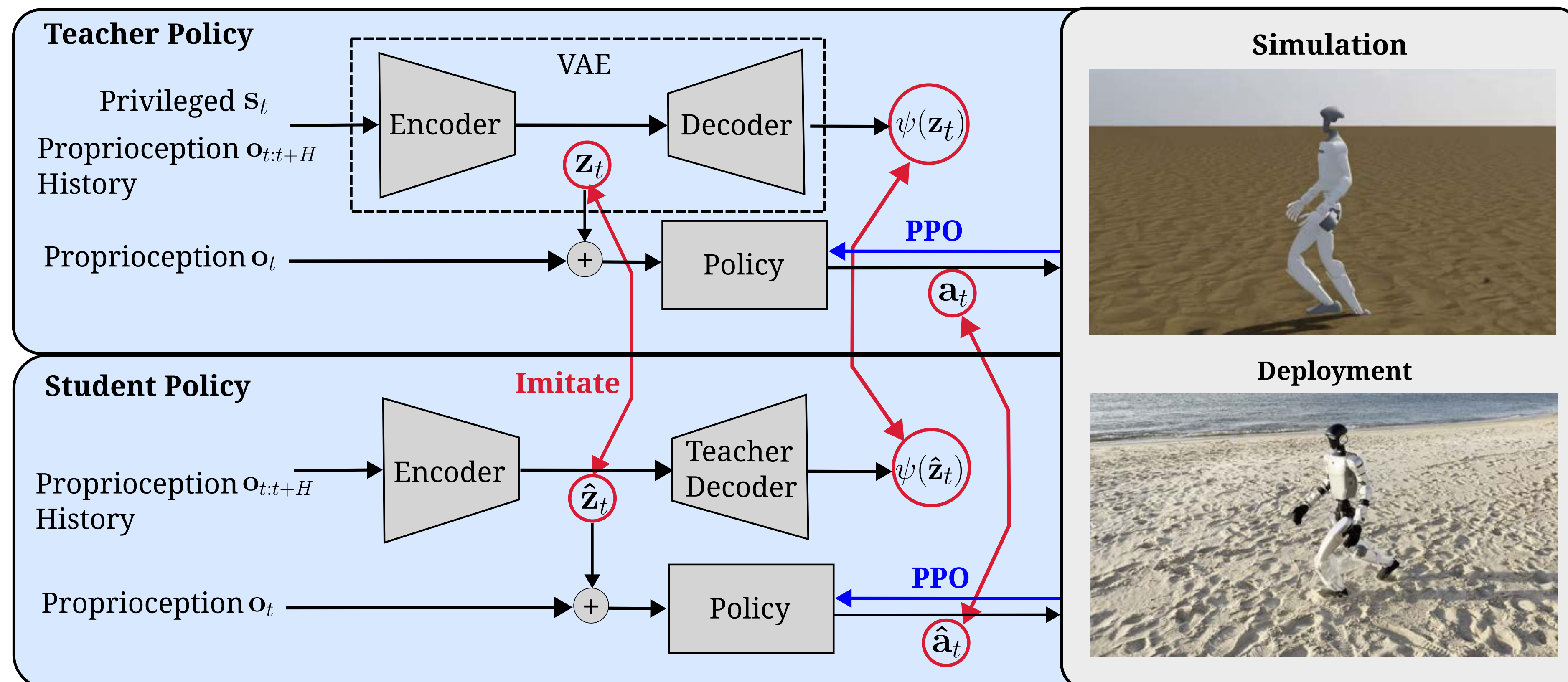
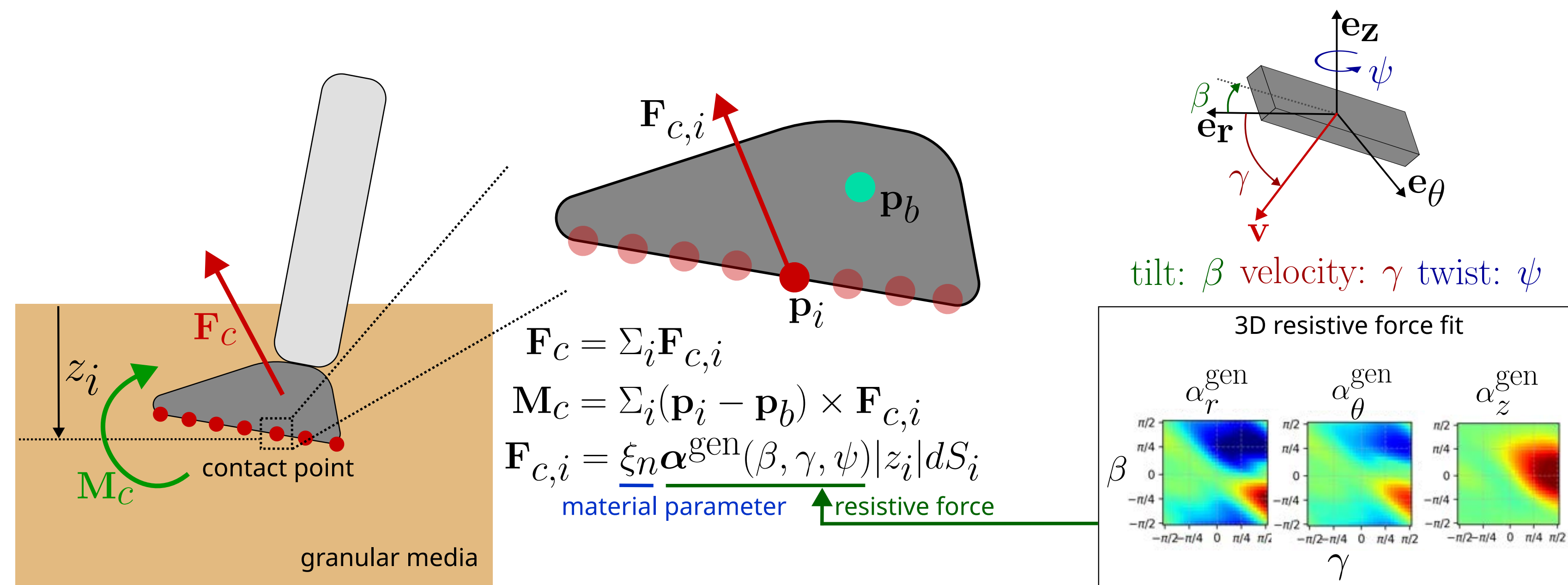




