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Yara Almubarak, Nicole Xiu Maly, Yonas Tadesse, "Fully embedded actuators in elastomeric skin for use in humanoid robots," Proc. SPIE 10594, Electroactive Polymer Actuators and Devices (EAPAD) XX, 1059416 (27 March 2018); doi: 10.1117/12.2300940

Event: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, 2018, Denver, Colorado, United States

Fully embedded actuators in elastomeric skin for use in humanoid robots

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ABSTRACT

Humanoid robot head designs that have embedded actuators within the elastomeric skin solve most of the problems of hardware integration and space requirement of perepheral elements. Presently, most humanoid heads use actuators such as servo motors and pneumatic actuators to achieve head movements and facial expressions. These actuators are expensive, bulky, heavy in weight, and take up a lot of space. The use of embedded actuators will closely mimic the natural human head that consists of numerious muscles and sensors. Here, we present soft actuators based on twisted and coiled polymer (TCP) muscles within elastomeric skin for the robot face design and development. The TCPs are made of silver-coated nylon 6,6 following the common fabrication process: twisting, coiling, annealing and training. The fabricated skin was mounted on a 3D printed humanoid head and facial expressions were tested. We showed head movements and basic facial expressions. It is for the first time such significant improvement is shown in humanoid robots with facial expressions due the embedded actuators in the silicone skin.

Key words: soft actuators, humanoid head, silicone elastomer, TCP muscles, nylon actuators, artificial muscles, facial expression, elastomer

1. INTRODUCTION

Within the last 10 years, major progress has been made in the development of humanoid robotic heads that are able to generate the same facial expressions as humans. A humanoid head with TCP muscles was introduced in 2017 [1]. The FACE robot made in 2012 uses 32 servo motors mapped on major facial muscles in order to simulate the 6 basic facial expressions (happy, sad, surprise, anger, disgust, and fear) [2]. Other more recent developments in "social robots" include the Phillip K. Dick robot, which utilizes servo motors as well as Faceshift facial tracking software in order to replicate human mouth and jaw movement and expressions [3]. The Buddy robot is a 3D printed humanoid robot that has the ability to dance and perform human-like facial expressions. It was made with the intention to assist children and the elderly [4]. Real world applications of humanoid robots are becoming increasingly evident as the technology improves. In 2013, a study performed by Industrial Research Ltd. used a humanoid robot in order to promote attention, communication, and social skills in children with autism [5]. In homes, there has been consideration of using humanoids as a housekeeper while the home owners are away. In the medical field, recent studies have brought up the use of humanoids as service robots to aid nurses and as a method of training healthcare professionals [6]. Currently, many robots use bulky, expensive, and heavy actuators such as servo motors and pneumatic actuators. The humanoid robot Sophia has made major headlines in the news as of late 2017, appearing on television shows and magazine covers. Composed of mostly servomotors, Sophia is known as the most lifelike and realistic humanoid robot to date and has even been granted citizenship in Saudi Arabia [7]. In 2016, researchers at the Tokyo Institute of Technology and Okayama University in Japan were able to develop a human-inspired musculoskeletal lower-limb robot made from thin multifilament McKibben muscles and pneumatic actuators. By grouping large bundles of these thin McKibben muscles together and attaching them to a human-size skeleton replica, they are able to move the skeleton in a natural and human-like way, such as walking. They have even been able to add these muscles to the jaw of the skeleton in order to replicate natural human jaw movements [8]. The motors used in the humanoids may produce vibration and noise, which are undesired attributes that preclude the use of the robot. These traits serve as a huge disadvantage to the robotic design and control. Unlike those conventional actuators, TCP muscles are light, flexible, inexpensive, and small in size. In addition, TCP muscles are able to be molded within the structure and actuated discreetly with minimal noise and vibration [9].

Electroactive Polymer Actuators and Devices (EAPAD) XX, edited by Yoseph Bar-Cohen,
Proc. of SPIE Vol. 10594, 1059416 · © 2018 SPIE · CCC code:
0277-786X/18/$18 · doi: 10.1117/12.2300940

This paper presents a novel artificial muscle embedded within the humanoid robot silicone skin. The muscles are twisted and coiled from a nylon 6,6 precursor fiber. We tested 13 samples of twisted and coiled polymer nylon 6,6 muscles that displayed a consistent strain average of 15%, and standard deviation of 2.4%. This paper also shows experimental results of tensile testing for different EcoFlex 30 composites. These tests consisted of three dog bone samples performed using ASTM D412 standard. The first test being EcoFlex 30, second using EcoFlex 30 with 10% by volume of silicone thinner, and third, EcoFlex 30 with 10% by volume of vinegar and sodium bicarbonate mix [10]. The TCP muscles were embedded according to human muscle anatomy in the silicone composite of EcoFlex 30 and (10% vol) silicone thinner. Muscle pairing was conducted in order to achieve symmetry between the two halved of the face during actuation. TCP muscles were used in the humanoid head and skin. Figure 1 (a) shows fully embedded TCP muscles in the humanoid elastomer skin, where the muscles are within the skin, only their lines of action are seen.
Moreover, figure 1 (c-d) shows some facial expressions presented using TCP muscles based robotic head. The results of this paper show the ability of the embedded TCPs to perform facial expressions as well as skeletal jaw movement. The introduction of fully embedded actuators within the humanoid elastomer skin plays an important role for future works such as the embedding of sensors; further enhancing the robotic design while still maintaining a smooth unobstructed robot design.

