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Bio-inspired Tensegrity Flexural Joints

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***Abstract*— Most robotics literature model the human's knee and hip as a revolute joint with limited range of rotation. Although somehow close to reality, this approach neglects a critical aspect of these joints, which is their internal flexibility.**

This paper presents a prototype tensegrity flexural manipulator whose kinematic behavior is inspired by human leg's gait. This prototype, which considers a hybrid (flexible-rigid) structure of the knee and hip would be able to better approximate real behavior and hopefully lead to a better design of artificial (prosthetic) knees and hips.

The behavior of the proposed tensegrity manipulator was firstly predicted using OpenSim simulation environment. The paper reports the comparisons between the simulations, physical prototypes and human leg behavior for a variety of ranges of motions and tension analysis.

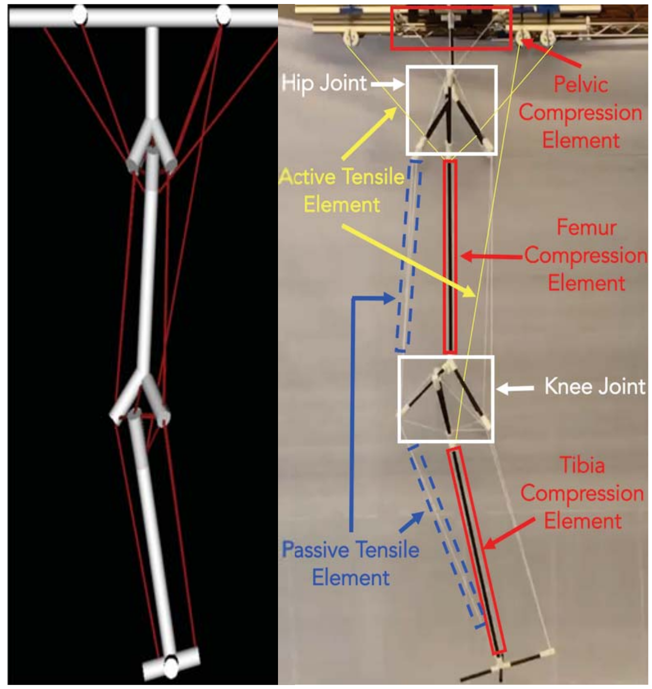
I. Introduction

Flexibility and structural compliance allow biological systems to deform under load, whilst maintaining their structural integrity. Solid skeletal systems work in concert with muscles and tendons to distribute load throughout the entirety of the system. Therefore, the anatomical shape adapts to the external applied forces and internal stresses distributed within the structure, enabling it to operate in unpredictable environments [1].

In contrast, most robotic systems (e.g., robotic industrial manipulators) are relatively stiff with little to no structural flexibility. These systems typically consist of rigid links and sliding or revolute joints that will compress beyond the point of failure when excessive load is applied. [2]. These could be classified as "powered systems" [3], [4], "passive systems", which do not have any electrical actuation, and use weight re-distribution, energy re-capturing, dampening and locking mechanisms (e.g., springs or shock absorbers) to alleviate strain [5], [6].

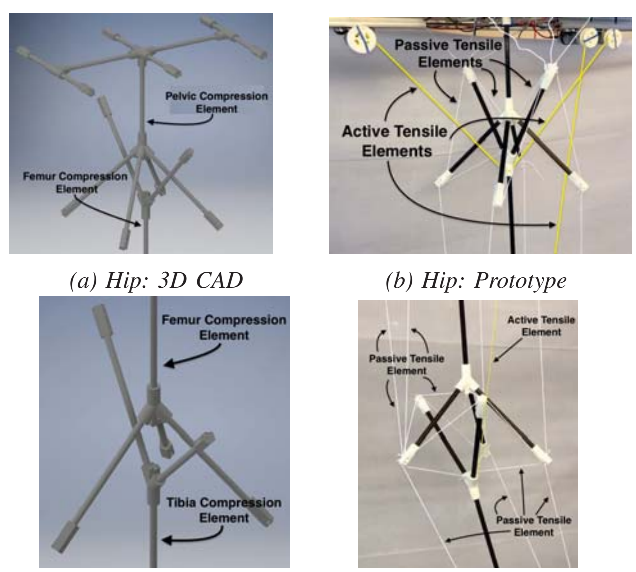
The advantage of stiff linkages is that under normal operating conditions, the behavior of these hard robotic systems is fully predictable leading to an easy (ideally analytical closed form) solution for its kinematics and dynamics [3].

