Inflatable Bipedal Locomotion

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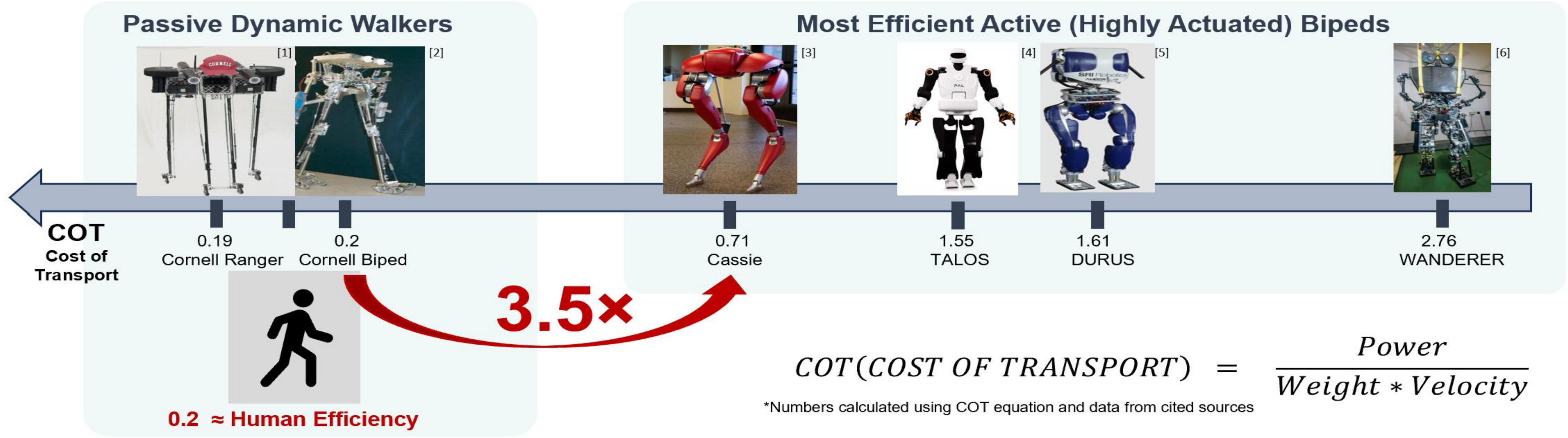
How do inflatable legs and feet affect bipedal gait dynamics, and can passive compliance replace heavy stabilizing actuators while reducing energy consumption and design complexity?



$$COT(COST\ OF\ TRANSPORT) = \frac{Power}{Weight * Velocity}$$

*Numbers calculated using COT equation and data from cited sources

GOAL & APPLICATIONS

This work aims to establish the first framework for understanding how completely deformable locomotion systems affect bipedal dynamics. Success could enable lightweight, compactable and deployable walking robots for space exploration, disaster response, and terrains where traditional heavy systems are impractical. The inherent safety of deformable structures could also transform healthcare robotics by enabling gentle physical assistance for patient mobility and elder care without complex force control systems.

MOTIVATION & BACKGROUND

The Efficiency-Stability Challenge

State-of-the-art humanoid bipeds achieve stability through complex, heavy, and energy-intensive actuator arrays. Even bipeds specifically designed for efficiency, such as Agility Robotics' *Cassie*, reach a COT (Cost of Transport) of 0.71—well above human efficiency (COT ≈ 0.2) [3][5]. In contrast, passive dynamic walkers like *Cornell Ranger* achieve human-level efficiency by leveraging natural dynamics and minimal actuation, but they sacrifice stability, requiring carefully tuned initial conditions and ideal environments (e.g., slopes or unobstructed flat terrain). Existing strategies, whether passive or highly actuated, each address only one side of the problem, leaving the combined goal of efficient and stable locomotion unresolved.

Why an Inflatable Biped?

