SYNTHESIZING THE SIT-TO-STAND MOVEMENT USING FUZZY LOGIC AND A SIMPLE BIOMECHANICAL MODEL

Robert K Prinz[1], Stephen W Neville[2], Nigel J Livingston[3]
[1]CanAssist, [2]Department of Electrical and Computer Engineering, [3]CanAssist, University of Victoria, Victoria, CA

ABSTRACT

In this paper, the sit-to-stand movement was artificially reproduced using a fuzzy-logic based control strategy and a simple biomechanical model. Not for the purpose of exactly replicating a healthy individual's movement, but rather for the purpose of directing an assistive device which might guide the mobility impaired individual through the sit-to-stand process. An explicit set of movement trajectories was not used in the movement planning process; instead, stability and goal-driven controllers provided the necessary motion directive. This approach resulted in a slow and controlled sit-to-stand movement.

INTRODUCTION

Sit-to-stand is simply the movement from a seated to standing position. It is regarded as one of the most mechanically demanding tasks undertaken during daily activities, and is generally accepted as a prerequisite for gait [1,2]. The biomechanical model employed in this work is one commonly used in sit-to-stand analysis (see Figure 1). It is a system of three rigid bodies (representing the shank, thigh, and HAT) articulated by three revolute joints (representing the ankle, knee, and hip) for a total of three degrees of freedom. Revolute actuators are present at each joint, and it is the goal of this work to find the set of joint torques required at each instance in time which yields a slow and controlled sit-to-stand movement.

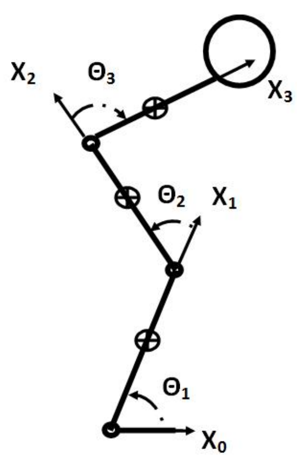

Figure 1. The biomechanical model employed.

Typically, the movement planning process for a system of rigid bodies (such as a robot manipulator) is two-part: 1) establish a set of trajectories which guide the mechanism from its current configuration to the desired one, and 2) develop a trajectory following control scheme. An alternative approach involves developing a series of simple (possibly linear) controllers for each stable point of operation. In the context of sit-to-stand, the stable points of operation are the extents of the movement - namely quiet sitting and quiet standing. An interpolating function or weighting scheme is then used to combine the control actions dictated by each of these controllers to form a single control directive valid over the course of the movement [3,4].

Fuzzy logic-based control is appealing because it does not require a predefined set of trajectories be established. Instead, "expert knowledge" of the movement task is stored in the controller's rule base. The difficulty then is: i) to find the best set of rules which encapsulate the desired controller response to each possible input combination, and ii) accurately describe controller input and output values using membership functions [5].

METHOD

Anatomical features, such as link lengths and inertial properties, were calculated using the methods proposed by Winter [6]. Frames of reference were attached to each body segment with the X-axis being aligned along the length of the body. Joint angles were defined using the right-hand-rule convention (i.e., counter-clockwise is positive going).

It was assumed that: i) an accurate measure of joint angle and joint angular velocity was available in real-time, and ii) a highly accurate estimate of gravitational loading effects (on the joints) could be known. A sampling frequency of 25 Hz was used.

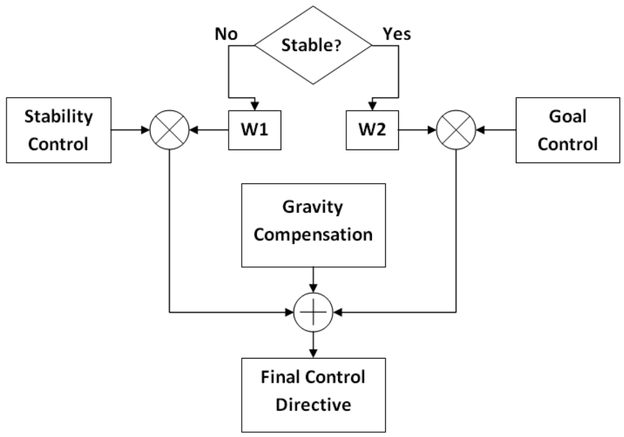

Figure 2. Control system overview.