Structurally soft robotic systems embody much of the opposite characteristics to those of their rigid counterparts. [7] Soft robots distribute strain and load throughout the system and therefore adapt better to unpredictable conditions (e.g., uneven terrain, unexpected impacts). However, the lack



(a) OpenSim Simulation *(b) Physical Model*

Fig. 1: Tensegrity manipulator consisting of three compression elements ("Tibia", "Femur" and "Pelvis") and two flexural joints ("Knee" and "Hip") controlled by three active tensile elements



(a) Hip: 3D CAD *(b) Hip: Prototype*

(c) Knee: 3D CAD *(d) Knee: Prototype*

Fig. 2: Prototype Design for the Tensegrity Hip and Knee Flexural Joints.

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of a rigid support structure lowers the load carrying capacity of the robot [5].

As a compromised solution, "tensegrity" (abbreviation for "tensile with integrity") robots consist of structurally compliant networks of relatively stiff compression elements suspended in a mesh of flexible tension elements. [8]

One of the major advantages of tensegrity inspired robots is that while the stiff compression elements could support the load, the elastic tension elements deform and distribute the load throughout the entire structure absorbing impacts in a similar way with passive robots. [8], [9].

Most tensegrity robots reported in the literature either travel over a relatively flat terrain and achieve locomotion as a controlled rolling by shifting their center of mass in the direction of motion [8], [10], [11] or travel through narrow passages by extending and shrinking their bodies, while changing the support points from one side of the robot to the other [12]. Biologically inspired tensegrity structures were firstly proposed by Tom Flemons [13], [14]. Anatomically influenced dynamics of gait through tensegrity robotics dates back to the TR-3 [10] where a simple triangular prism traversed with three active tensile elements. Mirletx et. al [15], [16] proposed an articulated spine that could travel rough terrain and Hustig et. al [17] proposed a quadruped robot that controls the locomotion through a coordinated oscillations of actuators on the spine and legs. Lessard et. al [9] proposed a tensegrity manipulator, which was extended by Lessard et. al [18], [19] to simulate a biologically inspired "arm" and a soft exoskeleton and by Baltaxe et. al [20] to propose several tensegrity "shoulders".

Human gait comprises five stages: *Support, Toe-off, Leg-lift, Swing, and Heel-strike*, where specific muscles activate during each stage to appropriately flex the leg. [21], [22] To simplify our notion, throughout this paper, we isolate gait into four main stages: *Heel Lift, Extension Forward, Step Through, and Equilibrium*.

Most traditional robotics models simplify anatomic joints as revolute joint constrained to one axis of rotation, however in reality, anatomical joints consist of bones, muscles, and fascia connected to form intricate, heterogeneous systems [18], [23]. Each type of tissue is unique in both its structural and material properties. Because of this diversity, anatomical joints are both strong and structurally compliant which makes the structure able to sustain impacts. Although relatively little research has been performed regarding fascia as a major component when building human-based robotic systems, its role as a connector between major compression elements in the body (e.g. bones) and major tension elements, within the body (e.g. muscles), cannot be overlooked when designing biologically-inspired joints [23].

The current paper presents a robotic (tensegrity-based) leg that has similar kinematics, gait and range of motion as a biological leg. Figure 1 (a) shows a screen capture of the OpenSim model of the proposed design, while figure 4 (f) a photograph of the physical prototype during testing. The manipulator consists of three compressive elements "Tibia", "Femur" and "Pelvis", which are connected using 2 flexural joints "Knee" and "Hip". The structural compliance of the entire system is maintained through a network of soft connective elements, which play a role similar with the one played by tendons and fascia in a biological leg. Figure 2 shows the design of the tensegrity hip (a, b) and knee (c, d). The CAD is shown on the left (a, c), while the physical prototypes during testing on the right (b, d). The compressive elements ("Tibia", "Femur" and "Pelvis") are connected using the "Passive tensile" and "Active tensile" elements. While the passive tensile elements provide the structural integrity of the joint and prevent the compressive elements from coming into direct contact, the active tensile elements provide the actuation, flexing the joints in the desired position. The proposed design uses 3 active tensile elements to achieve the proposed 4 stages of gait.

