in Figure 5.

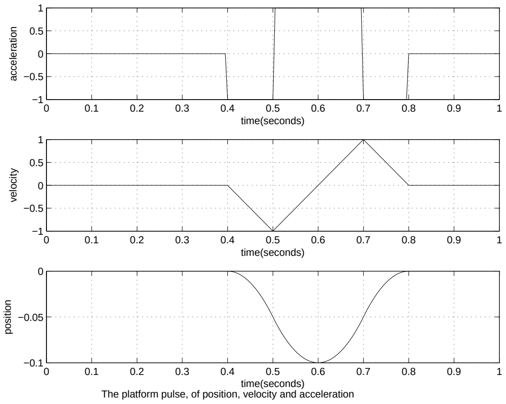

Figure 3. One cycle of the acceleration, velocity and position of the base of support due to platform movement

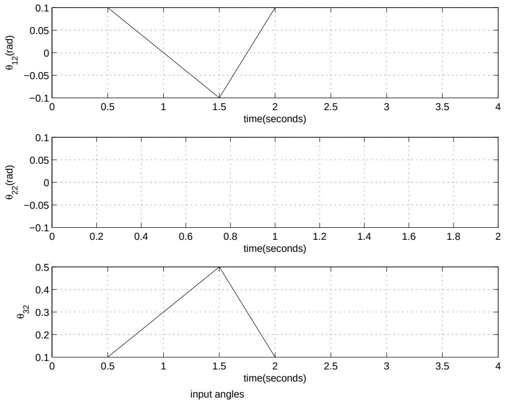

Figure 4. One cycle of the centrally generated ramp-like signals to maintain balance; the angles are for leg, thigh and the torso

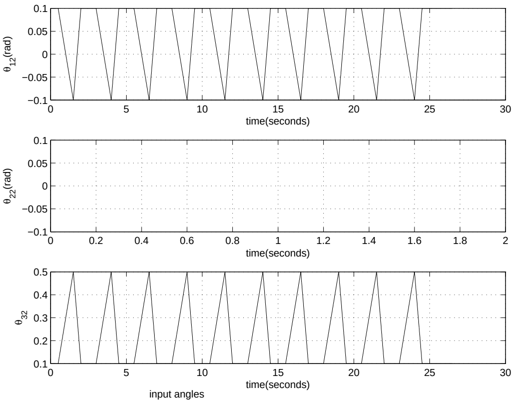

Figure 5. Ten cycles of the centrally generated ramp-like signals to maintain balance generated by central pattern generators

The humanoid maintains balance as shown in Figure 6. The periodic phase plane trajectory of the horizontal excursions of the center of gravity is displayed.

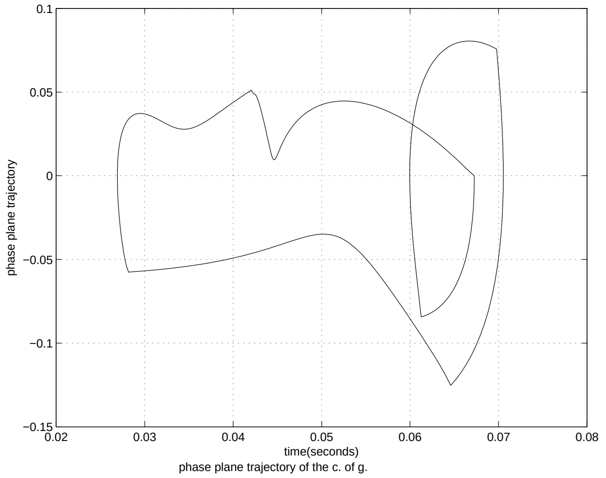

Figure 6. Periodic phase plane trajectory of the center of gravity

The periodic motion of the sagittal angles and angular velocities of the humanoid are shown in Figure 7.

