A Lightweight, Multi-Axis Compliant Tensegrity Joint

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***Abstract*— In this paper, we present a lightweight, multi-axis compliant tensegrity joint that is biologically inspired by the human elbow. This tensegrity elbow actuates by shortening and lengthening cables in a method inspired by muscular actuation in a person. Unlike many series elastic actuators, this joint is structurally compliant not just along each axis of rotation, but along other axes as well. Compliant robotic joints are indispensable in unpredictable environments, including ones where the robot must interface with a person. The joint also addresses the need for functional redundancy and flexibility, traits which are required for many applications that investigate the use of biologically accurate robotic models.**

I. INTRODUCTION

For many applications of robotic arms, flexibility and structural compliance are critical. In unpredictable environments especially, these two attributes provide robots with the ability to robustly handle stresses. Such environments are common within the fields of physical therapy and wearable robotics. The oftentimes unpredictability of human movement necessitates a robust robot that is capable of improvising to awkward and inconvenient motion. These features, however, are difficult to express through traditional robotics. Even typical series elastic actuators comply with impedances only along their axes of rotation.

Some robots, however, have already explored the concept of cable-driven robotic arms. Anthropomimetic robots like Anthrob use compressive elements that model human bones to support a cable network [1]. Cables are routed through nodes to direct tensile forces along the compressive elements. Other robots such as Kenshiro have extended these principles to an entire humanoid structure by grouping cables inbundles to better imitate muscle fibers. These muscle groups are then loaded onto a metal compressive frame where they can pull at the joints of the frame to produce around 70 degrees of freedom [2]. The emergence of cable-driven robotics has also spurred the study of the dynamics and control behind said articulation. The network of cables can be represented as an adjacency matrix with entries corresponding to connections to and from each node on the robot. D. Lau et al. illustrated that these matrices can then be operated on to approximate motion within the cable-driven structure, thus providing a method to controlling these often-chaotic robots [3].

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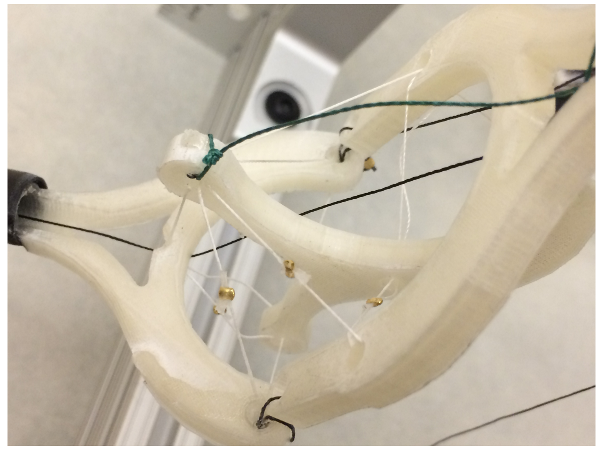

Fig. 1. A light-weight, multi-axis compliant tensegrity joint. This joint can actively control the pitch and the yaw of the arm to which it is attached by contracting and releasing strings which are paired antagonistically. These active string pairs can also be tuned for stiffness, creating a variable level of flexibility within the joint.

Our approach follows a similar philosophy to the aforementioned robots and also actuates according to a web of cables. Specifically, our robot adheres to the principles of tensegrity (“tensile-integrity”). Tensegrity robots are typically better able to to flex under stress and absorb impacts from many directions [4], [5]. These hybrid soft-rigid robots inherently resist impulses better than traditional robotic alternatives because their tension networks distribute applied forces more evenly throughout the structure. As a result, even lightweight robots can withstand relatively large impacts and loads [6].

These properties of tensegrity arms also address the need for biomimetic robotic arms to passively handle large moments applied out of phase of the main axis of rotation. Loads carried by arms can have detrimental effects on the structure of the arm if the induced moment is large enough. When these loads are applied at an unanticipated angle, unprepared systems will fail. Human arms, despite their inherent structural levers [7], observably avoid this shortcoming by complying with impacts from many different angles. This emerging tensegrity theory on biomechanics explains this phenomenon as the arm flexibly complying with impedances along multiple axes. The structural compliance observed in tensegrity robots, such as ours, mitigates this danger by mimicking human joints and distributing loads and stresses along multiple axes. In addition, the parallel nature of many tension elements within the tensegrity system prevent the failure of single components from destroying the entire structure.

