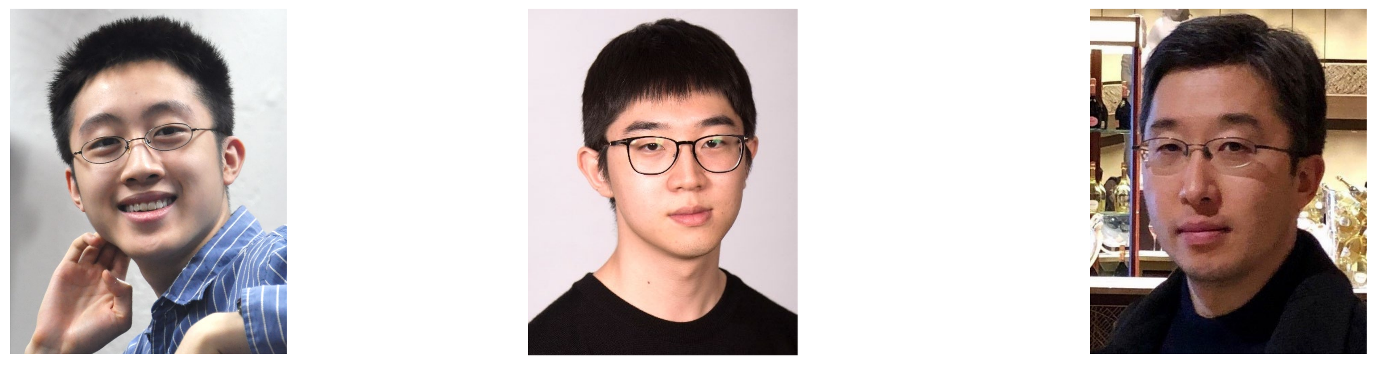
NEW YORK UNIVERSITY

Applied Dynamics & Optimization Lab

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



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Problem Statement

- Given: **SYSTEM, DESIRED CONTACTS, SYSTEM STATE** (position & velocity)
- Questions: **BALANCED** or **UNBALANCED?**

  And if the current contact configuration must be broken:

  Can a step be taken? **STEPPABLE** or **FALLING?**
- Solution: CONTACT-DEPENDENT **STATE SPACE PARTITION**

States of Balance – Definitions

- **BALANCED** vs. **UNBALANCED** states are defined relative to a specified contact configuration [1]:

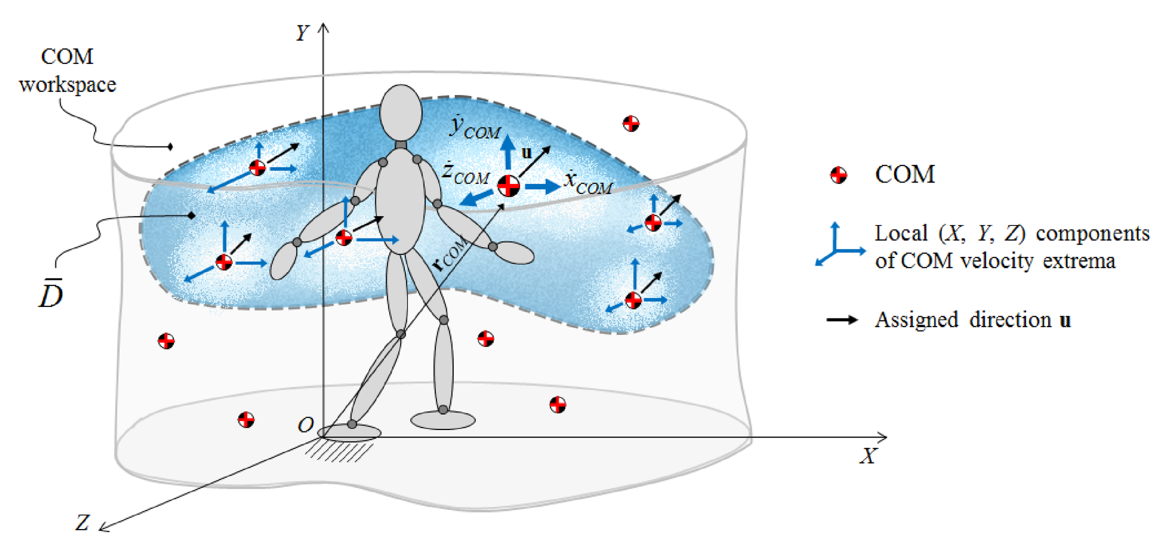
  BALANCED state: There exists a (controlled) trajectory starting from a given legged system's state such that the system does not ever alter its contacts

