ACTA IMEKO
ISSN: 2221-870X
September 2022, Volume 11, Number 3, 1 - 6

Twisted and coiled polymer muscle actuated soft 3D printed robotic hand with Peltier cooler for drug delivery in medical management

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ABSTRACT
This paper presents experimental studies on a soft 3D-printed robotic hand whose fingers are actuated by twisted and coiled polymer (TCP_{FL}) muscles, driven by resistive heating, and cooled by water and Peltier mechanism (thermoelectric cooling) for increasing the actuation frequency. The hand can be utilized for pick and place applications of drugs in clinical settings, which may be repetitive for humans. A combination of ABS plastic and thermoplastic polyurethane material is used to additively manufacture the robotic hand. The hand along with a housing tank for the muscles and Peltier coolers has a length of 380 mm and weighs 560 gm. The fabrication process of the TCP_{FL} actuators coiled with 160 µm diameter nichrome wires is presented. The actuation frequency in the air for TCP_{FL} is around 0.01 Hz. This study shows the effect of water and Peltier cooling on improving the actuation frequency of the muscles to 0.056 Hz. Experiments have been performed with a flex sensor integrated at the back of each finger to calculate its bend-extent while being actuated by the TCP_{FL} muscles. All these experiments are also used to optimize the TCP_{FL} actuation. Overall, a low-cost and lightweight 3D printed robotic hand is presented in this paper, which significantly increases the actuation performance with the help of cooling methods, that can be used in applications in medical management.

Section: RESEARCH PAPER

Keywords: robotic hand; artificial muscle; TCP muscles; fishing lines muscles; 3D printed hand; Peltier cooling; biomimetic; grasping; drug delivery

Citation: Rippudaman Singh, Sanjana Mohapatra, Pawandeep Singh Matharu, Yonas Tadesse, Twisted and coiled polymer muscle actuated soft 3D printed robotic hand with Peltier cooler for drug delivery in medical management, Acta IMEKO, vol. 11, no. 3, article 10, September 2022, identifier: IMEKO-ACTA-11 (2022)-03-10

Section Editor: Zafar Taqvi, USA

Received March 25, 2022; **In final form** September 27, 2022; **Published** September 2022

Funding: This work is supported by internal fund- Research Enhancement

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1. INTRODUCTION

Soft actuators such as SMA muscles and their composites are being widely studied currently. However, SMAs are expensive and are not manufactured easily in-house, and have high hysteresis behaviour. New actuators such as TCP_{FL} muscles are emerging as a new class of actuators recently. These muscles have a wide range of possibilities in robotics applications.

In this paper, the focus is on the application of TCP_{FL} muscles in a robotic hand and a method of improving the actuation frequency. The fabrication of TCP_{FL} muscles has been discussed in a study by Haines et al. where [1] different materials among Polyethene, Nylon 6, sand silver-plated Nylon 6,6 were investigated for applications in soft actuators. Twisted and Coiled Nylon 6,6 polymer as artificial muscles were found to be reliable, inexpensive, had high load carrying capacity, and a large stroke. Another study [2] discusses the use of TCP_{FL} muscles with nichrome wire, where nichrome acts as a heater wire for the muscles with quick heating capabilities.

The incorporation of this novel soft actuator in robotic arms can help reduce the size and weight of existing motor-actuated prosthetic hand models while producing similar actuation. Also, as proved in a study by Wu et al. [3] the temperatures of the muscle when actuated in the air can reach higher values in the range of 80 °C to 140 °C. While these high temperatures were optimal during the heat-induced compression cycle, they did not allow a proper relaxation of the muscles.

To initiate a proper relaxation, the cooling cycle would have to be configured for a long time which increases the time duration for each actuation cycle and reduces the actuation frequency. The use of cooling methods to optimize the high temperatures of the TCP_{FL} muscle brought about by Joule heating for proper relaxation is discussed in this paper. The main purpose of the paper is to reduce the cooling cycle of the TCP_{FL} muscles to reduce the time gap between flexion and extension and increase the overall actuation frequency.

