

Differentiable Co-Optimization of Mass-Limited Legged Robots Across Variable Gravity

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Abstract

We co-optimize quadruped morphology and control end-to-end through a differentiable physics simulator, with gravity treated as an explicit input swept across planetary destinations. Under a fixed mass budget, the optimal body shape, leg sizing, and gait pattern shift qualitatively across gravity levels. The framework yields destination-specific design trends for mass-limited planetary robots and shows that morphology gradients rival or exceed control gradients, meaning body design drives performance at least as strongly as the controller does.

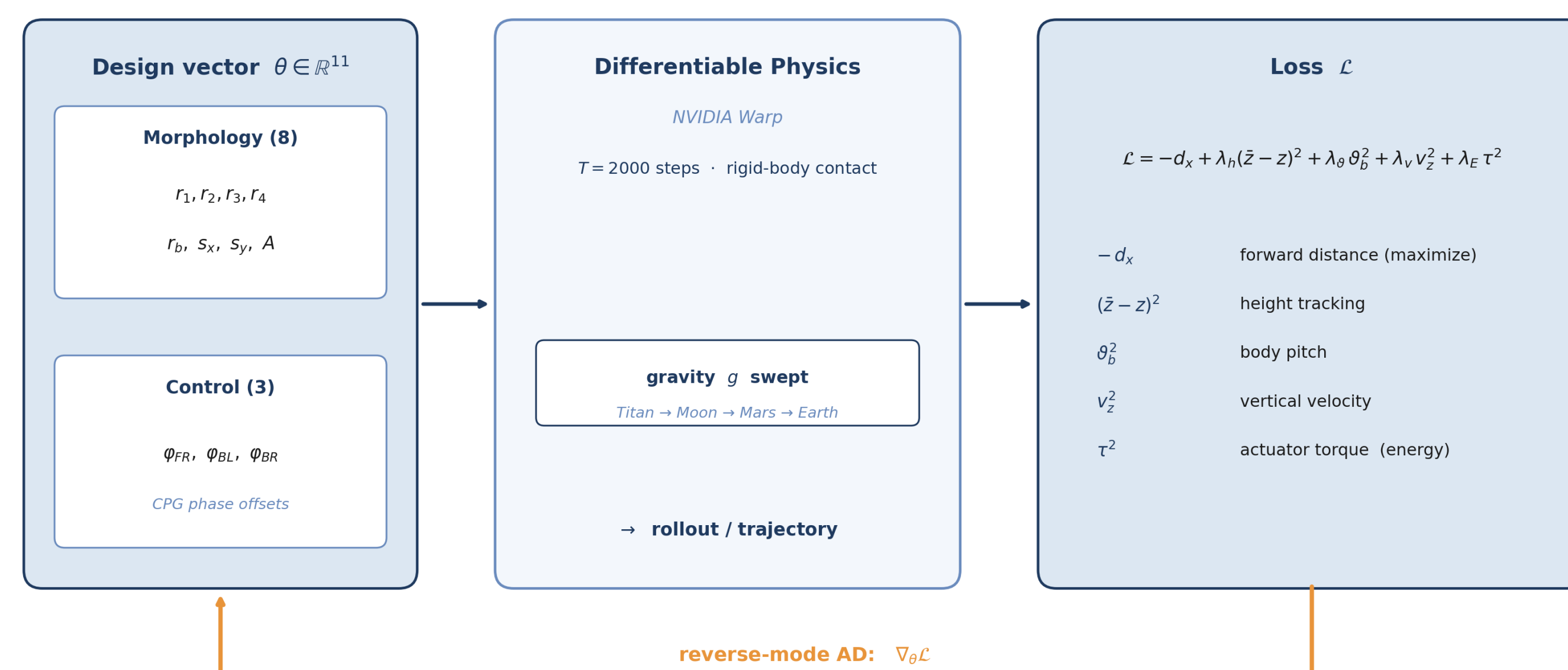
Introduction

Once a space mission is selected, the robot's design is fixed and hardware cannot change after launch. A robot on Titan operates in a fundamentally different regime than one on Venus: ballistic timescales, stance loading, and stability margins all shift in ways that reorganize which morphologies and gait patterns are feasible.

We sweep gravity not to design a universal robot, but to expose regime transitions and derive destination-specific design guidance under a unified co-optimization pipeline. Engineering practice typically decouples morphology and control: body first, controller second missing synergistic solutions that only emerge from joint optimization.

Materials & Methods

Robot model: five-sphere quadruped, total mass $M = 12$ kg, Locomotion: CPG-driven elliptical foot paths on a 25° slope. PD actuators with mass-proportional caps $a_{\max} \in \frac{\{30,60,120\}N}{kg}$. Simulator: NVIDIA Warp, 2000-step rigid-body contact dynamics, reverse-mode AD through the trajectory.