  UNBALANCED state: All (controlled) trajectories starting from a given legged system's state will lead to an inevitable change in the system's contacts [2]

  - **STEPPABLE state**: There exists a (controlled) trajectory starting from a given legged system's state such that the swing foot can reach the desired step length before other contacts are made
  - **FALLING state:** All (controlled) trajectories starting from a given legged system's state do not allow the swing foot to reach the desired step length before other contacts are made
- **STEPPABILITY** vs. **CAPTURABILITY:** ability to step vs. come to a stop [3] [4]
  - Steppability complements capturability
  - Inverse problem: final stepped state → initial COM states and vice versa
  - Incorporation of full-body, system-specific, nonlinear characteristics and capabilities (e.g., joint and actuation limits and angular momentum)
  - Iterative application for step-by-step analysis of a sequence of *N* steps

Stability Regions – Models and Construction Algorithms

- **Balanced** or **steppable stability region:** state space partition between **balanced and unbalanced** states or **steppable and falling** states relative to a specified contact configuration
- Stability boundary: set of maximum allowable center of mass **(COM)** velocity perturbations to maintain balance without undesired changes in contacts



Joint space
Full-body constrained dynamics in given contact configuration

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COM space
Optimization-based algorithm for constructing stability region

Figure 2: Stability region (blue) in the 6-dimensional COM state space

Results and Discussion

- Comparative analysis of biped robot vs. human stability regions

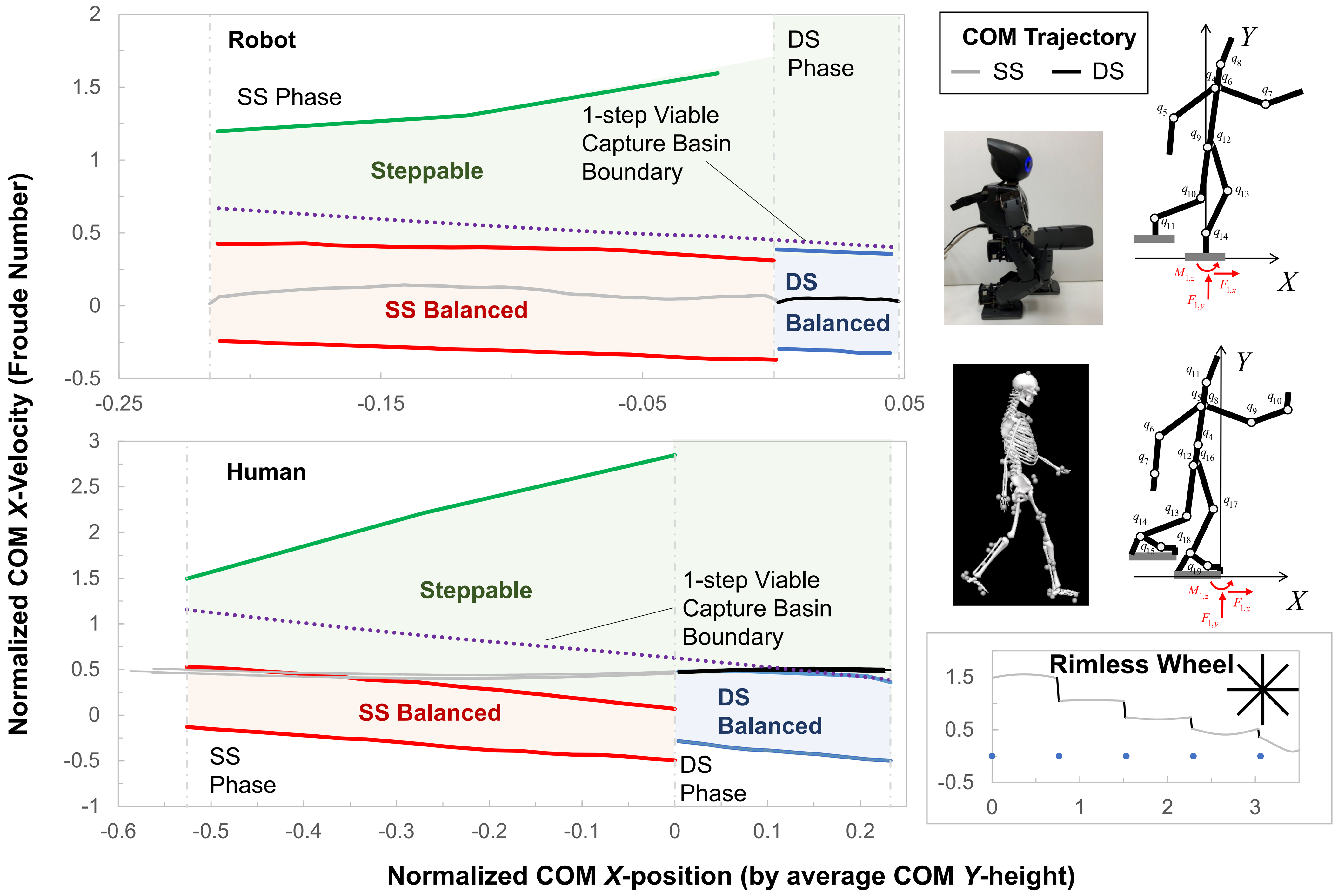
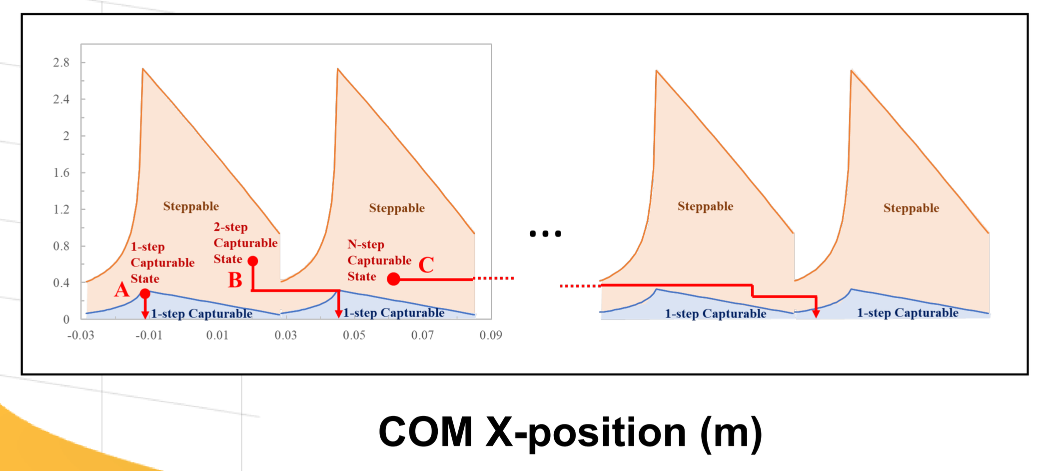


Figure 3: Normalized steppable, SS balanced, DS balanced, and 1-step capture regions for the DARwIn-OP humanoid robot vs. human subject with respect to walking COM trajectories at desired step lengths of 0.057 m and 0.74 m, respectively. Balanced region (blue points) and rolling COM trajectory of a rimless wheel are shown for comparison (bottom right).