Water is the most available resource which can act as a natural coolant. Water having a high specific heat capacity [4] can extract heat from the TCP_{FL} muscles at a fast pace. It has been used in other applications to optimize the actuation of artificial muscles including shape memory alloys (SMA) [5], [6], giant magnetostrictive materials (GMMs) [7], and liquid crystal elastomers (LCEs)[8]. Similar methods have been discussed with a robotic finger attached to TCP_{FL} muscles in previous work by Wu, L. et al [9] where the TCP_{FL} muscles were actuated with the help of hot and cold water. The use of water was also inspired by previous studies where NiTi SMA [10] and TCP [11] muscles were used in underwater jellyfish robots. It was noted that the actuation frequency drastically increased in a medium where heat was dissipated faster. This study was mimicked by submerging the muscles in a sealed container with water as a medium to dissipate heat.

A study by Astrain, D. et al [12] introduces a type of cooling system that uses voltage difference to generate a temperature difference between the top and bottom ceramic plates of the device. This uses alternating semiconductor couples to leverage the Peltier effect to produce Thermoelectric cooling. This type of thermoelectric cooler is called a Peltier cooler. Another study on Peltier coolers [13] incorporated it in a closed insulated container to lower the internal temperatures to the freezing point of water. Such Peltier-based coolers were also used with other artificial SMA muscles [14] to optimize their thermomechanical properties. Hence, they were considered for use in optimizing the actuation of TCP_{FL} muscles in this study.

The hypothesis of this paper focuses on implementing these water-based and Peltier cooling methods to optimize the flexion and extension of a prosthetic finger carried out by the TCP_{FL} muscles. The improvement of actuation frequency of the TCP_{FL} muscles for a faster prosthetic hand grasping movement was the major objective of the experiments designed for this study. This study involved collecting prosthetic performance data using flex and temperature sensors. Experiments were conducted using special housing tanks to incorporate the muscles, water, Peltier coolers, and sensors. Substantial improvement in actuation frequency, from 0.01 Hz in the air to 0.056 Hz due to the cooling methods, was observed through the sensor data obtained during the experiments. Submerging the TCP_{FL} muscles in water inside the container and further dissipating the heat from the container using Peltier Coolers proved to be very effective. This was especially helpful for improving the performance speed of a prosthetic hand for applications like pick and place of medical drugs in clinical settings.

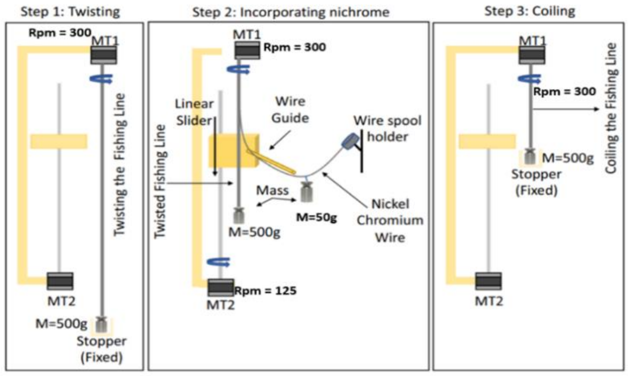

Figure 1. Schematic of the Fabrication process of the Twisted and Coiled Polymer (Fishing Line) muscles. Step1: The Fishing Line Twisting process. Step 2: The Nichrome winding process. Step 3: The Self Coiling process.

2. METHODOLOGY

Firstly, the fabrication of the core component of this experimental study, the TCP_{FL} artificial muscle is discussed in this paper. These muscles were made of Nylon 6,6 fishing line muscles wounded with nichrome wire. The nichrome wire was used to convert the power supplied into heat and this heat was used via conduction to heat the fishing line for it to contract.

2.1. TCP_{FL} Fabrication Process

An approximate 1.5m length of Nylon fishing line string was cut from a spool of fishing line. The ends of this cut length were tied with rings/washers to mount on motors that rotated and coiled the muscles. As shown in Figure 1 the Nylon fishing line was attached to a motor on the top and the other end was suspended with a weight of 500g. This was to ensure that enough tension was provided to keep the coiling uniform since the load should not be heavy enough to break the fishing line while coiling.

