Title: Using Neuron Activation as Way of Powering Artificial Muscle Fibers

Abstract:

Developing technologies and mechanisms that perform like our biological muscles have great potential of being useful for prosthetics research. Developing these technologies can be thought of as the easy part of the design, but the difficult part is having them work in synchronicity with all the accompanying muscle fibers within the body. This is important because biological muscles have high power to weight ratios, compliance, damping, and fast actuation. However, to date the robotic models are not able to perform up to the standards of biological muscles due to the complexity of the biological systems (Mirvakili et al., 2014). This is especially true in attempting to create prosthetics mechanisms that are as thin and small as the biological muscles. Novel technology, first developed by Disney, is the use of super coiled polymer actuators that perform extremely like biological muscle fibers when subjected to electrical current. These super coiled polymer actuators are super thin because they are constructed using nylon fishing line. The fishing line is coiled upon itself and then heat treated to set the fishing line in the coiled shape. In order to activate these super coiled polymer actuators two additional aspects, need to be added. First, the nylon fishing line needs to be coated in silver so that they can conduct current and furthermore be heated and cooled. When heated and cooled the fishing line coils will expand and contract, and in turn will act very similarly to biological muscle fibers (Yip & Niemeyer, 2015). Second, electrodes and computer coding need to be utilized so that the artificial muscle fibers are operating at the same time as the biological muscle. This technology has been proven in laboratory settings to be capable of lifting cars when the super coiled polymer actuators are coupled together. Combining these technologies can have a major impact on the prosthetics industry by providing an efficient and cost-effective method for creating powerful novel prosthetic devices (*Fishing Line Makes for Superhuman Artificial Muscles—IEEE Spectrum*, n.d.).

Introduction:

Knee injuries are typically treated with a brace in order to reduce the range of movement in the joint. These braces are expensive alone and solely act to restrict movement. An electronically motorized assistive system could provide more benefits by making it easier to lift loads, walk without crutches, or enhance lifting capabilities. These braces however come at a much steeper cost. The designed device can be used for both enhancing the ability for someone to improve their maximum squat and for rehabilitation purposes after injury. The device is to be powered by the mechanical motion of artificial muscle fibers. These fibers, made of fishing line, are thin and are also wrapped in silver threading. This gives the fibers increased electrical conductance. When the fibers are twisted to the maximum point at which the overall strand remains linear, they are heated and cooled 20 times in order to train them to act as muscle fibers. The electricity flowing through the fibers causes them to compress and cooling them back to room temperature allows them to relax. The fibers bundled together, function much like large muscle groups in the human body. This device is a custom design a knee brace in order to meet a plethora of specifications to be as user friendly as possible. The fibers are to be mounted onto the brace and using an Arduino Uno the device can be programmed to function in sync with similar activation to true muscle fibers. The device was designed to be capable of assisting the user in the lifting 30 pounds from a squatting position or if the user is seated, to flex the lower leg (below the knee) up and down for rehabilitation. Even though this technology has been utilized for a hand/arm prosthetic, this device is intended to be the first prototype that uses the new fiber actuation technology on a leg brace. This device will hopefully show the potential of future medical and assistive devices and how they can enhance human capabilities.

There is a need for a device that can provide partial support to athletes who are relearning movements in physical therapy. Performing a movement such as a squat can be difficult, even with no additional weight, for an athlete recovering from an injury. However, it is important for athletes specially to relearn these movements to reduce muscle atrophy and retain mobility. By providing a means of assisting the user through the motion, it is possible to accelerate the timeline for recovery following an injury or surgery. Additionally, such a device could be used with a healthy athlete who is seeking additional support with a difficult lift.

The exoskeleton market currently is predominantly targeted towards helping patients who are paralyzed and must learn how to walk again as well as reducing fatigue in soldiers who are carrying heavy loads over long distances. These devices typically rely on motors placed at the joints of the exoskeleton and have prices ranging from $40,000 to $98,000 (Gorgey, 2018). Insurance companies do not typically cover such devices, as they are not considered medically necessary. Therefore, there is a need for a more affordable exoskeleton targeted towards postoperative athletes to expedite their return to training and competition.

