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Capabilities of Conductive Thread Twisted-and-Coiled Actuators as Sarcomeres

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ABSTRACT

Twisted-and-coiled actuators (TCAs) have shown great potential as an artificial muscle for robotics in terms of material cost and production expenses. However, the power-to-force efficiency of these artificial muscles falls short of biological muscles. Soft robotics takes inspiration from biological organisms for more natural movement, and biological mimicry helps increase the efficiency of robotics. Taking inspiration from how sarcomeres are structured in natural muscles, improvements in the energy efficiency of artificial muscles are possible. In this paper, an experiment was designed to analyze the effects on the efficiency of emulating biological sarcomere structures in artificial muscles. Specifically, this experiment used a load cell to capture and compare data between conventional and biological-emulating applications of TCAs under concentric contraction conditions. The experiment used silver-plated sewing thread to fabricate TCAs. While many works have attempted to increase efficiency by changing the material of the TCA, we show that it is also possible to increase efficiency by changing the structure of the TCAs, and the electrical circuit that connects the TCAs. The resulting TCA was approximately seven times as effective as its unchanged counterpart. Additionally, for the same amount of input power, the changed TCA's contraction is approximately three times as much force as the unchanged TCA. Optimizing the resulting efficiency of this new TCA requires further study of the thermoelectrical properties of the material used for the TCA. Nevertheless, the increased efficiency of changing the structure of the TCA to mimic biological muscles may be worth a new endeavor.

INDEX TERMS

Artificial muscles, conductive thread, sarcomeres, twisted-and-coiled actuators (TCA).

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I. Introduction

Artificial muscles are synthetic smart materials or structures that seek to emulate natural movements or even surpass natural muscles' capabilities, including shape-memory alloys/polymers and pneumatics [1]. While shape-memory alloys/polymers allow for natural-looking movement, their fabrication process is expensive [1]. Pneumatics and electric motors are also viable options for their energy efficiency. However, their bulky components make it difficult to integrate with robots and prostheses that have biologically inspired shapes and functions [2].

Twisted-and-coiled actuators (TCAs) are another type of artificial muscle that accurately mimics the fibers of natural muscle [2]. TCAs are an emerging technology among artificial muscles that are accessible in terms of materials and production, but in recent years have been underutilized due to their low energy efficiency [1, 3].

Material engineers have attempted to resolve the efficiency issue of the TCAs by changing the materials and composition of the TCA. In many of these studies, experiments are run using a single or two TCAs in parallel, focusing on the effects of the material change on the efficiency of the actuator [2, 4]–[14]. While the material of a TCA is an important factor to consider when attempting to improve efficiency, the mechanics of the TCA's structure should also be considered.

In robotics, there are cases where bioinspired technology showed improvements in efficiency compared to their conventional counterparts [3]. With artificial muscles becoming more mainstream, there is a need for higher efficiency options for the continued development of soft robotics. The biological model for twisted-and-coiled actuators is proposed to combat high power consumption and increase efficiency.

In this study, we develop a mathematical model for the biological representation of artificial muscles and explore the effects of efficiency with a physical TCA. We show that a TCA that mimics the structure of biological muscle is more efficient compared to its conventional counterpart. Specifically, we explain the basic principles at work in a TCA, derive a mathematical model to simulate the expected force output of a TCA, experimentally verify the mathematical model, and identify areas of unknowns. Finally, we discuss the work that remains to fully optimize the efficiency of a TCA.

II. Background

A. Thermodynamics and Mechanics of Actuation

TCA artificial muscles are electrothermally activated, which means that they require electricity, so any conductive fiber is ideal for the fabrication of the TCA. Twisting a fiber causes the individual strands in the fiber to assume a helical shape. When heated, the volume of the fiber increases while the length of the fiber is kept approximately the same [4, 15]. In turn, the diameter of the fiber increases, which induces torque as the fiber slightly untwists (see Fig. 1).