In the current research we chose to simulate the behavior of the proposed tensegrity structure (as a multi-body dynamics system) using OpenSim's biomechanics simulation environment because our ultimate goal is to design tensegrity structures that could be used to augment human gait (e.g., for rehabilitation). OpenSim allows users to develop realistic simulations of the musculoskeletal structure, generate dynamic movements and track the dynamic response of the entire system. To our knowledge, the current paper is the first attempt to simulate a tensegrity structure using a simulation package primarily intended for biomechanics modeling.

II. Structural Design

Tensegrity inspired robots are flexible structures consisting of a series of compression elements suspended in a network of tension elements. These robots are typically made of rods and cables where the rods are the compression elements and the cables are the tension elements.

The external forces and impacts as well as the forces generated by the cable-driven actuation are distributed throughout the structure via multiple load paths [18], [24], [25].

Biological systems are structurally and functionally complex: consisting of bones, muscles and connective tissue, which are compliant, durable, and adaptable to outside loads. The propose tensegrity joint is inspired by the muscular and fascial connections within the human leg, specifically the hip and knee. Since the actuation is cable driven, the proposed design has the motors located off of the robot which reduces the weight of the robotic structure.

A. Compression Elements

The proposed design consists of three compression elements (carbon fiber rods). In figure 1b the upper compression element is our equivalent pelvic bone (for one leg), the middle structure is the femur, and lower combines the tibia and fibula into one single component. Our pelvic joint, shown in figure 2a and 2b, can be interpreted as a ball and socket joint that is not confined to one axis of rotation like most conventional robotic joint designs.

This led to the interlocking *Y-shape* design for the femur and tibia compression elements that open possibilities to create flexion, extension, adduction, or abduction motion.

Our tensegrity flexural hip joint is surrounded by a complex network of tensile components that imitated functionality of muscles and other fascial connections to the bone-mimicking compression elements. This specific tensegrity structure allows the femur compression element to position forward to produce a lifting motion for the leg to begin gait. The lower compression element, the tibia, follows the same *Y-shape* design that is attached to a three-rod base of the femur composing a knee flexural joint capable of knee flexion (shown in figure 2c and 2d). Through simulations of our proposed 3D flexural joint, we were able to test the range of motion and required input force to produce the targeted stages of gait.

B. Tensile Elements

The tensile elements in our system use cables (fish-line spectra cord and bungee cord in our physical model) that belong to two categories: active and passive. All tensile elements in our system represent muscles and fascia in the leg. The active tensile elements are coupled into antagonistic pairs, allowing the structure to create motion similar to the human leg muscles. Every contraction of an active cable has an antagonistic string, which relaxes and lengthens to mimic how muscles contract and extend. Passive cables represents the biological fascial connections of the the knee joint: the tendons and ligaments. These passive tension elements are arranged to absorb impacts and be structurally compliant to external forces. This structure consists of sixteen passive pairs which elastically deforms according to the actuation of the active muscles and conform the leg back into its original position of equilibrium.

Additional passive elements play an integral role, in stabilizing the leg and absorbing shocks, to prevent the destruction of the active tensile components or the compression elements. The *Y-shaped* structures are held together by tension element cables. As the tibia segment is pulled by the motor driven cable, the knee joints are contracted causing this cable-driven actuation to initiate knee flexion. Each motion produced through the tensegrity structure was a combination of active muscles contracting and relaxing to perform motions such as gait. The pretensioned cables help the structure stay in the original formation and then adjust accordingly, as the femur or tibia and fibula are pulled, allowing the structure, to move as a unit, to provide one fluid motion of gait.