Increased Stability:

- Compliant bipedal robots are proven to self-stabilize through passive mechanical responses with no sensor delays [8–9]
- Inflatable legs/feet act as distributed spring system—instant restoring forces during perturbations

Increased Energy Efficiency:

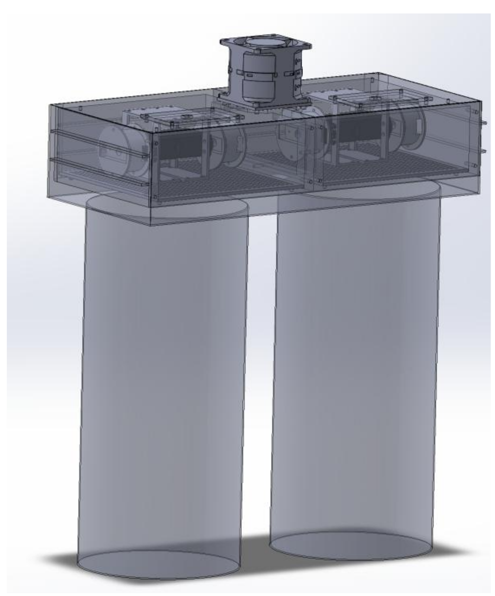
- Passive dynamics and compliant materials can store and release energy to reduce control complexity and energy required *[2, 8–11]*
- Pressure-tunable stiffness—adjusts stiffness for stability control and shock absorption

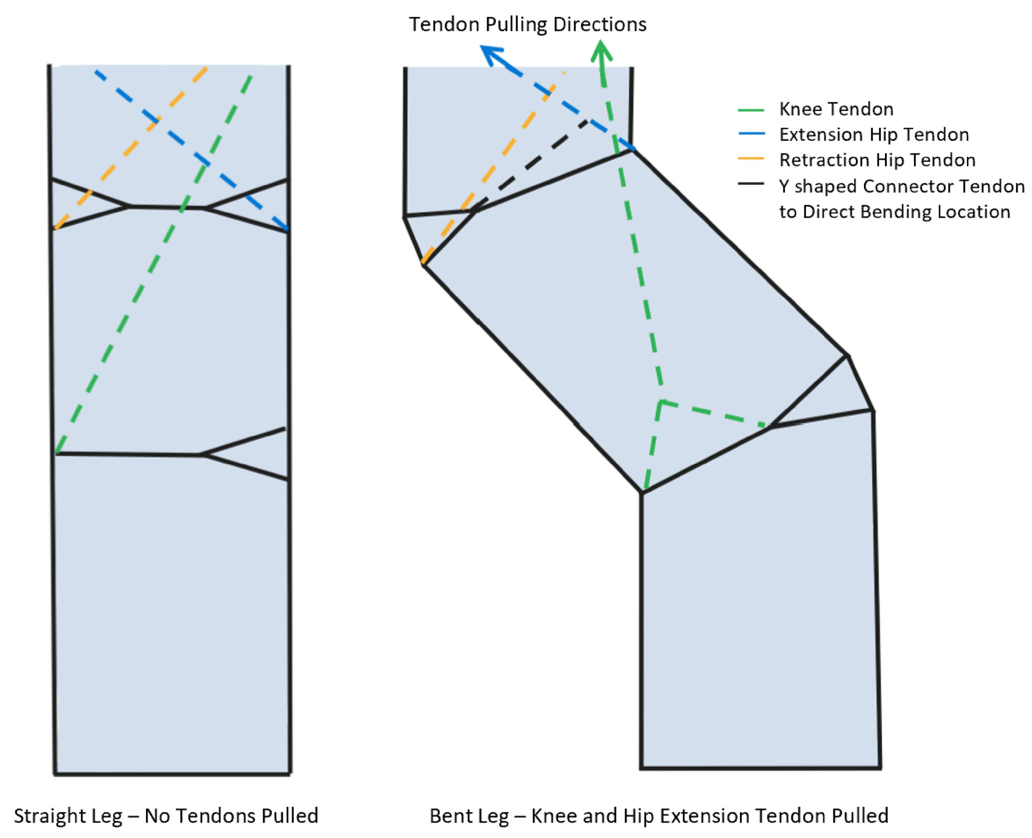
The Practical Benefits:

