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SIMULATING THE HUMAN SHOULDER THROUGH ACTIVE TENSEGRITY STRUCTURES

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1 Abstract

The flexibility and structural compliance of the biological shoulder joint allows humans to perform a wide range of motions with their arms. The current paper is a preliminary study in which we propose a structurally compliant robotic manipulator joint inspired by the human shoulder joint, which elastically deforms when actuated. The tensile actuation is similar to the contraction and extension of biological muscles. We present four separate models for the shoulder: a simple saddle, a complex saddle, a suspended tubercle, and interlocked tetrahedrons. The analysis explores the dynamics in each design to compare the inherent advantages and disadvantages, which gives insight into the design and development of better interfaces for biologically inspired human-oriented robotics.

2 Introduction

Traditional robots are relatively stiff, and each degree of freedom requires a dedicated actuator. Multi-DOF, soft robots have been proposed [1]. Although soft robots are versatile and can achieve intricate motions, the load caring capacity of such systems is usually limited due to the complete lack of rigidity. One compromise to this issue is *tensegrity robots*, which merge aspects of both rigid and soft robots.

Tensegrity robots consist of *compression elements:* relatively rigid structural elements, which are usually under compression and supported by *tension elements:* flexible elements which are in tension. It is interesting to note that this scheme exists in the musculoskeletal system of most vertebrates. The structural elements (e.g., bones) are compressed, supported by tendons and actuated by muscles. Since this template proved successful for a large variety of biological systems, it is has recently been a large inspiration for many of our designs.

Our simplistic designs offer a number of beneficial properties. Using solely compression elements suspended in a network of tension elements creates an inherently flexible structure, which most current traditional robots lack. As a result of the network of tensile elements, applied forces are distributed throughout the structure via multiple load paths [2]. Because of this redistribution of forces, a non-axial force that could harm a rigid robot would be much less likely to harm a tensegrity robot.

Biological systems are structurally and functionally complex, consisting of bones, muscles and connective tissue. Therefore, they are structurally compliant, but durable and adaptable to outside loads. The primary principle of tensegrity is the ability to flex and absorb non-axial impacts [3] [4]. Due to the elastic components, during an impact, forces are distributed throughout the tensegrity structure lowering the stresses on individual components.

Figure 1 shows a schematic representation of a human shoulder. The bones are drawn with black lines, while the groups of muscles are represented in pastel colors (red, yellow and blue). It should be noted that the interlocking structure of the shoulder provides the strength as well as the versatility and compliance under load.

This paper represents a first step towards designing a biologically-inspired tensegrity manipulator. Section 2 explains the modeling approach, section 3 presents some preliminary results and section 4 shows the early prototypes, which were designed to implement and validate the control algorithms developed in section 3.

3 Modeling Approach

In the current paper, the compression elements of the tensegrity structure are assumed to be rigid and actuated by elastic flexible cables. We have simulated the behavior of several tensegrity, biologically-inspired shoulder models using NASA Tensegrity Robotics Toolkit (NTRT) [5,6].

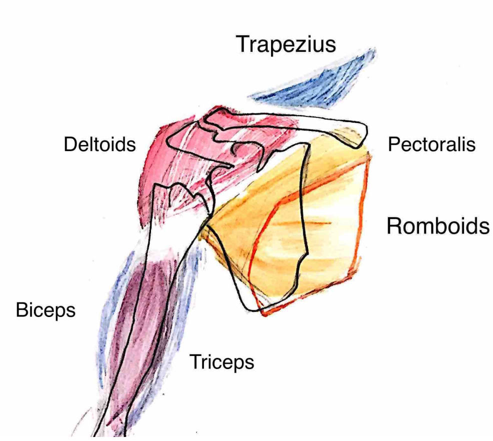


FIGURE 1. The schematic representations of the group of muscles in a human shoulder along with the involved bones.

