A Model for Human Posture Regulation

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Introduction

A properly designed biomechanics model and its computer implementation can help us understand how humans control their muscles to generate movements and how their muscles, joints, and ligaments interact during motor activity. Such a model could also be used to compute the joint forces and torques from knowledge of the external forces and limb trajectories.

- Proprioceptors
- Visual
- Vestibular
- Overall

Sensory System

- Muscle Strength
- Disease State
- Age
- Height
- Weight

Physical State

Measure Postural Sway

Postural Control

- Center of Pressure
- Mass
- Ankle Joint Angle

- LQR Control
- Effect of Delay
- (P/PD/PID)
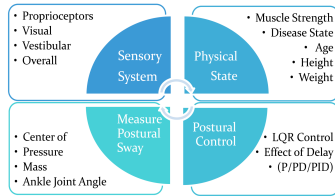
This inverse solution could provide insight into the joint reaction forces and the muscle activities at each joint. It would be particularly useful for clinical tests on humans as they perform motor tasks. This model could aid in the clinical diagnosis and treatment of motor control disorders, and the development of functional electrical stimulation for lost motor function recovery.

Dynamical Model

In this work, we present a computational model of a quietly standing human which uses three rigid and connected segments to represent the foot, leg (locked knee), and torso. This two joint, three segment model is controlled by torques on the ankle and hip joints is depicted in the figure below.

We first derived the basic equations of motion using the Euler-Lagrange method

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\phi}_1}\right) - \frac{\partial \mathcal{L}}{\partial \phi_1} = u_{ankle}$$

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\phi}_2}\right) - \frac{\partial \mathcal{L}}{\partial \phi_2} = u_{hip}$$

$$\mathcal{L} = \mathcal{K} - \mathcal{P}$$

$$\mathcal{K} = \frac{1}{2}\sum_{i=1}^{3}[I_i\dot{\phi}_i^2 + m_i(\dot{x}_i^2 + \dot{y}_i^2)]$$

$$\mathcal{P} = \sum_{i=1}^{3}gm_iy_i$$

K is the sum of the rotational and translational kinetic energy and P is the total potential energy (due to gravity). K and P can be written in terms of only the joint angles. It is then a simple exercise to write the dynamical equations for the system..
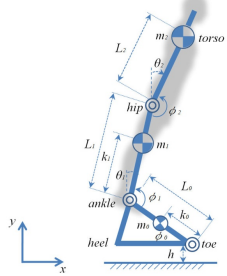
Figure. The model is composed of 3 rigid links. This is the simplest situation in which the coordination of the controls at multiple joints can be studied.

Nonlinear Optimal Control

Since the body dynamics during standing have been demonstrated to be well-approximated by a linear model for small perturbations, we linearise the double inverted pendulum model around the unstable equilibrium point and also define the small angular deviations from the vertical equilibrium.

$$\begin{pmatrix} \phi_1 \\ \phi_2 \\ u_{ankle} \\ u_{hip} \end{pmatrix} = \begin{pmatrix} \phi_1^* \\ \phi_2^* \\ u_{ankle}^* \\ u_{hip}^* \end{pmatrix} + \begin{pmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \Delta u_{ankle} \\ \Delta u_{hip} \end{pmatrix}$$

It is useful to convert this to a dimensionless model. This makes it easier to apply the model to a variety of humans having different height, weight, moments of inertia. We then introduce the state space variables and develop dynamics in the form and

$$\dot{\underline{z}} = A\underline{z} + B\underline{u}$$

$$\underline{z} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} \Delta\phi_1 \\ \Delta\phi_2 \\ \frac{d}{dt}(\Delta\phi_1) \\ \frac{d}{dt}(\Delta\phi_2) \end{bmatrix} \quad A = \begin{bmatrix} 0_{2\times 2} & I_{2\times 2} \\ \beta^2(\frac{Q}{ML^2})^{-1}\frac{F}{ML^2} & 0_{2\times 2} \end{bmatrix}$$

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \Delta u_{ankle} \\ \Delta u_{hip} \end{bmatrix} \quad B = \begin{bmatrix} 0_{2\times 2} \\ \frac{\beta^2}{ML^2}(\frac{Q}{ML^2})^{-1} \end{bmatrix}$$

We propose the hypothesis that the cost for state error is quartic or some higher even power. Note that this performance measure minimizes the actuator energy used by allowing small postural errors to be minimally corrected. This finite time problem involves a convex performance measure and a linear system.