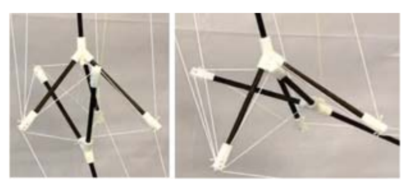
C. Modeling and Simulations

The goal of the current research is to create a biologically inspired manipulator, which could be used in the future as a starting point for a augmentative rehabilitative prosthesis. Consequently, we decided to used the OpenSim simulation environment to simulate the behavior of a virtual model of the proposed tensegrity manipulator during the desired hinged gait motion (tracking active forces, passive forces, and range of motions).

OpenSim is an open source biomechanics simulation and analysis environment developed by Stanford-based Simbios [26] to simulate the behavior of multi-body dynamic and kinematic systems, effects of surgical procedures, static optimization of models, etc. For our particular area of interest, OpenSim provides a forward dynamics multi-body dynamics solver that uses a fifth order Runge-Kutta-Feldberg integrator to solve the system's governing equations [27].

For mathematical simplicity, we chose to represent knee flexors with solely the long head of the biceps femoris and use the ilipsoas and gluteus maximus muscles as the anterior and posterior hip flexors respectively. As a guideline, we used the human body to approximate where the muscles on the knee and hip flexors should be placed on the physical model.

A custom six degree-of-freedom leg model similar to the proposed physical model (figure 1b) was built in OpenSim (figure 1a) showcasing the passive tensile elements in the physical model shown in figure 2 (b, d) were approximated in the simulation by "passive muscles". While the active tensile elements (actuation cables) in the physical model were approximated by active muscles. The passive tensile elements were set to have no ability to exert any force on the model, rather it prevents the structure from collapsing. The compression elements in the physical model were simulated by weld jointed rigid bodies (bones in a biomechanics OpenSim simulation) to form the Y-shaped connectors at the end of compression elements. Based from a human leg, the dimensions of the model are scaled up to easily visualize the knee and hip flexion as the model undergoes various stages of gait. Through the simulator, the weight of the structure is easily adjusted to the mass of the material we prototyped with, which in our case was based off of carbon fiber rods. The model was actuated by exciting the active tensile elements and the predicted kinematic behavior of the system was compared with the one of the human leg and was used to design the physical prototype of the manipulator.



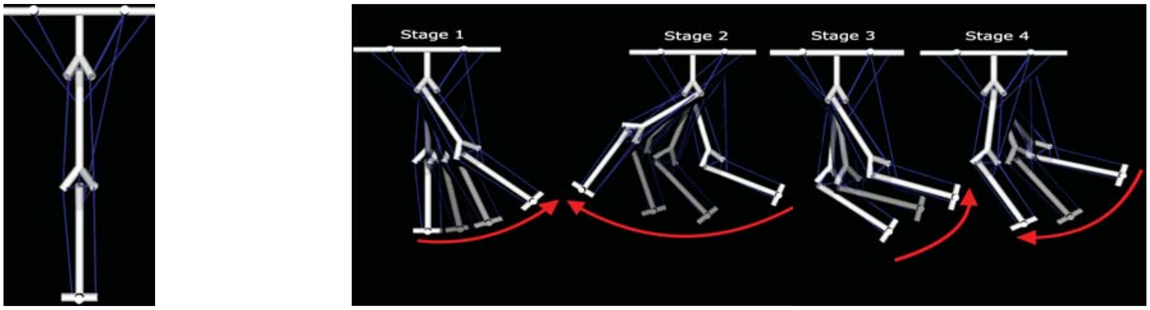
(a) Tensegrity Knee Joint: Equilibrium and Flexed Position