The existing exoskeletons are expensive and have not been extensively tested in exercise science applications. The exoskeleton offers many benefits for athletes as sports technology continues to advance and improve athletic performance. This exoskeleton will help athletes to specifically target and maximize explosive power generated from the legs. This design is based on a research study at the University at Dallas that demonstrated the use of nylon lines as artificial muscle fibers. The power output of the nylon muscle fibers yields a significant increase in mechanical power (Haines et al., 2014). A study in 2015 done by Micheal Yip and Gunter Niemeyer discusses how a 3D printed arm was created using artificial muscles controlled by current flow. This exoskeleton design replicates the method used by Yip and Niemeyer and then allows to mount the muscle fibers onto a modified leg brace. This technique gives the ability to create an electronically controlled exoskeleton (Yip & Niemeyer, 2015).

The following is a list of common medical procedures and injuries that typically require extensive postoperative rehabilitation and physical therapy: anterior cruciate ligament (ACL) repair, posterior cruciate ligament (PCL) repair, meniscus repair, hip labral repair, hip/knee replacement, fracture of the leg. There are several rehabilitation protocols for the surgeries/injuries, each of which will vary slightly for individuals. For ACL repair, patients can perform certain functional exercises such as “mini-squats” 2-4 weeks post-operation. It is not until 4-6 weeks post-operation that full squats are seen in rehabilitation protocols. Being sidelined by an injury or surgery can be as difficult mentally as physically for an elite athlete. It has been shown that, amongst elite athletes, the top priority is to return to training and/or competition as soon as possible. Inactivity as a result of an injury or surgery can quickly deteriorate the level of fitness of an athlete. Three weeks of inactivity has been shown to cause “a significant loss of cardiovascular fitness” and decreases in maximal oxygen consumption from 14-16% have been reported following six weeks of rest. One method that has been researched to investigate the potential to accelerate rehabilitation protocol for athletes is aquatic therapy. The buoyancy and viscosity of water are thought to be beneficial in the early stages of rehabilitation of injuries. There are claims that aquatic physical therapy speeds up the rehabilitation process by allowing for the early return to exercise following injury. The use of aquatic physical therapy has been argued to help maintain or even improve cardiovascular endurance while resting the injured area. Aquatic physical therapy also allows for the patient to move through a wide range of motions without excessive muscle activation, which can accelerate the transition to more advanced dynamic strengthening or conditioning exercises on dry land (Choi, 2015).

In recent years, there have been several exoskeletons designed; most of which are either intended for use in rehabilitation or in the military. The ReWalk system, C-Brace, Indego Personal, and Phoenix are exoskeletons that are designed to help paralyzed people walk again, costing $81,000, $75,000, $$98,000, and $40,000 respectively. The ReWalk system relies on motors at the knee and hip joints, as well as sensors to allow it to adjust with the user’s gait. The ReWalk system was the first personal robotic exoskeleton approved by the Food and Drug Administration (FDA). The C-Brace utilizes a hydraulic system to move the knee as well as a microprocessor to adjust ankle pressure. The Indego Personal functions similarly to the ReWalk, with computer-controlled motors at the knee and hip joints. The Phoenix relies entirely on two hip motors, compared to the typical motor powering each joint. Researchers at Virginia Tech have found that besides helping immobilized people move around, these devices can help users manage spasticity and help to improve bowel function. The main reason these devices are so expensive is the lack of a large user volume. Most insurance companies do not cover robotic exoskeletons because they are not medically necessary. Expanding the user base of such devices would drive prices down. Lowe’s Home Improvement recently outfitted a number of their warehouse employees with exoskeletons to assist them in lifting heavy loads (M et al., n.d.).

There have also been attempts from defense contractors to build exoskeletons designed to assist soldiers in the field. Raytheon Sarco’s “XOS 2” and Lockheed Martin’s Human Universal Load Carrier (HULC) are two such exoskeletons that stand out. These differ from those designed to help people walk again in that they are full body suits designed to bestow additional strength to healthy, adept soldiers. A major obstacle for both designs was the power supply, making the design too bulky and heavy. The XOS 2 was scrapped due to a lack of funding from the DOD and the HULC was put on hold after not meeting the military’s standards (Dunietz, n.d.).

Methods:

The design consists of two custom made knee braces that are capable of assisting the user in a squat movement due to silver coated nylon fibers used as artificial muscles. Using electrical current which is supplied from a standard US outlet of 120VAC, the fibers length and temperature change. The fibers are mounted in strategic fixed points to provide a mechanical advantage for the bending of the knee. Once the fibers are in their excited state, the fibers apply a force on the brace which assists the user into a squat position. Each of the following sections in the design description category are individual subsystems of the overall system.

Fibers – Artificial Muscles:

Few leg braces assist the user in generating mechanical advantage. From not enough support to high expense, so the design utilizes a material that has low cost but high output, hence the use of nylon lines as muscle fibers.

