APPENDIX

Poly-Saora Robotic Jellyfish: Swimming Underwater By Twisted and Coiled Polymer Actuators

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1. TCP muscle fabrication

Twisted and coiled polymer actuator (TCP) is a new type of smart actuator that is promising for application as an artificial muscle in biomimetic robots due to its ability to reproduce the important features of natural muscle such as power, stress, strain, and speed of response (frequency). TCP muscle developed by Haines et al. [1] is a polymer actuator that responds to the change in temperature gradient. TCP muscles are fabricated by suspending a dead weight at the bottom end of a highly drawn polymer fiber such as nylon 6 or nylon 6,6 [2] while connecting the top end to a motor. The twist is achieved by applying a rotation using a motor until the actuation strain reaches a steady state [3]. The fabrication procedure of the TCP muscle is shown in **Fig. S1**. This twisting process is allowed to occur until the entire length of the thread is twisted and then coiled. Certain material processing steps are followed to stabilize the actuation behavior of the material. After fabrication, the muscles are subjected to an electro-thermal treatment referred to as "annealing and training" (**Fig. S1 (d) and (e)**). This treatment ensures consistent performance of the muscles under the applied load. Annealing alters the microstructures; causing changes in the strength, hardness and ductility of the muscle. This enables the muscle to actuate reversibly and attain optimal inter-coil spacing. Training is a form of annealing. It imparts the muscle with the ability to maintain a steady state while actuating and carry a specific load. The annealing and training process can be divided into 4 phases: 3 annealing phases (6 cycles each) and 1 training phase (15 cycles). This process was developed through experimentation by testing different ways of training and annealing the TCP muscles [4]. The optimal parameters of the process were developed specifically for the TCP application in the jellyfish. By varying the number of cycles, deadweight and applied power, the optimal parameters for achieving an actuation strain of 19% were identified (**Table S1**).

Table S1. Annealing and Training Parameters for achieving an average actuation strain of 19%.

		Annealing I (6 cycles)	**Annealing II (6 cycles)**	**Annealing III (6 cycles)**	**Training (15 cycles)**
Type of TCP	**Load**	t_{heat} – 10s t_{cool} – 45s	t_{heat} – 13s t_{cool} – 45s	t_{heat} – 13s t_{cool} – 45s	t_{heat} – 15s t_{cool} – 45s
4 – Ply	600g	1.3A	1.3A	1.5A	1.5A
6 - Ply	900g	2.0A	2.0A	2.2A	2.2A
8 - Ply	1200g	2.6A	2.6A	2.8A	2.8A

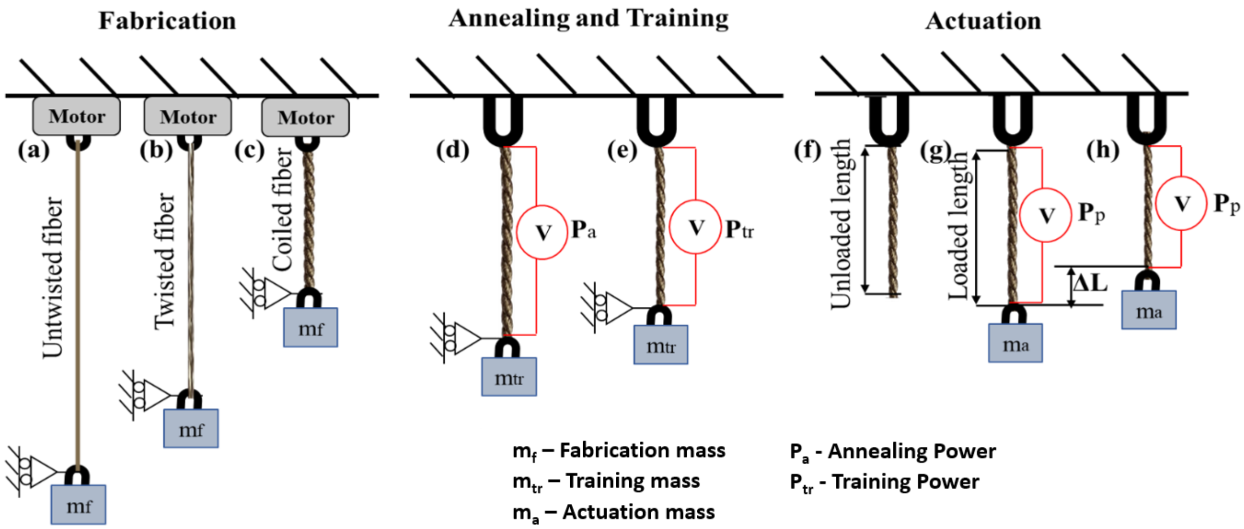


Figure S1. Schematic diagram of the TCP muscle fabrication and actuation process: (a) the top end of the nylon fiber is attached to a motor and a deadweight is suspended at the bottom end to keep the precursor fiber straight and taut, (b) inserting twist in the fiber by rotating the motor, (c) continuous, regular coils emerge throughout the thread length to form a TCP muscle, (d) the muscle is annealed by electro-thermal heating by applying power, P_a, across terminals. (e) After annealing, the muscle is trained by electro-thermal heating by applying power, P_{tr}, (f) the unloaded length without lifting the weight and (g) the loaded configuration is shown. (h)After annealing and training, the 1-ply TCP muscle is tested by applying powering voltage, P_P, showing the contraction [3].