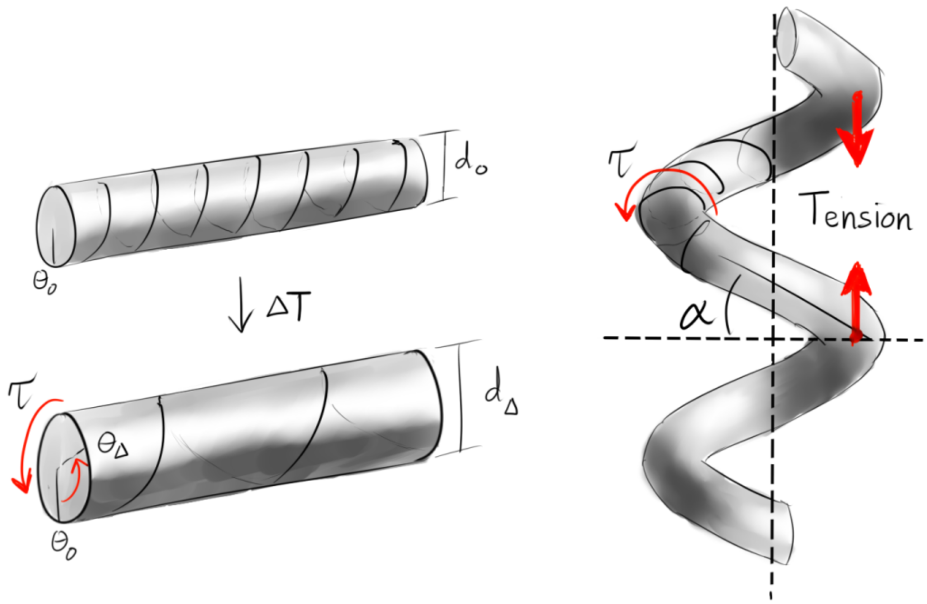


Fig. 1. Torque of a twisted-and-coiled actuator due to thermal expansion of the fiber (*left*), and the contractile force caused by the torque due to the decreasing helix angle (*right*).

A TCA is a twisted fiber that is also coiled, which is a secondary helical structure that resembles a DNA supercoil [3]. When heated, the TCA will untwist and increase in diameter, causing a torque along the fiber [4]. Due to the coiled structure of the TCA, the torque is utilized to decrease the helix angle of the supercoil, which causes the contraction of the TCA (see Fig. 1). While the length of the TCA fiber is kept approximately the same, the space taken up by the TCA is decreased as the coils become more tightly packed together from the decreased helix angle. This process is described by the equation derived from the geometric relationships and dynamic model of the TCA found in existing literature [4]. The higher the TCA fiber is heated, the smaller the helix angle becomes, the more force it generates.

The heating of the TCA fiber requires that electricity runs through the fiber. As with all materials, the conductive fiber that makes up the TCA also has an electrical resistance. Electrical resistance is the dissipation of electrical energy, but based on the first law of thermodynamics, electrical energy cannot be disappearing. The electrical energy is instead converted into thermal energy, which heats the TCA, just as a resistor in an electrical circuit does.

Aside from the actuation of the artificial muscle, heat is also an important factor in the fabrication of the unique twisted-and-coiled structure. Applying heat to the twisted fibers allows them to keep their shape and from untwisting, known as the annealing of the twisted-and-coiled actuator [2]. The annealing process is usually performed after the fiber is supercoiled.

B. Basics of Resistors in Electrical Circuits

Resistors are a common element in electrical circuits that reduce the electrical current that flows through the circuit. They create paths of resistance for the electrons to travel through, which transfers the kinetic energy of the electrons to the ions of the resistor's material that causes an increase in temperature. Through this process, electrical energy is dissipated by conversion to thermal energy in the form of heat.

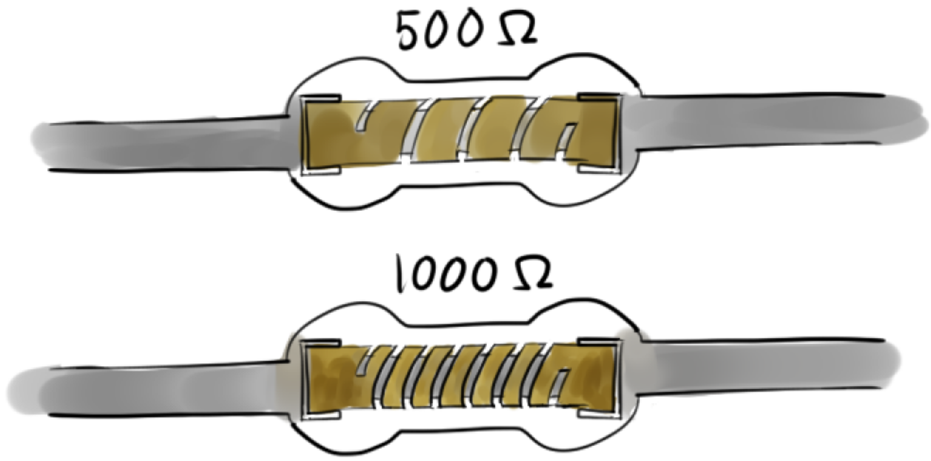


Fig. 2. The inside of a resistor shows a coil of metal. The more coils there are, the higher the resistance since the longer the path electrons have to travel, the chance of colliding with unexcited ions and transferring their kinetic energy into thermal energy increases.

The most common way of producing resistors is by cutting a coil out of metal (see Fig. 2). The number of coils present is a major factor in determining the resistance of the resistor. As each additional coil increases the path that electrons have to travel, the chance that an excited electron collides with an unexcited ion along the way increases. This means that the chance for the electrical energy to be transferred to the thermal energy also increases. Another way to understand this is that the total electrical energy is dissipated evenly among the electrons in the resistor in the form of heat. Since there are more ions in a resistor with more coils, less electrical energy is being transferred to each ion of the coil, causing the resistor to heat up less than a resistor with fewer coils.