Problem Formulation

- Humanoid locomotion on granular terrain remains a **significant challenge** due to its **complex interaction dynamics**
- Existing approaches either **ignore granular dynamics** or incorporate **simplified force models** [1]
- Present a **terrain-aware reinforcement learning (RL) framework** for humanoid locomotion on granular terrain that integrates a **three-dimensional granular media contact model** [2]

Proposed Method

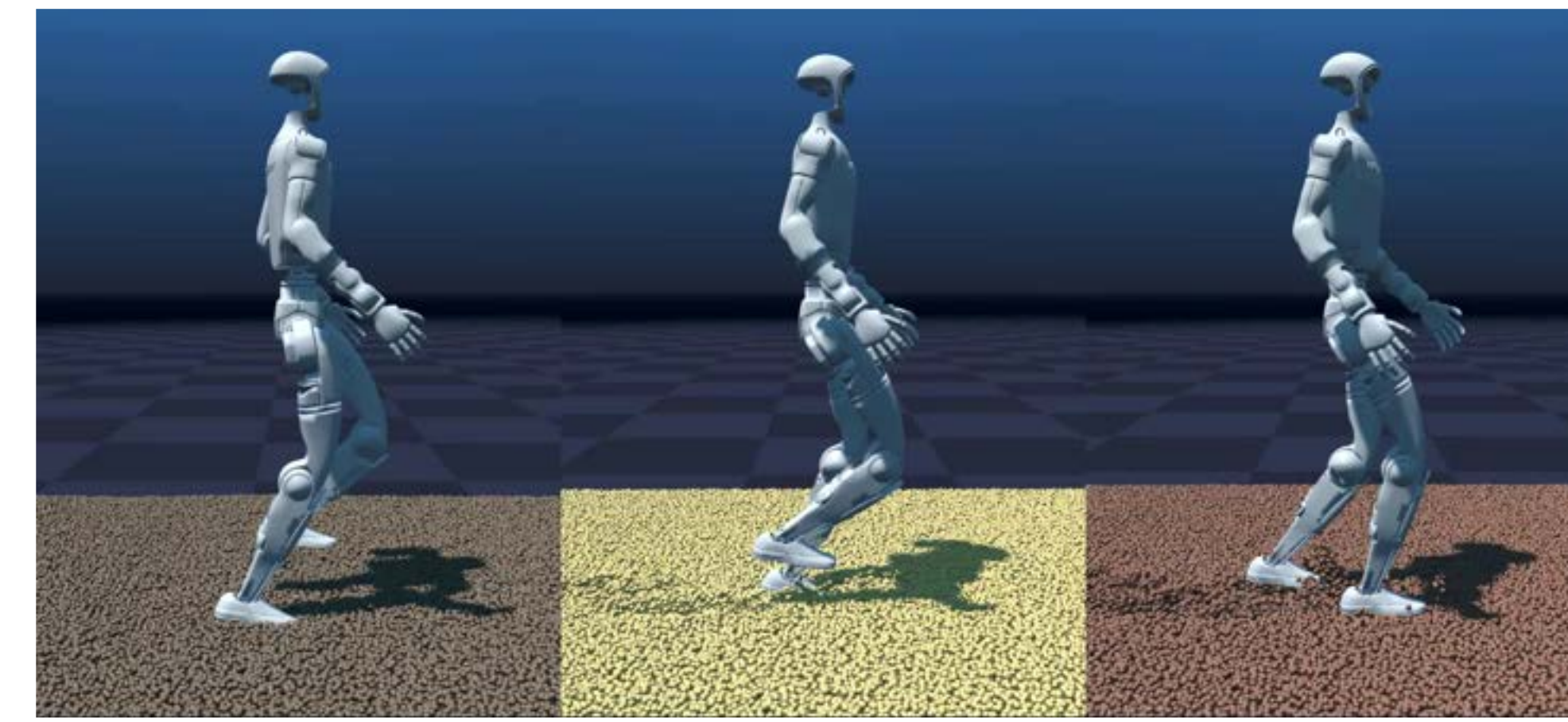


- Leverage **3D resistive force theory (3D RFT)** [2] to simulate **granular terrain interaction physics** in IsaacLab
- Employ **teacher-student RL** with **terrain-encoder** to train a terrain-adaptive locomotion policy
- Enable **policy to adapt its motion** to inferred terrain condition

Reference

*1 Choi, Suyoung, et al. "Learning quadrupedal locomotion on deformable terrain." Science Robotics 8.74 (2023): eade2256.
 *2 Agarwal, Shashank, Daniel I. Goldman, and Ken Kamrin. "Mechanistic framework for reduced-order models in soft materials: Application to three-dimensional granular intrusion." Proceedings of the National Academy of Sciences 120.4 (2023): e2214017120.
 *3 Daviet, Gilles, and Florence Bertails-Descoubes. "A semi-implicit material point method for the continuum simulation of granular materials." ACM Transactions on Graphics (TOG) 35.4 (2016): 1-13.