2. TCP muscle characterization for bell actuation

The effect of input power to the actuator in an underwater environment has an important role in providing efficient bell deformation for swimming. In this case, 4-ply and 6-ply muscle are both studied for direct actuation in water. The characterization results of 4-ply muscle actuation at high power (8.8 A) are presented in Fig. S2. The 4-ply muscle is actuated at three different frequencies, 0.5 Hz, 1 Hz and 5 Hz. It is shown that as frequency of actuation rises, the difference between the initial temperature (at time= 0s) and the minimum temperature of the muscle at the end of cooling cycles increases. This is due to the incomplete cooling of the muscle. Finally, both 4-ply and 6-ply muscles are applied for actuation a bell segment. As shown in **Fig. S3** the 6-ply muscle provided a maximum bell deflection of 13° at 9.5A which is twice the bending provided by 4-ply actuator at an input current of 7A. Therefore, 6-ply muscle is employed in Poly-Saora jellyfish for swimming. Moreover, **Fig. S4** shows the lifecycle test results of 4-ply TCP in water which is comparable with the 6-ply lifecycle test results presented in **Fig. 4** in the paper.

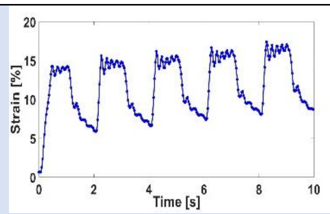
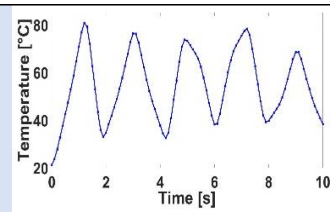
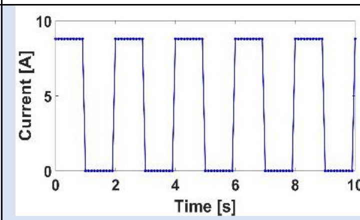
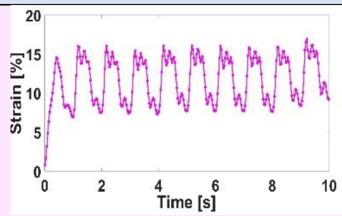
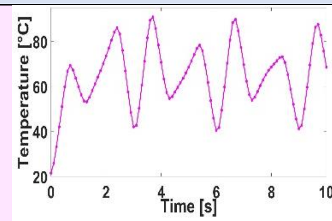
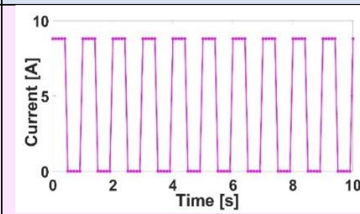
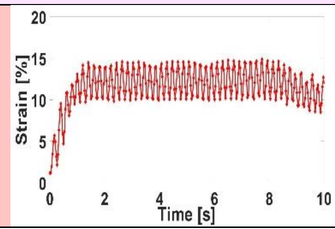
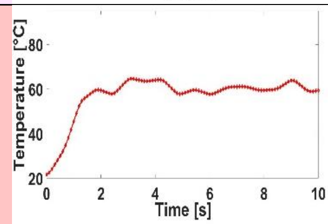
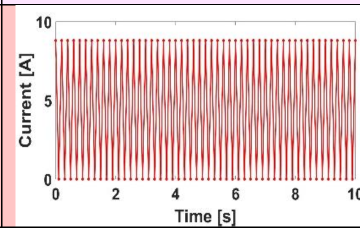
Frequency	Displacement	Temperature	Current
(a) 0.5 Hz			
(b) 1 Hz			
(c) 5 Hz			

Figure S2. Characteristics of 4-ply TCP muscle in water actuated at high power (8.8 amps and 32 V): (a) frequency =0.5 Hz (b) frequency= 1Hz (c) frequency=5 Hz.