CONTROLLER DESIGN

Two controllers were designed: i) one which motioned the model toward the next most stable region of operation with only minor regard to the goal configuration of the model, and ii) the other which motioned the model toward the goal configuration. A simple weighting scheme was used to combine the two controller outputs. The stability controller directive was weighted more heavily in regions of greater instability, while the goal-driven controller directive was weighted more heavily as stability was achieved. This weighted sum was then combined with a gravity compensation action to form the final control action. A high-level block diagram of the control system is provided in Figure 2.

<u>Stability Controller</u>

The stability controller uses center of mass estimates to bring the model into a region of stability. For purposes of simulation the center of mass of each rigid body is assumed to be located at its midpoint. This serves as a close approximation to the true location found using Winter's methods.

The center of mass (or center of gravity) of the whole-body composite object is represented by P_{cog123}. A vector can be drawn from the base of support (BoS) at the ankle to P_{cog123}. The orientation of this vector Θ_{cog123} and its rate of change ω_{cog123} are interpreted by a fuzzy inference system to give a measure of "closeness" to the stable configuration of the model

$$u_{cog123} = f(\Theta_{cog123}, \omega_{cog123}) \quad (1)$$

where u_{cog123} represents the sign and degree (a value existing on the range [0 1]) of the action required to bring the full body composite object to rest at its desired orientation, and *f*() is a fuzzy logic-based proportional-derivative controller. The degree of stability, represented by μ_{cog123}, is therefore

$$\mu_{cog123} = | u_{cog123} | \quad (2)$$

which again exists on the range [0 1]. Since the ankle is collocated at the base of support (BoS), its control action was intimately linked to the stability of the entire model, but it was also influenced by the desire to come to rest at the shank's goal orientation (represented by the control action u_{ank_goal})

$$u_{ank\_goal} = f(\Theta_1, \omega_1) \quad (3)$$

$$u_{stab(ank)} = u_{cog123} + (1 - u_{cog123}) \cdot u_{ank\_goal}$$

where ω_1 is the angular velocity of the shank, and $u_{stab(ank)}$ is the ankle control action (sign and degree) dictated by the stability controller.

Both the knee and hip stability control actions were linked to the orientation and movement of the thigh-HAT composite object. The controller must dictate whether or not to alter the orientation and movement of the thigh-HAT composite or rather hold it in place. The equations associated with the thigh-HAT composite are

$$u_{cog23\_hold} = f(\Theta_{cog23}, \omega_{cog23}) \quad (4)$$

$$u_{cog23\_move} = f(\Theta_{cog123}, \Theta_{cog23}, \omega_1, \omega_{cog23})$$

$$\mu_{cog23\_move} = | u_{cog23\_move} |$$

$$\mu_{cog23\_hold} = 1 - \mu_{cog23\_move}$$

where u_{cog23_hold} is the control action associated with maintaining the current thigh-HAT composite orientation, u_{cog23_move} the control action associated with altering its orientation or motion, and μ_{cog23_x} the degree to which the corresponding action is to be performed. The knee control action was formed as

$$u_{stab(knee)} = \mu_{cog23\_hold} \cdot u_{cog23\_hold} + u_{cog23\_move} \quad (5)$$

and

$$u_{HAT\_hold} = f(\Theta_3, \omega_3) \quad (6)$$

$$u_{HAT\_move} = f(\Theta_{123}, u_{cog23\_move}, \omega_{123})$$

$$u_{stab(hip)} = \mu_{cog23\_hold} \cdot u_{HAT\_hold} + u_{HAT\_move}$$

(where Θ_{123} is the orientation of the HAT with respect to X_0 and ω_{123} the associated angular velocity), dictates the hip control action $u_{stab(hip)}$.

Goal Controller

The goal controller moves the model into the goal configuration as directly as possible. This is accomplished by advancing both the model's center of gravity and the joint angles toward their respective goal configuration values. The model must be actuated at varying rates in order to achieve the desired effect. This effect was determined using a simple linear objective function of the form

$$f_{obj} = w_{cog} \cdot d\Theta_{cog123} + w_{\Theta} \cdot d\Theta \qquad (7)$$

where w_{cog} is the weight given to advancing the model's center of mass, $d\Theta_{cog123}$ is the change in Θ_{cog123} due to variations in joint angle, w_{Θ} is the weight associated with advancing the joint angles toward their individual goals, and $d\Theta$ the change in joint angle values with respect to the goal configuration.