The fibers have a nylon core with a silver outside coating. The combination of both materials provides a unique system. Other than the silver, these nylon lines are incredibly low in expense. A report through Disney Research is the most resourceful in understanding the characteristics of the lines, which ones to use, and some methods in production and control. After multiple fiber tests, they found that fiber from Shieldex Conductive Yarn (117/17, Denier: 240/34f, weight: 0.238g/m, coil diameter: 720 um) worked the best. The fiber was determined to have the best strain and stretch characteristics for mechanical applications through heating the line (Yip & Niemeyer, 2015).

The lines would be mounted onto the brace in a fashion which outputted the most power, known as the moment arm.

Characteristics of the lines:

The lines are twisted extensively with some minor tension until they begin to coil up on themselves. In its coiled form, when heated, the line expands outwards of the coil due to the desire for it to lengthen and the spring tension formed from coiling. At this point the line is now referred to as a fiber as it has a mechanical motion when heated and cooling. It compresses when heated and relaxes (or lengthens) when cooled.

When used in a fiber, the silver coated lines from Sheildex, can lift 50 grams not dependent upon length. The length determines how much it can compress, having a ratio of about 10% of the overall length of the fiber. This mechanical motion is one of the few that can cause linear motion from the material itself, unlike other linear motions that use rotation to linear screws or pulleys (Yip & Niemeyer, 2015).

Process on producing a muscle fiber from a line:

To properly produce a muscle fiber as mentioned in the previous section there are two steps to perform: coiling and training. During these processes, it helps to keep everything consistent such as not using nearby lighting (within 1 meter) that emits larger amounts of heat to the room temperature being as close to 25 degrees Celsius. To coil the lines, a desired length of line is cut from the spool and for testing purposes, tie each end to a non-coated, metal paperclip. A square knot is typically used. After the loops on each end are made the line is hooked to one paperclip on the “Fiber-Making Machine” (FMM), and the other end to a 50-gram weight to maintain tension. The FMM is the device that is utilized to create the spinning motion needed to coil the line. At this point the line may want to unwind, so the user must hold another, straightened, paper clip or equivalent straight tool into lower hanging paper clip to stop the unwinding. It’s worth noting not to apply any additional tension in the line from pushing down with the straight tool. Once ready, the motor in the FMM is turned on to about 5 DC volts via varying power supply to start twisting the fiber. It is about at 10 seconds when the fiber began to shorten slowly, then rapidly when coiling begins. As the fiber coils, it helps to slow the motor in the FMM down to easily see when the line is finished, an even coil will be seen across the fiber. Once coiled the FMM motor can be turned off and the straight tool can be mounted to the FMM to hold the fiber in place and not unwind.

The next step is to train the fiber. This process takes just a few minutes depending on your method of cooling the fibers. Take either the same power supply for the FMM or another if you have access to two and hook one lead (ideally the ground) to the top of the fiber and the positive one to the lowest part of the fiber. The ground lead is better on top such that if there is any conductivity to ground the coupling on the FMM, the positive lead will still have only one way to flow. Additionally, it helps to clip on the paper clip across the fiber knots to avoid off angled tension on the fiber. With the leads securely attached. The power supply can be turned on and provide a total wattage of about 0.2 W/cm of the fiber. While the reports desire that value to heat the fiber to around 150 degrees Celsius, starting out with about 0.15W/cm works better and proves to burn fibers less. A cycle of turning on power, turning off and cooling was performed about 15 to 20 times at a ratio of 5-8 secs to 20 secs. If the fiber is left on for too long (beyond 8 seconds) it can easily overheat, burn and snap. This repeating process is what “trains” the fibers and physically changes the characteristics of the nylon, making this new coiled structure as a permanent form - much like material memory when bending metal (Yip & Niemeyer, 2015).

Apply the Fibers to the Braces:

At this point once the fibers are made, they are attached to the leg braces at the specified locations to maximize the lever arm of the brace.

Leg Brace:

The brace for this design was designed to be manufactured out of 1/16-inch steel metal sheet and bent and cut into standard lengths for each specific part. Figure 1 below is a CAD model of the brace. To wear the brace, the user simply slides the brace like a leg sleeve. There are two independent braces, one being for each leg.