(b) Tensegrity Hip Joint: Forward, Equilibrium, and Backward Position

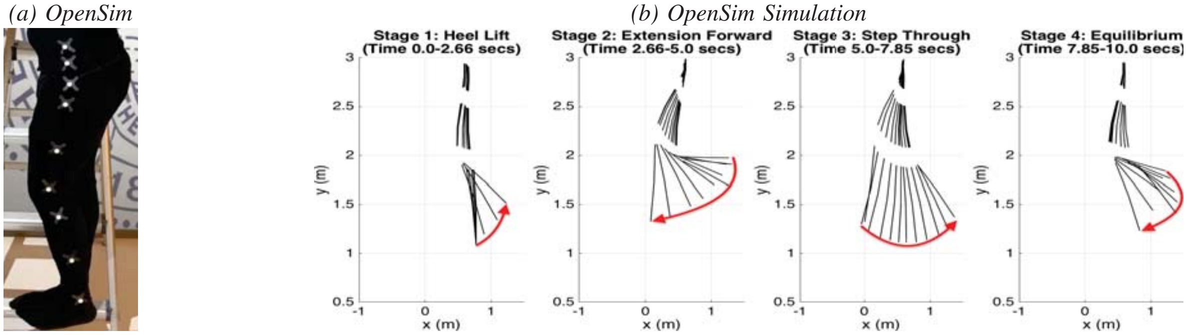
Fig. 3: Tensegrity knee and hip flexural joints in both compressed and relaxed at equilibrium positions.

III. Physical Prototype

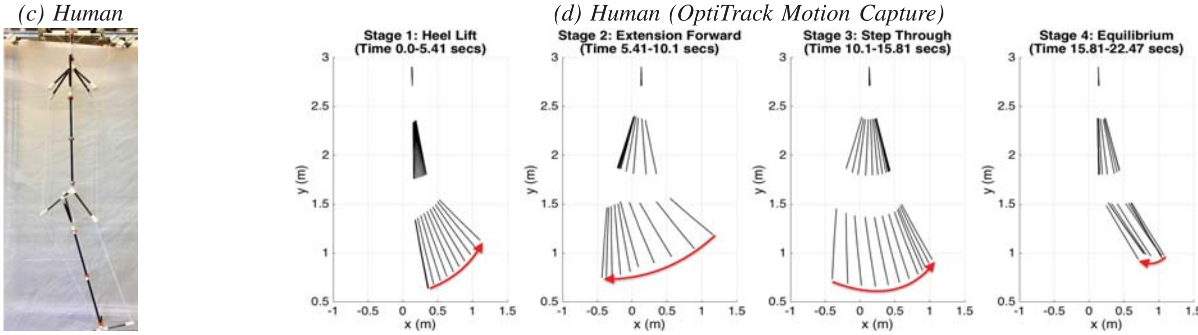
The proposed tensegrity model, (figure 1b), emulates the motions of the human hip and knee flexion. The compression



(a) OpenSim *(b) OpenSim Simulation*



(c) Human *(d) Human (OptiTrack Motion Capture)*



(e) Prototype *(f) Prototype Tensegrity Flexural Joint (OptiTrack Motion Capture)*

Fig. 4: Human Leg vs. OpenSim simulation vs. Prototype Tensegrity Flexural Joints: (left) Initial Position (right) Gait Stages 1-4

elements are carbon fiber tubes (equivalent to the bone structure in a human body), and the tensile elements are cables (muscles, tendons and fascia), which keep the structure in equilibrium through varying levels of tension.

The joints are constructed as interlocking Y-shaped compression elements (figure 2 and figure 3) suspended by a network of passive and active tensile components, which gives the tensegrity manipulator the ability to produce the specified four stages of gait: *Heel Lift, Extension Forward, Step Through, and Equilibrium*.

For simplicity, the manipulator is actuated by 3 active tensile elements, which correspond to three primary active muscles: iliopsoas (front hip), gluteus maximus (back hip), and bicep femoris long-head (hamstring). These are cable-driven tension elements, which are shortened or extended by electrical motors to achieve the motion shown in figure 4. These three main muscles are vital and must work in unison in order to flex different segments of the leg. The cable-driven actuator corresponding to the iliopsoas (front hip motor), is designed to pull the femur forward. The antagonistic active tensile element to the iliopsoas, the gluteus maximus (back hip motor), pulls the femur backwards to produce a follow through motion. The bicep femoris long-head (hamstring motor) is essential in emulating human knee flexion. Although this initial prototype robotic manipulator cannot stand on its own, it should be noted that much like the human hip, the two cables on the femur could emulate an action similar to walking. The single cable actuation is controlled by a motor, which has a single line spool, that reels in, to tighten the cable, and unwinds to lengthen the cable as needed in order to create gait. The tensegrity flexural hip joint propels the leg forward, while the hamstring releases the knee in order to create the extension forward and step through stages for a more human-like gait motion as seen in figure 4: Extension Forward. We based our goal trajectory positions off of the original five stages of gait motion, [21], [22] but decided to reduce the number of stages to four to simplify the explanation of motion.

