Bipedal gait is stabilized through simultaneous control of whole-body linear and angular momentum

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Summary

Previous studies assumed that linear momentum of the body center of mass (CoM) is controlled through changing the position of the center of pressure (CoP) or the foot relative to the COM. Neither of these variables is mechanically related to changes in linear momentum, but both affect whole-body angular momentum (WBAM). In walking, linear and angular momentum follow quasi-periodic functions with similar periodicity and phase. For this case, the equations of linear and rotational motion show that horizontal distances between CoP and CoM correlate to horizontal forces in the corresponding directions. This suggests that linear and angular momentum are simultaneously controlled. We show that sagittal and transverse ground reaction forces and moments can be predicted from the preceding CoM state and WBAM. The consistent, good predictive models indicates that linear and angular momentum are simultaneously controlled.

Introduction

Previous studies on how gait is stabilized have considered control of linear momentum of the body center of mass (CoM) as a necessary condition for stable gait. The position of the center of pressure (CoP), or of the foot, relative to the CoM was often used as an indicator of corrections of the CoM state [1-3]. However, mechanically, neither of these variables is directly related to changes in the CoM state, or in other words to horizontal ground reaction forces (GRF). Instead, they do directly affect whole-body angular momentum (WBAM), which has also been suggested to be controlled in walking. We aimed to assess the validity of the CoP as a predictor of corrections of linear momentum of the CoM, and to assess if linear and angular momentum are simultaneously controlled.

Methods

We used previously published [4] data of 14 healthy adults walking on an instrumented treadmill at slow and normal speeds. For all trials, 200 gait cycles were analyzed. We estimated CoP locations from the GRF and CoM and WBAM time series from whole-body kinematics. Pearson's correlations between horizontal CoP to CoM distances and horizontal GRFs were calculated. Subsequently, data were normalized to stride time and predictive models were fit to the data to predict horizontal GRFs from preceding CoM position and velocity deviations from the averaged gait cycle. Similar models were fit to predict the moments of the GRF from preceding WBAM deviations from the averaged cycle.

Results

Linear and angular momentum followed quasi-periodic functions with similar periodicity and phase in the frontal and sagittal planes. The equations of linear and rotational motion for a system of linked rigid segments show that, in this case, the horizontal distance between CoP and CoM should negatively correlate with the horizontal GRFs in the corresponding directions. Experimental data confirmed this, with all correlations < -0.90.

The predictive models fitted showed that the preceding CoM state and WBAM predicted the ground reaction forces and moments along the sagittal and transverse axes, respectively. Model parameters were consistent between participants and gait speeds but differed between planes. Angular momentum appeared to be continuously controlled, while linear momentum control was phase-dependent with most correction occurring in early stance.

Discussion

The strong, negative correlation between CoP-CoM distance and horizontal force explains the success of previous studies using CoP location or foot placement as indicators of control of linear momentum. This correlation is the result of simultaneous control of whole-body angular momentum. Delay estimates obtained and previous literature indicate [4, 5] that linear and angular momentum control are achieved through passive dynamics and active feedback. The consistent, good fit of both predictive models indicates that these control processes can be identified in human walking.

References

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