The joint angles were slightly perturbed from their current configuration at each step of the simulation. Every possible combination of perturbation ([flex, hold, extend] the ankle, knee, and hip) was considered. Each set of joint perturbations represented an action sequence. Using the objective function in (7), all possible action sequences were scored. The two highest-scoring action sequences were averaged together to form u_{obj}. $|u_{obj}|$ essentially provides a relative scaling of "how much", or rather the degree to which, a particular joint should be advanced toward its goal position.

Ankle control was directly linked to the action associated with moving the whole-body into its goal configuration

$$u_{goal(ank)} = u_{cog123} \qquad (8)$$

Proportional-derivative control was used to control joint position. This was implemented using a two-input, single output fuzzy logic controller

$$u_{\Theta x} = f(\Theta_x, \omega_x) \qquad (9)$$

where $u_{\Theta x}$ is the joint positioning control action associated with joint x.

If $u_{obj}(x)$ was in favor of advancing joint x toward its goal configuration value, then

$$u_{goal(x)} = \mu_{cog123} \cdot \mu_{obj} \cdot u_{\Theta x} + (1 - \mu_{cog123}) \cdot u_{\Theta x} \qquad (10)$$

otherwise

$$u_{goal(x)} = \mu_{cog123} \cdot u_{x\_hold} + (1 - \mu_{cog123}) \cdot u_{\Theta x} \qquad (10)$$

where $\mu_{obj} = |u_{obj}|$ is the degree to which a particular joint should be advanced toward its goal position.

The final control action is a weighted sum of the stability and goal controllers

$$u = u_{grav} + \mu_{cog123} \cdot \mu_{stab} + (1 - \mu_{cog123}) \cdot u_{goal} \qquad (11)$$

RESULTS

The simulation was run at 25 Hz for 12 seconds. Table 1 includes some final simulation results of interest. Snapshots of the simulation as the model progressed through the sit-to-stand movement are included in Figure 3. Figure 4 compares joint angle plots of the simulation against those generated using motion capture data collected from a single healthy male subject. The Vicon optical tracking system was used to collect this data. The path traversed by the center of mass is also included in the figure.

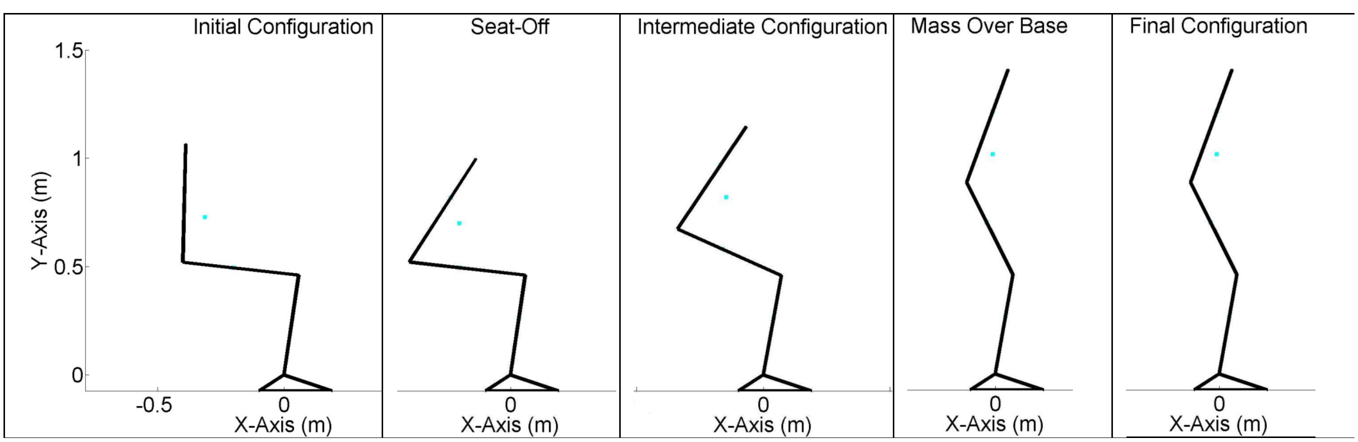

Figure 3. Sit-to-stand simulation snapshots. (Left to right) i) quiet sitting ii) seat-off iii) an intermediary configuration during vertical ascension iv) center of mass over base of support v) quiet standing.