Figure 4 demonstrates the four stages of gait trajectory that we achieved, tracked via the OptiTrack system and their optical tracking software Motive. Stage 1: *Heel Lift*, from the starting neutral position, the bicep femoris long-head muscle contracts in order to initiate knee flexion backwards. Stage 2: *Extension Forward*, the iliopsoas muscle contracts to pull the entire tensegrity structure forward, while the bicep femoris long-head slowly releases the hamstring, and gluteus maximus muscle the releases the posterior hip. Stage 3: *Step Through*, is a combination of "leg-lift" and "swing", this is when the gluteus maximus flexes the lower limb at the hip, slowly driving the entire leg backwards. The gluteus maximus continues to pull the entire structure back until it is behind the body. Stage 4: *Equilibrium*, returns the tensegrity structure back to its starting, neutral position. At equilibrium, one cycle of gait has been completed and the structure has the ability to continue repeat the gait cycle, if desired.

IV. RESULTS AND DISCUSSION

The kinematics of the proposed robotic leg as well as of the kinematics of the human leg were monitored using an Optitrack motion camera system consisting of 8 Prime 13W cameras mounted in a 3.5[m]x3.5[m]x3.5[m] cube, which capture the motion of retro-reflective markers at $60Hz$. Figure 4(c) shows the tracking markers installed on the human leg and figure 4(d) shows the motion captured during the 4 stages of gait. Figure 4(e) shows the tracking markers on the robotic leg and figure 4(f) the motion captured.

Figure 5 shows the forces applied by the three virtual "muscles" during the OpenSim simulation figure 4(a). It should be noted that during each stage of gait only one of the actuators was active, that represents the main group of muscles active in a biological leg. Figure 4(b) shows the leg motion due to the applied forces. Since the main goal of the current study was to ascertain the feasibility of building a robotic tensegrity leg that behaves similarly with a biological one, for simplicity, the forces applied on the physical model were constant (the dotted lines in figure 5). The active tensile elements in the physical model are cables that are spooled by electrical motors. The torque generated by the electrical motor was monitored and the force applied on the prototype was computed as $F_{tangential} = \frac{\tau}{r}$ (where τ is the torque and r is the radius of the spool).

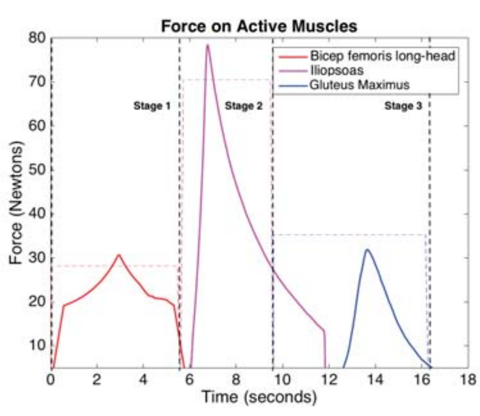


Fig. 5: The excitation applied on the 3 virtual "muscles" in OpenSim simulation environment (full line) and on the prototype robotic leg (dotted lines)

Figure 4 above shows the behavior of the OpenSim Simulation, Human leg and robotic prototype during the 4 stages of motion. However, to better understand the similarities between the three systems, figure 6 shows the predicted and measured angles between the ground and tibia (red) and femur (blue) during the 4 stages of gait. Figure 6(a) shows the angles predicted by the OpenSim simulation, figure 6(b) the angles measured using the OptiTrack motion capture system for the human leg and figure 6(c) the angles for the measured angles for the robotic prototype. The first observation is that all three systems behave similarly during the 4 stages of gait. The orientation of the tibia and femur are comparable in the 3 plots. The differences between the model and experiment in this first generation of model will be addressed by better understanding the material properties of the physical system and calibrating the input parameters (e.g., tensile element's elastic modulus, the magnitude of the input forces).