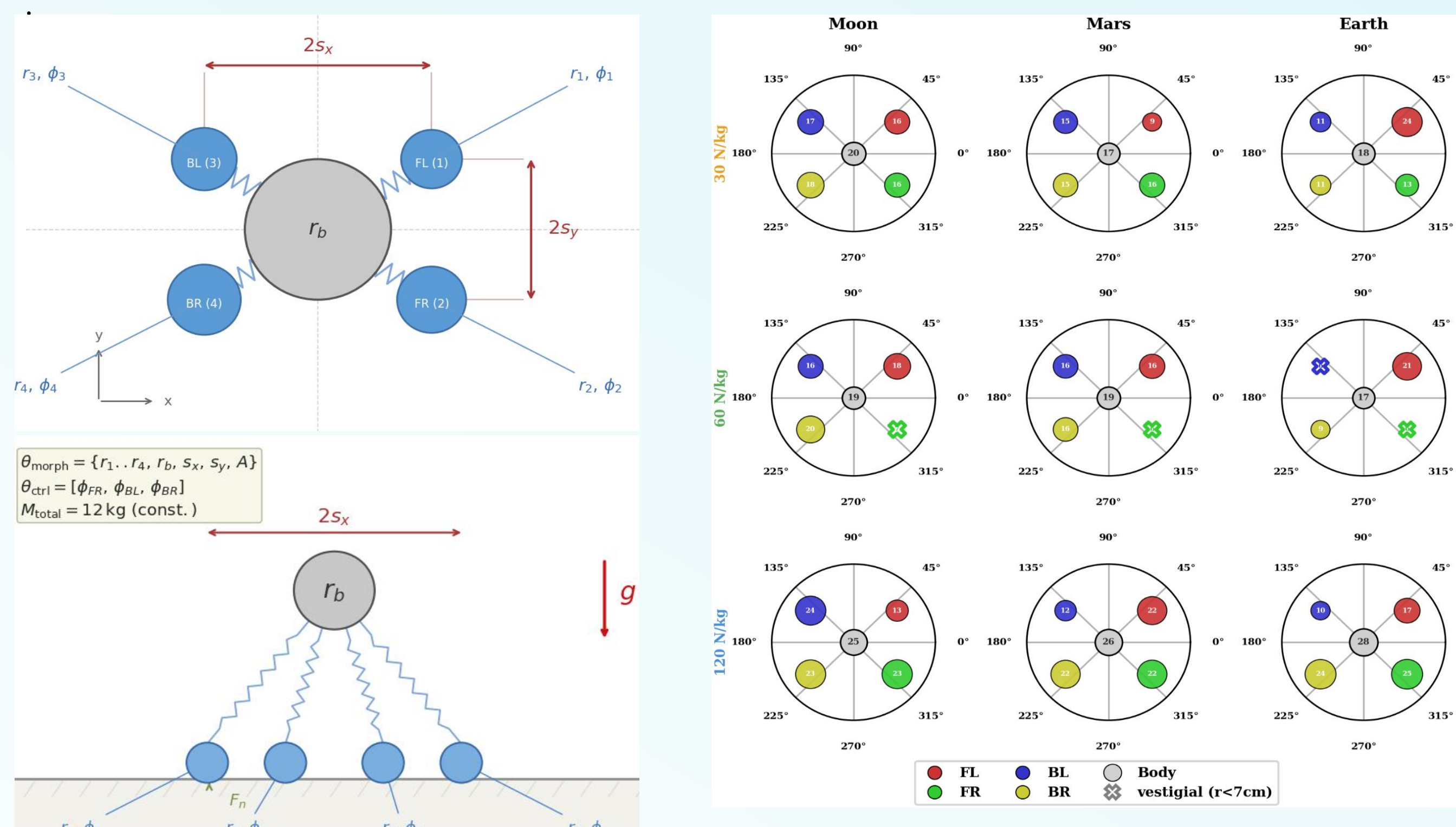


Results

Body mass fraction falls monotonically with gravity. At 60 N/kg it drops from 84 % on Titan to 50 % on Earth: mass migrates outward to grow legs and raise per-leg force capacity.

At 120 N/kg the shallower range (84 % \rightarrow 67 %) reflects that stronger actuators reduce the imperative to grow legs. Under high gravity and tight force caps, some legs shrink below 7 cm and become dynamically inactive: the optimizer concentrates mass into the remaining limbs. The plateau appears near 8 m/s².

Contact-load statistics confirm vestigial legs contribute negligible ground reaction force.