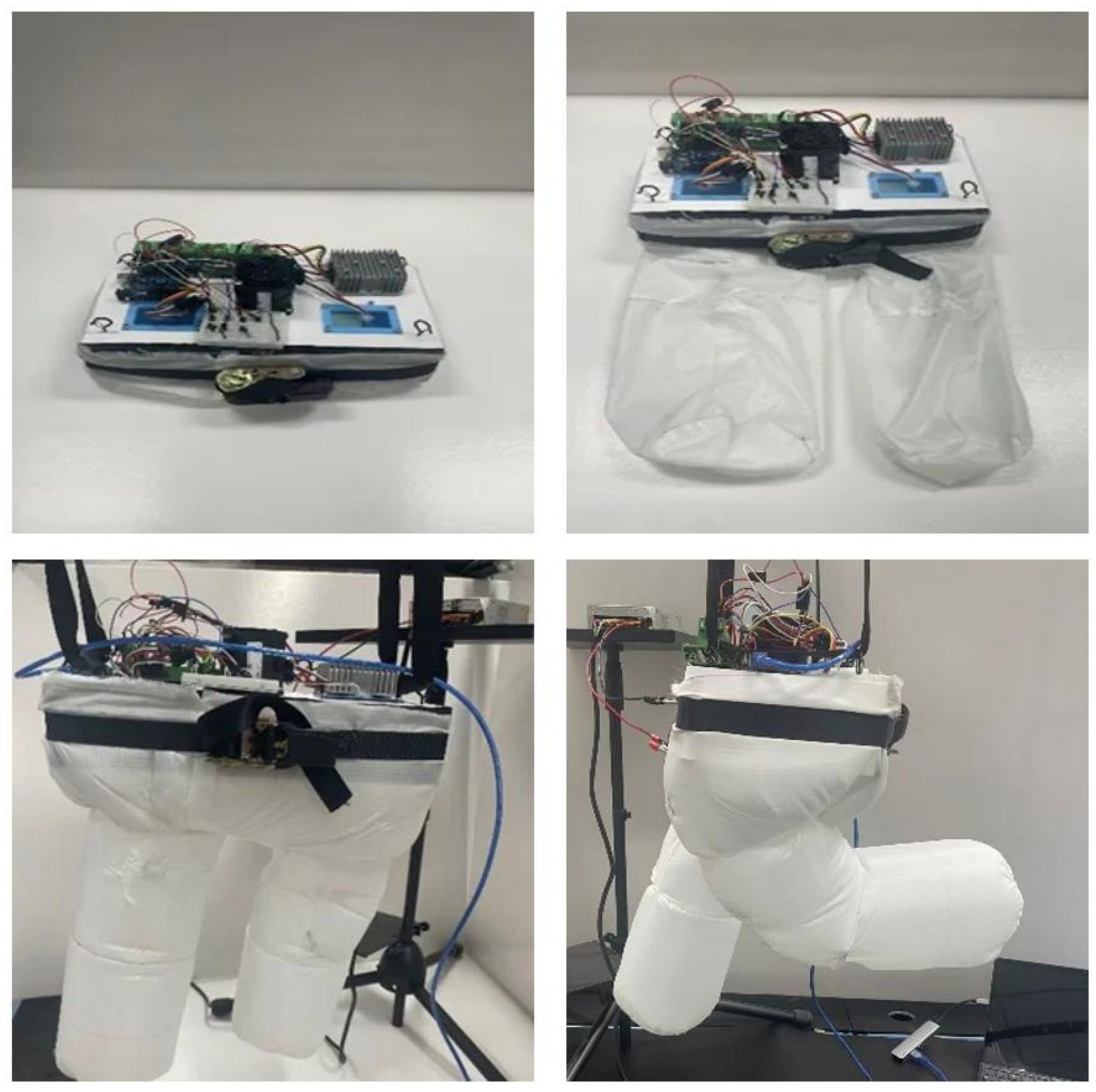
- Lightweight construction—reduces inertial costs of locomotion
- Fully deflatable—compact storage and rapid deployment
- Inherently safe—soft contact for human-robot interaction environments

PROTOTYPE DESIGN

- Single inflatable lower body chamber (legs + feet)
- Rigid torso frame – houses electronics & servo motors
- No rigid joints
- Blower inflates "pants" and pressurizes fabric for support
- Inflatable pants attached to rigid torso frame via belt