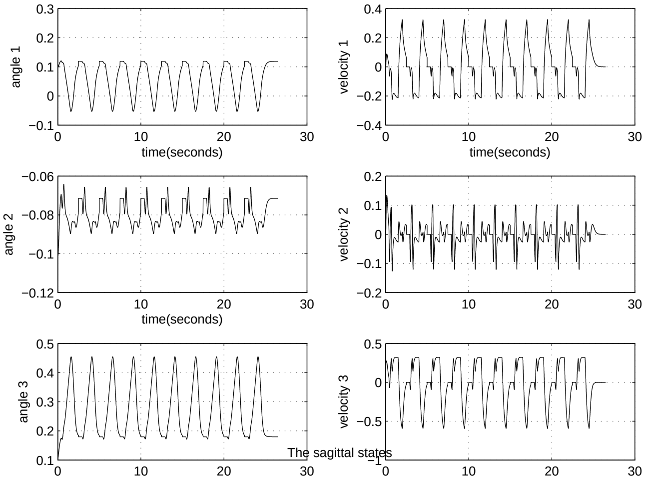

Figure 7. The periodic response of the humanoid in the sagittal plane; the three angles and the three angular velocities are shown for 10 cycles

In order to make sure that the movement is a natural human movement, the knee and the hip angles are monitored and shown in Figure 8. The figure shows both angles remain positive. This means the knee and the hip do not bend backwards. In other words, both angles are in natural range.

4. Response to Visual Input

We consider a two- segment sagittal arm that responds to and imitates the observed motion (Dariush et al., 2009). The input to the system is the recording of the motion via a vision system imitating human observation, and storage of the motion in a brain-like environment. The output of the system is a similar or duplicatemotion by the end point of the arm in the sagittal plane.

A simple control strategy is proposed and applied to the nonlinear model of the two-link sagittal arm. The central controller produces, via nominal trajectory generators, reference signals which are the desired angular positions

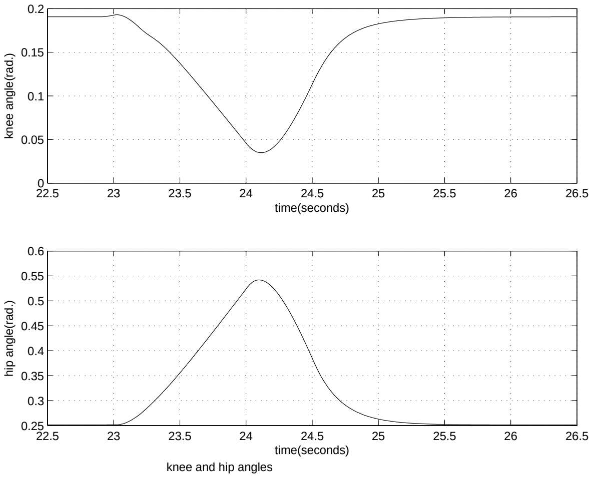

Figure 8. The knee and hip angles for one cycle; both angles remain positive, so that the natural constraints are maintained

and velocities. The basic tenet of the control strategy is the use of high gain state-feedback control, which imitates the effect of agonist-antagonist co-activation in natural systems. The method of generating basic stroke trajectories such as line segments and circular arcs is indispensable in writing a letter of the alphabet: P, that involves line and circle strokes. The simulation shows the effectiveness of the strategy. A tentative approach to generating a set of reference signals of handwriting from human beings would be desirable for the extention of this work. The control strategy proposed here to stabilize the system is by using the state-feedback control.

The plant model could be linearized around the equilibrium point and techniques such as pole placement or linear quadratic regulator (LQR) be used to find the feedback gains. Due to the high nonlinearity of the reference signals, it is difficult to use this method to deal with the error in the tracking problem. Instead, larger position feedback gains are used here to get smaller steady-state error.

