Comparative Analysis of Full-body Legged Stability Using Balanced and Steppable Regions

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***Abstract*—This work presents normalized criteria for the analysis of legged system stability based on balanced and steppable regions for comparative analysis between humanoid and human systems. The steppable, single support balanced, and double support balanced regions are evaluated for models with full-order system dynamics and joint actuation limits. The normalized regions are also compared with the capturability of an equivalent reduced-order model.**

I. INTRODUCTION

The emergence of *N*-step capturability as a center of mass (COM-) state space-based approach for the analysis of balance stability during walking [1] [2] inspired previous work towards a COM-state space-based and contact-specific definition of balance. According to that definition, the state of a legged system is balanced if and only if it can remain indefinitely within its specified contact (e.g., single support (SS) or double support (DS)) without having to change its original contact. Otherwise, the system is unbalanced. This boundary between the balanced and unbalanced region identifies a partition in COM-state space (COM position and velocity).

II. BALANCED AND STEPPABLE REGION FORMULATION

The steppability concept was proposed to explicitly consider the unbalanced regions of COM-state space. By augmenting the COM-state space with the swing foot position as an additional state, the unbalanced region can be further partitioned into steppable unbalanced and falling (i.e., neither steppable nor balanced) regions with respect to a given desired step length. States within the steppable region are able to achieve the desired step length given the kinematic and actuation limits of the legged system. These regions are not controller-specific and represent reachability for all possible controllers. The construction of the balanced and steppable regions can be formulated as a series of constrained optimization problems [3]. The full-body dynamics of the legged system are considered, including the complete angular momentum effect of each link (Fig. 1). For comparison between the biped robot and four human subjects, the COM *X*-position and velocity were normalized with the average COM *Y*-height and Froude number, respectively.

III. RESULTS AND DISCUSSION

Both SS and DS balanced regions lie within the 1-step capture region of an equivalent linear inverted pendulum model (LIPM) whose point foot is located at the front stance foot toe during DS (Fig. 1). All SS balanced states are 0-step capturable and thus 1-step capturable. By definition, all *N*-step capturable states must also be steppable. The DS balanced boundary approaches the 1-step capture region boundary at the end of the DS phase, suggesting that the balancing capability of the robot and human models are similar to the capturability of the equivalent LIPM at the end of a step.

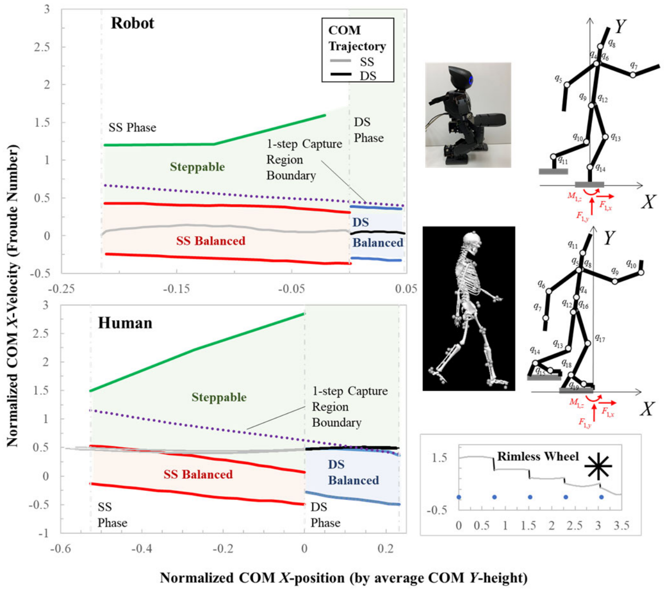

Fig. 1. The steppable, SS balanced, DS balanced, and 1-step capture regions are obtained for a biped robot (top) and human (bottom) with respect to walking COM trajectories with desired step lengths of 0.057 m and 0.74 m, respectively. The balanced region and rolling COM trajectory of a rimless wheel are also shown for comparison. Its balanced region consists of points of zero velocity where each spoke contacts the ground during rolling (bottom right).

The gap between the SS and DS balanced boundaries at the SS to DS transition of the human is larger than that of the humanoid robot. Due to this gap, about half of all constant-COM-velocity human walking trajectories that originate in the SS balanced region must also exit it (i.e., exhibiting dynamic gait) before entering the DS balanced region. On the other hand, most constant-COM-velocity robot trajectories will remain in both SS and DS balanced regions.

In general, when an SS balanced state becomes unbalanced, balance may be recovered with respect to a new DS contact by stepping if the unbalanced state remains within the steppable region and evolves to a stepped state within the new DS balanced region. If not, the system does not necessarily enter a falling state, which must be both unbalanced and unsteppable. As long as the state remains within the steppable region, subsequent steps to enter another SS or DS balanced region are possible.

REFERENCES

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[2] Zaytsev et al., *IEEE ICRA*, pp. 6295–6300, 2015.
[3] Peng et al., *IEEE ICRA*, (accepted), 2020.