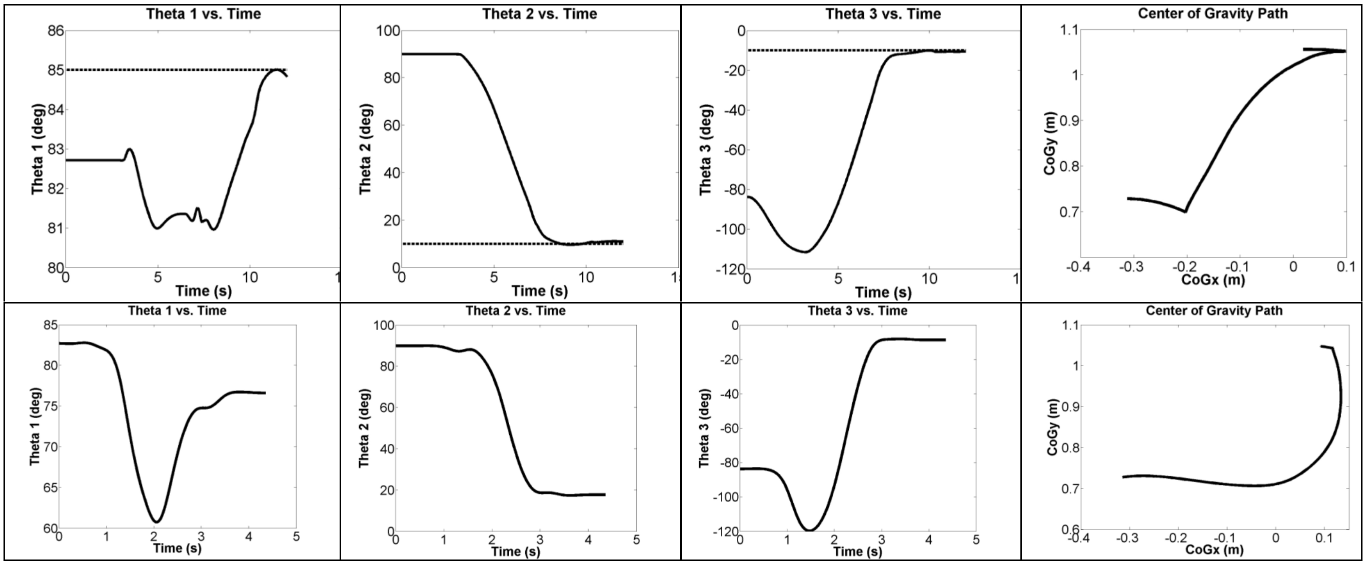

Figure 4. (Top row) Simulation results. (Left to right) i) ankle joint plot ii) knee joint plot iii) hip joint plot iv) center of mass path through space. (Bottom row) Motion capture trial results in the same order.

Table 1: Final Simulation Results

	Θ_{Err} (deg)	ω_{joint} (deg/s)	ω_{body} (deg/s)	$\Theta_{cog123Err}$ (deg)
ankle/shank	0.1525	-0.6342	-0.5097	
knee/thigh	-0.9691	-0.3697	-1.0542	-1.5967
hip/HAT	0.6170	0.3387	-0.6056	

DISCUSSION

It can be seen from Table 1 that the model very nearly reaches the desired goal configuration (each joint to within 1 degree) and that it has essentially come to rest (relative joint motion to within 0.65 deg/s and absolute body motion to approximately 1.0 deg/s or less).

Looking at the joint angle plots in Figure 4, it can be seen that the knee and hip joint angles progressed in very much the same manner in both the simulation and motion capture trial. The ankle joint angle however progressed quite differently. The movement about the ankle in the simulation was much more rigid and constricted than that of the motion capture trial - an observation worth noting, but not a particularly bad result in itself. From the center of mass plots of the same figure, it can be seen that vertical ascension began far earlier in the sit-to-stand cycle of the simulation than it did in the motion capture trial. This likely indicates that more work was done by the joint actuators in the simulated model than by the able-bodied test subject.

The limited number of degrees of freedom in the upper body portion of the biomechanical model (i.e., zero) is evident in the center of mass path plot for the simulation case. But despite the simplicity of the model, a close approximation to the sit-to-stand movement resulted. The control scheme put forward in this work has merit in terms of bringing artificial intelligence to an assistive mobility device.

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