In order to write alphabets in the two-dimensional space, each letter is decomposed into several basic strokes. For the simplest case to write alphabetical and numerical characters, there are two basic strokes: circular arcs and line segments. Since circular arcs are segment of the circumference of circles, the trajectories of circles could be derived at first and then the desired circular arcs could be acquired by adjusting the drawing time duration. If a constant speed is used to write all the time, it would require large initial and final effort.

Alternatively, a quadratic function is a desirable choice since intuitively, the desired velocity increases gradually. A time interval between the beginning and the end is used with a constant speed. The physical parameters of the arm are given in the Appendix.

The first segment is anchored to the origin and angles Θ_1 and Θ_2 are the angles with the vertical axis. The robot arm is actuated with two torque generators at the joints (Golliday Jr & Hemami, 1976). The physical parameters of the robot are given in the Appendix. The robot can draw circles, semi-circles and a straight lines (Hemami & Dariush, 2010). The central control problem has been formulated with pattern generators (Wang & Alkon, 1993; Bay & Hemami, 1987; Wang, 2003). We will not consider issues of scaling for the amplitudes and the speed of motion here. The speed of the writing can be implemented by contraction or expansion of the trajectories of motion in time. The magnitude scaling is a more complex issue in natural systems and may involve attention sets (Evarts, 1975) and other issues (Brooks, 1986).

The block diagram of the simulated system is shown in Figure 9.

The drawing of a specific circle is shown in Figure 10. The circle and the trajectories of the two robot angles Θ_1 and Θ_2 are also shown.

Finally the trajectories of the robot angles and the resulting letter *P* are shown in Figure 10.