- Comparative analysis of steppability vs. capturability



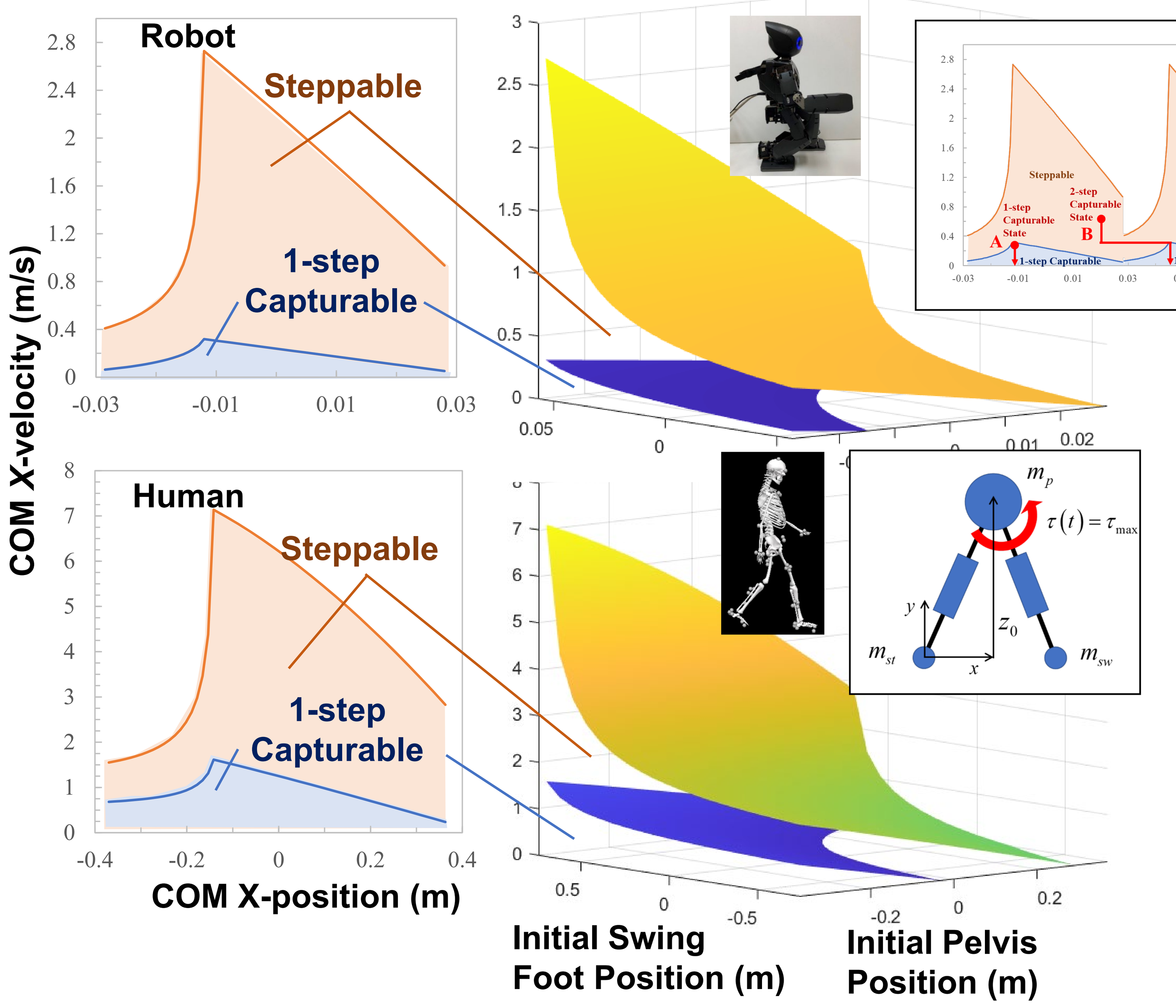


Figure 4: Steppable and 1-step viable capture basins for reduced-order models (center inset) of robot vs. human at varying COM *X*-positions (left) and initial poses (center). Two hypothetical trajectories are shown where the system is captured after two steps and *N* steps (right).

Conclusions

- Balanced and steppable region analysis accounts for:
  - System-specific capabilities, limitations, and nonlinearity
  - Full-body system dynamics
  - Characteristic COM regulation and angular momentum effects

References

[1] Mummolo et al., *ASME JMR*, vol. 10, no. 2, pp.021009-1–13, 2018.
[2] Peng et al., *IEEE ICRA*, (accepted), 2020.
[3] Koolen et al., *IJRR*, vol. 31, no. 9, pp. 1094–1113, 2012.
[4] Zaytsev et al., *IEEE ICRA*, pp. 6295–6300, 2015

Acknowledgements

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WHERE DISCOVERIES BEGIN
National Robotics Initiative