2. TWISTED AND COILED POLYMER MUSCLES (TCP)

Twisted and coiled polymer muscles made of silver coated nylon 6,6 were developed by Haines et al. [11]. The high strength polymer fibers are thermally actuated using an electrical voltage and current. Thermal actuation of the nylon 6,6 produces a strain of 4%. However, twisting and coiling can be introduced to the nylon 6,6 thread which can amplify the strain to as high as 22%[9]. These muscles are inexpensive (~$5/kg for the material) compared to the commonly used servomotors and pneumatic actuators. Thermal annealing and training of the muscles under certain loads help to prevent the untwisting of the fiber during actuation.

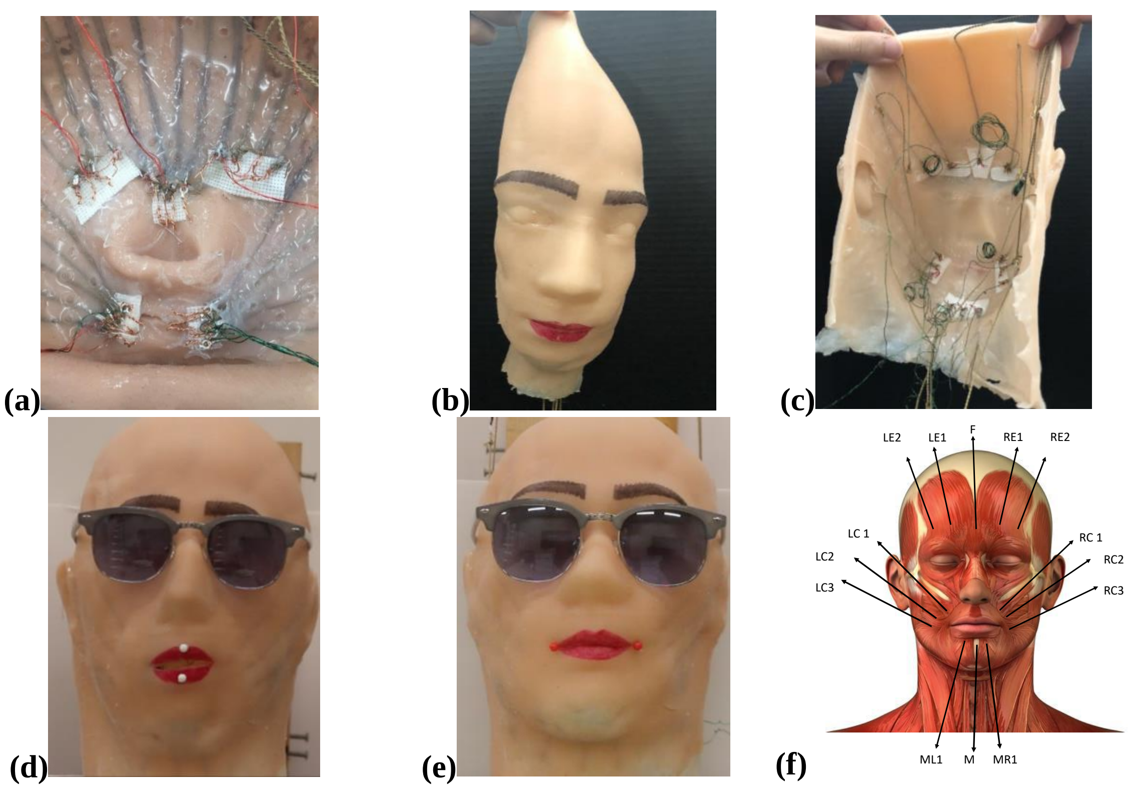


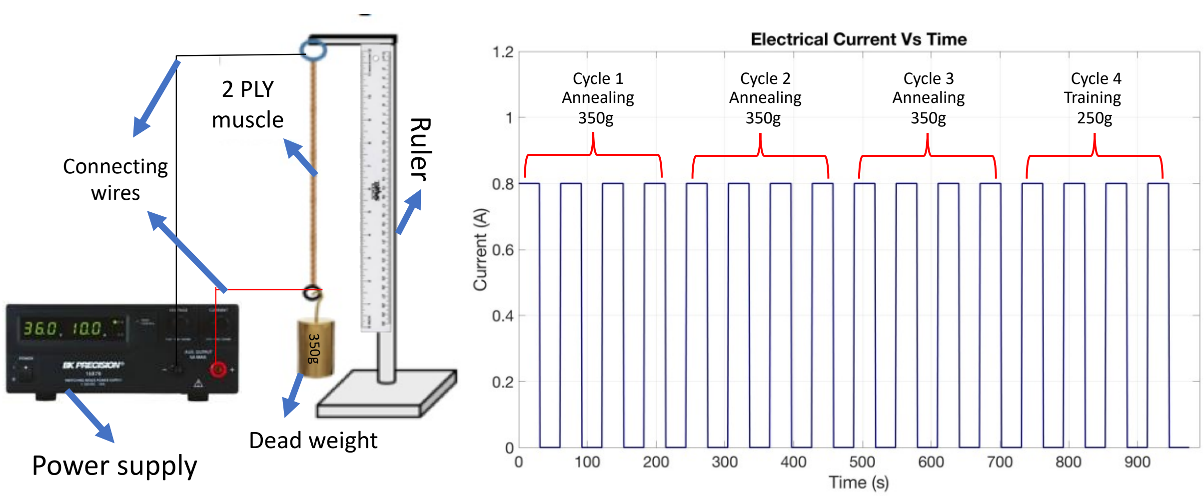
Figure 1: TCP based head Lilly 2.0 (a) Fully embedded TCP muscles in silicone skin as seen in the back. (b) Front view of humanoid head with embedded TCP muscles. (c) Back view of humanoid head embedded with TCP muscles (d-e) Fear and Happy facial expression actuated using embedded TCP muscle. (f) Anatomy of TCP muscle distribution in the human face.

