# MAE 263F Project Midterm Report: Simulation of tendon-driven meta-material

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*Abstract*— **Bipedal locomotion offers significant advantages in human-centric environments, but traditional rigid robots face challenges with impact absorption and stability. Soft robotics presents a promising alternative, yet the development of agile, soft bipedal robots remains limited. This work focuses on a novel soft humanoid platform constructed from 3D-printed Thermoplastic Polyurethane (TPU) meta-materials, utilizing variable stiffness distribution and tendon actuation for inherent impact absorption and accessibility. A critical prerequisite for developing dynamic control for this platform is a fast and physically accurate simulation. However, simulating such materials is non-trivial; the variable stiffness renders explicit integration methods unstable, while position-based methods often lack physical fidelity. In this midterm report, we propose a simulation framework based on implicit integration, which offers unconditional stability for high-stiffness systems. We present preliminary results using a standard Implicit Euler solver with a Newton-Raphson method, demonstrating the stable deformation of a discretized mass-spring model. Our simulation captures the non-linear relationship between tendon actuation and actuation output, observing a bending angle of approximately 50 degrees at 50% tendon contraction. Future work will extend this baseline by implementing Projective Dynamics (PD) on CUDA to achieve real-time performance.**

## I. INTRODUCTION

Legged locomotion has always been prevalent in robotics, inspired by the nature of most of the land animals. It advantages in obstacle avoiding, unstructured terrain adapting yet achieving agile and fast mobility. Among legged locomotion strategies, biped locomotion, mimicing human's walking gaits, is distinctly advances in its adaptability to human-centric environments and is potentially able to have a lower energy consumption compared to multi-legged locomotion due to less actuation effectors[1]. Biped robot is a well-studied area since the first creation of the humanoid robot, the P series by Honda[2]. Research on biped dynamic locomotion has been mainly focused on rigid mechanisms[3] and achieved great success in dynamic locomotion. For instance, Atlas, the hydraulic driven humanoid robot developed by Boston dynamics[4], is able to walk in challenging environments, jump, and maintain balance when performing pick and place tasks for human body sized or heavy objects. RoMeLa developed a biped robot named ARTEMIS recently. Taking advantage of the proprioceptive actuators for torque-force control, ARTEMIS is capable of agile locomotion[5]. Multiple humanoid robots platform with rigid bodies for research purposes have been proposed[6], [7], [8].

Dynamic locomotion for rigid robots has been challenging. Traditional servo motors for biped robot with a high gear ratio has less capability to properly handle contact impact. To address this issue, apart from hydraulics on Atlas and proprioceptive actuators on Cheetah or ARTEMIS, series elastic actuators (SEAs) might be promising[9], but there is still disadvantage on low control bandwidth. As opposed to rigid robots, soft robots advantages in absorbing impact benefiting from its low stiffness and compliant capability to deform continuously. And it can be potentially safe from falling down or even dropping from high, which is a eager need for biped robot due to it's difficulty on balancing and more frequently to fall compared to multi-legged robots. Unfortunately, although soft robotics is a well-studied area, and many multi-legged soft robot has been developed[10], limited research has been conducted on soft agile biped robots. In [11], the authors proposed a soft octopus like biped soft robot, but it only works in underwater environment and slow in locomotion. Soft humanoid robot is proposed in [12], but it only works in simulation and failed in real hardware due to huge sim-to-real gap.

A soft humanoid robot platform whose limb and outer body are all soft can take advantage of it's capability of absorb impact, it is safe from falling down or dropping from a high place which benefits for the unstable nature of biped robots. With design of stiffness distribution and driving with tendons by motors, the limb may have multiple degree of freedom and achieve agile motions and fast locomotion. Using TPU as the material and 3D-printing as the fabrication method, the robot would have great accessibility with a low cost. Simulation of the soft joint is essential for control or using Reinforcement Learning(RL) for the robot locomotion. In this project, we propose a simulation platform for the tendon-driven 3D printed meta-material.

