Balance Stability Characteristics of Human Walking with Preferred, Fast, and Slow Speeds

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Abstract

This work presents a model-based method of evaluating and quantifying stability characteristics of human walking in the sagittal plane. The stability criteria used for this analysis are boundaries in the state space of the center of mass (COM), which represent the maximum capability of a human to maintain balance in single support (SS) and double support (DS) phases or to make a desired step without falling. Complete models of the system dynamics, biomechanical characteristics, its contact interaction with the ground, and gait parameters, are considered. Experimental human COM trajectories during walking are analyzed against computed stability boundaries to quantify the nature of human gait across walking speeds. Stability comparisons with other robotic platforms, an exoskeleton and a humanoid robot, are also provided.

Keywords: Balance Stability, Center-of-Mass State Space, Walking

Introduction

The definitions of stability states considered here (Peng et al., 2022) are with respect to a specific contact configuration (SS or DS balanced) or transition (steppable), where a balanced state is a state from which a given biped can maneuver such that its (SS or DS) contact can be indefinitely maintained and a steppable state is one from which a desired step is achievable before any undesired contact occurs (Figure 1).

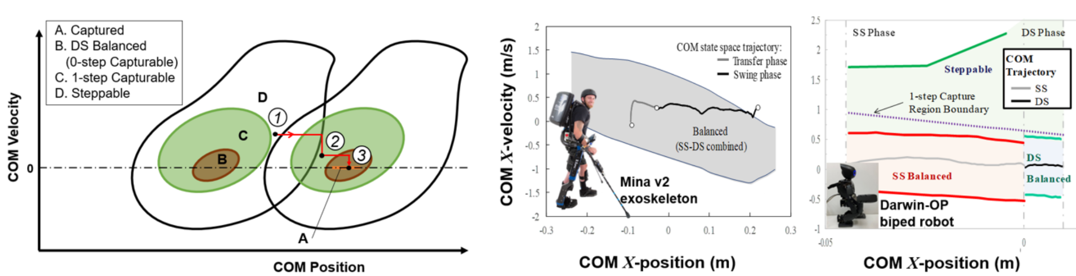

Figure 1. Schematics of general stability regions (left) and with mostly balanced walking trajectories of Mina v2 exoskeleton (Mummolo et al., 2018) (center) and DARwIn-OP robot (Peng et al., 2022) (right)

Methods

The stability boundaries are computed as the solutions to a series of constrained optimization problems subject to dynamics, system-specific (e.g., joint (Norkin & White, 2009) and torque (Anderson et al., 2007) limits), and region-specific (for consistency with the corresponding state definition) constraints evaluated at COM states along the given walking trajectory. Two healthy subjects of similar mass and height were recruited and provided informed consent for the walking experiments. The COM trajectories were obtained at 85% (slow), 100% (preferred), and 115% (fast) of their self-selected preferred walking speeds.

Results

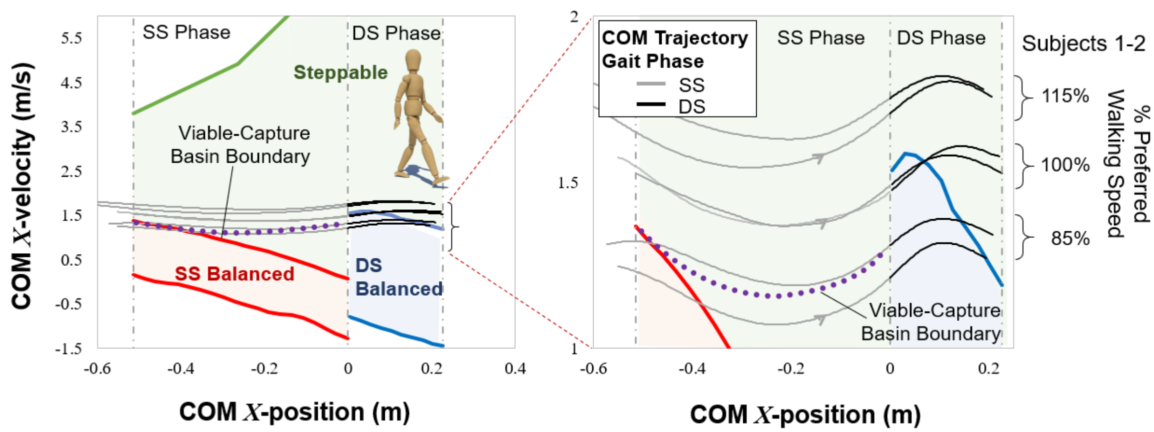

Figure 2. Experimental walking COM trajectories for two subjects. The human stability regions are shown for one subject, along with the viable-capture basin boundary for 1-step capturability (Peng & Kim, 2020).

Discussion and Conclusions

The results show that normal human walking at preferred, fast, and slow speeds is mostly unbalanced, with the exception of slow walking during the DS phase (Figure 2). For accurate comparison, each COM trajectory should be compared to the stability region corresponding to that COM trajectory. In this work, stability regions are only shown for the preferred walking speed of one human subject, due to the spatial similarity of the COM trajectories across walking speeds. For extremely slow speeds, the walking will be highly balanced, similar to that of robotic gait (Figure 1), as opposed to during extremely high speeds, when the walking will be highly unbalanced. This framework can be used for the analysis of gait impairment and the associated rehabilitation and for the design and control of powered lower-limb exoskeletons.

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