The top motor was started at a speed of 300 rpm while restricting the rotation of the bottom end of the fishing line. The fishing line was allowed to coil upwards while twisting. Only the axial rotation was arrested once coiling started, either from the top, bottom or middle. The motor was stopped, and the rotatory restriction was removed. At this stage, the winding of nichrome over the uncoiled fishing line was initiated. The nichrome was coiled over the fishing line at a speed of 125 rpm. Once the nichrome was uniformly wound over the fishing line muscle, the rotatory restriction was applied again so that the nylon coiling process could be carried out. At the end of the coiling process, the weight was removed. At the end of this entire process the bottom end of the coiled muscle must be held firmly before and after removing the weight, slightly releasing the hand pressure and once the weight was removed so that the muscle could ease a bit of the torsional tension. The muscle would not get uncoiled but only get untwisted a few rotations.

After this, the muscle was removed from the coiling setup, and each of its ends was mounted on a small platform that could be used to heat treat the muscle. A furnace was heated up to 180 degrees and the muscles were placed inside the hot furnace for 90 min. Once the muscles were heated the ends of the same were crimped firmly with the nichrome in contact with gold crimps. The muscles were then placed under a 500-gm load and trained under various power cycles that were supplied to their crimped ends. Various currents supplied brought about different compressions in steps as shown in

Table 1. Power Supply supplied across both ends of the TCPFL muscles during the Training procedure.

Current (A)	Deformation (%)
0.18	10
0.2	14
0.24	20
0.26	27

Table 1. This training step later supports similar compressions and relaxations when provided with a current across its ends.

2.2. TPU Hand Setup

A Single piece robotic palm was 3D printed with the Thermoplastic polyurethane (TPU) material. TPU is a flexible material that can provide strength in higher thicknesses and toughness and flexibility in lower thicknesses. This hand was previously utilized in combination with other artificial SMA muscles [15]. So, this is adequate to test the TCP_{FL} muscles used in the design presented in this paper. The container was made of transparent acrylic material, to ensure clear visibility of the movement of the muscles inside the container. Dedicated slots were accommodated for the Peltier plates on the bottom of the container.

The container was assembled and sealed with the help of M-Seal and silicone. The M-Seal provides strength to the container and the silicone ensures water saleability. Holes were provided to accommodate ten TCP_{FL} muscles, two for each finger - one for flexion and the other for extension. The openings were sealed with silicone to allow flexibility and to ensure water saleability. One end of the muscle was fixed to the back of the container. The other end was connected to a finger of a single piece TPU hand as shown in Figure 2.a using fishing line strings. When power was applied across the muscles, they contracted at the same time pulling the fishing line string connected to the finger.

2.3. Peltier Cooler and Sensors

Two Peltier coolers were inserted into the dedicated slots inside the same muscle housing container. These Peltier coolers each consist of 127 couples of n-type and p-type semiconductor blocks that operate at 12 V 2A to create thermoelectric cooling across their plates. So, both were connected in series to a 24 V 2A battery as seen in Figure 3.c. The effect of these Peltier coolers on lowering the temperatures of water that is exposed to the cooling plate was observed using underwater temperature probes. The probe used was the DS18B20 digital single-bus intelligent temperature sensor [16] and that has been seen in previous studies involving underwater applications [17], [18]. This sensor when connected across a circuit as shown in Figure 3.a provides a digital output of the temperature probe to an Arduino microcontroller. The temperature data recorded from the probe attached underwater inside the container during the experiments helped in assessing the benefits of the cooling methods for TCP_{FL} actuation.

There are many instances where standard flex sensors have been used along with hand prosthetic applications to either control the bending of the prosthetic fingers [19], [20] or recognize [21], [22], [23] the gestures of hands. Also known as stretch sensors, they can be used in wearables [24] to track the bending of a finger. This is a resistive sensor that alters its resistance value as it is bent along its length. Hence this resistive property was manipulated for characterizing the bending action