The solver used within these simulations is Bullet, a physics engine capable of simulating contacts and impacts between elastic and rigid body dynamics [7]. This simulation environment uses a Cartesian mapping system to describe the geometrical shape of the tensegrity structure, Euler-Lagrange formulation to describe the dynamics and Hooke's law to predict the elastic forces developed inside the elastic cables [8] [9]

The force f_i applied by cable i to the elastic structure can be computed as:

$$f_i = \begin{cases} k_i(x_i - l_i) + b\dot{x}_i & x_i > l_i \\ 0 & x_i \leq l_i \end{cases} \tag{1}$$

where k_i is the spring stiffness, b_i is the linear damping, and l_i is the initial length of the cable and x_i is the length of the deformed flexible cable.

The length of each cable during the simulation is computed as:

$$x_i = ||\mathbf{p}_{i,0} - \mathbf{p}_{i,1}|| \tag{2}$$

where $\mathbf{p}_{i,0}$ and $\mathbf{p}_{i,1}$ represent the position vectors of the two ends of elastic cable i.

In the tensegrity simulation the cables provide not only structural integrity, but also the ability to actuate the elastic structure. Actuation is obtained by changing the undeformed length (l_i) of the cables in the NTRT simulation environment. Practically, this could be achieved by reducing the length of active cables using a brushless DC motor [10] [9]. In the simulation below this actuation technique was used to simulate yaw, pitch, and roll movements of the manipulator.

A controller in the NTRT environment is a time dependent function, which could be trained using a machine learning algorithm to alter the length and tension of actuated cables. This approach is biologically influenced and represents distributive and hierarchical displacements. The implemented controllers are adapted to individual members of a tensegrity structure, making our equation for tension scalar and compatible with controlling both the length and tension with the following equation: [11] [9]

$$T = T_0 + K(L - L_0) + B(V - V_0) \tag{3}$$

where T is the tension setpoint, To is a tension offset, K is the position displacement between the cable's length L, and V is the control input from the CPGs or sinusoidal input waves. [12]

3.1 Proposed tensegrity manipulators

To test the capability of the proposed method to simulate biologically inspired manipulator shoulders, in the current paper we modeled four possible shoulder configurations.