2.1 TCP muscle fabrication

Twisted and Coiled Polymer muscles (TCP) were fabricated using an automated fabrication system. This system includes a DC motor, power supply, dead weights, and measuring tools. The TCP muscles were fabricated following prior related work [12]. The precursor silver coated nylon 6,6 fiber was obtained from Shieldex Trading Inc. and several precursor fibers of TCP spools were used in these experiments. The muscles can be triggered thermally by applying an electrical current across the length of the samples, which will cause them to actuate linearly similar to several other artificial muscles such as shape memory alloys (SMA). For fabricating a TCP muscle, the thread is connected to the electric motor on one end while a dead weight is attached to the other end. To achieve the initial twist, the motor applies a counter clockwise rotation to the thread, causing it to coil. This coiling can continue until the entire length of the thread is coiled. This is observed by a change in diameter of the thread. The initial coil produces a 1-Ply muscle. To achieve a 2-Ply TCP muscle, we fold the 1 ply in half. Due to the initial twisting and coiling stress, the thread will manually coil itself into a 2ply muscle. Applying more coiling will achieve 3,4, or higher ply muscles which will produce higher force. Finally, each end is crimped connected to the power supply for training and annealing. The set up for annealing and training is shown in figure 2.

2.2 Annealing and training

To use the newly fabricated muscles for actuation, the muscles must undergo heat treatments in order to ensure a consistent actuation parameter every time they are used. These heat treatments are referred to as "annealing and training". Annealing is a process that alters the microstructures of a material; causing changes in properties such as strength, hardness, and ductility. Training is a form of annealing. It is used to train the muscle so that it can carry a specific required force. It results in the muscle's ability to maintain a steady state while actuating at the forces required. The annealing and training process can be divided into 4 cycles; 3 annealing cycles and 1 training cycle.. This process was developed after testing multiple different ways of training and annealing the TCP muscles. By varying the number of cycles and the amount of weight used for each, it was found that the optimal method for achieving the desired amount of percent strain in each muscle was the 3 annealing and 1 training cycles. Each cycle consists of four 60 s periods with 50% duty cycle (30 s ON and 30 s OFF) as shown in figure 2.



(a) **(b)**

Figure 2: 2-Ply TCP muscle preparation of diameter ~ 1.8mm and 110 mm length (a) Schematics of TCP muscles annealing and training set up. (b) Annealing and training parameters.

2.3 TCP muscle actuation experimental set up

Twisted and coiled polymer muscles were fabricated using nylon 6,6 precursor fiber. Experiments were conducted on the newly fabricated TCPs. The experimental set up included several 2-ply TCP muscles, NI DAQ 9219, keyrence laser displacement sensor, thermocouples, laptop, power supply, and dead weight as shown in figure 3.

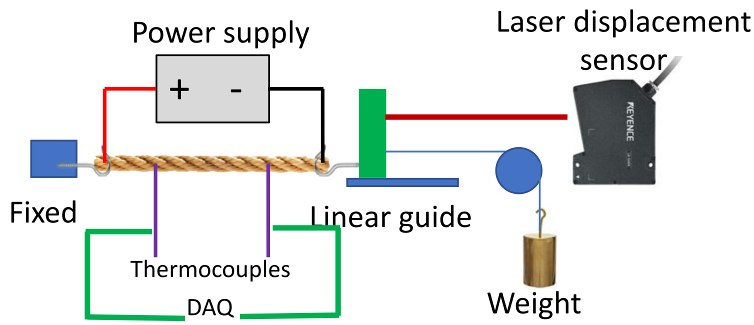


Figure 3: TCP muscles displacement experimental set up.