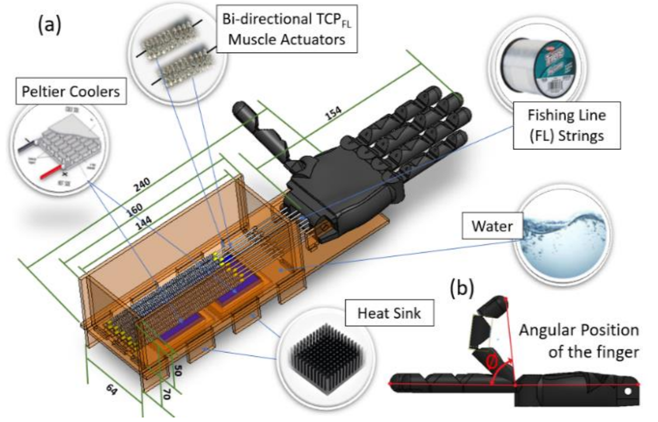

Figure 2. (a) The Schematic of the Experimental Setup. The fingers of a TPU prosthetic hand are attached to TCP_{FL} muscles using fishing line strings. Bi-directional flexion and extension actions of the finger are produced by the actuation of two TCP_{FL} muscles. The muscles are housed in an acrylic tank filled with water. This tank has integrated two Peltier coolers on its base. (b) The angular position of the finger with respect to the horizontal is calculated using data recorded from Flex sensors during flexion or extension actions.

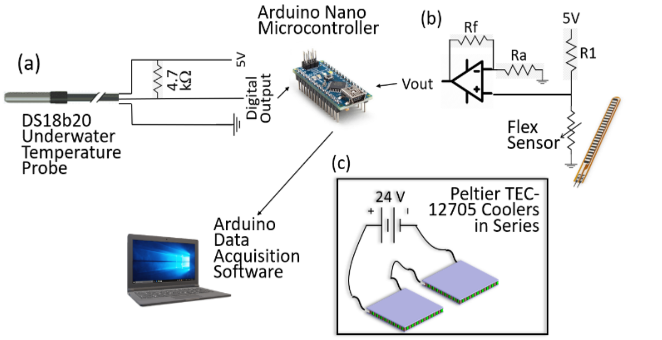

Figure 3. Schematic of the electronic circuits of the sensors and Peltier coolers. (a) DS18b20 Temperature Probe used to monitor the heating and cooling of the water during TCP_{FL} actuation and Peltier cooling. Data collected by the Digital Pins of the Arduino microcontroller. (b) Flex Sensor used to monitor the finger bending movements during the finger's actuation. Sensor integrated with an amplification circuit. (c) Peltier Coolers used to cool the water in the TCP_{FL} housing tank. Connected in series with a 24V Power Supply.

of the prosthetic hand mentioned in this paper. The data obtained from the flex sensor helped characterize the TCP_{FL} muscles for their actuation frequency and optimization of the actuation with cooling methods.

For this design, the resistance was converted to a voltage reading using an amplification circuit as seen in Figure 3.b and read through the ADC pins of the Arduino. This voltage reading was recorded with respect to time and linearly interpolated to previously obtained angle-vs-voltage flex sensor calibration data. This calibration data helped in calculating the angular position of the finger with respect to the horizontal as shown in Figure 2.b. The angle-vs-time results obtained from the flex sensors helped in observing the actuation frequency of the muscles with different cooling conditions.

3. EXPERIMENTAL METHODS AND RESULTS

The experimentations conducted for the TCP_{FL} muscles included a characterization setup utilized in other studies to understand various properties of NiTi SMA [10], TCP [11], and

Table 2. Informational Data of the fabricated TCP_{FL} Muscle obtained through characterization experiments performed during similar other studies on TCP muscles [10], [11].

Property	**Value**
Material	Nylon (6,6) fishing line
Type of actuation	Electrothermal
Type of resistance wire	Nichrome (Nickel, Chromium)
Resistance wire diameter	d_w = 160
Precursor fibre diameter	D = 0.8 mm
Length of precursor fibre	L = 1500 mm
Weight for fabrication	M_f = 500 g
Annealing temperature/time	T_a = 180 °C / (90 min)
Diameter after cooling	D = 2.8 mm
Length after cooling	L = 120 mm
Resistance	R = 110 Ohm
Current (Input)	I = 0.16-0.26 A (During training: I = 0.26 A is provided to the muscle)
Voltage (Output)	V = 57.6-115.2 V
Actuation power	P = 9.2-36.8 W
Heating time	T_h = 10 s,15 s
Cooling time	T_c = 90 s, 85 s
Actuation frequency (Air-cooled)	F = 0.16-0.1Hz
Actuation strain, at 500g load	Epsilon = 27-10%
Life cycle	2400 cycles in air at 9 mHz and 1 % duty cycle.