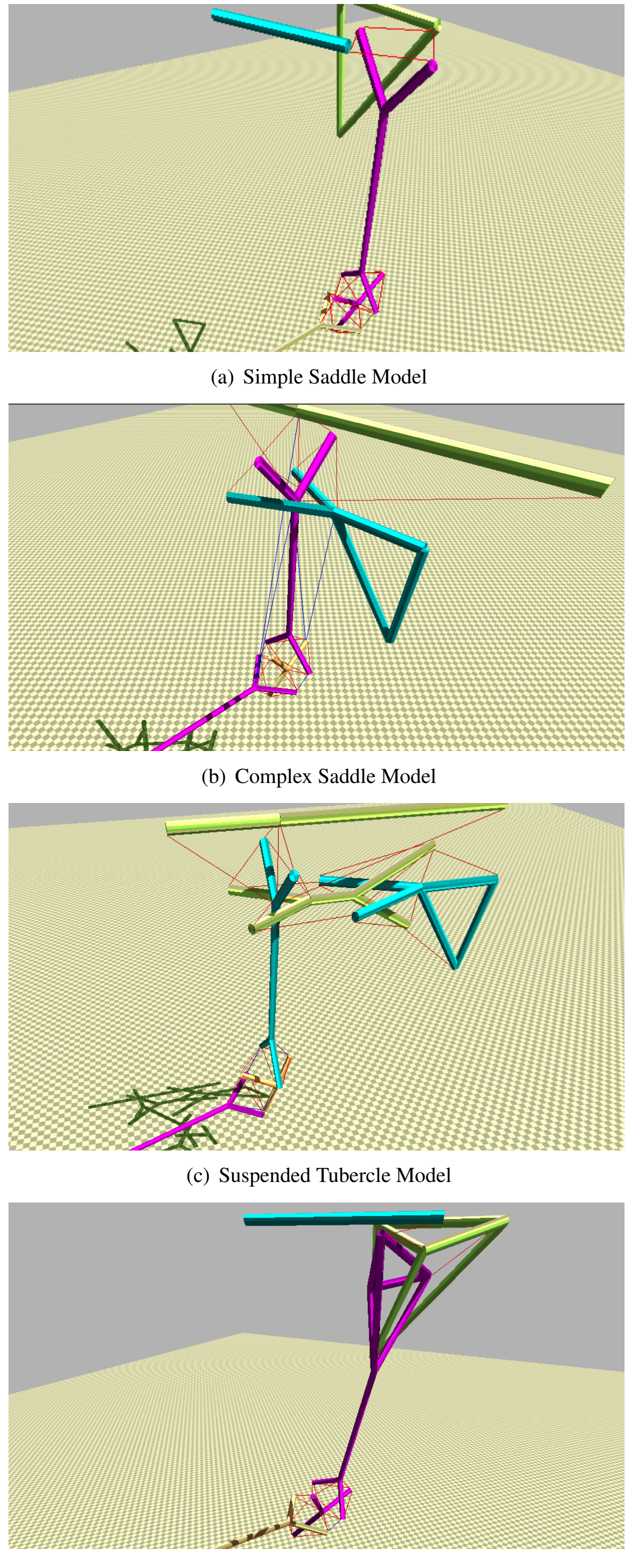
Figure 2(a-d) shows four screen-shots of the simulation environment. The thick lines represent the compression elements and the thin lines the flexible tension cables. Although the focus of the current paper is on understanding the behavior of a shoulder–inspired manipulator, in figure 2 all four models were connected with an elbow model, which was proven to approximate some of the flexural and yaw capabilities of a human arm [13].

(2a) *Simple Saddle Model*
The Simple Saddle Model, shows the simplest form of an anatomical representation of the human shoulder. The most significant advantage of this model is its simplicity (very limited number of components).

(2b) *Complex Saddle Model*
The Complex Saddle Model is the most anatomically correct model we propose. The model consists of a relatively accurate representation of a clavicle bone (yellow in the figure), which is connected with a scapula bone (turquoise in the figure) and a humerus section (magenta in the figure). The active cable elements in this model mimic the biceps, triceps and deltoids.

(2c) *Suspended Tubercle Model*
The Tubercle model is our most structurally complex shoulder model proposed in the current research. This model consists of a clavicle bone (yellow horizontal element in teh upper part of the figure), a scapula (the horizontal turquoise element), acromion (yellow, double "Y" element) and humerus head (vertical turquoise element).

(2d) *Interlocked Tetrahedrons*
The Interlocked Tetrahedron tensegrity shoulder is the least bio-



(a) Simple Saddle Model

(b) Complex Saddle Model

(c) Suspended Tubercle Model

(d) Interlocked Tetrahedrons

FIGURE 2.

logically inspired model proposed in the current research. However, due to the manufacturing simplicity and mechanical stability [14], this design is one of the 2 computer models we have prototype and briefly present in the section 4.

The interlocked tetrahedrons allow for the compression elements of the shoulder to extend further outward, downward and retract into a smaller form(in comparison with the models shown in 2)

4 Simulation results and discussions

The ultimate goal of investigating the behavior of a bio-inspired tensegrity structure is to design a light, flexible and versatile manipulator. One characteristic of a flexible structure, is that it has the freedom to behave in an unconstrained manor due to vibrations after and during actuation. Fully directing its path requires alternative forms of control to operate the cables and replicate the actuation of biological shoulders.

The NTRT modeling environment is an optimal tool for the first level validation of the mechanical prototyping of each design. To understand the advantages and disadvantages of each tensegrity shoulder, each prototype (Figure 2) was coupled with an identical tensegrity elbow [13]. To test the response of the flexible shoulders, each was actuated by contracting one tension cable (the equivalent of the "biceps" muscle), to monitor the trajectory of the end effector. Figure 3 shows the bicep length as a function of time, which was used as an the input to the NTRT model.