## II. RELATED WORKS

### A. Freeform Fabrication of Soft Robots

Fabrication of soft robots has been time consuming. Taking advantage of the capability of rapid prototyping and freeform fabrication, additive manufacturing techniques can make robot parts rapidly in complex shapes with limited human effort. Many 3D-printing soft robots has been proposed[13], [14], [15]. However, most of them are using uncommon materials and can not take advantage of great accessibility of 3D-printing. Among those, Boxi et. al used Thermoplastic polyurethanes (TPU) as the material of their soft robot[16]. They demonstrated that with different infill density and flow rate, the printed part can achieve varying meta-material stiffness as shown in Figure 1. In this work, the authors just use a certain infill density and flow rate for their quadruped robot limbs. However, this material has great potential if applying varies stiffness on the robot, the robot limb may have multiple degree of freedoms, and also can be the one of the most accessible soft robot platform as TPU is a widely used material in fused deposition modeling (FDM).

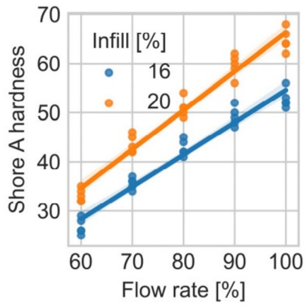


Fig. 1: Shore hardness vs. flow rate and infill density of TPU with gyroid infill pattern

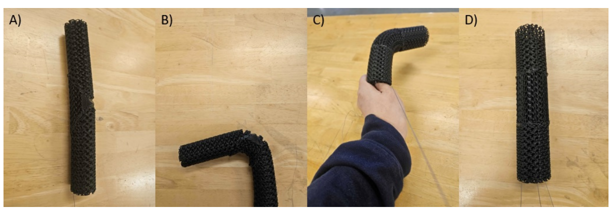


Fig. 2: A) test print part with one tendon. B) test print part with tendon pulled. C) test print part with one of the tendons pulled. D) test print part with three tendons.

### B. Simulation methods of soft body

The simulation of soft bodies involves a fundamental trade-off between computational speed and numerical stability, particularly when dealing with high-stiffness materials. Explicit integration schemes, such as the Explicit Euler method, are computationally efficient and highly parallelizable, as demonstrated by the Titan library [17], which utilizes NVIDIA CUDA for large-scale robotics simulation. However, explicit methods are only conditionally stable and fail when high stiffness (large $k$) or necessitating very small time steps to ensure stability. Conversely, implicit integration methods, like the standard Implicit Euler, are unconditionally stable and can handle high stiffness, but traditionally require solving a large, non-linear system of equations at each step, which is often too slow for real-time applications. To achieve real-time interactivity, Position-Based Dynamics (PBD) [18] was introduced, offering exceptional speed and robustness by omitting the force/velocity layer and directly solving positional constraints. PBD's critical drawback, however, is that its material stiffness is not a physical parameter but an unphysical artifact of the solver's iteration count, leading to unreal behavior. This was directly addressed by eXtended Position-Based Dynamics (XPBD) [19], which modifies the PBD algorithm to correctly decouple stiffness from the iteration count, allowing for physically-based compliant constraints. Bridging the gap between implicit methods and PBD, Projective Dynamics (PD) [20] formulates the simulation as an implicit Euler integration step that is solved using a fast, alternating local/global optimization. This allows PD to be robust, efficient, and accurate, achieving real-time performance even for complex models by pre-factoring the most expensive computational step.

## III. Proposed approach and anticipated contributions

Our proposed simulation strategy addresses the limitations of existing methods for this specific application. While our preliminary investigations using explicit Euler with a spring-mass discretization achieved parallel computation in CUDA (reaching a $dt$ of $10^{-5}s$), this method proved unstable for the high-stiffness components of the meta-material, failing to capture its true mechanical properties. Furthermore, methods like PBD are unsuitable due to their non-physical handling of material stiffness, which would likely introduce a significant sim-to-real gap. We, therefore, propose an approach centered on implicit integration, which is unconditionally stable for high-stiffness systems. We will begin by implementing a standard Implicit Euler solver with a Newton-Raphson method to establish a baseline. Subsequently, to achieve real-time performance suitable for high-frequency control or reinforcement learning applications, we will explore the implementation of Projective Dynamics (PD) on CUDA. The anticipated contributions of this work are twofold: 1) A stable and physically-accurate simulation platform for tendon-driven, 3D-printed TPU meta-materials. 2) A validated model that provides a precise mapping from tendon actuation (length) to the resulting kinematic output (bending angle) of the soft structure.