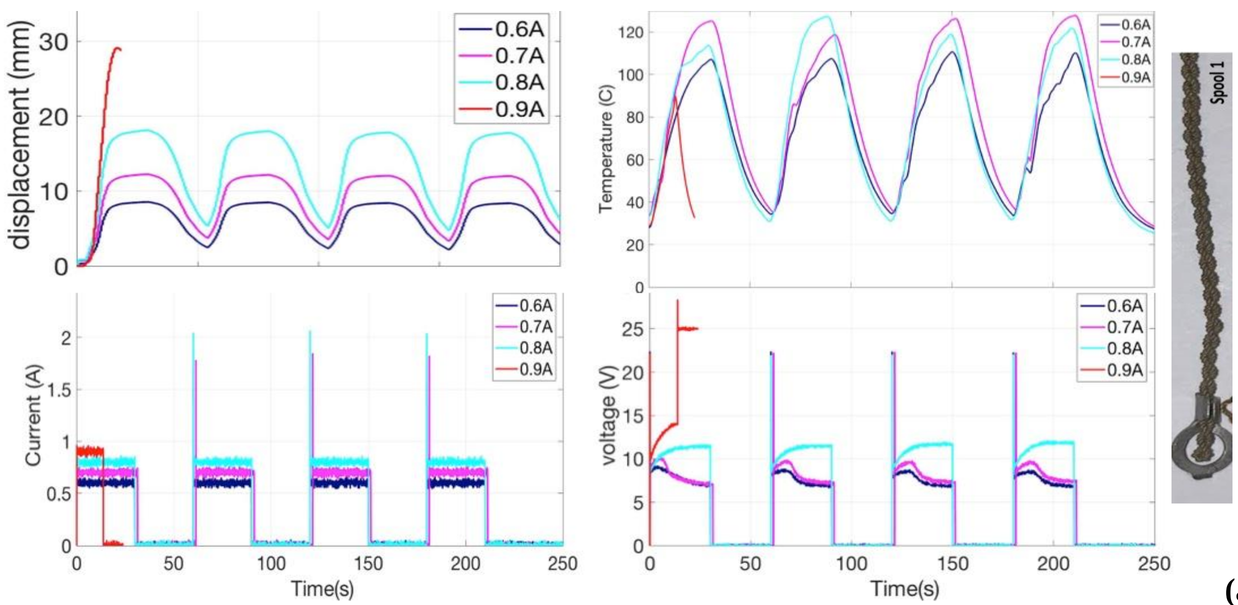
2.3.1 Current (A) driven heat treatment

It is observed that the heat treatment process can differ slightly due to the percentage of conductive silver particles that are found in the precursor fiber. Heat treatment is applied using electrical current averaging between 0.6A and 0.9A. Several muscles are initially tested under different current values to determine the training and annealing electrical current input for each new precursor fiber batch. Two 2-ply samples were fabricated from spool 1 and spool 2. The two samples differ slightly in color as shown in figure 4 and that is due to the percent change of silver particles found in each precursor fiber. Recently, it was found that the silver layer in the silver is around 100nm [13].

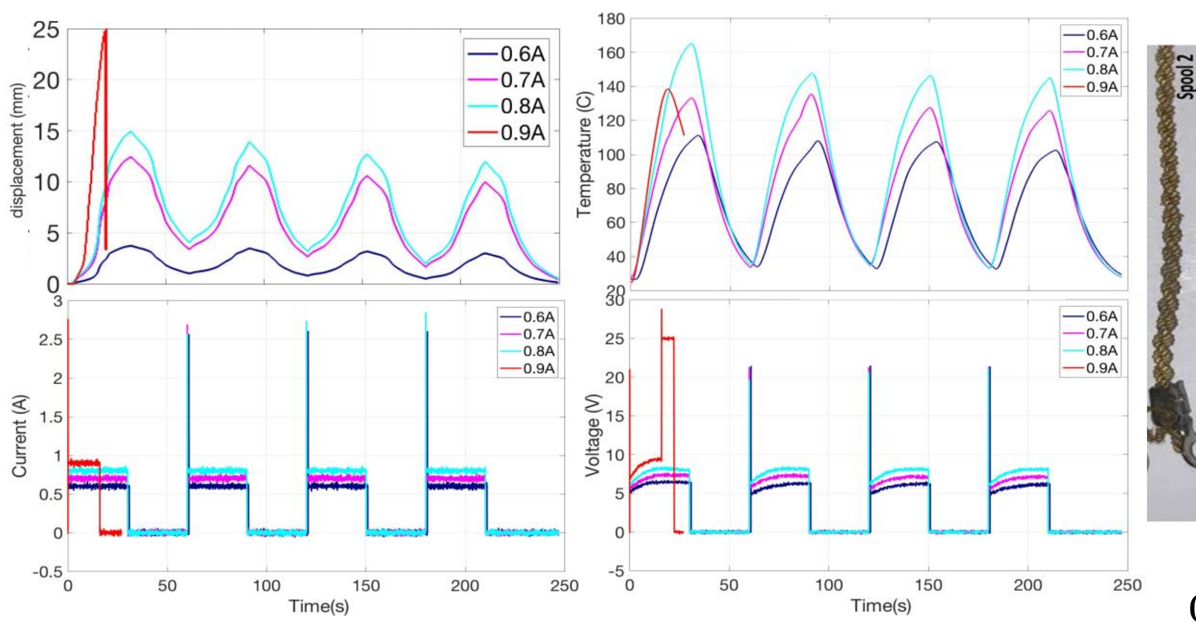
Figure 4: Samples of fabricated 2-ply muscles from spool 1 and spool 2.

Experiments were conducted varying the set electrical current while keeping the voltage open for a duty cycle of 30s ON and 30s OFF. Displacement, temperature, current and voltage versus time were plotted using MATLAB for all tested samples. The data was collected using National Instruments data acquisition (DAQ 9219). The tested samples were of equal length, 110 mm. Figure 5 (a) shows the data plotted for the darker muscle fabricated from the precursor fiber spool 1. While the data in figure 5 (b) shows the results for the lighter muscle fabricated from precursor fiber spool 2. The average strain displacement of all actuated TCP is shown in table 1. The temperature in spool 1 varies from 100C^o up to 120 C^o while in spool 2, it varied between 100C^o up to 160 C^o. The increase in temperature can be due to the increase of percent silver found in the lighter muscles which will cause the TCP to heat up to higher temperatures or due to the uneven distribution of silver within the thread. It is also observed that there is a consistent variation between the voltage of spool 1 and 2. Here, spool 1 has higher voltage which is an indicator that the resistivity in the darker TCP is higher. It is observed that both muscle broke at 0.9A. Furthermore testing should be conducted to quantify the difference.

Table (1): Average strain of actuated TCP muscles under varied electrical current (A)				
Electrical current	0.6 A	0.7 A	0.8 A	0.9 A
Spool 1	8%	10%	17%	27%
Spool 2	4%	11%	13%	22%



(a)



(b)

Figure 5: Experimental data of displacement , temperature, voltage, and current vs time for 2 ply TCP muscles from spool 1 & 2.

