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USING ZERO-MOMENT POINT TO SYNTHESIZE SUBJECT-SPECIFIC, TASK-LEVEL PREDICTIONS OF BALANCE RECOVERY WITH STEPPING

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INTRODUCTION

Falls are the leading cause of both fatal and nonfatal injuries in elderly people [1], resulting in approximately $31 billion in medical costs annually in the U.S. [2]. These injuries motivate balance control studies focused on identifying prevention strategies for reducing the number of fall events. Experimental methods provide data about subjects' kinematic response to a loss of balance. However, simulations can offer additional insights, and may be used to make predictions about functional outcomes of various interventions. To make these predictions, simulations require accurate musculoskeletal modeling and robust control-system architecture. Several approaches already exist in biomechanics to generate accurate models on a subject-by-subject basis. Moreover, roboticists have developed control systems approaches for humanoid robots simultaneously accomplishing multiple complex tasks, including balance recovery [3]. Predictive subject-specific simulations of balance recovery can be generated by synthesizing approaches from both fields of study and creating surrogate models of task-level coordination from experimental data.

Related to fall prevention, roboticists use the Zero-Moment Point (ZMP) concept [4] to maintain dynamic stability during inherently unstable tasks, such as stepping and gait. In human balance recovery, stepping is one of the primary reflexes used when it becomes impossible to keep the center of mass (CoM) over the base of support (BoS) [5]. The step(s) redefine the area of the BoS in the horizontal plane to maintain control of the CoM, thereby preventing a fall.

In this study, we investigated the potential of using the ZMP approach for simulating human balance recovery during single-leg stance in response to perturbations at the BoS. Specifically, we examined support surface perturbations large enough to destabilize the subject (and model) to the point of making it impossible to recover balance without stepping. Our goal was to determine whether the ZMP approach could control the task-level motion of the model to generate a predictive, closed-loop simulation of stepping response that matches the subject's own balance recovery.

METHODS

Experimental motion data was collected (female 25 yrs | 1.72 m | 68.0 kg) during perturbation from single-leg stance. An OpenSim [6] 3D model with 17 degrees of freedom was scaled to match the subject. Trials in which a step was necessary to recover balance after perturbation (anterior | 6 cm | 40 cm/s) were identified and inverse kinematics determined model kinematics by matching the recorded marker trajectories. Body kinematics determined the body segment center of mass positions during the motion. The experimental positions of the CoM, swing foot, and torso were represented by surrogate second-order polynomial response surfaces in the anterior, vertical, and lateral directions:

$$y_{task}^{desired} = b_0 + \sum_{i=1}^{2} b_i x_i + b_{12} x_1 x_2 + \sum_{i=1}^{2} b_{ii} x_i^2$$

where coefficients (b) are found to best fit the surface to the desired task (y) as a function of the center of mass horizontal position (x_1, x_2) (Fig. 1).

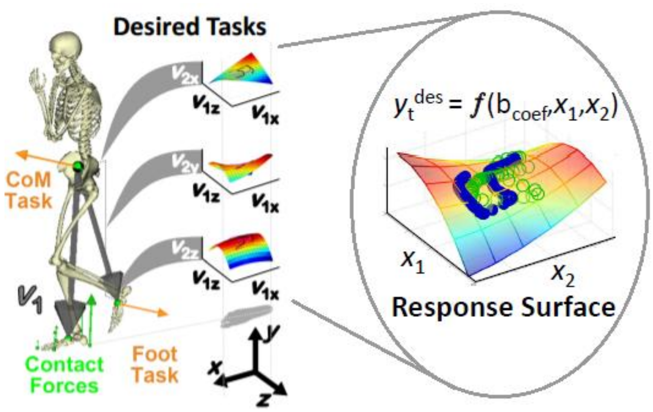

Figure 1: The operating spaces of each task were represented by response surfaces fit to the experimental data. Each response surface defined the region in 3D space that the desired task occupies over the course of the motion. This information provides a mathematical surrogate for subject-specific movement simulations.

Proportional-integral-derivative (PID) controllers were used to calculate the task vectors needed to move the model by reducing errors between surrogate response surfaces and predicted body kinematics. The CoM horizontal plane position was controlled to be above the ZMP position, while vertical position followed its surrogate response surface. ZMP position was calculated from residual forces and moments acting on the pelvis [7]:

$$[M_x \quad M_y \quad M_z]_{zmp} = M_{pelvis} + r_{pelvis} \times F_{pelvis}$$

$$[F_x \quad F_y \quad F_z]_{zmp} = F_{pelvis}$$

$$zmp_x = M_z/F_y$$

$$zmp_x = -M_x/F_y$$

where $M_{x,\,y,\,z}$ and $F_{x,\,y,\,z}$ are the ZMP moments and forces calculated from the residual moments (M_{pelvis}) and forces (F_{pelvis}) at the pelvis and the pelvis position (r_{pelvis}) in the ground frame.

Robotic control systems were used to generate prioritized joint torques necessary for synthesizing the subject-specific stepping response [3]. Tasks were prioritized as (1) CoM, (2) swing foot, and (3) posture. Subsequent tasks were limited to operate in the cumulative null space, $N_{prev(k)}$, of all previous tasks to prevent interference with higher priorities. The compound torque vector, Γ, used to move the joints to accomplish the tasks was calculated as follows:

$$\Gamma = \Gamma_{task(1)} + N^T_{task(1)}\left(\Gamma_{task(2)} + N^T_{task(2)}\left(\Gamma_{task(3)} + \cdots\right)\right)$$

$$N_{prev(k)} = I - \sum_{i=1}^{k=1} \bar{J}_{i|p(i)} J_{i|p(i)}$$

RESULTS AND DISCUSSION

The simulations resulted in a predicted stepping response to perturbation at the BoS (Fig. 2). CoM position was predicted well with the smallest RMS error (0.6 cm in the horizontal plane) among the 3 tasks. The ZMP control played a crucial role in the predicted CoM position. The largest RMS error (3.4 cm) was observed for the swing foot's vertical position, which undergoes the largest accelerations of the bodies during the stepping response. The redefined BoS stabilizes the model by enclosing the ZMP within new bounds (Fig. 3).

CONCLUSIONS

ZMP control with surrogate response surfaces is an effective approach for simulations predicting task-level stepping response during balance recovery. Future work will explore the role that ZMP trajectories play in decision making for stepping response during balance recovery and gait.

a

b

Root Mean Square Error (cm)			
Task	*Anterior*	*Vertical*	*Lateral*
Center of mass	0.6	1.3	0.6
Swing foot	2.0	3.4	2.0
Torso	0.8	1.5	1.4

Figure 2: (*a*) Comparison of experimental motion (*green*) and predictive simulation (*red*); (*b*) root-mean-square (RMS) error between experiment and predictive simulation.

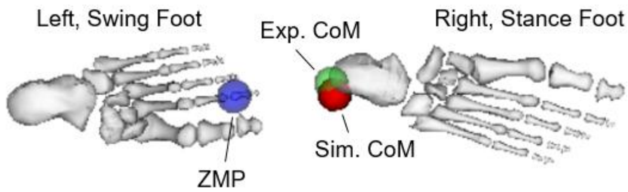

Figure 3: Locations of feet and points of interest just before double support. The perturbed model expands its original base of support (right, stance foot) by correctly predicting the backward step (left, swing foot) in the direction of ZMP movement (blue). The simulated CoM position (red) controlled by the ZMP approach predicts a movement consistent with the experimental CoM position (green).

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