Our multi-axis approach (Figure 1) also has the additional bonus of being able to articulate the arm around an atypical axis. Although anatomically correct human arms generate yaw motion through shoulder muscles, our robotic joint is able to generate this movement directly from the elbow. Multi-axis movement in the elbow both protects the joint from imposed moments and allows it a larger range of motion.

The flexibility and structural compliance in our particular arm can be attributed to the tensegrity joint we have developed. Unlike a simple hinge, this joint features two independent axes. Actuation along these axes control the pitch and the yaw of the end-effector of the arm. For each axis, we have a pair of antagonistic cables which actively control motion in opposing directions around a particular axis. In addition to these actuated cables, there are five additional pairs of antagonistic, passive cables in the joint for stability and force distribution. The pairing scheme of our tensegrity joint is inspired by the muscular and fascial connections within the human elbow. Because all actuated movement of the joint is generated by pulling and releasing cables, the motors can be located off of the robot itself. This lightens the weight of the robotic arm, allowing it to be actuated more easily.

In this paper, we first discuss the background that demands a more flexible and compliant robotic joint. Then, we present the design of our system: both the specific layout of the elbow and the methods to control it. We then show how we use the NASA Tensegrity Robotics Toolkit (NTRT) simulator for rapid design and testing of tensegrity joints. Next, we illustrate the capabilities of our constructed model as well as the hardware we have used to verify our simulated results. We conclude with a summary of our contribution as well as the focus of future work.

II. BACKGROUND INFORMATION

A. Biological Inspiration

In human joints, bones, muscles, and fascia connect to form intricate, heterogenous systems. Each type of tissue is unique in both its structural and material properties. Because of this diversity, human joints support many functions which range in strength, precision, and support. These joints are also simultaneously durable and structurally compliant, improving their ability to react to impedances. Although relatively little research has been performed regarding fascia as a major component when building human-based robotic sytems [8], its role as a connector between major compression elements in the body (i.e. bones) and major tension elements within the body (i.e. muscles) cannot be overlooked when designing biomimetic joints. Robots that possess these abilities can likewise accomplish numerous, and often unanticipated, tasks.

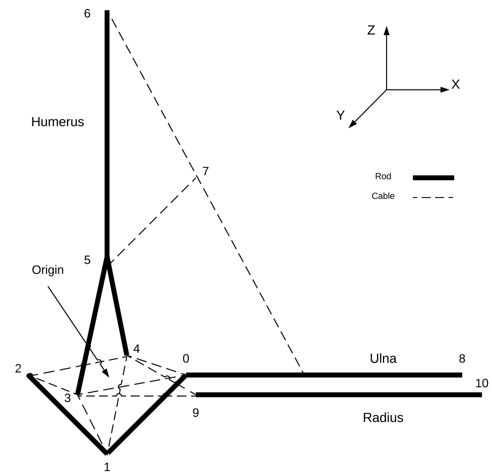

Fig. 2. The design for the first passive structure simulated. This was based upon Scarr's passive tensegrity elbow [10]

B. Tensegrity Structures and Robotics

Our robot is based upon the tensegrity design paradigm: a biologically founded method of designing both passive and active structures. Tensegrity structures are composed of two main components: compression elements and the tension elements that connect them in suspension. In a traditional tensegrity structure, compression elements are simple rods, whose end points act as hubs through which tension elements, such as cables, pass. As a result, tensegrity structures invariably feature no two compression elements directly contacting each other. The resulting structure is flexible and structurally compliant. Impact forces are distributed throughout the entire structure, decreasing the often detrimental consequences of strong mechanical impulses. As a result, sudden impedances can be handled relatively elegantly and passively by the structure itself. In the context of a tensegrity arm, this means that joints can better resist the torques applied by potential levers (such as the component analogous to a forearm).

As research into tensegrity structures has increased, so has the demand for active tensegrities which model specific joints within the human body. Turvey and Fonseca [9] discuss the need to build and study active tensegrity joints of the elbow based upon the passive elbow design of Scarr [10]. In this design, the elbow is treated as compression elements (i.e. metal rods) held in equillbirium by string. The compression elements are meant to emulate bones and the strings to emulate muscles and fascia. Although this model does not heavily focus on anatomical accuracy, it illustrates that the basic hinge seen in traditional elbow models can be redesigned with the tensegrity principles.