Figure 1. CAD Model of the Brace (Source: Amit Bachar, 2018)

The leg brace consists of two main components, the thigh and quad components. These parts were designed to fit a tall athlete and be slightly adjustable. The fibers can be attached to a shaft with grooves which prevents the fibers from moving from their fixed position. In order to ensure comfort for the user, the inside of the brace may be padded with a soft padding which prevents any discomfort caused by friction from the steel brace and the leg of the user. To create a customizable feature for the brace Velcro straps can be utilized so that the user can tighten the brace. Safety is also a concern when working with technology of this nature. So, safety blocks can be attached to the brace to make sure that the user could not bend his knee past the defined conditions.

<u>Electronics / Control System:</u>

While the brace alone is a unique, custom component, the electronic system that controls it all is also specialized for the device. From providing appropriate wattage to the fibers and to sensing the pressure of weight in the user's hand. There is a lot that the electronic system must control, output, and read. Figure 2 is an overview of the subsystems within the overall electronic system. The last paragraph in this section will explain setup and operation of the electronic system while in use.

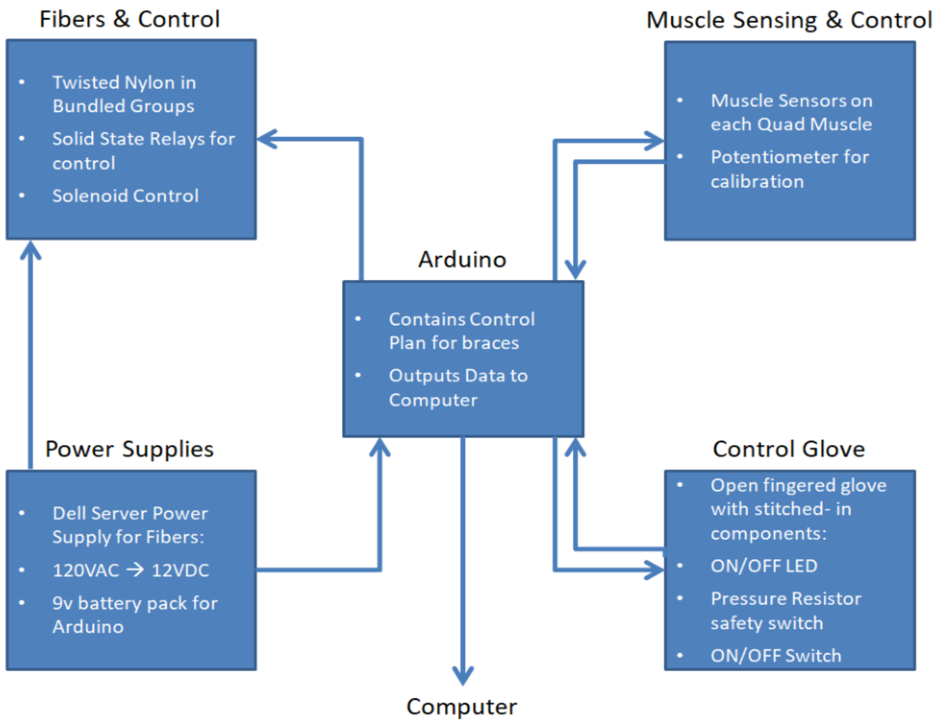


Figure 2. Overview of the Subsystems (Source: Matthew Gill, 2018)

The Arduino is the control system. It is an Arduino Mega because of the many IO pins it has over other Arduino boards (like the UNO). The control system is simplified to just turning the fibers "on" or "off" by time based while loops and mechanical relays.

While the control system is functioning, it also had predetermined variables that only allowed the braces to function to a certain extent. This included a timer to make sure fibers don't run under continuous load and wattage for around seven seconds to avoid burning, snapping, or deformation. Additionally, the Arduino outputted muscle data, power levels and timers out to a computer via USB to observe and ensure user safety.

To ensure ease of use, user control, and safety of the user, a weightlifting glove was modified to have an electronic sensor, switch, and indicator LED. A weightlifting glove is picked since this device will be tested in a weight room setting to test if the users maximum squat can be increased as a result of the device. The sensor is a pressure resistor placed in the palm to detect that the user is attempting to lift weight. If the user's primary goal is rehabilitation, then a timer in the Arduino code would recognize no weight was added and they're just doing "free lift" movements. For both situations, the user has ten seconds after the switch on the glove is flipped for no weight or weight to be determined. If the user is lifting and they release the weight due to a failed lift, the lack of pressure would signal an off trigger in the Arduino program to stop the fibers from functioning. Additionally, in free lift, if the user squeezes their palm to trigger the resistor, the fibers will turn off. The indicator LED is just to tell the user if the program is on. It will blink while waiting to sense weight and then solid indicating the sensors are on and reading. The decision was made to use a bright LED instead of a speaker or buzzer because oftentimes in a weight room it's loud and the buzzer might not be heard over a LED that will be seen.

