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Effects of stance width on control gain in standing balance

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Abstract— **Standing in a wide stance during a lateral perturbation is considered to be easier than standing in a narrow stance, but the basis for this ease of stance is not understood. To study the effects of increased stance width in balance control, we created a standing model of a cat with variable stance width and subjected it to lateral displacement perturbations. We studied balance control while varying postural orientation and control parameters that are not accessible in a biological cat. We determined that delayed feedback in the postural controller necessitates the reduction of active feedback gain as stance width increases from narrow to wide stance. By establishing the change in control requirements in a system that resembles a biological configuration, we can predict that similar control changes may occur in biological systems.**

I. INTRODUCTION

BALANCE control is an important function for the life and survival of animals of all different sizes, shapes, and configurations. The mechanisms of balance control must work to maintain balance across a wide range of postural configurations. In general, balance control comes from the rejection of disturbances to posture. The mechanism of rejection is the generation of a force to counteract the disturbance. This force may come from an active muscle response or the passive viscoelestic properties of the physical system or body. The magnitude of the required force response is heavily dependent on the perturbation and shape and orientation of the body. Together, the passive viscoelestic properties and orientation of the body provide mechanical stability to reject some of the perturbation (Kubow and Full 1999). Active control may then be required to provide additional response and maintain a stable posture. A system with high mechanical stability may require less active response to perturbation than less stable one. An example of this is the difference in effort to stand with ones legs together vs. legs apart while on an accelerating train. Standing with legs apart is considered easier, but the implications on active control are not understood.

The active response to postural perturbation is the generation of corrective muscle activity. In humans and cats these postural responses can be described as a feedback control mechanism called the automatic postural response (APR) (Kuo 1995, Macpherson 1988a,b). This response can be based on the feedback of kinematic variables (Lockhart 2005). The magnitudes of these feedback responses are the products of the feedback variables and control gains.

Due to the redundancy of the musculoskeletal system, an animal may respond to postural perturbations using a number of different muscle combinations and activation patterns. The combination and pattern used (response strategy) may depend upon perturbation magnitude, postural orientation, fatigue, etc. Different strategies are used for a variety of postural conditions. A shift in response strategy has been observed in cats under changing stance length. As the cat shifts from a long stance to a short stance, the response shifts away from the force constraint strategy that limits the direction of force produced by each leg. This shift occurs gradually with decreasing stance indicating a scaling of the response with stance length (Macpherson 1994).

A similar effect of stance has been observed in humans under changing stance width. Increasing stance width shifts the perturbation response from an active strategy at narrow stance to a more passive strategy at wide stance. This trend is confirmed with EMG data showing reduced muscle activation with increasing stance width (Henry 2001).

Our study seeks to show that feedback gains are scaled due to changes in mechanical stability, particularly stance width. This result would help explain the decrease in EMG activity observed with increasing stance width. We developed a model system of postural control based on the physiology of a cat to help us understand the interaction between stance width and postural control. The model mimics the movement and activity of an automatic postural response to lateral displacement perturbations.

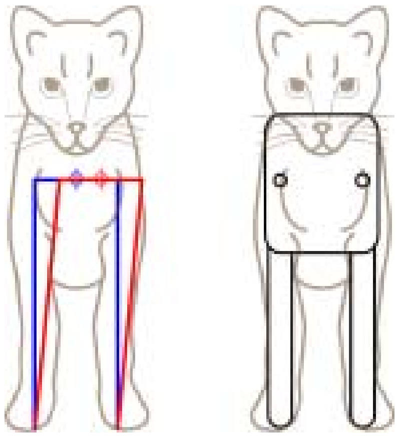

Fig. 1. The model mimics the movement of a cat subjected to lateral displacement perturbations. The response is based on feedback of the angle, velocity, and acceleration of each hip joint.

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II. MODEL DESIGN

A. Mechanics

Our system models the movement of a cat subjected to lateral perturbation. Active response is the generation of abduction/adduction torque at the hips and shoulders. Since the motion of the response is the same for the fore and aft halves of the cat, the model can be lumped to a single plane where the left and right legs of the model represent the fore/aft leg pairs of the cat. It is also assumed that the model has no foot slip and that there is minimal bending of the knees and ankles in response to perturbation. The motion of the model in response to lateral perturbation is that of a four bar linkage. The four bar linkage is a one degree of freedom system with an actuator on each hip. The two actuators affect the dynamics of the system differently due to the differences in the kinematics of each joint.