3. SILICONE SKIN AND MOLD FABRICATION

To continuously produce the same silicone skin quality, a mold was created using polyurethane. Polyurethane mix (PMC 746) was obtained from Reynolds Advanced Materials is a 2:1 ratio mixture of part A and part B. This material has a shore hardness of 00-60A. Similar to platinum cured silicone, polyurethane is initially in liquid form and then becomes very rigid after curing. The advantages of using this material are that it can be molded into any shape. Moreover, its molding ability produces a smooth surface which is very hard to achieve when using materials such as wood or plaster for molding. In this case, we have molded the 3D printed head. The 3D printed head was generated using a computer facial recognition program called FaceGen [14]. This program allows the user to create 3D heads from 2D photos. By uploading several photos of the front and side views, it will instruct the user to click on several significant points such as eyes, edges of lips, and nose to calculate the depth and dimensions of the face to create the 3D head as shown in figure 6.

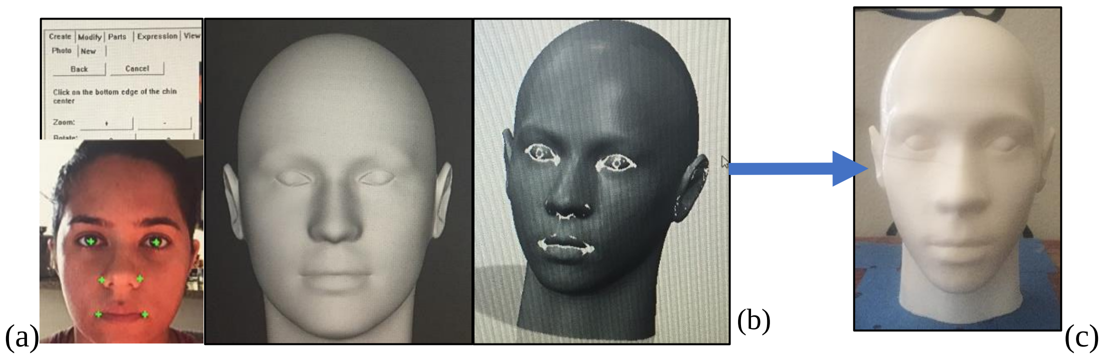


Figure (6): Developing head model (a) FaceGen 3D interface (b) STL file produced from FaceGen 3D (c) 3D printed head for mold fabrication.

Figure 7 (a-c) shows the steps of creating the polyurethane mold. Liquid PMC is poured into an enclosure and the 3D printed head is placed in the material while its curing overnight. Figure 7 (d-e) show the placement of the smaller sized 3D printed head in the PMC mold after curing. Figure 7 (f-g) shows the final schematics of fabricated silicone skin on 3D printed head.

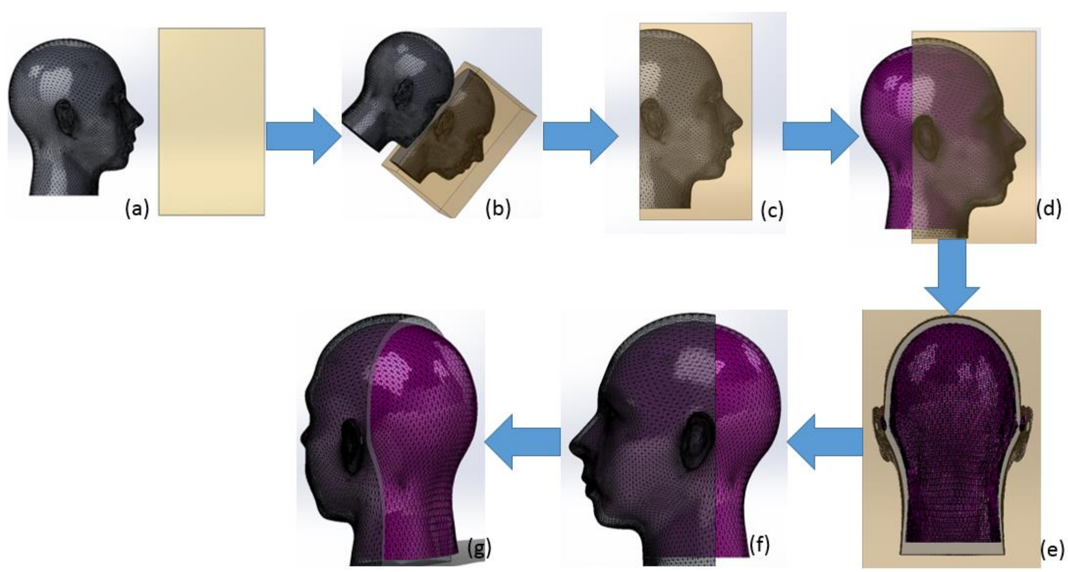
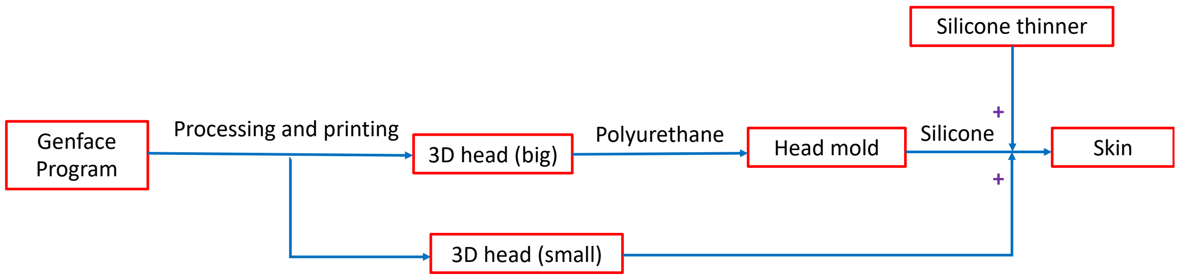


Figure 7: Polyurethane mold fabrication.