C. Structural Compliance in Robotic Joints

Traditional robots are rigid and often cannot bear significant weight when loaded at an unanticipated angle. As a result, they often lack the ability to resist impedances from unpredictable directions. This is an especially important problem since many traditional robotic joints have only one axis per joint. For robots in environments where not every impedance can be predicted, like when imitating human activity, the structure of that robot must be able to endure unanticipated forces. This handling can be done actively through intelligent control or passively through structural compliance.

Series elastic actuators are one solution to passive impedance resistance. These actuators are built with an elastic, like a spring, along their axis of actuation. These springs serve as a cushion which can resist sudden strains, thus preventing system failure. One downside of these components is that they are only able to resist strains along their axis of actuation. In systems where forces may not necessarily be applied along this axis, the internal spring does little to mitigate the shock.

Other solutions to the problem of structural compliance lie in the materials used for the actuator. Pneumatic actuators, like McKibbens artificial muscles, inflate and deflate elastically [11]. In this regard, they function very similarly to the skeletal muscle found in many animals. Some soft robots are constructed using soft materials, such as dielectric elastomers [12]. These actuators distribute stresses throughout their structure well, but are limited in their flexibility.

While these solutions seek to improve the compliance of actuators, the tensegrity principle offers a solution on the structural level. They are designed to be passively stable and since all tension elements are connected in a network, each strain on a tension element propagates to the other tension elements. As a result, robots which adhere to the tensegrity principles can resist impedances in multiple dimensions.

III. SYSTEM DESIGN AND CONTROL

To construct the tensegrity structure behind our lightweight, multi-axis joint, we defined the characteristics and placement of the compression elements and the tension elements. After multiple iterations of design, we developed the following structure which enables actuation along multiple axes within a single elbow joint.

A. Compression Elements

The designs of the three compression elements (made of plastic and carbon filament, in our prototype) in the tensegrity elbow are inspired by human arm bones. Our elbow, however, segregates compression elements slightly differently than true bones in the human arm. The first compression element mimics the humerus and is located above the elbow joint itself. The compression element within the tensegrity joint is analogous to the olecranon (the hook end of the ulna). The third and final compression element condenses what would be the radius and the ulna into a single piece, forming the ”forearm” of the tensegrity arm. This particular partitioning of compression within the arm was determined after iterating over multiple designs. This design alone featured a centralized joint within which multiple degrees of freedom were realized. To achieve this, we diverted from the true anatomy of the arm by “dettaching” the olecranon from the forearm. The rationale behind this choice was that we found a way to maintain the observed function of the olecranon (i.e. connecting the humerus to the forearm) while supplying the arm as a whole with the mechanisms necessary to implement a two degree-of-freedom joint with passive elements for stability. This added ability does not exist within biological elbows (such movement is performed by shoulder, back, and chest muscles), but it does enhance the capability of our constructed arm. These compression elements define the overall structure of the arm while anchoring and routing the tension elements.

B. Tension Elements

The tension elements (strings, in our physical prototype) in this design can be segregated into one of two categories: active and passive.

Active strings are coupled into antagonistic pairs, mimicking how many muscles, including those in the human arm, are organized. For every contraction of an active string, its corresponding antagonistic string will relax and lengthen. In the biceps and triceps specifically, these two muscles coactivate each other. As a result, the flexure of one muscle modulates the workload of the other muscle, allowing for variable strength and precision in movement along that particular degree of freedom.

The passive strings in the model approximate the fascial connections of the elbow as well as the tendons and the ligaments. There are five pairs of these passive tension elements, which are arranged to absorb impact from a large variety of angles. These tension elements elastically deform according to the actuation of the active muscles and spring the arm back into its original position of equilibrium. Although these strings are never directly controlled by a motor, they play a crucial role in stabilizing the arm as a whole. The added tensile connections also abosorb shock, preventing the destruction of the active tensile components or even the compression elements.

IV. SIMULATION

A. NASA Tensegrity Robotics Toolkit

To simulate our tensegrity joint, we used NASA's Tensegrity Robotics Toolkit (NTRT). NTRT is an open-source simulator for the design and control of tensegrity structures and robots which has been built ontop of the Bullet Physics Engine (version 2.82)[1]. Real-time video can also be recorded with NTRT.