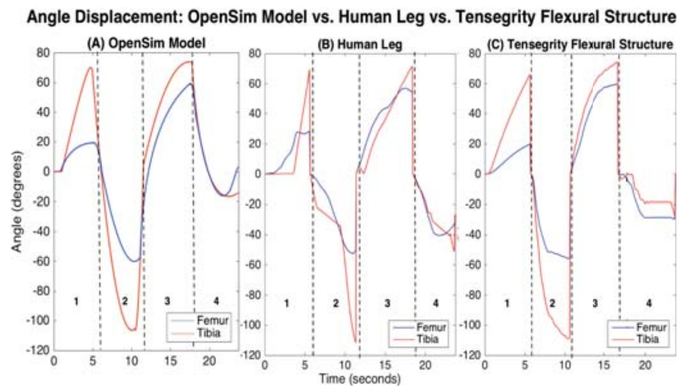


Fig. 6: Predicted and measured angles between the ground and tibia (red) and femur (blue) during the 4 stages of gait (a) OpenSim (b) Human Leg and (c) Prototype

Figure 7 shows a test of the range of motion for the 2 proposed flexural joints during full hip swing and full knee flexion. The hip joint range of motion was computed as the angle between two vectors ($\vec{u}$ and $\vec{v}$), which are aligned with the leg at the two extreme positions of its range of motion. Both vectors have the origins at the lowest point of the hip compression element and the tip at the lowest point of the femur, when the leg is in extreme position of the swing. The range of motion of the hip was computed as:

$$\theta = \frac{\arccos(\vec{u} \cdot \vec{v})}{||u|| \cdot ||v||}$$

The range of motion of the knee joint was computed in a similar manner, using the lowest point on the femur as the origin for the two vectors. It was found that the range of motion for the proposed joints are similar with the human ones. The proposed hip joint can flex $\theta_{hip} \approx 40°$, which is comparable with $\approx 30°$ for a human joint [28] and the proposed knee joint can flex $\theta_{knee} \approx 110°$, which is comparable with $130°$ for a human joint [28].

V. CONCLUSION

The ultimate goal of the proposed research is to develop assistive wearable device that maintains stability and guidance for users through rehabilitation. Robust tensegrity

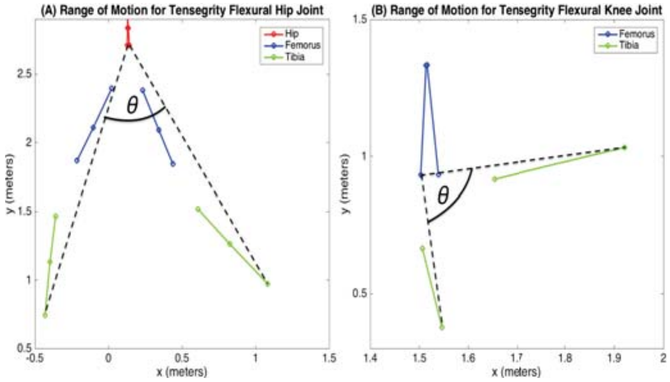


Fig. 7: Measuring the range of motion for the two robotic flexural joints.
(A) Hip Joint $\theta_{hip} \approx 40°$ (30° for a human joint [28])
(B) Knee Joint $\theta_{knee} \approx 110°$ (130° for a human joint [28])

flexural joints allow prosthetics or wearables to handle unanticipated impedances and increase joint strength with higher quality actuators or materials. This paper presents a tensegrity manipulator that consist of 3 compression elements ("hip", "femur" and "tibia") connected by two flexural joints ("hip" and "knee"). The design is inspired by a human leg, and therefore, its behavior was simulated in the biomechanics open source environment OpenSim. A prototype was built and its kinematic behavior was monitored using an OptiTrack motion capture environment and compared with a human leg. It was found that the behavior of the proposed manipulator is comparable with a biological leg. Although the proof of concept prototype presented here was not intended to carry load, it could be envisaged that future research would lead to load carrying tensegrity legs.

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