3.1 Skin Fabrication

Platinum cured silicone ExoFlex-30 elastomer was used as the basis of the artificial skin for the humanoid head. Ecoflex-30 has a shore hardness of 00-30, up to 900% elongation at break, and a tensile strength of 200 psi(1379kPa) [15]. Platinum silicone is a medically approved material that is translucent, making it safe material for human interaction and enabling us to freely customize its color in order to achieve a more human-like look for the humanoid robot. Excoflex-30 part A and part B are mixed together in a 1:1 ratio and allowed to cure for up to 6 hours before using. In order to achieve a more flexible, fast movement for a skin actuation of 10% by volume of low viscosity, silicone thinner was added to the mix. Figure 8 shows block diagram schematics of silicone skin fabrication



Figure(8): Block diagram of silicone skin fabrication for humanoid head.

The addition of silicone thinner lowers the ultimate shore durometer of the cured silicone rubber (resistance to permanent indentation). ASTM D 412 tensile test for elastomer material was conducted for the 3 silicone composite samples at a rate of 500 mm/min. Figure 9 below shows experimental results for stress vs. stain and load vs. extension. Both results consistently show that the silicone + silicone thinner mix and silicone vinegar sodium bicarbonate (VBS) mix is significantly better than 100% silicone. These results show that the new enhanced composites can produce higher deformation at a lesser force. Calculating the % elongation of each sample was obtained from the percentage, L_f is the final stretched length and L_i is the initial length.

$$\% \, Elongation = \frac{L_f - L_i}{L_i} * 100 \qquad (1)$$

It can be observed that the silicone thinner preformed drastically better than the other 2 silicone composites. Figure 9 (a) shows that the silicone thinner resulted in ~1200% elongation compared to EcoFlex 30 which was at 600% elongation while the silicone VSB composite was between at ~670% elongation. Moreover, Figure 9 (b) shows that both the silicone VSB and Silicone thinner composites showed better elongations at lower load values than EcoFlex 30. Taking into account the maximum force capacity of the TCP muscle at ~4N it can be observed silicone thinner composite produce 1200% strain at break and at 0.2 MPa stress(4N load), it produced 600% strain (200mm displacement). However, EcoFlex 30 produced a 620% strain at break and 400% strain (100mm displacement) 0.2 MPa stress (4N load). These results show that using either the silicone VSB or thinner composites will help maximize the performance of the robotic skin or other soft robots.

Table 2: Experimental results of Instron tensile test using 3 different silicone composites

Sample	Initial length (mm) L_i	Final length (mm) L_f	Elongation (%)
EcoFlex 30	33	240	627
EcoFlex 30 + VSB	33	255	672
EcoFlex 30 + Thinner	33	430	1203

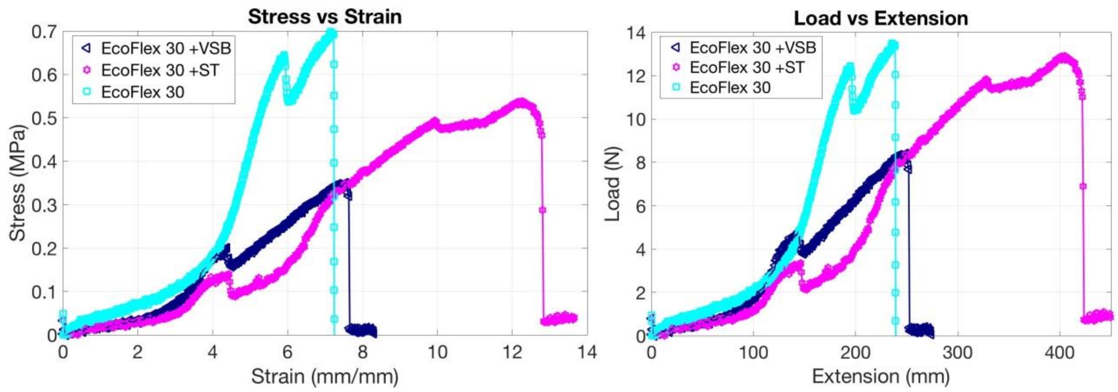
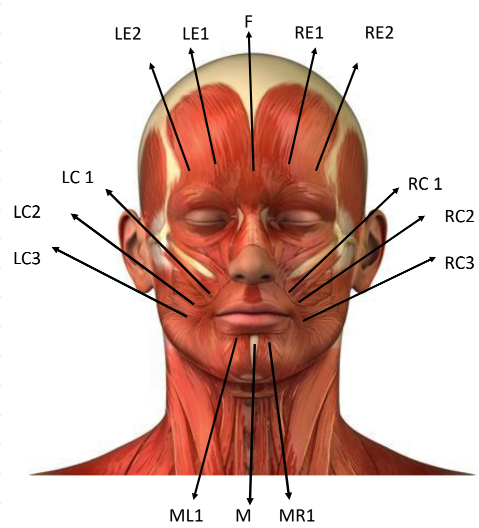


Figure 9: Tensile testing of silicone composites at rate 500 mm/min using ASTM D412 standard (a) Stress Vs Strain. (b) Load Vs Extension

4. MUSCLE PAIRING

The TCP muscles prepared for the humanoid were paired together depending on their performance. In order to create as much symmetry in the face in terms of muscle movement, muscles with similar amounts of percent strain and actuation were grouped together. As shown in figure 10 (a), we aimed for roughly equivalent actuation in the left and right rides of the face. With regards to the muscle placement, LE and RE stand for left eyebrow and right eyebrow, respectively, while F stands for forehead. LC and RC stand for left cheek and right cheek, while ML, M, and MR stand for mouth left, mouth (center), and mouth right, respectively. Figure 10 (b) is also provided to coordinate the acronym.