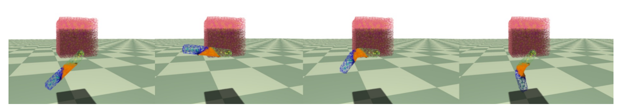

Fig. 3: Simulation of the tendon-driven meta-material with explicit Euler.

## IV. PRELIMINARY RESULTS

Tendon-driven metamaterials are typically characterized by regions of varying stiffness. As illustrated in Fig. 2A, the central cylindrical wedge is designed to be more compliant than the adjacent sections. Consequently, when the embedded tendon is actuated, the softer region undergoes significant deformation, inducing global bending in the structure (Fig. 2B). In this preliminary study, we discretize the compliant wedge using a mass-spring system. Throughout the simulation, the top surface of the cylindrical wedge is assumed to be fixed. Additionally, the bottom surface of the wedge is assigned a slightly higher Young's modulus to model the interface with the stiffer adjacent sections. The system dynamics are simulated by solving Eq. 1 using the Newton-Raphson method. The tendon is similarly discretized as a mass-spring system but is assigned a significantly higher Young's modulus. To embed the tendon, each tendon node is coupled to its four nearest neighbors within the cylindrical wedge. Actuation is simulated by progressively reducing the rest length of the tendon springs, thereby driving the deformation of the wedge. Figures 4-9 depict the deformation sequence, in which the tendon contracts to 50% of its initial length over a duration of 1.0 s.

$$M\ddot{q} + \frac{\partial E^{\text{stretch}}}{\partial q} - W = 0 \tag{1}$$

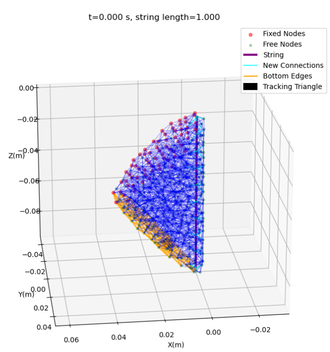


Fig. 4: Simulation of the tendon-driven meta-material with Implicit Euler at t=0s, 100% original tendon legnth.

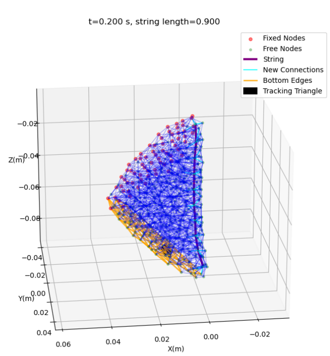


Fig. 5: Simulation of the tendon-driven meta-material with Implicit Euler at t=0.2 s, 90% original tendon legnth.

To quantify the bending deformation, a representative triangular element located on the bottom surface of the cylindrical wedge was selected for analysis, as indicated in Fig. 10. We monitored the angular displacement of this element relative to the fixed top surface throughout the simulation. The relationship between tendon contraction and

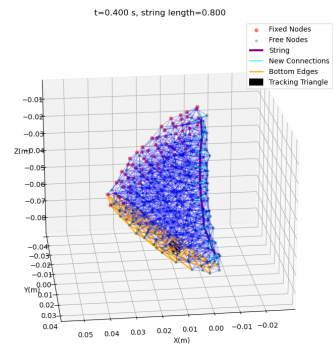


Fig. 6: Simulation of the tendon-driven meta-material with Implicit Euler at t=0.4s, 80% original tendon legnth.