In order to create structures within the toolkit, a set of builder tools are utilized which specify geometric rods and connecting cables as a set of Cartesian coordinates. These structures can then be specified as substructures and manipulated in three dimensional space as necessary to build complex tensegrity structures (Figure 3).

$$F = -kX - bV \quad (1)$$

[1] Additional information about NTRT can be found at http://irg.arc.nasa.gov/tensegrity/NTRT

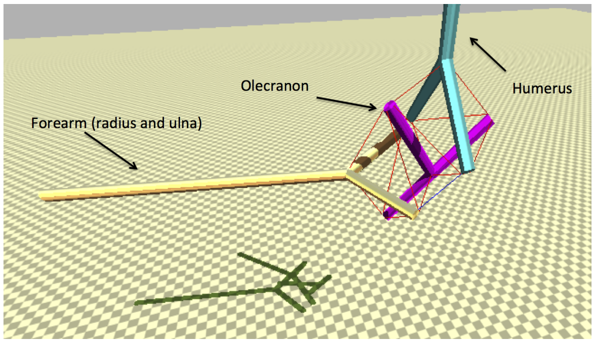

Fig. 3. An elbow constructed in NTRT. The bold colored cylinders are compression elements and the thinner red lines connected to their end points are the cables (tension elements).

Within the simulator, cables are modeled as two connected points whose medium lengthens and shortens according to Hooke's Law for linear springs with a linear damping term as well (Equation 1). Cable control is dictated by functions within a controller class, meaning that the exact length of the cable can be set at each timestep according to a control policy. Real-world limitations, such as the max acceleration of the motor used and the target velocity of cable lengthening are added to the simulation as well at the structural level. In addition, maximum and minimum lengths can be applied to each individual cable to prevent unnatural deformations. These features assert that the robot in simulation is never given extraordinary means to accomplish its goal. The use of NTRT has already been shown in previous papers to have produced accurate statics and dynamics for SUPERBall, a tensegrity rover designed for extraterrestrial missions [13], [14]. As a result, these simulated robots are able to retain realism.

In addition to modeling the physical aspects of tensegrity structures, NTRT is also useful for testing control policies. A controller, whether that is a simple, closed-loop periodic function or a more complex machine learning algorithm, can dictate the desired forces in each of the simulated cables, and consequently the desired lengths of each of those cables. By also implementing restrictions on cable lengths, the full reach of the arm can be tested via simulation. These simulated models can illustrate the flexibility and compliance in each variation of the robot as they form different poses.

The simulation can also track changes in string lengths similar to how the encoders in the physical prototype measure change in string length. This common feature means that control policies developed in simulation are more easily portable to the physical prototype.

V. RESULTS AND DISCUSSION

A. Actuation Capability

With our joint, we have demonstrated the ability to rotate an arm around two axes independently (Figure 4). By contracting and releasing tension elements, we can change both the pitch and the yaw of our tensegrity arm.

Pitch motion is achieved by changing the lengths of the strings in the antagonistic pair of strings highlighted in Figure

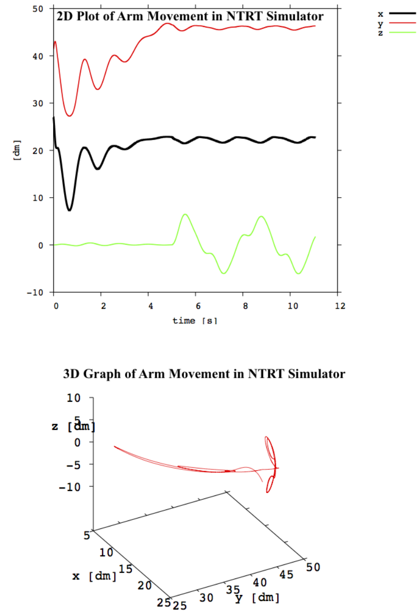

Fig. 4. The movement of the end-effector of our simulated tensegrity arm with respect to time. The plotted path illustrates the effect of the joint as it demonstrates pitch motion and then yaw motion. Since the actuation of tension elements effect their neighboring tension elements easily, oscillations propagate quickly when moving tensegrity structures.

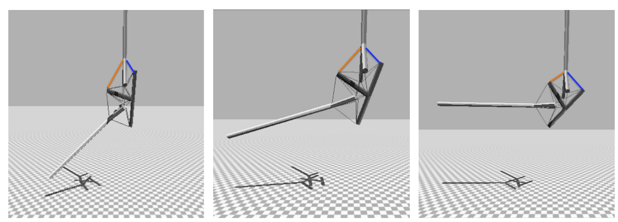

Fig. 5. A simulated tensegrity elbow demonstrating pitch movement. Two cables (orange and blue), mimicking the bicep and tricep in function, act as the antagonistic pair responsible for generating this movement.