The power that is dissipated by resistors in series can be calculated using the equation:

$$P = I^2 R_{eq} = I \times V \tag{1}$$

where P is the power, I is current, V is voltage, and R_{eq} is the equivalent resistance of the resistors. Similarly, the power dissipated by resistors in parallel can be found by the equation:

$$P = \frac{V^2}{R_{eq}} \tag{2}$$

Resistors of the same resistance in parallel will have an equivalent resistance that is smaller than the resistance of any single resistor series. Given the same voltage, the power dissipated by resistors in parallel will be greater than resistors in series since the current has more paths to flow through in the parallel resistor circuit with the same amount of input power (see Fig. 3).

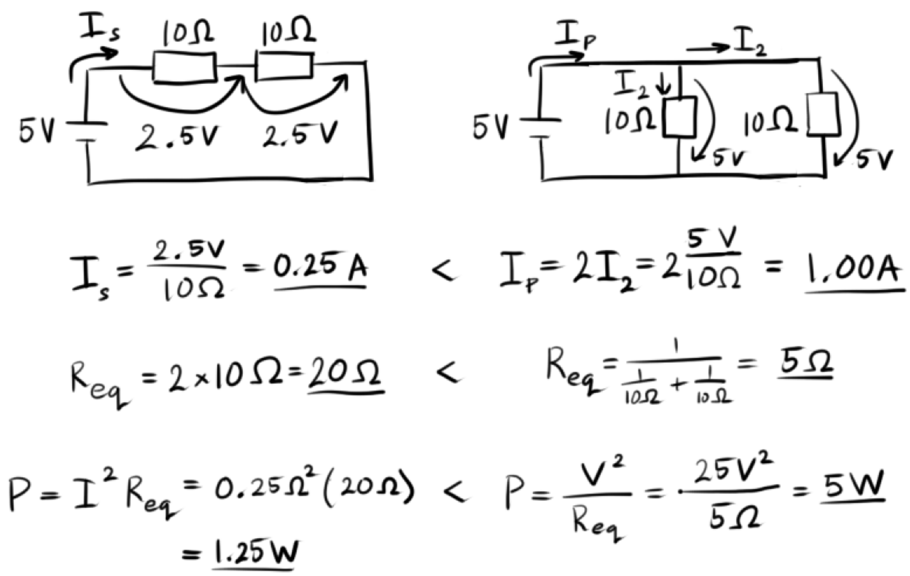


Fig. 3. Resistors in a parallel (right) dissipate more power than resistors in a series (left) for the same resistance and input voltage. The parallel circuit has more paths for the current to flow, decreasing the equivalent resistance.

C. Biological Muscle Structure

Biological muscles are composed of microscopic structures known as sarcomeres [16]. Sarcomeres are the most basic cellular unit that is able to contract in the muscle cell. When many sarcomeres are linked together, they form an organelle of a muscle cell called the myofibril. Myofibrils can produce a higher contractile force than a single sarcomere due to the simultaneous contraction of each sarcomere in a myofibril. The TCA resembles the long, tubular structure of a myofibril and mimics the contractile function of the myofibril, making it an ideal artificial muscle.

D. Design Considerations

A major constraint that governs the design includes the fact that this artificial muscle is a novel design, having little information about it. Other constraints require that the functionality of the artificial muscle must fit within the physical size of existing artificial muscles of its type and not increase existing power requirements. The novel muscle components should consist of commercially available materials that are readily available for purchase.

A requirement of this design focuses on the cost of the artificial muscle, where it should be no more expensive than other current artificial muscles, e.g., water, pneumatics, DC motors, stepper motors, or linear actuators, which cost a minimum of $150 [17]. Another requirement that will be developed is that the novel artificial muscle design should improve efficiency by 10-15%. The safety requirements for this design include having a voltage lower than 100 volts [18].

To evaluate the design against the requirements, the artificial muscle must be statistically more efficient than existing designs of this type of muscle, i.e., efficiencies produced by single actuators, actuators in parallel, and actuators in series, both electrically and mechanically [15], and must cause displacements longer than currently used muscles of this type, i.e., 10% of its initial length [2]. The cost required to fabricate this artificial muscle will be compared to the cost to fabricate other current artificial muscles and should reflect a cost that is at or lower than the lowest cost. To evaluate the safety requirements, the artificial muscle must be able to activate with commercially available batteries, which should all be under 100 volts—the lethal voltage for a human [18].

There were no professional standards and codes that currently govern this design due to its novelty. Additionally, no human subjects testing will be conducted, however, future design may require this.

III. Design and Implementation

In the following section, we outline the process to design and implement a mathematical and experimental model of the TCAs with inspiration from biological muscle structures.

A. Mathematical Model Implementation

For the development of a mathematical model, some simplifications were made. While the actuation of a TCA depends on the geometrical relationships of the fiber, the thermoelectrical properties of the fiber and the thermomechanical effects from the untwisting of the fiber is a good enough approximation for the purposes of verifying the efficiency of the biological muscle-inspired TCA. The mathematical models can be derived from these equations:

$$T(t) = \frac{V(t)^2}{R_{eq}} - e^{-\frac{\lambda}{C_{th}}t} \tag{3}$$

$$F(t) = T(t)c + b\ddot{x} - k\dot{x} \tag{4}$$

where T is the temperature, V is the input voltage, R_{eq} is the equivalent resistance, λ is the absolute thermal conductivity, C_{th} is the thermal mass of the TCA, x is the distance the TCA contracted from its original length, and F is the force generated [15]. These equations are then simulated in Simulink (ver. R2021a, MathWorks), a MATLAB modeling environment (see Fig. 4).