TCA [25] muscles using multiple sensors as shown in the study by Hamidi, A. et al [26]. The setup as shown in Figure 4 included a Keyence laser displacement sensor to measure the muscle's actuation strain, thermocouples used to measure the muscle's temperature during actuation, and NI DAQ 9221 used to measure the output voltage due to change of muscle's resistance during actuation. Using this setup characterization experiments were conducted with the TCP_{FL} muscles fabricated in this paper. The properties of the muscle were obtained from these experiments and are listed in Table 2. It included an actuation strain ranging from 10 % to 27 %. The voltage across the muscle could rise to 115 V due to a change in resistance after being actuated.

The experimental setup of the TPU hand actuated by two TCP_{FL} muscles as described in the methodology and shown in Figure 5 was used to obtain results to justify the hypothesis of this paper. There was a separate power supply for each of the two TCP_{FL} muscles. Each power supply was configured to form different heating and cooling cycles to respectively compress and relax the muscle. The lower TCP_{FL} muscle responsible for an extension usually followed a flexion by the upper TCP_{FL} muscle. Hence the lower muscle required more energy to compress to additionally loosen the upper muscle's compression. The actuation cycles for flexion (by the upper TCP_{FL} muscle) and extension (by the lower TCP_{FL} muscle) were set separately on the two power supplies.

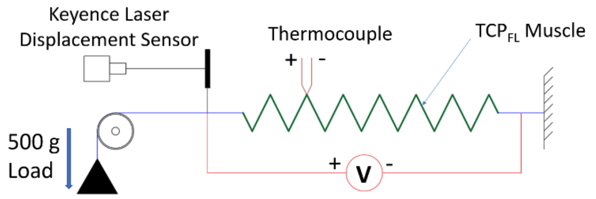

Figure 4. Experimental Setup for the characterization of TCP_{FL} muscles.

The temperature data obtained from the DS18B20 sensor showed an increase in the temperature of the water when TCP_{FL} muscles were actuated in it. Figure 6 portrays the same behaviour when one muscle was actuated inside different volumes of water at a heating cycle of 5 seconds and a cooling cycle of 10 seconds. Higher volumes of water had a high capacity to dissipate more heat from the muscles and had a lower rise in temperatures. Figure 7 portrays the cooling ability of Peltier coolers with respect to the volume of water. These cooling rates show that Peltier Coolers can be instrumental in optimizing the actuation frequency of the muscles. A 150 ml water was finally chosen as optimal for the experiments of this study as it would get heated more slowly by the muscles as compared to lower volumes. Although the cooling rate is smaller than that of lower volumes it would be enough for this application.

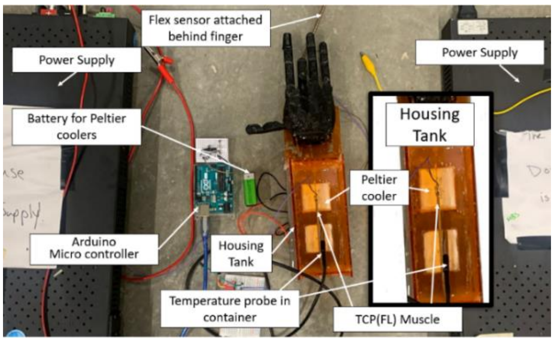

Figure 5. Experimental Setup of TPU hand with TCP_{FL} muscles and Peltier Coolers installed housing tank. Two Power supplies used to actuate each of the two muscles for the movement of one finger. The Flex sensor and Temperature probe circuits utilized inside the setup.