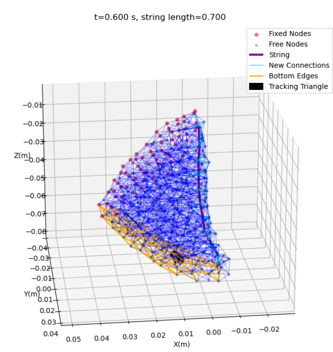


Fig. 7: Simulation of the tendon-driven meta-material with Implicit Euler at t=0.6 s, 70% original tendon legnth.

the resulting bending angle is presented in Fig. 11. The results demonstrate that as the tendon contracts from 100% to 50% of its original length, the angular displacement increases from $0^\circ$ to approximately $50^\circ$.

## V. FUTURE WORK AND IMPLEMENTATION PLAN

Building upon the preliminary validation of the implicit integrator, the next phase of this project focuses on increasing geometric fidelity and computational efficiency to bridge the sim-to-real gap.

First, the simulation domain will be expanded to include the adjacent stiff components of the limb. While the current study isolates the compliant wedge, the physical prototype includes stiffer cylindrical sections above and below the joint. Integrating these boundary conditions is essential for capturing the complex interaction forces at the interface between the varying stiffness zones.

Second, we will refine the kinematic evaluation metrics. As observed in the preliminary results, the bottom surface of the soft wedge undergoes non-uniform warping during varying tendon loads, rendering the single-element angular

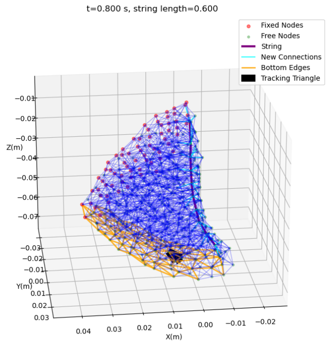


Fig. 8: Simulation of the tendon-driven meta-material with Implicit Euler at t=0.8 s, 60% original tendon legnth.

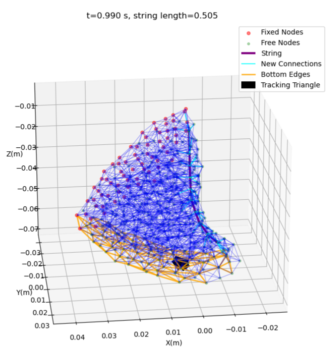


Fig. 9: Simulation of the tendon-driven meta-material with Implicit Euler at t=0.99s, 50.5% original tendon legnth.

measurement prone to noise. To address this, we will implement a centerline extraction algorithm to define a robust vector along the central axis of the adjacent stiff cylinder. This will allow for a more stable and physically meaningful calculation of the bending angle, independent of local surface deformations.

Finally, to achieve the real-time performance required for closed-loop control, we will transition from the standard Implicit Euler solver to a Projective Dynamics (PD) framework. While the current Newton-Raphson approach ensures stability, it is computationally expensive for larger mesh densities. We plan to implement the local-global optimization steps of PD on CUDA, exploiting the parallel nature of the constraint projections. This transition aims to maintain the unconditional stability demonstrated in this report while significantly reducing the computation time per time-step.

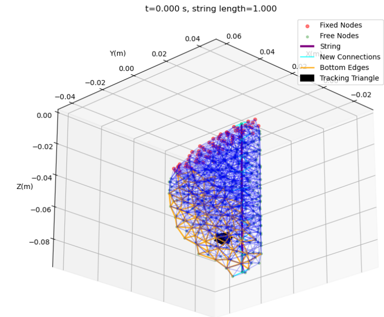


Fig. 10: The studied Triangle position.

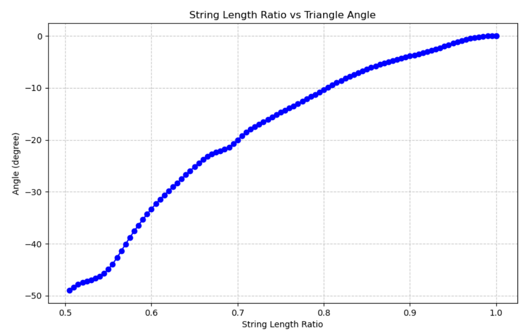


Fig. 11: Bottom angle displacement vs tendon length.

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