TABLE I
CONTROL VARIABLES AND RANGES

Symbol	Quantity	Values
S	Stance width	4.445(0°) - 8.89cm (30°)
L	Leg length	13.97cm
M	Mass	2 kg
D	Feedback delay	30 ms
g_a	Acceleration gain	0 N cm/rad/s^2
g_b	Velocity feedback gain	0.005 – 0.10 N m/rad/s 0.15 – 1.0 N m/rad/s
g_k	Position feedback gain	0.05 – 1.0 N m/rad/s 1.5 – 5.0 N m/rad/s

Perturbations were performed across a range of feedback gain values. Independent gain values were used for each mode of kinematic feedback. The subscript on each gain denotes mode to which the feedback was applied.

The dimensions of the model are based on established physiological measurements of a cat. Details of this configuration are listed (Table 1). Equations of motion describing the dynamics of the model were derived using Autolev software. The calculations were based on the four bar linkage system with the size and inertial properties of a cat. The control inputs for this model are torques applied at the hip joints.

CoM motion is determined by the torque of each joint, the angular configuration of the system, and the external perturbation.

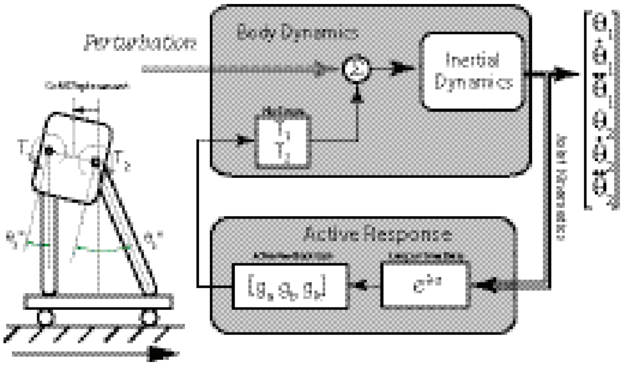
$$M\ddot{x} = f(\mathrm{T}_{\mathrm{lead}}, \mathrm{T}_{\mathrm{trail}}, \theta_{\mathrm{lead}}, \theta_{\mathrm{torso}}, \theta_{\mathrm{trail}}, \mathrm{Perturbation})$$

A. Control

Control of the system is based on a feedback model of automatic postural response. It generates torques at the hips in response to perturbations. The magnitude of the response is a function of feedback kinematics and control gains. The modes of kinematic feedback are joint angle, angular velocity, and angular acceleration. The kinematic data is passed directly to the controller with a 30 ms delay. This feedback delay replicates the transmission and activation delays of physiological systems.

A. Simulations

Simulations were run to determine the combinations of gains that produce stable operation of the system across the range of stance widths. Perturbations were simulated using a lateral acceleration waveform that was recorded from postural experiments and simulates a 20cm/s velocity step for 2cm.



$$\text{Torque Response} = g_a\ddot{\theta}_d + g_b\dot{\theta}_d + g_k\theta_d$$

Fig. 3. The model mimics the movement of a cat subjected to lateral displacement perturbations. The response is based on feedback of the angle, velocity, and acceleration of each hip joint.

We performed simulations across a range of gains that produce a visible response to perturbation. Input variables for each simulation included stance width, delay and the feedback gains for acceleration, velocity, and position feedback. For each stance the CoM was given an initial velocity and displacement of zero. The perturbation was applied at a time of 0.1s. The output of each trial was a time record of CoM position and velocity. Each trial was performed for a duration of 3.1s.

II. RESULTS AND ANALYSIS

Center of Mass (CoM) position, velocity, and acceleration traces were evaluated to determine stabilizing behavior. We broadly defined stability as the system coming to rest in an upright posture by the end of the simulation (3s).

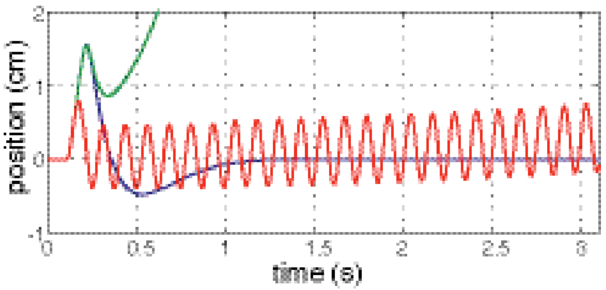


Fig. 2. Sample CoM traces for Stance 1
Insufficient response (green) occurs when feedback gains are below the stable region. A damped response (blue) occurs when the feedback gains are within the stable region. An oscillatory response occurs when gains are above the stable region.
Gain Values: trace color (velocity gain, position gain)
Green(0.05,0.25) Blue(0.08,0.8) Red(0.35,1.0)