Placement	Muscle	Length (cm)	% Strain	Actuation (cm)	Optimal Current(A)	Spool #
Left eyebrow						
LE1	t113	20.7	14.7	3.528	0.9	2
LE2	t111	23.8	16.3	3.879	0.9	2
Forehead						
F	t54	35.5	16	5.68	0.8	1
Right eyebrow						
RE1	t114	20.5	17	3.485	0.9	2
RE2	t116	20.8	17.8	3.702	0.9	2
Left cheak						
LC1	t117	20.7	15	3.105	0.9	2
LC2	t112	26	16	4.16	0.9	2
LC3	t9	22.5	11.2	2.52	0.8	1
Right cheak						
RC1	t118	21	15	3.15	0.9	2
RC2	t110	24.6	17	4.182	0.9	2
RC3	t119	20	15	3	0.9	2
Chin						
ML	t36	21.1	11	2.321	0.8	1
M	t28	18	20	4.64	0.8	1
MR	t55	23.2	12.75	2.295	0.8	1



(a) (b)

Figure 10: (a) Table of TCP muscles parameters and location anatomy (b) TCP muscle location in reference to human anatomy

4.1 Anatomy of Facial Expressions

In order to determine the placement of the muscles in the face during the embedding stage, it was very important that we studied the anatomy of the face. This included studying the muscles necessary to perform the six basic facial expressions [16].

Happiness: Happiness is comprised of the levator labii superioris, zygomaticus major, zygomaticus minor, and the levator anguli oris. The muscles are all generally located in the cheeks, and are responsible for making us smile. The zygomaticus muscles in particular are known as the "smile muscles." The muscles embedded in the cheeks (LC1-3 and RC1-3) of the humanoid are placed in order to replicate the movement and anatomy of these specific muscles.

Sadness: Sadness involves the corrugator, procerus, depressor anguli oris, and the depressor labii inferioris. These muscles are mainly located at the bottom center (under the bottom lip) and bottom corners of the mouth, and are what allow us to frown. Muscles ML, M, and MR, located in the humanoid are representative of these muscles, and are what replicate this emotion on the robot.

*Surprise:*Surprise consists of the mandible rotation (open jaw), epicraneous frontalis (inner, medial, and outer), as well as the zygomaticus major and minor. All of these muscles together are what cause our jaws to drop and our eyebrows to raise when we are in shock. The muscles in the humanoid that are responsible for recreating this facial expression are LE1-2, RE1-2, F, and M.

*Anger:*Anger is shown using the corrugator, procerus, levator labii superioris, depressor anguli oris, and the mentalis. The corrugator and procerus are responsible for showing angry, down-pointing and disapproving eyebrows, and are shown on the humanoid using the LE1-2, RE1-2 and F muscles. Meanwhile, the depressor anguli oris and mentalis are responsible for making us frown when we are upset and angry. This movement is replicated on the humanoid by actuating muscles ML, MR, and M.

Fear: Fear contains the corrugator, epicraneous frontalis, risorius, and small angle mandible rotation. Small angle mandible rotation is what is seen when some people open their mouths slightly when they are afraid. This movement is accompanied by a raise in the eyebrows (epicraneuos frontalis). Fear is created in the humanoid by actuating the forehead and eyebrow muscles (F, LE1-2, and RE1-2) and the center mouth muscle (M).

Dislike: Dislike is demonstrated with the use of the levator labii superioris, zygomaticus major and minor, epicraneous frontalis, mentalis, and depressor anguli oris. This expression is characterized by a distinct pinching of the center of the face. The nose and eyebrows scrunch inward towards each other with the help of the levator labii superioris, zygomaticus major and minor, and the epicraneous frontalis. This movement is replicated on the humanoid when the forehead (F), eyebrow (LE1-2, RE1-2) and upper cheek (LC1, RC1) muscles are actuated. The frown that accompanies this expression is created in human anatomy using the mentalis and depressor anguli oris, and in the humanoid using the mouth muscles (ML, MR, M).

5. EMBEDDING TCPS IN HUMANOID HEAD

The fabricated TCP muscles are embedded within the silicone skin and skeletal head. Fully embedding the TCP muscles allows us to create a safer interaction environment between the robot and the user, while also providing more room for additional sensors and equipment to be installed within the skull, as well as closely mimicking the biology and anatomy of humans and muscle distribution. TCP muscles are cost effective and far less bulky compared to electrical motors and pneumatic actuators. In this paper, we fully embed the TCP muscles in the silicone skin by cutting slits throughout the inside of the silicone skin, embedding the muscles, and pouring silicone (EcoFlex 35) on top as shown in the figure 1.

5.1 Skeleton Head Jaw Actuation

In this experiment, Three TCP muscles were embedded into 3D printed ABS plastic skeleton head. Two muscles (TCP_a left of the skeleton, TCP_b right of the skeleton) were connected to either sides of the skeleton head and jaw while the third muscle (TCP_c) was connected to the bottom jaw and back of the skeleton. Both $TCP_{a,b}$ are used to close the jaw while TCP_c is used to open the jaw. When simultaneously actuated, the jaw is able to open and close; mimicking actual human jaw movements. Jaw actuation is shown in figure 11.