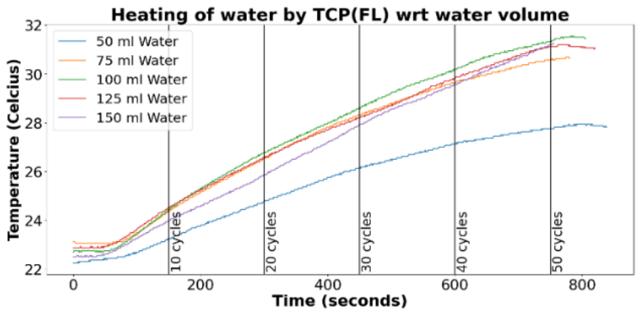

Figure 6. Heating effect of the TCP_{FL} muscle actuation on water. The muscle was actuated with a heating cycle of 5 seconds and a cooling cycle of 10 seconds. The steady rise in temperature was observed by the DS18b20 temperature probe over 50 cycles of actuation. The heating effect of the muscle was observed for different volumes of water.

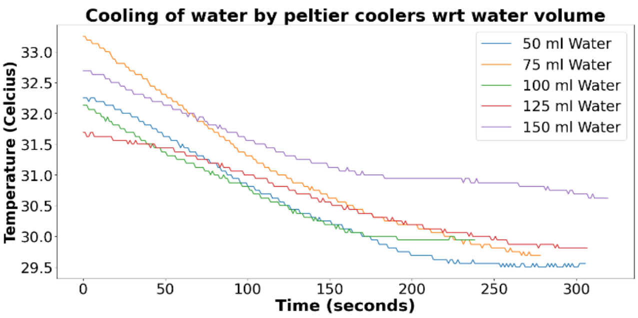

Figure 7. Cooling the water in the housing tank with Peltier coolers. The reduction of temperature in the water was observed over time by the DS18b20 temperature probe for different volumes of water.

Flex sensor data was obtained for different actuation cycles for the TCP_{FL} muscles and different environmental conditions (in air, in water, and in Peltier-cooled water). For actuating the finger in the air at 0.26 A the heating and cooling cycles were set as 10 seconds and 90 seconds respectively for the upper muscle (flexion) and 15 seconds and 85 seconds respectively for the lower muscle (extension). This setting resulted in an actuation frequency of 0.01 Hz for the TCP_{FL} muscles.

When shorter cycles were selected for actuation, the upper muscle could not relax from its compressed state during its cooling cycle. This prevented the extension of the finger through the lower muscle's actuation. Therefore, longer cooling cycles of 90 seconds were selected for proper in-air actuation of the two muscles as was proved by the flex sensor results (Figure 8).

The actuation frequency of the TCP_{FL} muscles improved by about five times to 0.056 Hz when the muscles were completely submerged in 150 ml of water. The heating and cooling cycles operating at 1 A were set as 5 seconds and 13 seconds respectively for the upper muscle and 7 seconds and 11 seconds respectively for the lower muscle. As was seen from the angles interpolated from the flex sensor results (Figure 9.a) there was a very good frequency of actuation. The time to bring about these actuations was minimized from previous experiments in-air.

An even smoother actuation was observed during the extension of the finger when the Peltier Coolers were utilized to remove the heat accumulated in the water medium. The same actuation cycles were used, like before with water. Through the interpolated flex sensor results obtained in Figure 9.b, a significantly faster extension was observed. The extension angle-vs-time slope is much steeper in Peltier-cooled waters as compared to the same in just water. Peltier coolers help in maintaining the water at lower temperatures to aid in the cooling/relaxation phase of muscles.

4. CONCLUSIONS

The cooling methods proposed proved to have an impact in optimizing the actuation performance of the TCP_{FL} muscles. The frequency of the muscle's actuation was increased by over five times from 0.01 Hz when they were actuated in-air to 0.056 Hz when they were actuated in water. The major cooling effect observed was due to the presence of water as a medium to dissipate heat from the actuators. The finger movement as a result was very smooth and fast-paced. The Peltier coolers ensured that the temperature of the water was maintained close to room temperature. This was achieved as the coolers dissipated the heat from the water that was accumulated from the actuating muscles. Due to this behaviour, the improved frequency of actuation was maintained at a high of 0.056Hz for multiple cycles.