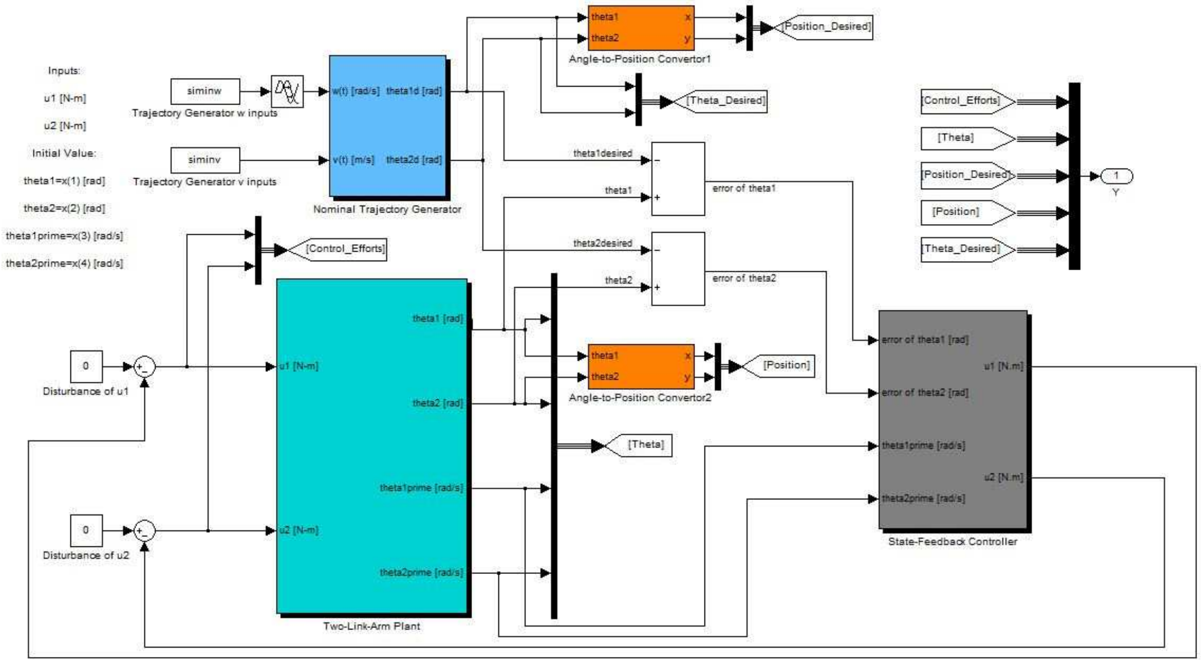

Figure 9. The block diagram of the two-segment arm control

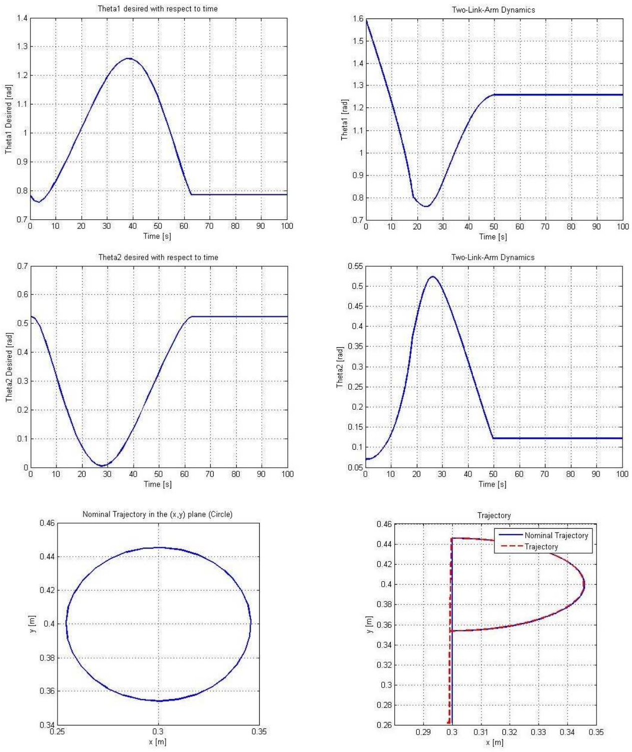

Figure 10. The angular trajectories for drawing a circle and the resulting output circle; The angular trajectories and the resulting letter P

5. Response to Auditory Input

This simulation involves audio processing, a pattern generator to produce rhythmic squatting commands for all actuators, and a three link model that, under coactivation, rhythmically squats with the music. The processing unit converts audio signals into beats using a filterbank analysis of the signal (Scheirer, 1998). The beats drive the pattern generator. The outputs of the pattern generator drive the three link model. The three link model performs a periodic squatting movement.

A percussive sound file was used as the input signal to the audio processor. The signal waveform is shown in Figure 11.

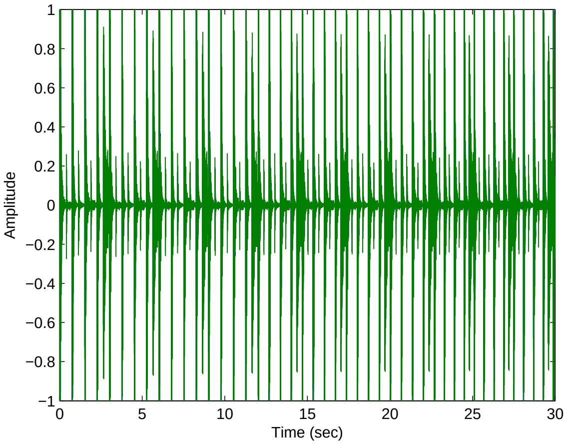

Figure 11. Waveform of input sound file

The input signal was processed to detect transients that occurred across frequencies indicating ’beats’ in the signal. Briefly the processing is as follows:

- The original signal was divided into frequency bands using a logarithmic filter bank.
- The envelope in each of the frequency bands was calculated using half-wave rectification and low-pass filtering.
- Large changes in the signal were detected by a first-order discrete differentiator with respect to time.
- Each of the discrete derivative signals was half-wave rectified because only large increases and not decreases were relevant.
- The rectified derivative signals in each frequency band were summed together to create a signal where large amplitudes indicate the time when there were transients that occurred across a wide frequency range.
- A threshold was selected for the summed signal to indicate when a transient occurred for the synthesis part of the system.

