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Identifying novel strategies for controlling step response during balance recovery simulations

Nicolas Vivaldi, Jeffrey Reinbolt
University of Tennessee, Knoxville, USA

Abstract

Introduction

Worldwide, falls cause 37.3 million hospital-related injuries and 646,000 fatalities yearly [1]. To reduce falls, coordinated balance recovery simulations may offer new insights, but they need to be controlled in a complex, variable environment (e.g., perturbation, decision making, step response) [2, 3]. Center of mass (CoM), extrapolated center of mass (xCoM) [4], and Zero-Moment Point (ZMP) [5] are well-known in biomechanics and robotics and may fill this control strategy gap. We aimed to identify relationships between these three measures and experimentally observed balance recovery to determine the best physiologically-consistent control strategy for simulations.

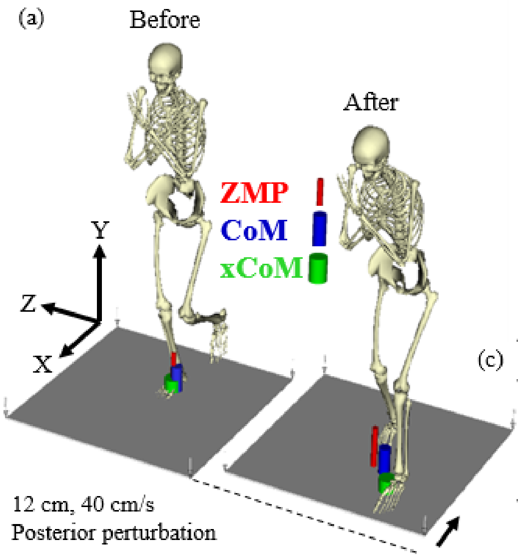
Methods

We collected experimental data (250 Hz) from 2 subjects (female 25 yrs | 1.72 m | 68.0 kg; male 25 yrs | 1.79 m | 84.5 kg) standing on one foot (Fig. 1a) during random anterior or posterior perturbation trials (6, 12 cm | 40 cm/s). We performed inverse kinematics, inverse dynamics, and body kinematics for each trial using OpenSim [5] and Matlab batch scripts. We calculated the ZMP using pelvis residual forces and moments and xCoM using an inverse pendulum model [4]. We fit polynomial models (ranging linear to quintic) to determine the best fit (using R-squared values) between the three biomechanical or robotic measures and balance recovery.

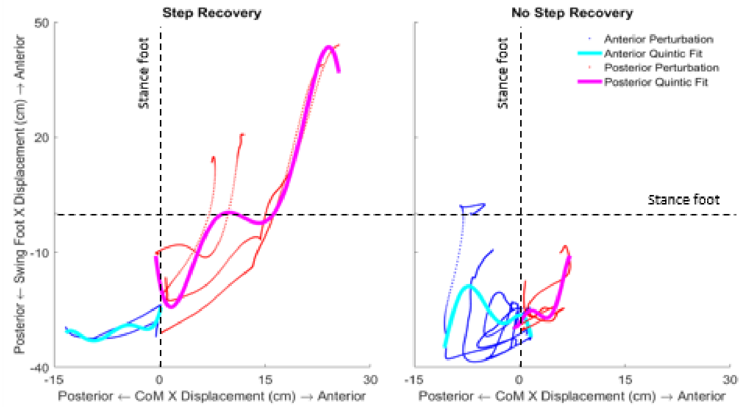
Results

A combination of biomechanical and robotic measures using higher degree polynomial models fit the experimental data better with higher R-squared values (Fig. 1b, c). The CoM allowed the best overall fit to the step recovery in the ±X-direction ($0.67 \leq R^2 \leq 0.71$). For posterior perturbations without stepping, the ZMP allowed best, but marginal, fit in the Z-direction ($R^2 = 0.21$). For anterior and posterior perturbations with stepping, the xCoM allowed the best fit for the Z-direction ($R^2 = 0.93$) and Y-direction ($R^2 = 0.25$).

(a)



(b)



(c)

Perturbation	*Recovery*	*Direction*	*Strategy*	*Model*				
				Linear	*Quadratic*	*Cubic*	*Quartic*	*Quintic*
Anterior	**Step**	**X**	**CoM**	0.44	0.54	0.54	0.61	0.67
		Y	**CoM**	0.04	0.21	0.46	0.46	0.47
		Z	**xCoM**	0.71	0.73	0.83	0.84	0.93
	No Step	**X**	**CoM**	0.02	0.08	0.14	0.17	0.18
		Y	**CoM**	0.71	0.74	0.75	0.81	0.82
		Z	**CoM**	0.58	0.67	0.67	0.70	0.70
Posterior	**Step**	**X**	**CoM**	0.58	0.61	0.64	0.65	0.71
		Y	**xCoM**	0.16	0.20	0.22	0.23	0.25
		Z	**CoM**	0.76	0.84	0.84	0.85	0.86
	No Step	**X**	**CoM**	0.37	0.47	0.59	0.59	0.61
		Y	**CoM**	0.75	0.77	0.81	0.82	0.82
		Z	**ZMP**	0.11	0.11	0.18	0.18	0.21

Fig. 1: (a) Depiction of before and after perturbation. CoM, xCoM, ZMP, and swing foot locations were reported as displacements from the stance foot. (b) CoM plotted against swing foot for X direction displacement. Data was separated by perturbation (anterior, posterior) and recovery (step, no step). Polynomial fits of order 1 to 5 were calculated for each control, perturbation, recovery, and direction and best fits (highest R-squared) are reported in (c).

Discussion

For generating simulations to study falls and fall-related injuries, we identified relationships using CoM, xCoM, and ZMP that may be used to control balance recovery simulations. Although one control strategy would be the simplest design, balance simulation is a complex, dynamic control problem that may benefit from hybrid control strategies using biomechanics and robotics measures. The stepping response can be controlled using the CoM (X-direction), xCoM (Y-direction), and ZMP (Z-direction); using other fits (sinusoidal, Fourier) did not change this control strategy ranking. In the future, we will apply hybrid controls to predictive simulations.

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