Air System:

An air system was designed to accelerate the process of cooling the fibers. The process of running electric current through the fibers to heat the fibers and cause them to contract raises their temperature to approximately 150 °C. In the fabrication of a single fiber, this heat dissipates just seconds after turning off the current to the fiber. However, placing tens or hundreds of these fibers in close proximity to one another will cause this time to increase. One reason why it is desirable to have a system to cool these fibers is the safety of the user. Limiting the time at which the fibers are at a potentially harmful temperature increases the safety of the overall system. Additionally, maintaining the fibers in their contracted state for extended periods of time can compromise the fibers integrity and increase the chance of a break. Therefore, an effective air system to cool the fibers will increase the lifetime of the fibers as well as the overall safety of the device. In previous works involving these fibers, CPU fans were implemented to increase the rate of cooling. Due to the proximity of the fibers to the user, alternative methods of cooling were investigated. A standard 120 mm CPU fan can produce an air flow up to 0.03912 m3/s. The diameter of the fan, 120mm, was approximated to be the diameter of the tube through which this air would flow. This results in airflow with a velocity of 3.46 m/s. The film temperature was calculated to be 358.15 K by averaging room temperature with the estimated temperature to which the fibers would be heated. The dynamic viscosity, Prandtl number, and thermal conductivity of air at this temperature were linearly interpolated from property tables of air. From there, the convective heat transfer coefficient was calculated. The Lumped Capacitance method was used to calculate and predict the temperature of the fiber after the onset of cooling as a function of time. It was found that it would take 5.3 seconds to cool the fiber to 25 °C with the use of the CPU fan system. A pressurized cooling system was then investigated. A standard 6-gallon air compressor can produce an airflow of 0.001227 m3/s at 90 PSI. Connecting this air flow to 1/4-inch tubing results in a velocity of air of 38.7 m/s. Following the same calculation as prior with only velocity changing, the cooling effects of this system were investigated. This system can cool the same fiber to 25 °C in only 1.7 seconds. A plot of the rates of cooling of these two systems is shown in Figure 8. (See Appendix A for sources of calculations and graphical output; MATLAB)

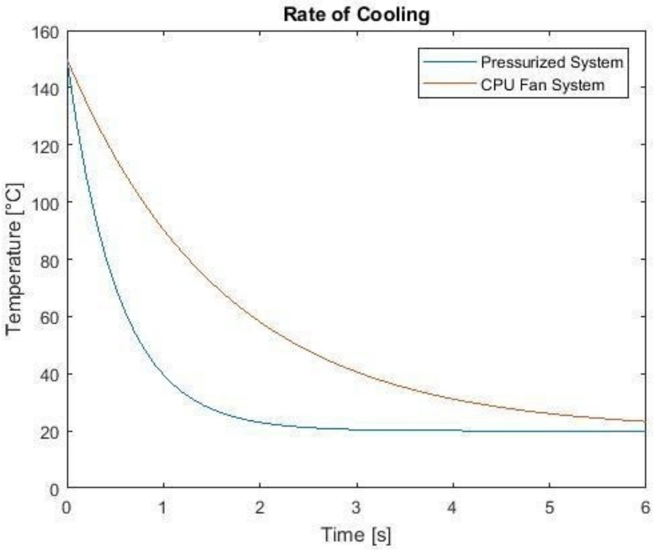


Figure 3. Rate of Cooling of Pressurized System Versus CPU Fan System

Results/Discussion:

Even though the device is designed to be worn by a human user, testing the device in this manner is not practical. This is because of the subjectiveness of the user and the potential for the placebo effect to be mistaken for true results. In order to test the effectiveness of the device the knee brace will be placed in a 90-degree angle, mimicking the user being at a 90-degree squat where the knee joint is bent at 90-degrees. Then a weight is attached to the top portion of the leg brace. This weight is placed at the spot correlating to the top part of the user's thigh. Then the brace is turned on, and if the leg brace ends in an upright/straight position then this means the test is a success, and if the brace is not able to the lift the weight then the test is deemed a fail. Computerized angle measurements can also be used to measure the angle change of the top portion of the leg brace during testing. This is useful since the brace might not be able to fully straighten depending on the strength of the current fibers, but any angle change can be deemed as a success/working model.