The summed signal is shown in Figure 12 along with a dotted line to indicate the chosen threshold.

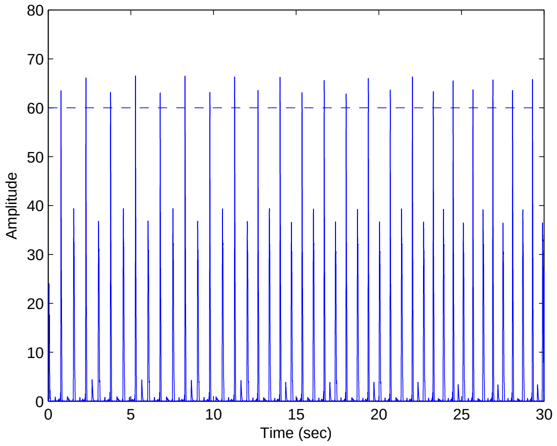

Figure 12. Summed envelope signal across frequency bands

The synthesis section, i.e., the pattern generator, triggers motion in the three link model by using each detected ’beat’ to generate signals as the necessary angular inputs to the model. The input signals are initialized such that the model is ‘at rest’ and in the steady-state balanced position shown in Eq. 4. When the summed envelope signal is above the chosen threshold, each of the angular input signals ‘ramp on’ and ‘ramp off’ to initiate a squatting motion in the model. Short segments of the angular input signals are shown in Figure 13.

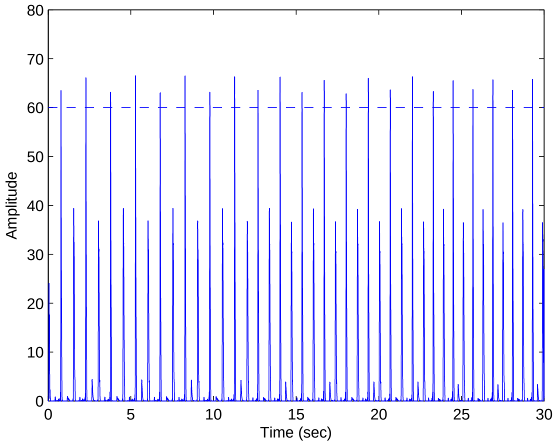

Figure 13. Angular input signals to the three-link model

The angular input signals were fed to the three-link model system, and the output responses were recorded. The result is shown in Figure 14 - the squatting motion.

6. Conclusion

A three-dimensional humanoid model was subjected to three experiments. Under kinesthetic periodic inputs, the system was able to maintain balance. A simpler model was used to respond to visual inputs and implement slow and careful writing of letters from the alphabet. The computer simulations demonstrate the stable behavior of the humanoid and confirm the control structure proposed. The alphabet writing system could be expanded to include free hand writing, drawing and perhaps entailing the chaotic, unregulated or randomness that in involved. A third experiment implemented a rhythmic response of the humanoid to auditory signals that excited an internal pattern generator.

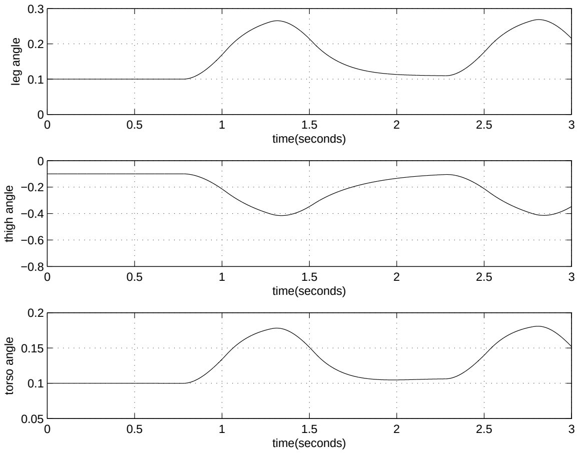

Figure 14. Output response of the 3-link model due to audio input signals

The model could be expanded to have more limbs and perform more human-like movement. It could be expanded to multiple humanoid models that could be endowed with a common brain or a common central controller. Such a multi-humanoid could produce new movements, dances and rhythmic movements that are not possible presently for more than two human beings. Hence, a whole plethora of computer produced art becomes possible.