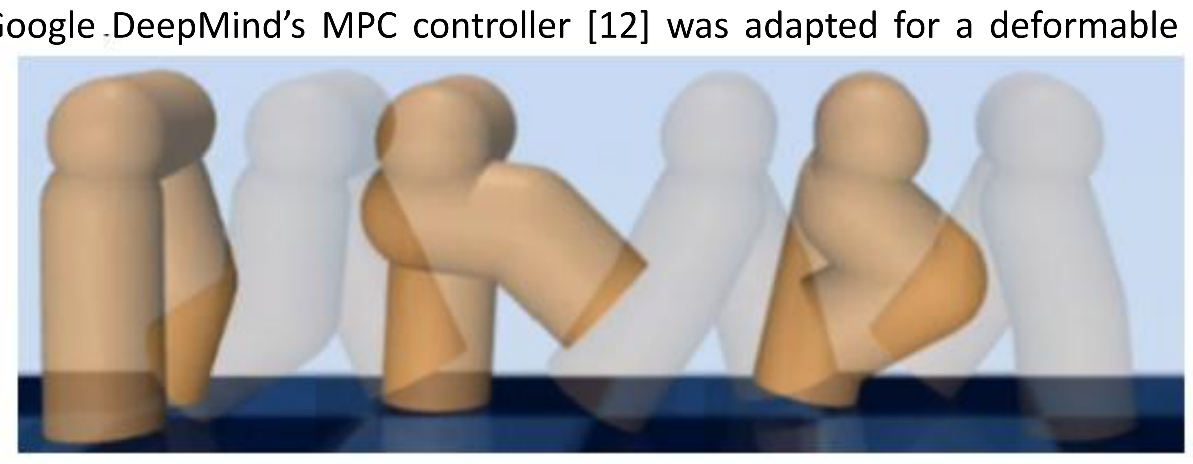
- Tendon-driven mechanism adapted from Niiyama et al. [12]
- Servo tension on tendons bends the pressurized fabric to form joints
- Inflatable body designed to act like a spring to self-correct balance
- Air pressure adjusts stiffness for stability control

SIMULATIONS

Surveying existing bipedal models revealed that none adequately captured the required features for an inflatable walking system: 3D walking and modelling capability, knee and hip joints, leg and foot compliance, and input torque actuation for completely deformable structures without rigid skeletal elements. To address this gap, Google DeepMind's MPC controller [12] was adapted for a deformable walker, leading to three MuJoCo dynamic simulation models that each achieved stable bipedal gait.

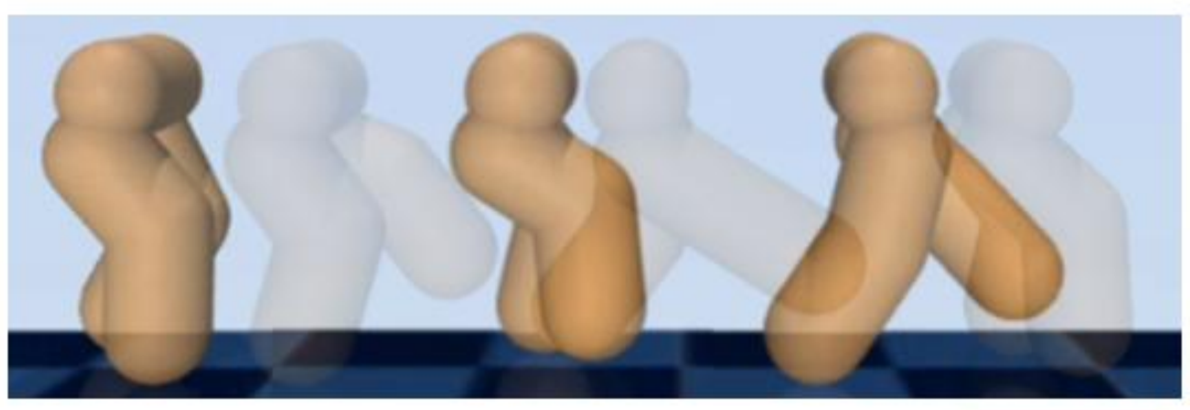
Model 1: Rigid Walker with Flat Feet

This baseline model employs a rigid structure with flat, non-compliant feet to establish a performance benchmark.