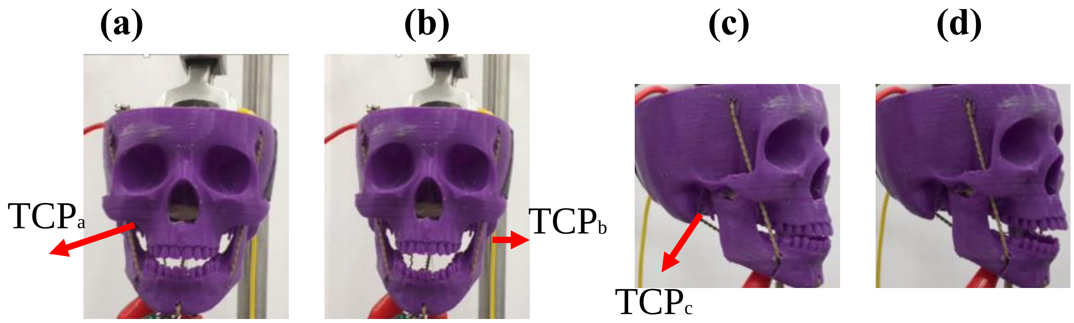


Figure 11: TCP muscles embedded in 3D printed humanoid skeletal Jaw. (a) Skeleton with $TCP_{a,b,c}$ in initial unactuated position. (b) Skeleton with $TCP_{a,b}$ actuated. (c-d) side view of jaw actuation.

5.2 Facial Expressions

The TCP skin was placed on a 3D printed skeleton head. Some clips were added to keep the skin stable on the printed skeletal head. The design of the 3D printed parts allows for less friction with the silicone skin therefore decreasing the friction between the silicone and the printed head. Using the muscle anatomy in figure 9 the muscles were actuated for several cycles to produce some facial expressions. Figure 12 (a) shows the humanoid with neutral expression, TCP muscles are not activated. Figure 12 (b-e) shows several facial expressions presented using fully embedded TCP muscles in the elastomer skin.

A preliminary survey was sent out in order to determine the accuracy of the facial expressions acquired in the experimentation process. Each picture shown above was featured in the survey and the responders were asked to label the expression that they believed matched the picture. The Survey results are shown in figure 13 with the responses of 100 participants from various ethnic backgrounds. The survey shows a maximum accuracy of 58% of the facial expression produced by the humanoid robot with embedded TCP muscles.

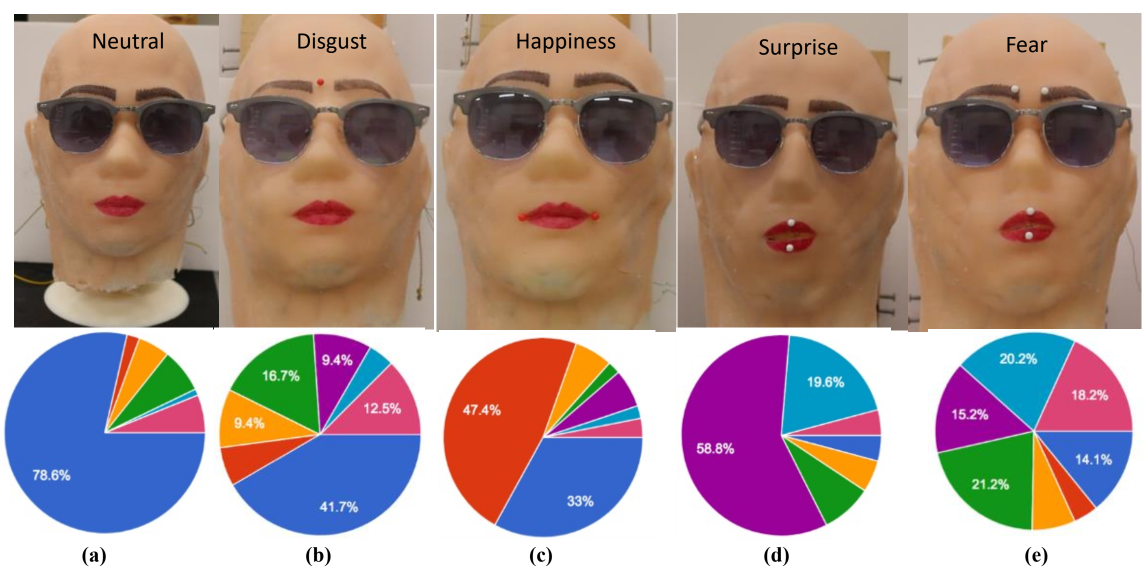


Figure 12: Humanoid head with facial expressions. (a) Neutral (b) Disgust (c) Happiness (d) Surprise (e) Fear.

6. CONCLUSION

This paper presents a 3D printed affordable humanoid face. Polyurethane is used to create a mold for casting the skin. Ecoflex-30 mixed with silicone thinner is used for skin material. Inspired by human anatomy TCP muscles were fully embedded into silicone skin to create several facial features. Conventional electrical servomotors are power efficient as compared with artificial muscles; however, they take more physical space and are much more expensive. Moreover, unlike TCP muscles, servos and pneumatic actuators produce unwanted vibration and noise that preclude the use of the robot. We have successfully demonstrated several facial expressions as well as jaw actuation using artificial muscles based on TCPs. Further studies can be done in order to make power consumption and actuation frequency more efficient.

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