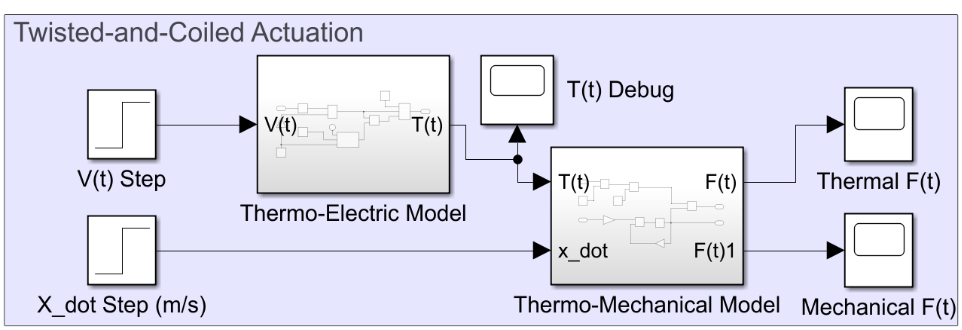


Fig. 4. The mathematical model of a twisted-and-coiled actuator

represented in Simulink blocks, including the thermoelectrical and thermomechanical relationships. V(t) is the input voltage, X_dot is the velocity of contraction in meters per second, T(t) is the temperature in Celcius, and F(t) is the force of contraction in Newtons.

B. Material Selection

It is understood from previous literature that the material of the TCA will greatly impact its efficiency [15]. However, for the purposes of comparing the efficiency based on the structure of the TCA, and not the material composition of the TCA fiber, conductive sewing thread is the main material used in this study. Due to the availability of silver-plated sewing in a local Makerspace, we used a Shieldex Conductive Sewing Thread (117/17 2ply, denier: 252) to fabricate the TCAs used in this paper. The conductive sewing thread has a relatively lower resistance to electrical energy compared to other types of conductive yarns and can only withstand low voltages, but is readily available during the time of this experiment and can still produce a noticeable strain during actuation.

C. TCA Fabrication Process

For the fabrication of the TCA, a short length of conductive thread is tied to two, 6.35mm-diameter brass rings. A 100kg weight is hung on one of the rings while the other ring is clamped into a power drill. The power drill is activated while the end with the weight is kept from twisting with the drill, causing the thread to form a helical spiral. The twisting continues until supercoils start to form. When the thread reaches its critical coil, meaning that no other supercoils can fit, the coiled thread is transferred from the drill into an oven to anneal. The weights on the end are increased to 250% of their original value, which was 250kg instead of the 100kg that was originally on the thread. This increases the helix angle between each coil, allowing space for the helix angle to decrease when electrothermally heated during actuation. The coiled thread is then heated to 150℃ for a total of 30 minutes, at which the TCA is completed and does not untwist itself.

D. TCA structural Models

The structural design of the sarcomere-inspired TCA requires that the TCAs are connected mechanically in series. Based on the fundamental laws of thermodynamics and electricity, the system of TCAs is connected electrically in parallel with each TCA being half as long as a single TCA. Reducing the length of the TCA reduces the equivalent resistance of a parallel electric circuit, causing the flow of electric energy in the form of current to increase. This increase in current causes each TCA to dissipate more power than the TCAs that are connected electrically in series. To verify this sarcomere-inspired design of the TCA, other TCA systems were tested. These included a control, single TCA, a system of two TCAs that are mechanically and electrically in parallel of the same length as the single TCA, and a system of two TCAs that are mechanically and electrically in series of half the length of the single TCA.

E. Model Validation

1) Experimental Setup

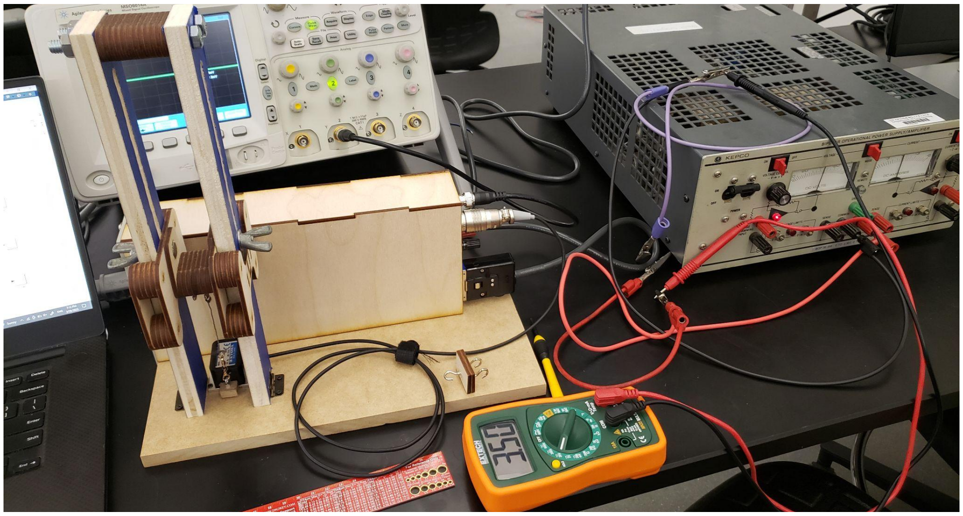


Fig. 5. Testing rig for the twisted-and-coiled actuators consists of a wooden frame, a power supply, a vertical load cell, a multimeter, an oscilloscope, and a strain amplifier.