5: one string is shortened while the other is elongated. The motion shown in this figure mimics bicep contraction and tricep extension.

The yaw of the tensegrity arm is a function of the lengths of the strings in the antagonistic pair of strings highlighted in Figure 6. one string is shortened while the other is elongated. Unlike the demonstrated pitch movement, yaw motion in the elbow does not have a true anatomical corrollary. Yaw rotation in the human arm is not generated in muscles which connect to the elbow joint, it is instead generated at the shoulder joint. This gives our tensegrity elbow greater mechanical capability than biological elbows in that aspect.

B. Hardware Validation of Software Models

After developing the software models of our tensegrity joint, we proceeded to validate these results by constructing physical models. These models were mostly constructed by 3D-printing compression elements out of polylactic acid (PLA) and by connecting them with either simple string or braided spectra string. The result was both passive models

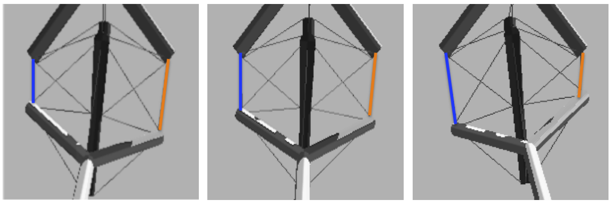

Fig. 6. A simulated tensegrity elbow demonstrating yaw movement. Unlike pitch movement, yaw movement is not generated in the elbow, but instead in the shoulder in an anatomically accurate human arm. The antagonistic cable pair is highlighted blue and orange.

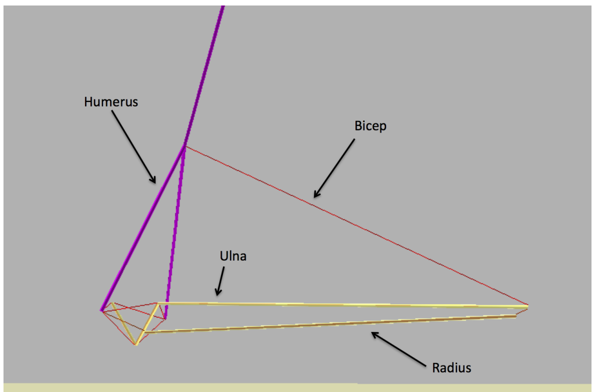

Fig. 7. The simulation off of which the initial passive physical prototypes were based. This was influenced by the designs in Figure 2

and an active model, all of which demonstrated the structural robustness expected of tensegrity structures.

1) Passive Models: The passive models were first constructed to verify the claims made by Scarr [10]. These models did not use motors for actuation, but could still be manually controlled by pulling on specific strings. Initially, we recreated a simulated version of Scarr's designs in NTRT (Figure 7) inspired by the designs from Figure 2.

In the first generation of passive models seen in Figure 8, an elbow joint was constructed using string and elastic bands. This simple model succesfully demonstrated the ability to move the forearm of our model while still applying external stresses, forcing the model to comply as it moves.

The second model illustrated a miniaturized elbow joint and strings that were routed through the upper compression element. A basic end-effector was added to this robot that could carry a small payload.

In the third model, we disjointed the end of our forearm (most closely resembly the olecranon in a true elbow). This new model featured an addition degree of freedom in our joint for moving the forearm (yaw). All active movement in this model can be controlled through 4 strings, all of which are routed through the top compression element.

TABLE I
WEIGHT CONSTITUTION OF THE ACTIVE PROTOTYPE

PLA Arm (g)	Both Motors (g)	Combined
55.6	416.6	472.2

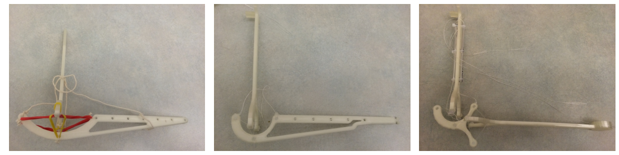

Fig. 8. Three iterations of passive tensegrity elbow joints. These prototypes demonstrate the flexibility and compliance of the tensegrity elbow without using motors.