Simulation Results



basalt sand poppy seed

Results of a comparative study with MPM simulation

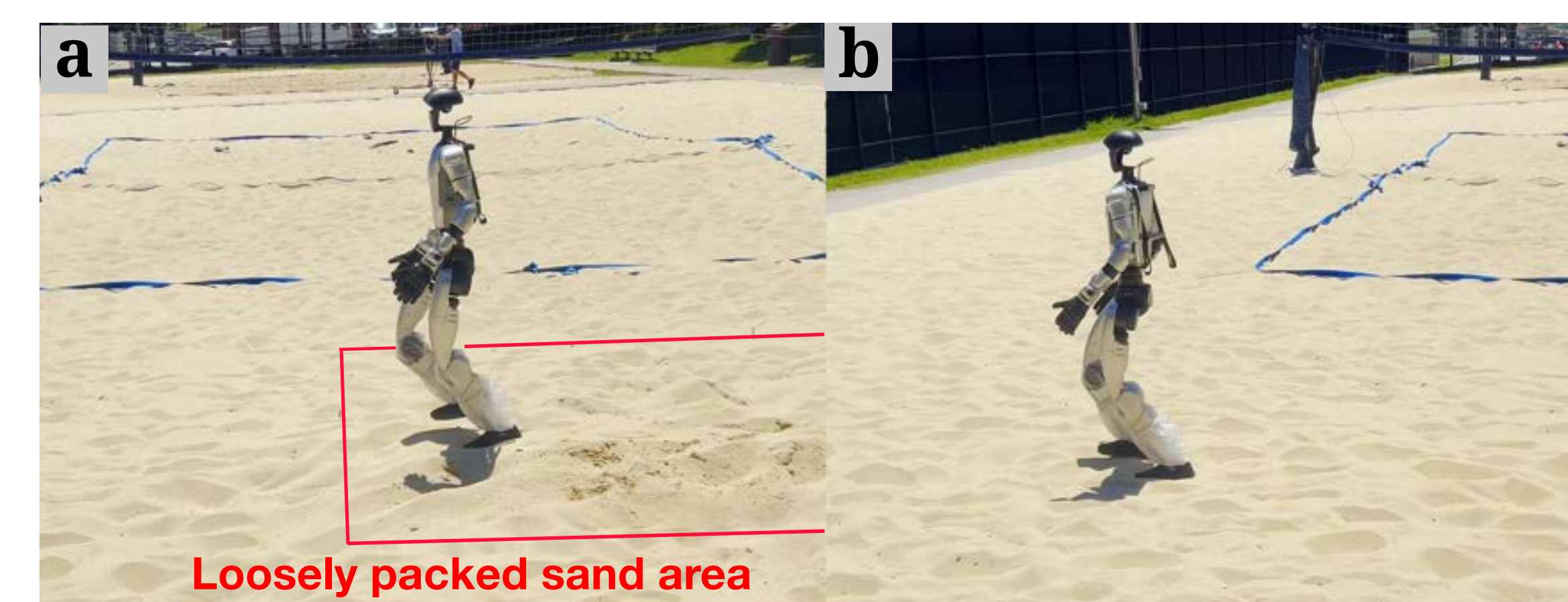
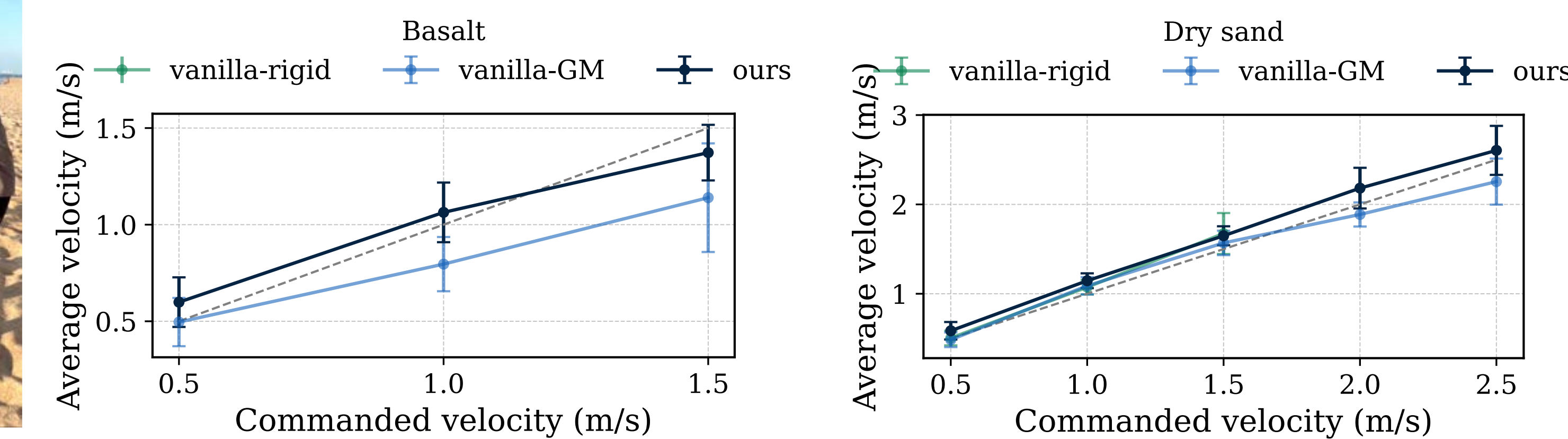
Terrain	Name	success rate $\uparrow$ (%)	error vel. $\downarrow$ (m/s)	error yaw $\downarrow$ (deg)
basalt	<i>ours</i>	99.0 ± 9.9	0.25 ± 0.43	0.84 ± 0.60
	<i>vanilla-GM</i>	99.0 ± 9.9	0.29 ± 0.37	2.79 ± 1.67
	<i>vanilla-rigid</i>	60.0 ± 49.3	0.23 ± 0.33	1.71 ± 1.18
sand	<i>ours</i>	99.0 ± 9.9	0.3 ± 0.42	2.18 ± 1.63
	<i>vanilla-GM</i>	100 ± 0	0.3 ± 0.38	2.18 ± 1.45
	<i>vanilla-rigid</i>	0	N/A	N/A
poppy seed	<i>ours</i>	96 ± 19.6	0.31 ± 0.41	2.43 ± 1.82
	<i>vanilla-GM</i>	87 ± 33.6	0.33 ± 0.43	2.33 ± 1.34
	<i>vanilla-rigid</i>	0	N/A	N/A

- Evaluate policies on diverse granular terrain simulated by **material point method (MPM)**[3] (grains rendered for visualization)
- Vanilla-rigid*** can only walk on hard surface (basalt), but **no success** on soft terrain (sand and poppy seed)
 - Explicit granular contact modeling** is critical for **robust locomotion**
- Ours*** performs better than ***vanilla-GM***
 - Adapting gait to inferred terrain condition** also stabilize locomotion