The models could be used to test a variety of hypotheses about how the central nervous system works, and its different components are inter-related in any particular task, mission or maneuver (Maurer, Mergner, & Peterka, 2006).

With a more comprehensive neuro- musculo- skeletal system, three dimensional viewing(Dariush et al., 2009) and availability of projections, the model could be used in teaching anatomy, physiology, sport (Sheets & Hubbard, 2008) medicine, and the design of compensatory or supportive prostheses.

The methodology above can be extended to audio induced motion provided that the system is supplemented by an ear-like device that imitate the human processing of musicby the ear, and extracts the pitch. Subsequently, central pattern generators that follow the rhythms could be coupled to the muscular system of the body through the mechanisms of the spinal cord and the lower brain.

It is shown that, a computational framework can be constructed that deals realistically with the physiological, anatomical and neural constraints of the human body. The dynamics of the skeletal system and its interaction with the CNS and the muscular system were formulated. The system was stabilized by muscular feedback alone. The interactions and the behavior were confirmed by digital computer simulations. No effort was devoted to optimize the model, or to tune its parameters to correspond to an exact human movement.

Effects of all physiological constraints were not taken into consideration. Future work must additionally take into consideration the three-dimensional case, and the whole body and involvement of actual muscles rather than abstract torque actuators at the joints as well as the selection and identification of the involved “set” as elaborated by Evarts. Finally, the dynamics of the controller must be improved to correspond to the mechanisms and algorithms of the CNS and physiologically-based motor control.

Appendix: Physical parameters and gains

The physical parameters of the humanoid are given in Table 1.

Consider the three-link sagittal biped with three pairs of muscle-like actuators crossing single joints, and a pairs of two-joint muscles. One pair is analogous to the rectus femoris, hamstrings pair that spans the thigh. The other pair spans the leg. The latter pair is analogous to the Gastrocnemius and part of the Tibialis anterior that controls thigh motion. The assumption made here is that when the ankle strategy is in effect, $\theta_1 = \theta_2$, and hence, the Tibialis, under this condition, shares part of the thigh load. When the pair of muscles is co-activated, the net effect is the production of a torque at that joint. Following the development in (Hemami, Barin, & Pai, 2006), the stiffness of

Table 1. Definition, Numerical values for the three segments rigid body.

Segment	mass	Dim. 1	Dim. 2	Moments of I1	I2	I3
symbol	*mi*	*ri*	*si*	i_1	i_2	i_3
leg	5	-0.27	0.24	0.2411,	0.21,	0.567
thigh	8	-0.25,	0.20	0.2963,	0.18.	0.1735
trunk	50	-0.28	0.28	2.35	0.900,	0.4570

the five pairs of actuators is taken to be

$$K = [500, 300, 300, 300, 300].$$

The velocity feedback matrix L is constructed by assuming that the diagonal $5x5$ matrix L is a fraction of the diagonal matrix K. The fraction is taken to be 0.25 here.

For the two-link system the physical parameters are:

$$l_1 = 0.28m$$

$$l_2 = 0.27m$$

$$m_1 = 8.00Kg$$

$$j_1 = 0.90Kg - m^2$$

$$m_2 = 4.00Kg$$

$$j_2 = 0.11Kg - m^2$$

$$c.g_1 = 0.18m$$

$$c.g_2 = 0.2m$$

The feedback gains are

$$K = \begin{bmatrix} 97602.23 & 19016.22 & 83.8151 & 16.3495 \\ 24234.77 & 6295.40 & 18.1214 & 9.5964 \end{bmatrix}. \tag{5}$$

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