The actuation for the extension of the robotic finger by the lower TCP_{FL} muscle took a longer time than the actuation for the flexion of the finger by the upper TCP_{FL} muscle. This was because of the tension remaining in the upper muscle from the compression during the flexion action. This in turn kept the finger tightly flexed and did not allow it to be extended in the other direction. The Peltier coolers shortened the extension actuation phase of the robotic finger. The extension phase of the setup depended on how fast the upper TCP_{FL} muscle cooled down and relaxed itself. This faster cooling was achieved due to lower temperatures of water produced by the Peltier coolers.

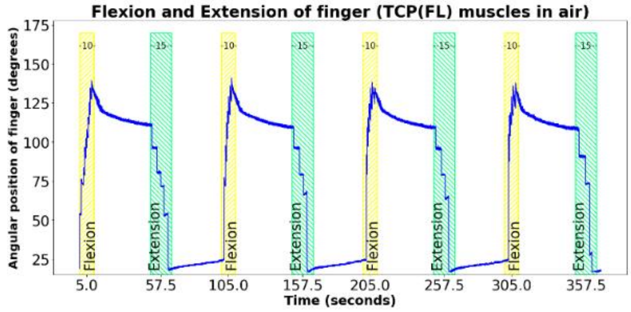

Figure 8. The angular position of each finger during bi-directional actuation by two TCP_{FL} muscles. This flexion/extension angle of the finger was calculated from the data obtained from the Flex sensor. The muscles were actuated in the air with a heating cycle of 10 seconds (for the flexion action shown in yellow) and a cooling cycle of 90 seconds for the upper muscle and a heating cycle of 15 seconds (for the extension action shown in green) and a cooling cycle 85 seconds for the lower muscle. Both the muscles complete each cycle in 100 seconds, so the actuation is 1/100 = 0.01 Hz.

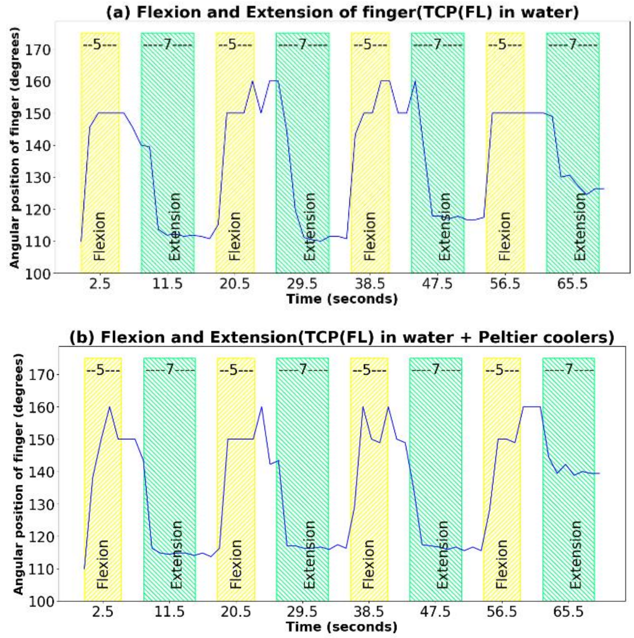

Figure 9. The angular position of each finger calculated from flex sensor data during bi-directional actuation by two TCP_{FL} muscles. The muscles were actuated for a heating cycle of 5 seconds (for the flexion action shown in yellow) and a cooling cycle of 13 seconds for the upper muscle and a heating cycle of 7 seconds (for the extension action shown in green) and a cooling cycle 11 seconds for the lower muscle. Both the muscles complete each cycle in 18 seconds, so the actuation is 1/18 = 0.056 Hz. The TCP_{FL} muscles were submerged inside (a) 150 ml of water, (b) 150 ml of water that was cooled by two Peltier coolers-

Further studies and experimentation are required to improve the performance of these muscles in an enclosed setup. Some new housing tanks designs and materials are being explored to augment prosthetic actuation efficiency.

ACKNOWLEDGEMENT

The authors would like to thank Akash Ashok Ghadge for his support in the experimentation and design and Eric Wenliang Deng for his support with the TPU palm used for the experimentation, they both are affiliated to the Humanoid Bio-robotics and Smart systems Lab, the University of Texas at Dallas.

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