A testing rig consisting of a wooden frame allowed us to anchor the TCA to a vertical load cell (LVS-1k, Kyowa Industries) (see Fig. 5). The TCA was connected via alligator clips to a power supply, and a multimeter was used to gauge the voltage and current running from the power supply. The vertical load cell was connected to a strain amplifier which was calibrated to show one voltage for every Newton. The measurement was then fed into an oscilloscope to record the force over a period of approximately 18 seconds.

2) Data Analysis

The data were exported from the oscilloscope and analyzed using MATLAB (ver. 2021a, MathWorks) and Google Sheets (Javascript-based web application, Google). An independent, two-sample, upper-tailed t-test was conducted between the sarcomere-inspired TCA system efficiencies with each of the other systems' efficiencies, where the null hypothesis is that the mean values of the efficiencies were different, and the alternative hypothesis is that the sarcomere-inspired TCA mean value is larger than the other system type's mean value.

F. Unknown Variable Validation

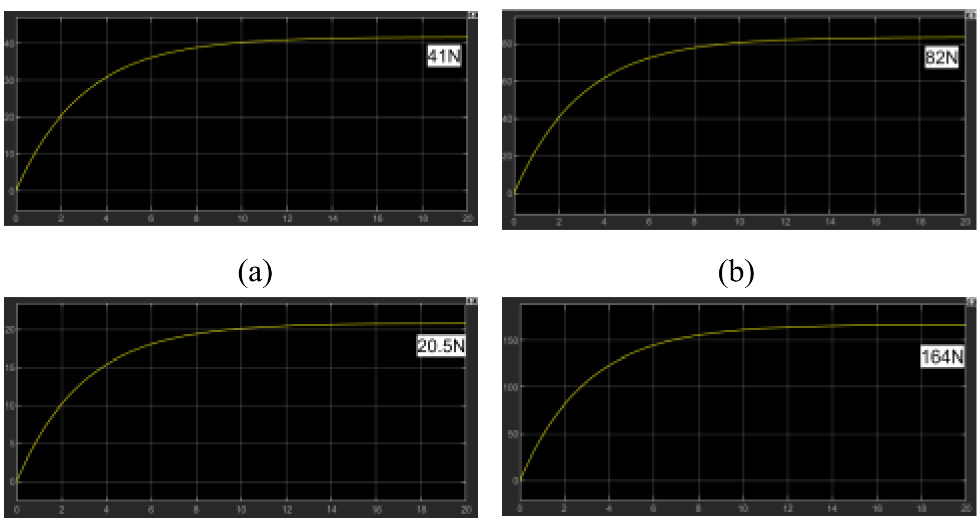
Although there was a noticeable improvement in efficiency due to emulating biological muscles in TCAs, iteration requires further study to determine the thermoelectrical properties of the conductive fiber used. To identify the unknowns in the mathematical model, each variable in the simulation was adjusted and their effects were analyzed. For this experiment, we only analyzed the effect of varying the effective thermal mass of the TCA in the Simulink mathematical model.

IV. Analysis and Discussion

In the following section, we analyze the design of the TCAs that mimic the structure of natural muscle and assess their ability to meet the design considerations.

A. Mathematical Model Simulation

The simulation of the mathematical model was run using parameters found in previous literature to simulate the TCA [15]. A basic model was run using the derived equations (3) and (4) to use as a baseline [see Fig. 7(a)]. Mathematical simulations for TCAs that are connected both mechanically and electrically in parallel resulted in a force that was double that of the baseline [see Fig. 7(b)]. On the other hand, for TCAs that are connected both mechanically and electrically in series, the simulated force was half of the baseline [see Fig. 7(c)]. For TCAs that are connected mechanically in series, but electrically in parallel, the simulated force was four times greater than the baseline [see Fig. 7(d)]. Since the output force of this simulated model is directly proportional to the efficiency of the TCA; hence, we can analyze the relative efficiencies between the different system models. Thus, according to the mathematical model simulation, the effective efficiency of the sarcomere-inspired TCA model is expected to be way greater than the efficiencies of any other TCA system model.



(d)

Fig. 6. (a) The reference force curve, in newtons over seconds, for a single twisted-and-coiled actuator (TCA) produced by the mathematical model simulation. (b) The force curve, in newtons over seconds, for TCAs that are both mechanically and electrically in parallel. (c) The force curve, in newtons over seconds, for TCAs that are both mechanically and electrically in series. (d) The force curve, in newtons over seconds, for TCAs that are mechanically in series, but electrically in parallel.