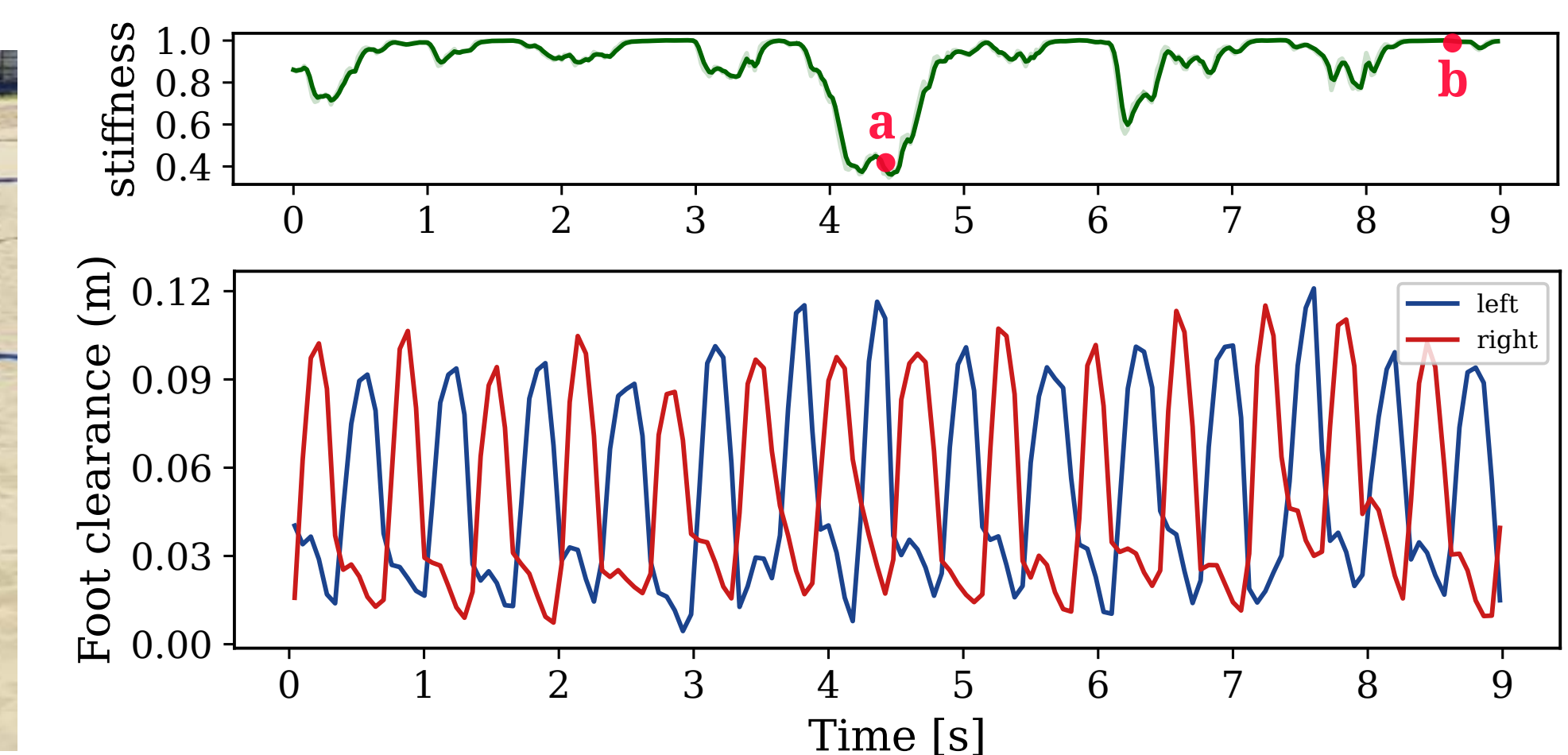
Hardware Results



basalt dry sand beach sand



Loosely packed sand area



- Deploy RL policy on the Unitree G1 over **basalt, dry sand, and beach sand**
- Our policy (*ours*) **outperforms the baselines (*vanilla-rigid*, *vanilla-GM*)** across **all tested terrains**, particularly at higher speeds
- Ours*** predicts **low terrain stiffness** and **adapts swing foot clearance** on loosely packed sand area

Future Work

- More extensive hardware experiments** on beach sand
- Locomotion on terrain with **heterogenous materials**