Conclusion:

The use of artificial muscle fibers is a technology that is yet to be mainstreamed for the general public, however several academic institutions and high-level biotechnology laboratories are working on perfecting the technology so that it can have applications in several facets of the world. As a result, it is relatively unknown and not many people appreciate the power that this technology holds, and would be appalled to know that this technology has been shown to be capable of lifting cars. The technology can be used in so many different devices and products but is mostly researched for us in prosthetics and robotics. Many research studies have proved that the technology works, and the hope is that this product design has an impact on the field as well in a positive manner. The product is applicable to either elderly patients who need some extra help going up stairs or the high-level athlete that wants to cut down on the recovery time from an injury, or applied to the combat world for soldiers that are walking treacherously all day long. Either way the product is of great value to the user moving forward with their day to day life and achieve their goals, and there is not a more powerful end result for a product than that.

References:

Choi, E. (2015). Aquatic Physical Therapy in the Rehabilitation of Athletic Injuries: A Systematic Review of the Literatures. *Journal of Yoga & Physical Therapy*, *05*. https://doi.org/10.4172/2157-7595.1000195

Dunietz, J. (n.d.). *Robotic Exoskeleton Adapts While It’s Worn*. Scientific American. Retrieved March 30, 2020, from https://www.scientificamerican.com/article/robotic-exoskeleton-ldquo-evolves-rdquo-while-its-worn/

Fishing Line Makes for Superhuman Artificial Muscles—IEEE Spectrum. (n.d.). IEEE Spectrum: Technology, Engineering, and Science News. Retrieved March 30, 2020, from https://spectrum.ieee.org/tech-talk/robotics/robotics-hardware/fishing-line-makes-superhuman-artificial-muscles

Gorgey, A. S. (2018). Robotic exoskeletons: The current pros and cons. *World Journal of Orthopedics*, *9*(9), 112–119. https://doi.org/10.5312/wjo.v9.i9.112

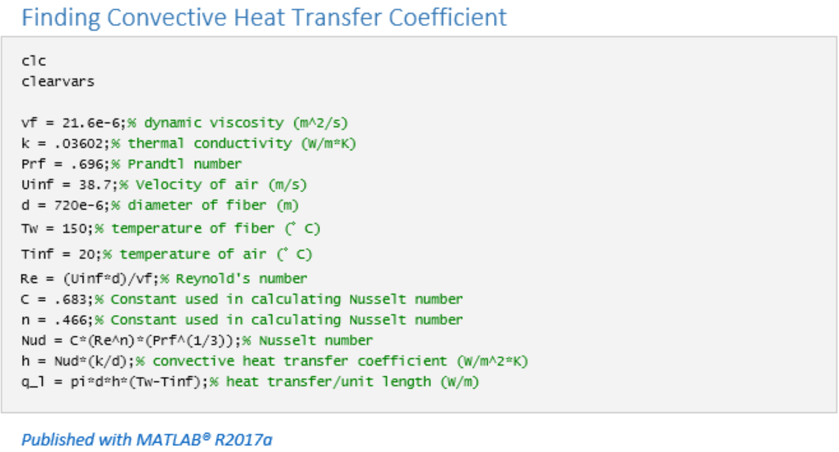
Haines, C. S., Lima, M. D., Li, N., Spinks, G. M., Foroughi, J., Madden, J. D. W., Kim, S. H., Fang, S., de Andrade, M. J., Göktepe, F., Göktepe, Ö., Mirvakili, S. M., Naficy, S., Lepró, X., Oh, J., Kozlov, M. E., Kim, S. J., Xu, X., Swedlove, B. J., … Baughman, R. H. (2014). Artificial Muscles from Fishing Line and Sewing Thread. *Science*, *343*(6173), 868–872.

M, T., M, rews closeTravis, music, rewsPop culture reporter covering, movies, TV, comedy, & cultureEmailEmailBioBioFollowFollow, celebrity. (n.d.). *Robotics are helping paralyzed people walk again, but the price tag is huge*. Washington Post. Retrieved March 30, 2020, from https://www.washingtonpost.com/news/morning-mix/wp/2017/06/10/robotics-are-helping-paralyzed-people-walk-again-but-the-price-tag-is-huge/

Mirvakili, S. M., Ravandi, A. R., Hunter, I. W., Haines, C. S., Li, N., Foroughi, J., Naficy, S., Spinks, G. M., Baughman, R. H., & Madden, J. D. W. (2014). Simple and strong: Twisted silver painted nylon artificial muscle actuated by Joule heating. *Electroactive Polymer Actuators and Devices (EAPAD) 2014*, *9056*, 90560I. https://doi.org/10.1117/12.2046411