B. Experimental Model

The baseline, single TCA had average dimensions of approximately 7.24 centimeters in length and 0.01 cm in diameter. On the other hand, the average total length of the TCA system that was connected in series that mimicked the structure of sarcomeres was approximately 7.56 centimeters with the same average diameter. This meant the size constraint was not met in this design with a difference of 0.32 centimeters; however, it was a small enough difference to consider the two approximately the same during testing.

TCAs are made of readily available, conductive sewing threads. The type that was used in this study had a market price of $19.95 for a roll of 137.16 meters of conductive thread. Each TCA only requires a tiny fraction of the 137.16 meters, such as 0.17 meters for a single TCA in this study, to fabricate. Consequently, the price to fabricate one TCA does not come close to costing one cent. Compared to the minimum price of $150 for most other actuator types in the market, such as pneumatics and hydraulics, TCAs are cost-effective.

During testing the input voltage was limited to 2.40 volts. This voltage was found experimentally by varying the voltage until the TCA can still visibly actuate but not burn and break. The input voltage of 2.40 volts does not exceed the 100 volts that was set by the design constraints. Additionally, by not exceeding 100 volts, accidentally touching the TCA while it is on will reduce the likelihood of death.

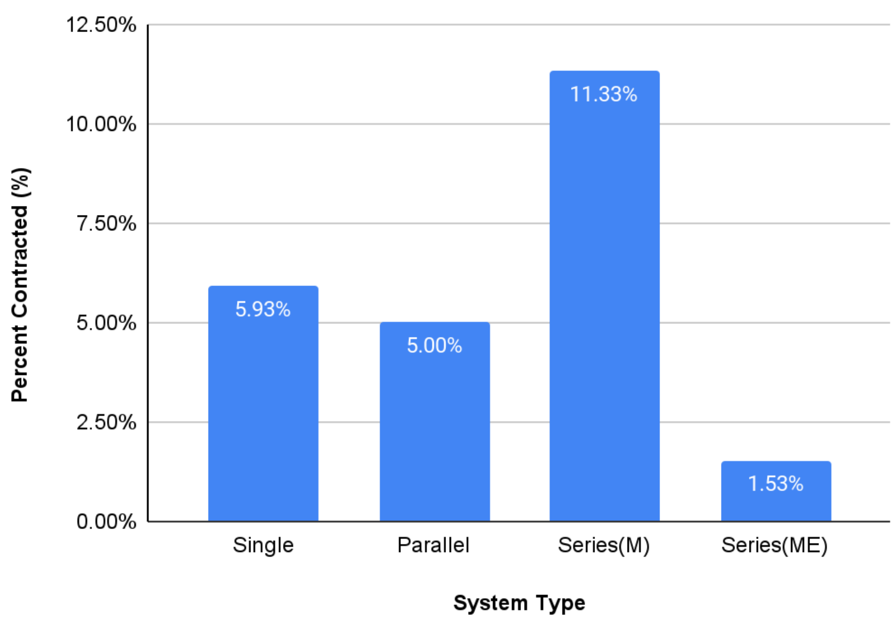


Fig. 7. Average percent contraction of the four different types of twisted-and-coiled actuator systems that were tested in this study. (M) means only mechanically in series, but electrically in parallel, while (ME) means both mechanically and electrically in series

Examining the length measurements for all TCAs before and after contraction, it is apparent that the sarcomere-inspired TCA had the highest percent length contraction at 11.33% (see Fig. 6). In addition to being the highest percent length contraction, the contraction percentage of 11.33% is above the threshold of 10% contraction that constrained this design.

The forces, voltage, and time of all the different TCAs were collected from a sample size of 21 for each type. The efficiencies were calculated and plotted to compare (see Fig. 8). It was shown that there was no significant overlap between the efficiency values of the sarcomere-inspired TCA with any other TCA system types that reflect the ones in the existing literature. Additionally, the efficiencies of the sarcomere-inspired TCA are relatively higher than the other systems. This means that the sarcomere-inspired TCA is producing significantly higher efficiencies than the other types of TCA systems.