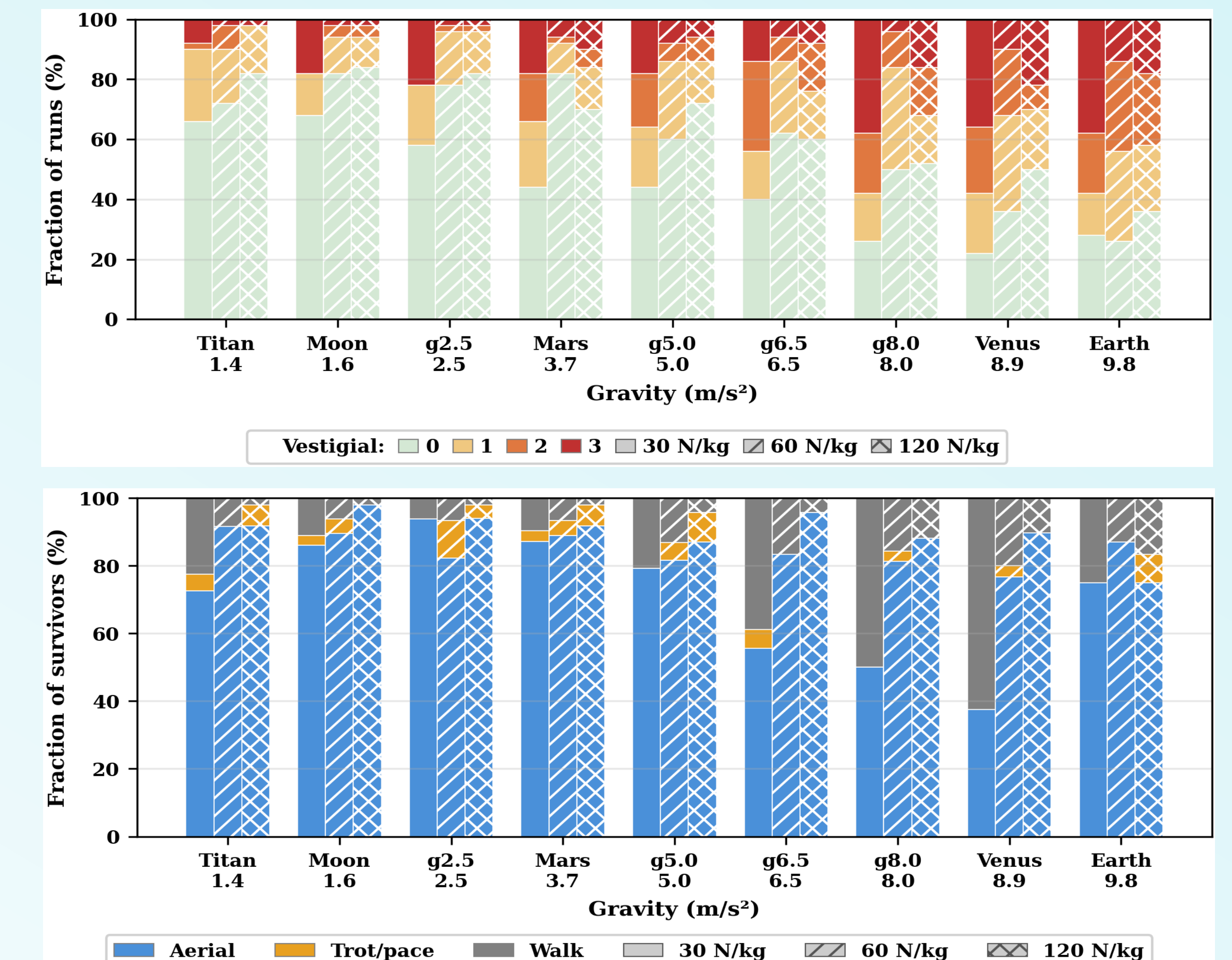
Gait coordination shifts from aerial flight phases under low gravity to ground-bound walking under high gravity. At 30 N/kg aerial patterns account for 65 % of Moon survivors, declining to 0 % at Earth where walk coordination takes over entirely. At 120 N/kg, aerial gaits persist above 24 % even at Earth: stronger actuators retain the ability to generate ground-clearance forces.

Conclusion

Morphology gradients rival or exceed control gradients at every gravity level: body design influences performance at least as much as the controller.

- **Body mass fraction tracks gravity**
- **Vestigial legs emerge at high g**
- **Aerial \rightarrow walk transition with gravity**
- **Morphology gradients \geq control gradients**

Future work: bridge five-sphere abstractions to articulated kinematic chains with realistic joint limits and motor torque curves.



References

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