Yip, M. C., & Niemeyer, G. (2015). High-performance robotic muscles from conductive nylon sewing thread. *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2313–2318. https://doi.org/10.1109/ICRA.2015.7139506

Appendix A: MATLAB Air System (Source: Matthew Gill, 2018)



Finding Convective Heat Transfer Coefficient

```
clc
clearvars

vf = 21.6e-6;% dynamic viscosity (m^2/s)
k = .03602;% thermal conductivity (W/m*K)
Prf = .696;% Prandtl number
Uinf = 38.7;% Velocity of air (m/s)
d = 720e-6;% diameter of fiber (m)
Tw = 150;% temperature of fiber (˚ C)
Tinf = 20;% temperature of air (˚ C)
Re = (Uinf*d)/vf;% Reynold's number
C = .683;% Constant used in calculating Nusselt number
n = .466;% Constant used in calculating Nusselt number
Nud = C*(Re^n)*(Prf^(1/3));% Nusselt number
h = Nud*(k/d);% convective heat transfer coefficient (W/m^2*K)
q_l = pi*d*h*(Tw-Tinf);% heat transfer/unit length (W/m)
```

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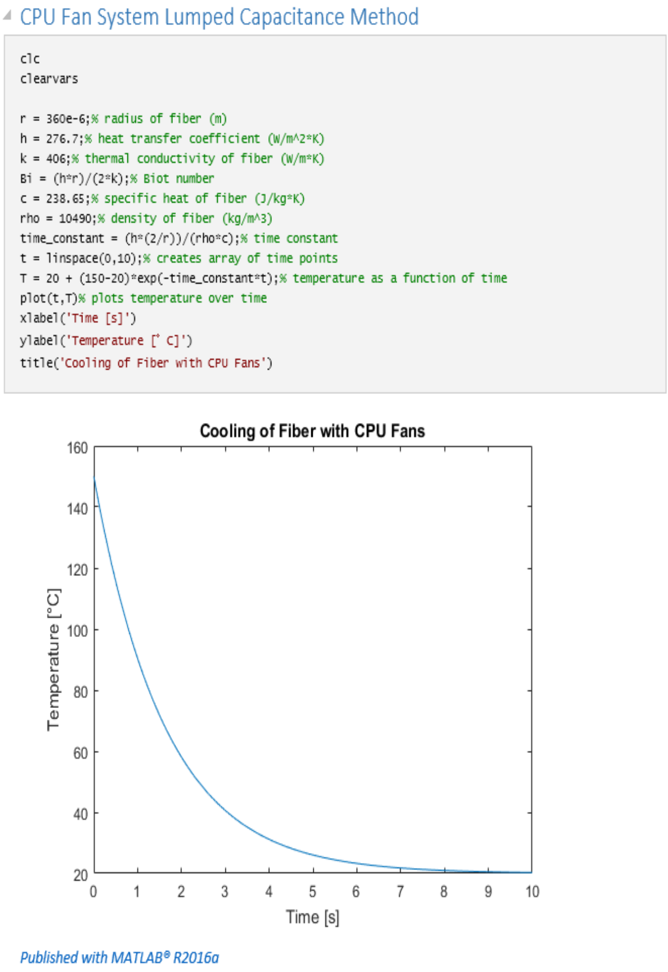
Figure F1. MATLAB Code for Heat Transfer Coefficient Calculation



CPU Fan System Lumped Capacitance Method

```
clc
clearvars

r = 360e-6;% radius of fiber (m)
h = 276.7;% heat transfer coefficient (W/m^2*K)
k = 406;% thermal conductivity of fiber (W/m*K)
Bi = (h*r)/(2*k);% Biot number
c = 238.65;% specific heat of fiber (J/kg*K)
rho = 10490;% density of fiber (kg/m^3)
time_constant = (h*(2/r))/(rho*c);% time constant
t = linspace(0,10);% creates array of time points
T = 20 + (150-20)*exp(-time_constant*t);% temperature as a function of time
plot(t,T)% plots temperature over time
xlabel('Time [s]')
ylabel('Temperature [˚ C]')
title('Cooling of Fiber with CPU Fans')
```