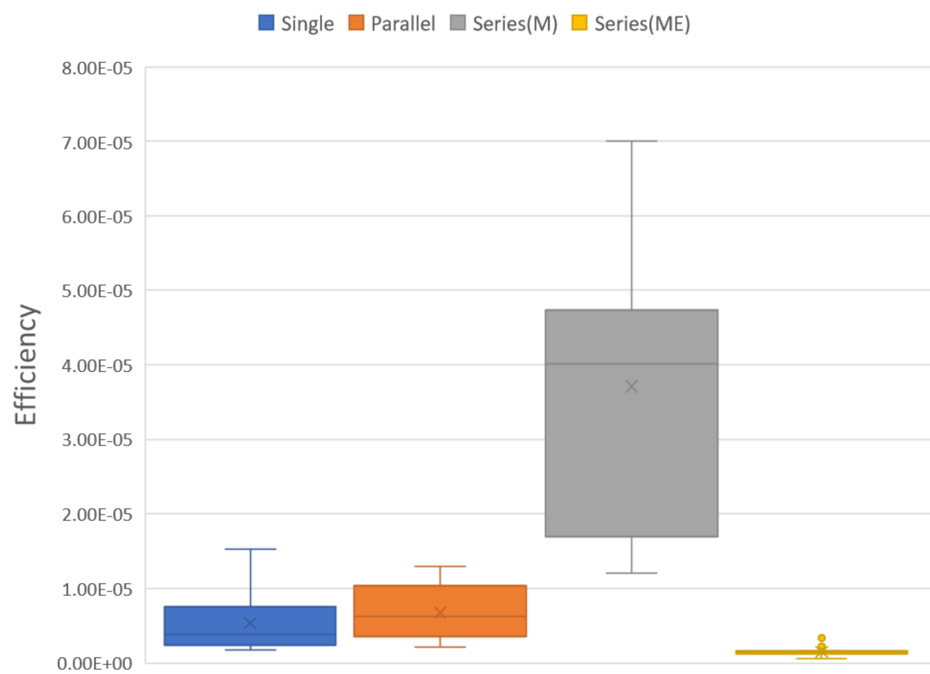


Fig. 8. Box-and-whisker plot of the efficiencies of the four different types of twisted-and-coiled actuator systems. (M) means only mechanically in series, but electrically in parallel, while (ME) means both mechanically and electrically in series. The vertical axis of this plot is in log scale.

Additionally, it was found that all t-tests resulted in p-values that are less than 0.001. This also confirms that the is enough evidence to accept the alternative hypothesis that the mean efficiencies of the sarcomere-inspired TCA are greater than the other TCA system types' mean efficiencies. Consequently, the efficiency of the sarcomere-inspired TCA is statistically more efficient than the existing TCA system types, which conform to the design constraint.

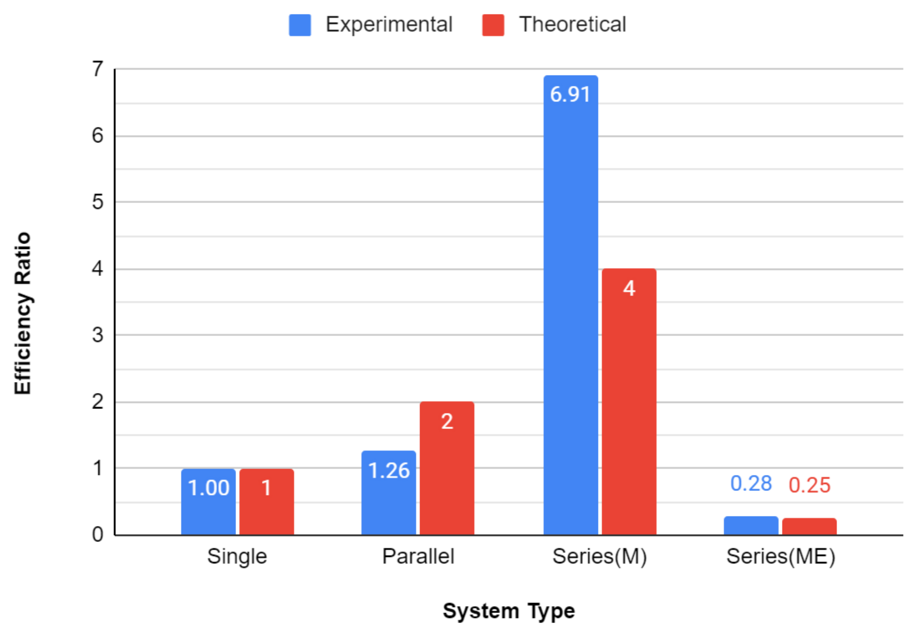


Fig. 9. Efficiency ratios between each of the four twisted-and-coiled actuator (TCA) systems and a single TCA compared to the efficiency ratios simulated by the mathematical mode. (M) means only mechanically in series, but electrically in parallel, while (ME) means both mechanically and electrically in series. The vertical axis of this plot is in log scale.

By comparing the ratios of the efficiencies between each of the TCA system types and a single TCA, it is visible that the TCA system that is in parallel increases the efficiency by 26% from a single TCA (see Fig. 9). Likewise, the sarcomere-inspired TCA system effectively increases the efficiency by 591% from a single TCA. Conversely, the TCA system that has TCAs both mechanically and electrically in series has a reduced efficiency of 75% from a single TCA. Since the sarcomere-inspired TCA improves the efficiency by 591%, it is able to meet the design criteria of increasing the efficiency of a single TCA by 10-15%. Comparing the ratios of the efficiencies with the ratios of the efficiencies from the simulated mathematical model, it is apparent that the experimental data follow the mathematical prediction quite closely (see Fig. 9). Since the mathematical model is a simplified model that does not take into account the intricacies of variable properties of the material that changes as its physical geometry changes, it is expected that there are differences between the experimental data and the simulated data.