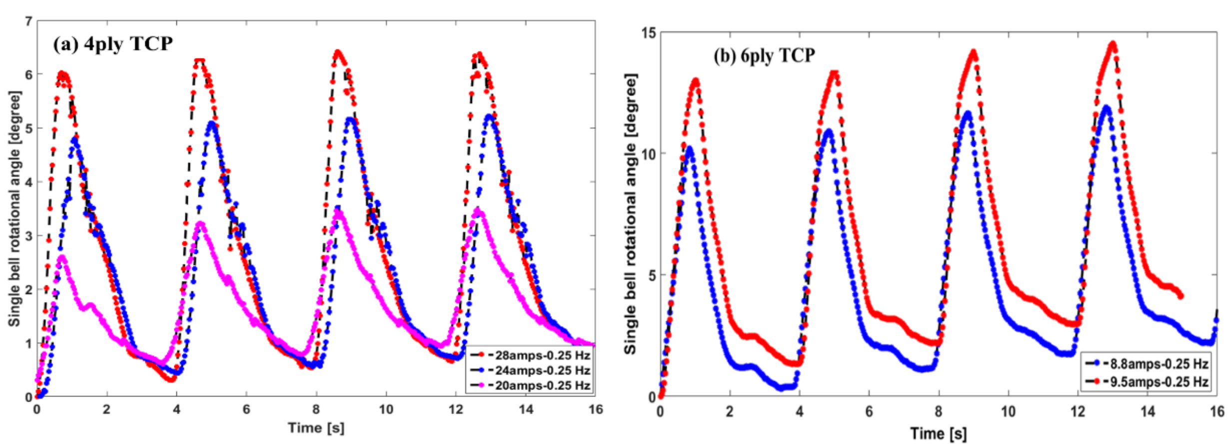


Figure *S3*.Fig. Comparison of a single bell actuation (a) with 4-ply TCP and (b)with 6-ply TCP at0.25 Hz.

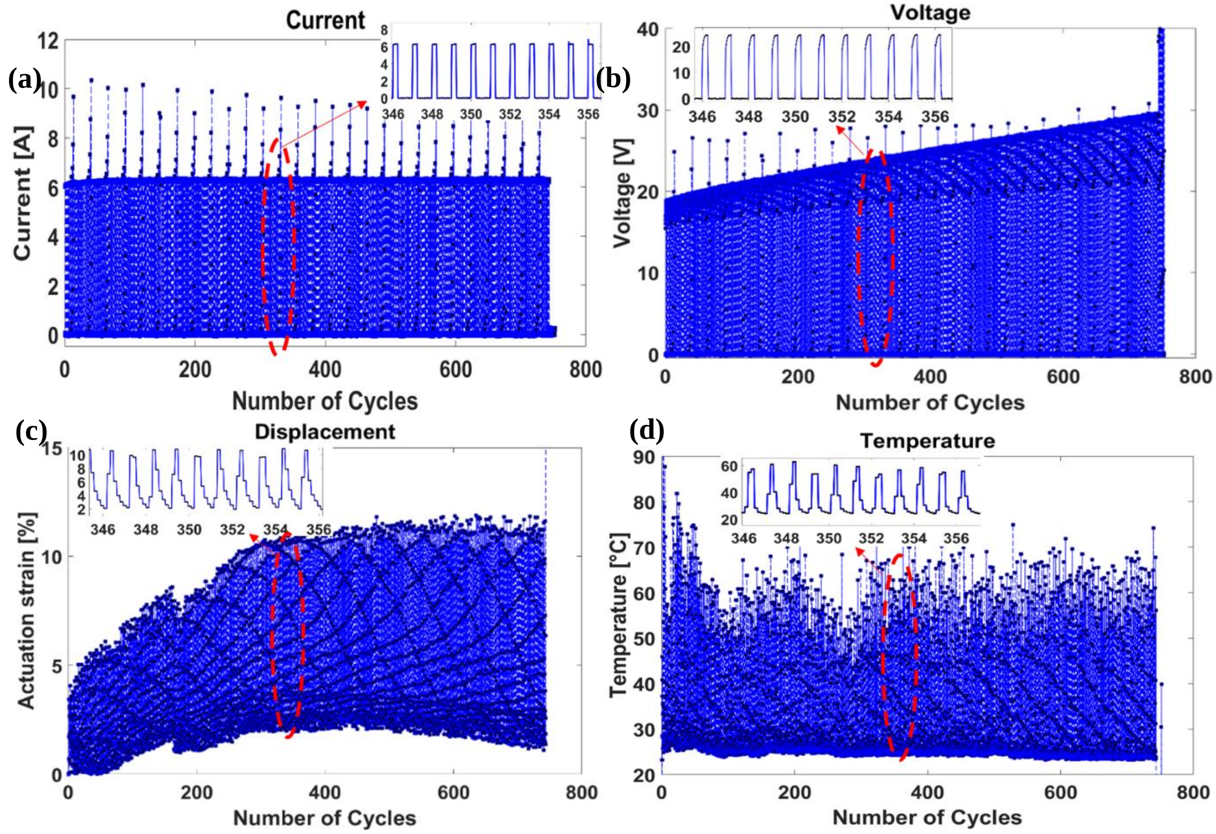


Figure S4. Life cycle test of 4 ply TCP at 6 A current and frequency of 0.25 Hz (1 s heating and 3 s cooling: (a) input current ;(b) output voltage, (c) actuation strain (output) and (d) actuation temperature.

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[2] Saharan, L. and Y. Tadesse, *Novel twisted and coiled polymer artificial muscles for biomedical and robotics applications*, in *Materials for Biomedical Engineering*. 2019, Elsevier. p. 45-75.

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