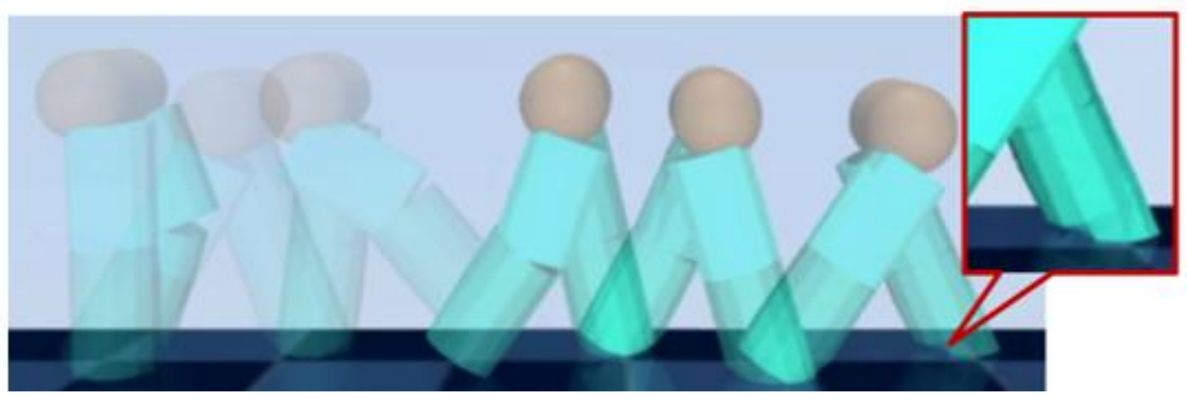
Model 2: Rigid Walker with Hemispherical Feet

This model approximates inflatable foot compliance through hemispherical foot geometry. Both hemispherical and flat inflatable feet produce similar center-of-pressure progressions during walking. The rigid structure enables faster computation and leverages existing control algorithms while mimicking compliant contact dynamics.



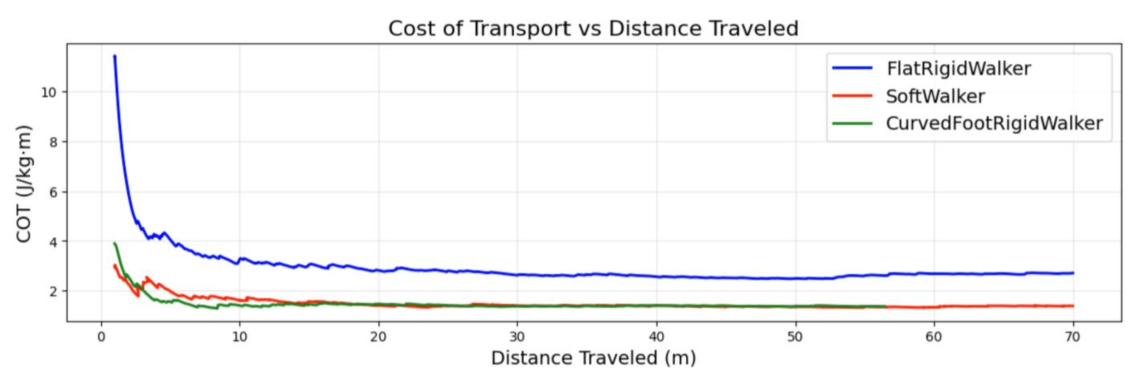
Model 3: Soft Walker with Deformable Legs/Feet

Implemented using MuJoCo's flexcomp system, this model creates a deformable cylindrical shell structure where the mesh expands and contracts radially under load—directly mimicking the pneumatic behavior of the inflatable prototype. The system generates restorative forces that maintain structural integrity while replicating pressure based variable stiffness.



PRELIMINARY RESULTS

All models successfully demonstrate stable walking gaits and preliminary simulation results show that the rigid curved feet and the soft flat feet both provide roughly a 2.3 times lower COT than the rigid flat-footed walker (Model 1).



PLANNED EXPERIMENTS

Once finishing the MPC integration with the inflatable walker prototype, systematic testing in simulation and physical experiments will quantify how inflation pressure affects walking stability, comparing elastic storage vs. active control approaches, energy consumption, ground reaction forces, COM trajectories, and gait variability across terrains.

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