C. Unknown Variable Simulations

To explore how variable properties affect the efficiency of the TCAs, different thermoelectric properties in the mathematical model were varied. In particular, the thermal mass property value of the conductive thread was varied and simulated using the simplified mathematical model. The output force for the model was used as a relative measurement for the efficiency of the conductive thread that has a particular thermal mass value since the efficiency is directly proportional to the output force. Seven different values of thermal mass were used and their respective simulated output forces were plotted (see Fig. 10).

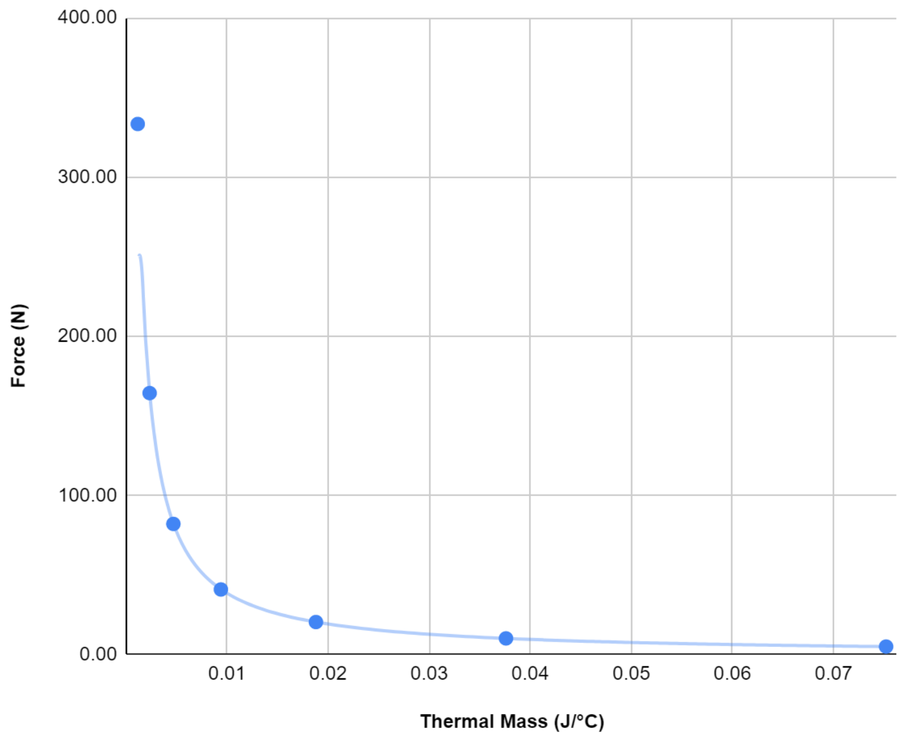


Fig. 10. Resulting force output, and thus the relative efficiency of a twisted-and-coiled actuator due to varying the thermal mass value using the mathematical model.

From the best-fit line of the plot, it is clearly visible that the output force and thermal mass are inversely proportional to each other. This finding agrees with what is known about the thermal mass of materials. Materials with a high thermal mass value will absorb and store thermal energy better than materials with a low thermal mass [19]. Thus, as the TCA's thermal mass decreases, less thermal energy is absorbed, causing the material itself to heat up. This will cause the material to be affected by thermal expansion, and due to its helical geometry, a larger torque and tension will occur. Future studies with other thermoelectrical properties, such as electrical resistance and thermal conductivity, will also help reveal their effects on the efficiency of the TCAs.

While it is found that TCAs in a sarcomere-like structure increase efficiency, the shortening of each individual TCA length causes the TCA to burn, similar to how electrical resistors burn when provided a voltage that is too high, overloading it with current. This can be resolved by identifying a power rating for the TCAs in future studies using the thermoelectrical properties of the conductive thread used for the TCA. Since the thermoelectrical properties, such as electrical resistance, are affected by the length of the TCA, finding the optimal thermoelectric properties that produce the highest efficiency will also help define the optimal length of a TCA.

V. Summary/Conclusion

A multitude of research groups have designed and developed testing procedures to test different applications of the TCAs [2, 4]–[14]; however, none of these are designed to test sarcomere-mimicked TCAs. TCAs that follow a biological structural design, such as sarcomeres in myofibrils, perform more efficiently than conventional methods of increasing efficiency through purely mechanical TCA systems. Utilizing the understanding of electrical systems and mechanical systems together allows for the increased efficiency of TCAs. Combined with materials science and uncovering the unknown variables of the thermoelectrical properties of the fiber used, the efficiency of TCAs can be greatly improved to match that of biological muscles.

This study encountered many issues with shorter TCAs burning and breaking during testing. Iteration of this design to obtain an optimal length for the TCAs where maximum allowable efficiency would require further exploration of the electrothermal properties that define the conductive thread used in the TCA. Through variation of these properties as parameters in a mathematical model, the resulting simulations will provide insight into defining a power rating for TCAs of different conductive thread materials and lengths. Developing these theoretical power ratings be the next step to aid in the development of experimental models that will be as close as possible to the optimal length that a TCA can be. Through this new method of improving the efficiency of TCAs, the possibility of reviving interest in this type of actuator for robotics is projected to increase.

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