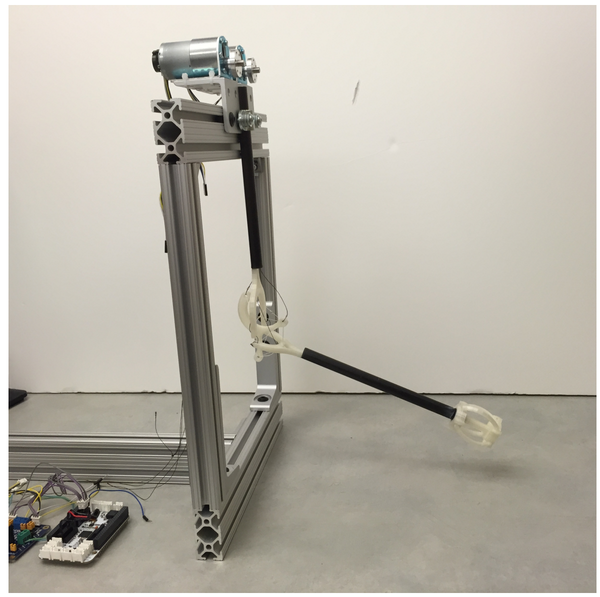

Fig. 9. The physical prototype of our tensegrity elbow. Compression elements are composed of 3D-printed Polylactic Acid (PLA) and tension elements are composed of spectra braided fishing line. This model is actively controlled by motors seen mounted off of the robot and onto the chassis.

2) Active Model: The hardware prototype (Figure 9) also reaffirmed the ability of keeping the arm lightweight. A reduction in weight means that the arm is more reactive to actuation and that it is inherently safer. For applications that involve or interface with people, safety is an important factor. The motors were still able to actuate the arm despite being off-loaded onto the chassis. In this prototype, the motors constituted 88% of the total mass of the robot (Table I). This reduction in weight means that less power is required to operate the tensegrity arm.

VI. CONCLUSION, CONTRIBUTION, AND FUTURE WORK

By expanding upon the ideas central to the passive tensegrity elbow model constructed by Graham Scarr, we have developed an accurate software model of a new tensegrity joint. We have further improved this model by discovering a method in which to construct the tensegrity joint such that is has multiple-axes of actuation. We have also found a way to lighten the weight of the joint and the arm, thus making them more reactive to actuation and safer to operate around. These added features better equip the tensegrity elbow joint for use as an articulation in bio-inspired robotic arms. Our software model also provides a manner in which to test both the mechanical properties of our robotic joint as well as the efficacy of different control policies. This simulator produces real-time video of tensegrity joints functioning according to the control policies they have been given. We have validated these simulations by constructing physical prototypes, both passive and active. We have also begun to experiment with complex controllers, such as ones governed by neural networks, to tackle the difficult problem of efficiently and effectively actuating an arm with precision and efficiency.

A. Applications in Physical Therapy and Wearable Robotics

The flexibility and structural compliance seen in these robots are valuable traits when constructing human-oriented devices. For the field of upper-limb physical therapy and prosthetics, compliant and durable systems with tune-able strength and support are essential. Many people who own body-powered or electric-powered prosthetics report that their current devices lack the necessary mobility and dexterity required to perform basic tasks [15]. Users with body-powered prostheses in this study also cited poor cabling as a major concern. Emphasizing robust joints in future wearable robotics can potentially address this complaint among upper-limb prosthetic users. Robust joints will allow prothetics to handle unexpected impedances and higher joint capability, properties which tensegrity joints have illustrated.

In addition, these improvements could be applied to rehabilitative technology as well as prosthetic limbs. By better understanding the underlying anatomy and its dynamics, wearable devices, such as exoskeletons, can better harmonize with users as they perform bilateral stroke rehabilitation [16]. As a result, our light-weight, multi-axis joint could be an excellent candidate for future study of wearable robotics as they apply to stroke rehabilitation. These discoveries may show the potential for our tensegrity elbow to model biological joints in a new manner.

B. Future Work

Our future work will explore how to more effectively control these tensegrity joints and others through machine learning. Although simple control is currently possible, high level control decisions, such as moving an end-effector to a position in space while minimizing wobble within the tensegrity structure remains an open question. High level control could enable the tensegrity elbow to precisely and efficiently manipulate the arm into complex poses by using a generalized algorithm.

In addition to improved control, we will also investigate the possibility of combining this tensegrity joint with other joints in order to construct a more complete and biologically accurate arm. Finding a better way to model the shoulder as a tensegrity, for example, could significantly improve the functionality of our current arm without sacrificing any of the capability of this elbow joint.

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