Min $\quad \sum_{i=1}^{4}\sum_{n=0}^{N} d_i z_i^{2p}[k] + \sum_{n=0}^{N} d_5 u_1^{2q}[k] + d_6 u_2^{2q}[k]$

Subject to $\quad \underline{z}[k+1] = \bar{A}\underline{z}[k] + \bar{B}\underline{u}[k]$

Define $\quad \underline{s} = [\underline{z}(0), \underline{u}(0), \underline{z}(1), \underline{u}(1), \ldots, \underline{z}(N), \underline{u}(N)]^T$

The Newton-KKT method is a good choice for solving this problem. The key step is the repeated solution of the following system of linear equations involving the gradient and the Hessian.

$$\begin{bmatrix} \nabla^2 J(\underline{s}^{(i)}) & A_s^T \\ A_s & O \end{bmatrix} \begin{bmatrix} \triangle\underline{s}_{nt}^{(i)} \\ \underline{w} \end{bmatrix} = \begin{bmatrix} -\nabla J(\underline{s}^{(i)}) \\ O \end{bmatrix}$$

The designed system includes a Kalman filter as a state estimator. Delay in actuator and sensor feedback is also considered.
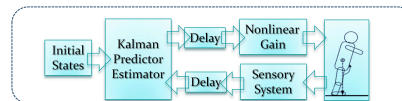
Results

We have successfully solved the constrained nonlinear optimal control problem using the method described before. We demonstrate that the proposed control could automatically adjust and coordinate different balance strategies according to the state information and the disturbance level.
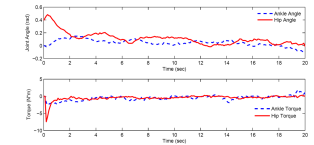
Ankle Strategy

ANKLE STRATEGY SIMULATION PARAMETERS

p	2	$z_1[0]$	$\frac{\pi}{8}$ rad
q	2	$z_2[0]$	$\frac{\pi}{800}$ rad
d_1	80	$z_3[0]$	$\frac{\pi}{16}$ rad/sec
d_2	350	$z_4[0]$	$\frac{\pi}{1600}$ rad/sec
d_3	100	$u_1[0]$	$0\,Nm$
d_4	200	$u_2[0]$	$0\,Nm$
d_5	1	$\|\epsilon\|$	0.01
d_6	1	$\|v\|$	0.01
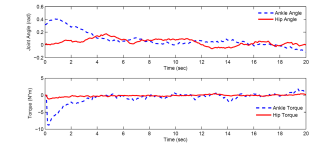
Hip Strategy

HIP STRATEGY SIMULATION PARAMETERS

p	2	$z_1[0]$	$\frac{\pi}{800}$ rad
q	2	$z_2[0]$	$\frac{\pi}{8}$ rad
d_1	350	$z_3[0]$	$\frac{\pi}{1600}$ rad/sec
d_2	80	$z_4[0]$	$\frac{\pi}{16}$ rad/sec
d_3	200	$u_1[0]$	$0\,Nm$
d_4	100	$u_2[0]$	$0\,Nm$
d_5	1	$\|\epsilon\|$	0.01
d_6	1	$\|v\|$	0.01

Ankle + Hip Coordination

PARAMETER FOR ANKLE HIP COORDINATION STRATEGY DURING BALANCE MAINTENANCE

p	2	$z_1[0]$	$\frac{\pi}{800}$ rad
q	2	$z_2[0]$	$\frac{\pi}{8}$ rad
d_1	350	$z_3[0]$	$\frac{\pi}{1600}$ rad/sec
d_2	350	$z_4[0]$	$\frac{\pi}{1600}$ rad/sec
d_3	200	$u_1[0]$	$0\,Nm$
d_4	200	$u_2[0]$	$0\,Nm$
d_5	1	$\|\epsilon\|$	0.01 and 0.1
d_6	1	$\|v\|$	0.01 and 0.1
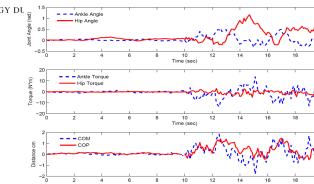
When the disturbance increases, bending the hip creates an additional restoring torque to help maintain a stable posture. Still, the hip torque is relatively low and the hip angular sway relatively large. Note the hip motions needs to be complementary to the angle motion in order to keep the COP close to the middle of foot.

Conclusion

The work reported here suggests a reasonable hypothesis about the fundamentals of motor control. In reality, all the states are measured but with significant delays. It is clear from our model that a state predictor must be included in the feedback loop. We are presently performing additional simulations using our model to more fully understand its implications regarding coordination of muscles in posture regulation. We are also working on neuronal implementations of Kalman filters and Luenberger observers using realistic models for neurons rather than those in studies of neural networks.