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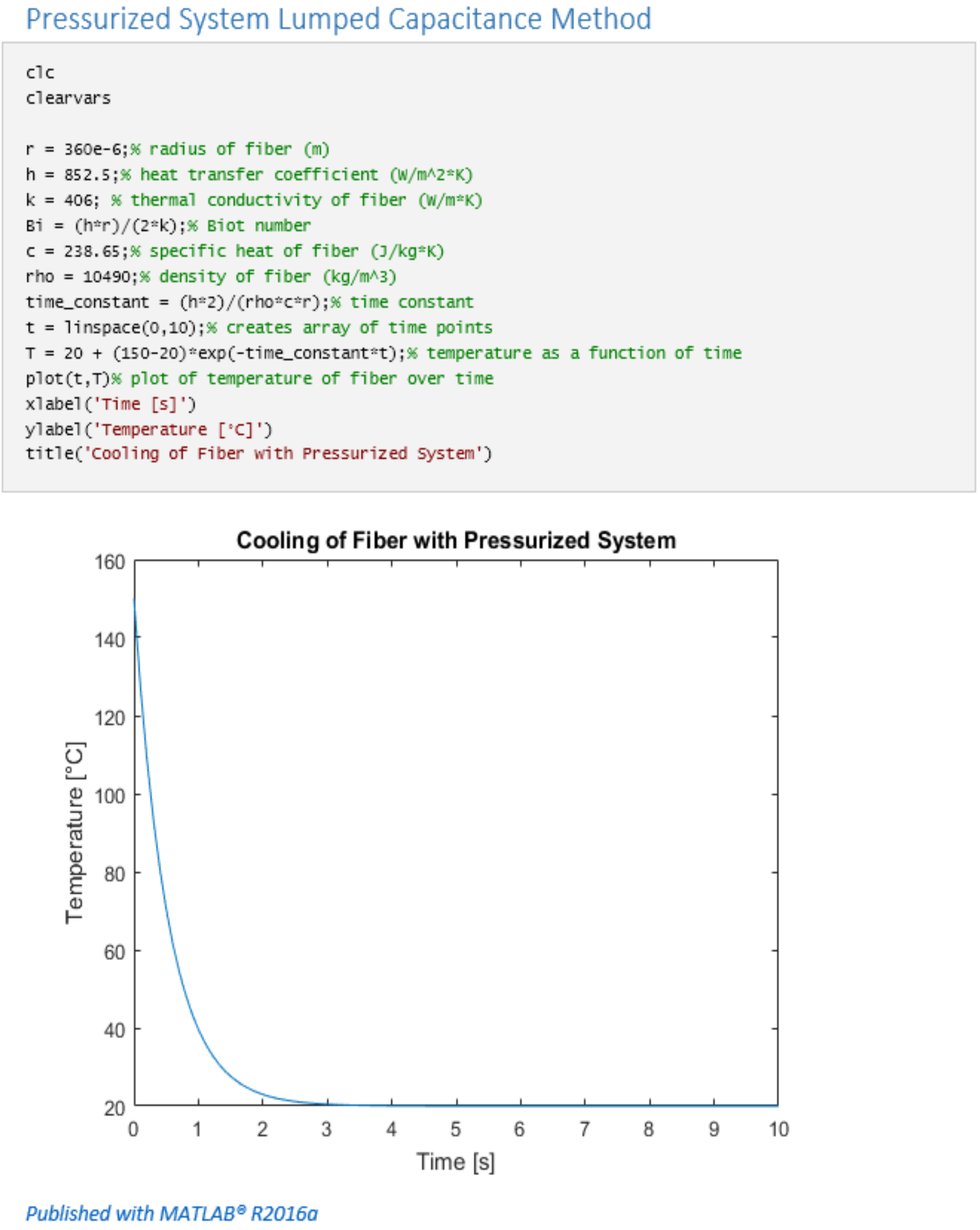
Figure F2. MATLAB Code for Lumped Capacitance Method of CPU Fan System



Pressurized System Lumped Capacitance Method

```
clc
clearvars

r = 360e-6;% radius of fiber (m)
h = 852.5;% heat transfer coefficient (W/m^2*K)
k = 406; % thermal conductivity of fiber (W/m*K)
Bi = (h*r)/(2*k);% Biot number
c = 238.65;% specific heat of fiber (J/kg*K)
rho = 10490;% density of fiber (kg/m^3)
time_constant = (h*2)/(rho*c*r);% time constant
t = linspace(0,10);% creates array of time points
T = 20 + (150-20)*exp(-time_constant*t);% temperature as a function of time
plot(t,T)% plot of temperature of fiber over time
xlabel('Time [s]')
ylabel('Temperature [°C]')
title('Cooling of Fiber with Pressurized System')
```

Published with MATLAB® R2016a

Figure F3. MATLAB Code for Lumped Capacitance Method of Pressurized Air System