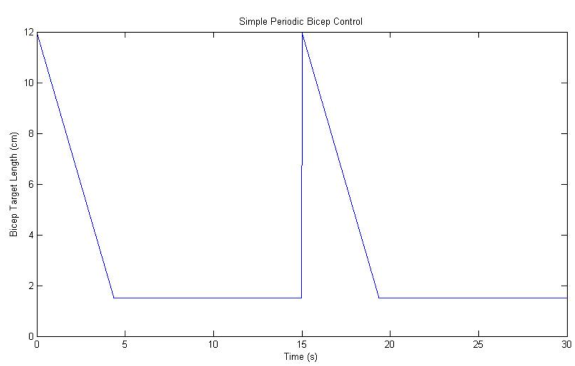
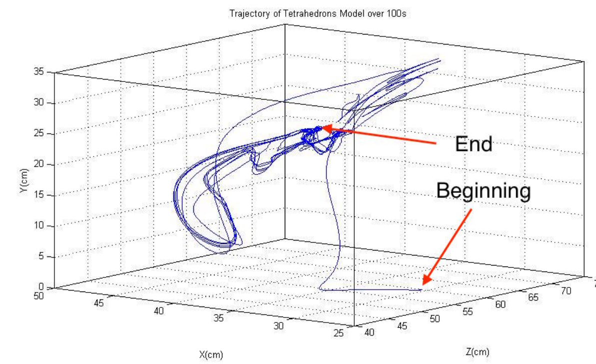
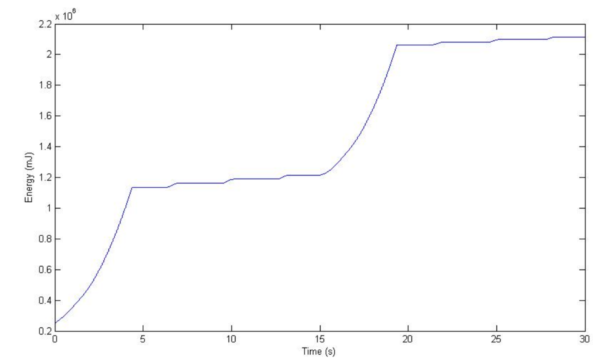


FIGURE 3. The control policy to illustrate movement in the tensegrity arm due to bicep motion

Figure 3(a) shows the trajectory of the end-effector of the tetrahedrons model for the first 30 seconds of simulation. It should be noted that the simulation shown in the figure it is the results of a single actuator. In reality (e.g., in a biological system) several groups of muscles are counterbalancing each other



(a) The trajectory f the end effector during simulation



(b) Total energy spent

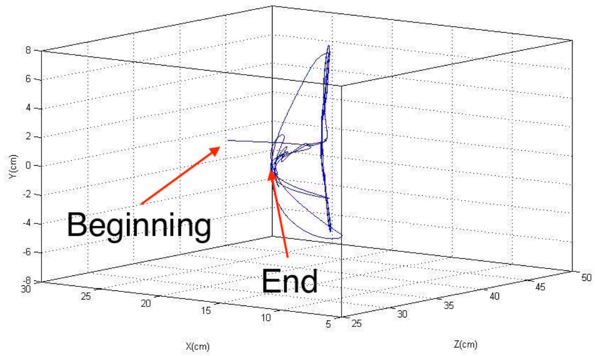
FIGURE 4. Interlocked Tetrahedron shoulder: Trajectory of the end-effector during actuation and the total energy spent (for 100s simulation)

- resulting in a smooth, viscoelastic damped behavior. However, for this, the model proposed here must be adapted to include a machine learning algorithm.