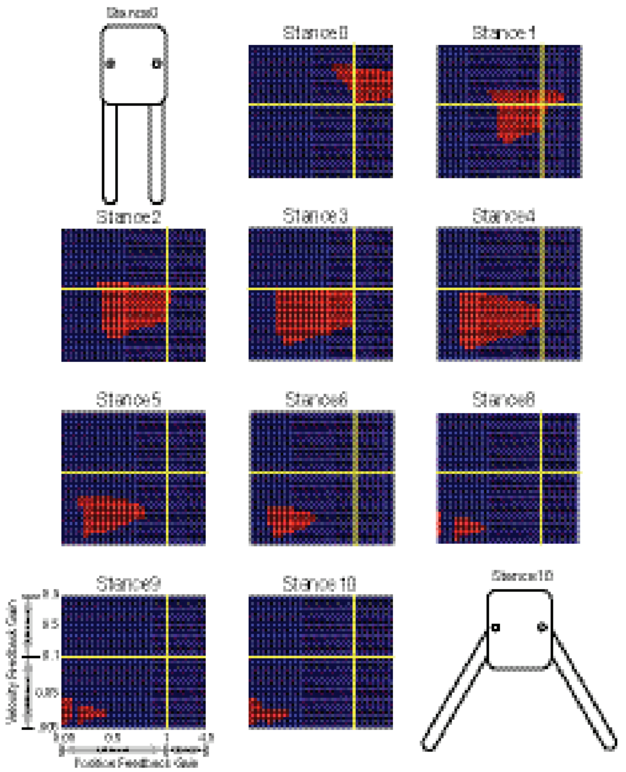


Fig. 4. Increasing stance width reduces the range and amplitude of stabilizing feedback gains in the delayed feedback model. In these plots, the red regions indicate stabilizing gain combinations for each stance width. The heavy gridlines indicate the regions of gain increment.

The range and magnitude of the control parameters that produced stabilizing behavior decreased as stance width increased. As stance increases from a narrow (0° leg angle) to wide stance of (30° leg angle), the average magnitude of stabilizing position and velocity feedback gains decreases by 93%.

The change in behavior with increasing stance width is the result of both increased passive stiffness and increased mechanical feedback gain. Passive stiffness is the ability of the uncontrolled mechanical system to resist displacement due to perturbation. As stance width increases, perturbation causes decreased displacement of the CoM (Figure 5). This increased resistance to displacement is one component of the system stiffness. The active feedback provides another component of stiffness that resists CoM displacement by resisting leg angle displacement. Mechanical feedback gain is the ratio of leg angle displacement to CoM displacement. As stance width increases, CoM displacement corresponds to greater leg angle displacement (Figure 6). The effect of this changing ratio is an increased response for CoM displacement at wide stance or increased stiffness.

With delays in the feedback control loop, these combined effects cause the controller response to excessive with higher gains and wide stance. This results in an unstable oscillatory response that limits the magnitude of stabilizing gains for any given stance width.

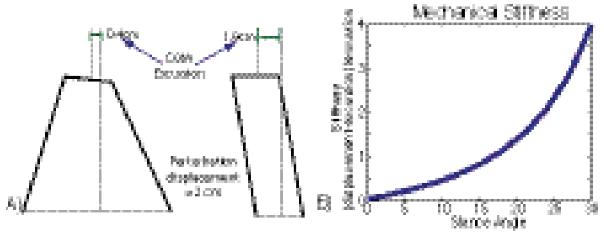


Fig. 5. Without active feedback, increasing stance width enables the system to resist CoM displacement when subjected to perturbation.
mech. stiffness=(perturbation – CoM excursion)/(CoM excursion)
Increasing stiffness decreases CoM excursion. With a stiffness of 0, CoM excursion = perturbation displacement

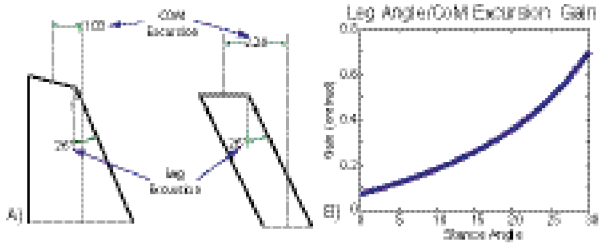


Fig. 6. The feedback model uses joint kinematics in the control loop. As stance width increases, CoM excursion results in a larger leg angle excursions and therefore larger control signals for CoM excursion.

III. CONCLUSIONS AND FUTURE WORK

Increasing stance width provides mechanical stability that helps to recover stable posture following lateral perturbation. Because of the stabilizing effects of increased stance width, there is a reduced requirement for active feedback control to compensate for the perturbation. Also, because of the unstable oscillations that occur with excess gain, the gains of delayed feedback control must be reduced with increased stance. Future studies using this model will investigate the influence of intrinsic non-delayed stiffness on postural control. We will also implement the control strategies developed with this model on a robotic cat.

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