MODEL OF LATERAL STABILIZATION DURING ONE-LEGGED QUIET STANDING

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1 Motivation

It is challenging for humans to balance on one leg, in part because the stance foot can only exert limited torques on the ground. Balance therefore depends much more on motion of the other limbs, which can move the body center of mass (COM) only indirectly. Many can perform such one-legged balance with little conscious thought, but it is unclear which limbs should be moved and in what way to keep the body stabilized. Here we employ a simple balance model to examine how balance corrections might be coordinated.

2 State of the Art

Human balance has been modeled as inverted pendulums in both quiet standing and walking [1,2,3,4]. The key to balance corrections is inertia. Unlike the stance leg, body segments such as the torso, arms, and opposite leg cannot produce forces and torques against the ground. Their inertia must instead be used to affect the COM more indirectly. While previous models have included the trunk in the generation of feedback corrections, few have considered how multiple appendages should be coordinated for balance correction. Hence, we will use a multi-link model to study how feedback control should be distributed between the limbs.

3 Own Approach

We determine a simple control law for controlling balance through inertia and compare it against experimental observations of human balance. The control law helps to demonstrate that the seemingly complex nature of balancing can be distilled into dynamically sensible use of angular momentum by the limbs. A simple summary of the model prediction is that, if the COM is falling in a particular direction, all free appendages should be rotated in the same angular direction to correct balance.

The effect of rotating the appendages is to impart a reaction torque on the stance leg. This is because the angular momentum of the body about the stance foot must remain balanced with the effect of gravity. If the stance foot cannot slip on the ground, the reaction torque induces a ground reaction force directed against the fall, which therefore causes the body COM to be restored toward upright. We seek to demonstrate this with a simple multi-link model that includes a main pelvis mass atop an inverted pendulum stance leg, two generic appendages to represent the swing leg and trunk, and a momentum wheel on top of the trunk to represent arms. The appendages and momentum wheel may be moved to control balance. We assume the stance leg's ankle torque is small, and the only stabilization possible is from the appendages.

We developed linearized equations of motion for the model and used a Linear Quadratic Regulator (LQR) design to determine the gains that would deliver the stabilizing torques. LQR calculates the optimal gain matrix for a given weighting on the states of the system and on the control of the system. The state weighting favors stabilization of the body about an equilibrium, and the control weighting penalizes high effort. The gains from our control law will indicate how the limbs should move to stabilize the body. For the purposes of this demonstration, the actual values of feedback gains are immaterial, and we focus instead on the main direction of torque through the gain signs. To simulate spontaneous fluctuations as humans attempt to stand quietly on one leg, we introduced random process noise into the system to disturb the stance leg.

4 Current Results

The model yields a control law with gain signs that conform to our main prediction. The appendages use angular momentum to stabilize the body, and the torque exerted by the appendages should all be directed in the same direction as the angular displacement of the stance leg. For example, both torso and swing leg should be rotated counter-clockwise if the stance leg is perturbed in that direction.

We also empirically identified controller gains from 7 healthy adult subjects to compare model results to human behavior. Limb movements were captured using Xsens Inertial Measurement Units. Effective gains were estimated from a least squares fit between the appendage torques and the angles and angular velocities. The signs of the experimental gains matched the signs of the model gains, suggesting that humans indeed rotate their appendages in the same angular direction as their falling COM.

5 Best Possible Outcome

We demonstrated how appendages are rotated to aid balance but only through the signs of the controller gains. We also wish to examine model parameters necessary to match magnitudes of model gains to experiment. We hope to quantitatively identify a linear control law appropriate for describing one-legged balance.

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