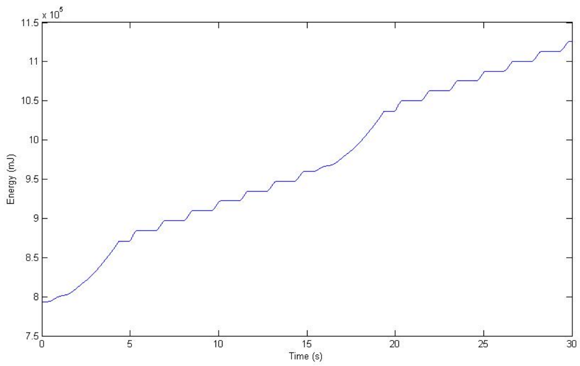
Figure 3 shows the actuation strategy for the current test. It should be noted that although this condition seems simple, a natural muscle never actuates alone. Muscles act in antagonistic pairs to provide the main actuation while other groups of muscle provide the stability, suppressing parasite vibrations and global oscillations. Since in this early "virtual experiment" we have only actuated one muscle, we expect that the end-effector's oscillations would be significant.

Figure 4(a) shows the trajectory of the end effector coupled to an "Interlocked Tetrahedrons" shoulder design during the first 100 seconds of simulation, while figure 4(b) shows energy consumption during the same period. It should be noted that the 2 actuation events in figure 3 could be found in 4(b) as well: each one provides additional energy to the flexible system.

Figure 5shows the trajectory of the end effector coupled to an "Complex Saddle shoulder" shoulder (a) during the first 100 seconds of simulation, while (b) shows energy consumption during the same period.



(a) The trajectory f the end effector during simulation



(b) Total energy spent

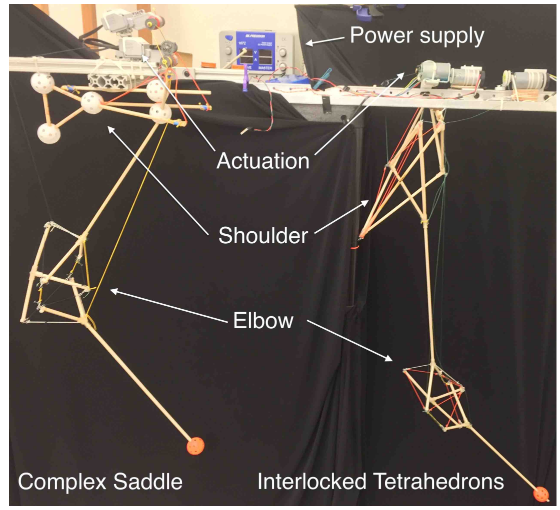
FIGURE 5. Complex Saddle shoulder: Trajectory of the end-effector during actuation and the total energy spent (for 100s simulation)

4.1 Physical Models

Figure 6 shows the early physical prototypes, of the Complex Saddle model and Interlocked tetrahedrons. The compression elements are constructed using balsa wood and 3D-printed connectors (6b). Passive tension elements are made up of colored shock cording, chosen for its elasticity and pre-tensioned for stability. Active tension elements are made from fishing line. To actuate these lines, we have programmed an Arduino controller. We are using small motor-driven reels to shorten and lengthen the active components.

5 Conclusion

This paper proposes several models of flexible bio-inspired tensegrity manipulators. The main advantages of the proposed approach is that a tensegrity manipulator could potentially be significantly more dexterous than a traditional "rigid" one and carry more load than an entirely "soft" manipulator. The main disadvantage of a tensegrity manipulator is that it would require advanced control techniques (e.g., machine learning) to actuate reliably. Future goals include applying the techniques observed



(a) Complex Saddle model (left) and Interlocked Tetrahedrons model (right)

(b) 3D printed joints used to manufacture the "rigid" sections of the tensegrity structure

FIGURE 6. Actuated prototypes: two different shoulders

here towards creating upper-arm tensegrity wearable robots or prostheses and enforcing our controlling capabilities via machine learning.

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