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Carbon Nanotubes - Elastomer Actuator for Soft Prosthetics

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Abstract: *Prosthetics play an important role as a substitute for any essential part of body. Soft prosthetic is an attempt at making these artificial devices more human-like. The main focus of this paper is the use of a carbon nanotube- elastomer based compound material as an actuator for prosthetic devices. One of the main limitations of Electroactive Polymer (EAP), which is high applied voltage, is overcome in this approach by using carbon nanotube (CNT) yarn permeated with a mixture of elastomer and methanol. The actuation is based on phase transition and this concept can be implemented for soft prosthetics.*

Keywords: Carbon nanotubes, elastomer, actuator, soft prosthetic, etc

I. INTRODUCTION

Soft robotics is a niche area of robotics that focuses on making robots or devices with compliant materials that can make them more relatable to biological organisms. Conclusively, Soft prosthetics is gaining more importance as this can help in faster rehabilitation of the patients and better acceptance of the prosthetic device. Presently, the controlling mechanism responsible for movement of soft robots, known as actuators, tends to depend on hydraulics and pneumatics. These actuators are slow to respond[8]. Alternatively, polymers can be used for actuation of these devices. Dielectric elastomers (DE) measure well in terms of typical stress, strain, response speed and efficiency. However, they require very high voltages to the range of 1kV – 5 kV. Electroactive polymers (EAPs) too, can be considered as an option. But, the practical application of these actuators is difficult to implement due to incomplete reversibility and high applied voltage[7].

1.1 Electroactive Polymers for Actuation

Electroactive polymers (EAP) are polymers that alter their shape or size when stimulated by an electric field[7]. They can be broadly categorized into:

- Ionic EAPs
- Electronic EAPs

With ionic EAPs, the shape change is due to mobility and diffusion of ions. In electronic EAPs, the applied electric field causes coulomb forces in electrodes which in turn cause the shape change. Electronic EAPs can be further classified into three categories: dielectric, electrostatic and liquid crystal elastomers.

But, in order to actuate the electronic-EAPs, a high operating voltage is needed. This greatly limits their use for many applications due to safety concerns. This disadvantage of electronic EAPs can be overcome by considering phase change materials as an alternative. The approach considered in this paper is an actuator based on phase transition that is achieved by infiltrating carbon nanotubes yarn with a mixture of elastomer and methanol.

II. DESIGN OF THE ACTUATOR

The actuator in consideration is a hybrid coiled yarn muscle infiltrated with an elastomer–methanol composite, termed as the HCYM[1]. The actuation is caused by the gas pressure of vaporized methanol at low voltage. With the use of HCYM, a work capacity of 0.49 kJ kg−1 and a maximum contraction of 30.5% can be achieved within 3 s approximately under an applied stress of 3.1 MPa at low input voltage (5 V). The HCYM actuator also has a short driving period and a higher shape recovery rate.

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The HCYM is fully coiled with a diameter of around 220 µm. The coiled structure provides a high actuation performance. Also, the infiltration of materials into the neatly coiled CNT yarn improves the performance of the actuator, and effective distribution of foreign materials helps to achieve high contraction output and good stability.

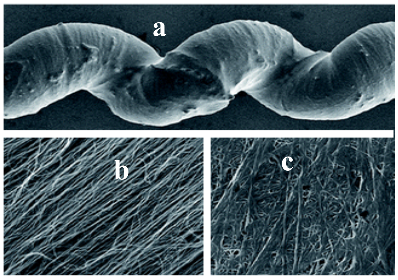

Fig 1.a) SEM image of HCYM (scale 500µm). SEM image of surface morphology b) before and c) after infiltration of elastomer-methanol mixture.

The HCYM is prepared by twisting a Multi-Walled carbon Nano Tube (MWNT) aerogel sheet drawn from a MWNT forest that is grown by chemical vapor deposition method. The number of layers of CNT sheet greatly controls the resistance of the material. Resistance decreases from 56.1 Ω cm−1 to 6.1 Ω cm−1 as the number of layers increases from 5 to 50. With the number of layers as 50, the applied voltage generates a temperature that exceeds the boiling point of methanol.

III. WORKING

The HCYM is electro thermally driven. The working mechanism of the HCYM actuator is illustrated in Fig. 2[1]. In the power-on mode, methanol is converted vapor when the temperature reaches the boiling point of the liquid. This causes actuation, as the gas pressure in the coiled yarn increases causing an expansion of the volume of the elastomer. With continued heating, the temperature is slightly higher than the boiling point of methanol, causing further expansion due to the increase in elastomer pressure. Once the applied voltage is switched off, heat loss results in the phase transition of vapor to liquid methanol, and the actuator is restored to its initial state.

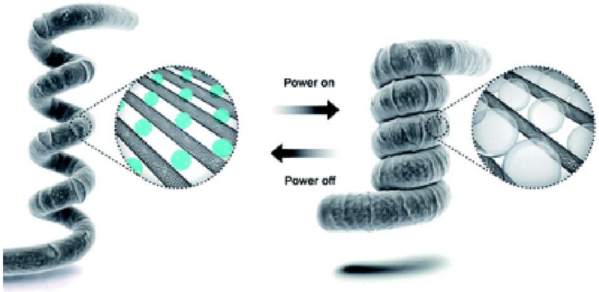

Fig 2: Actuation mechanism of HCYM

3.1 Factors Affecting Actuation Performance

The amount of methanol is one of the factors affecting the actuation performance of the HCYM. When the weight ratio of methanol to elastomer is 3: 1, a maximum contraction of 30.5% is observed, as compared to other samples[1].

The twist insertion of the yarn coil is another factor. When the twist insertion of initial yarn is decreased, the low-inserted twist yarn provides a lot of internal void space in the yarn. Therefore, a relatively large amount of elastomer–methanol composite exists in the HCYM, which results in an excellent actuation performance. Consecutively, an increase in the yarn twist insertion reduces the performance.

The stress applied, too, affects the contraction of the HCYM actuator. An applied stress of 3.1 MPa has a maximum contraction of 30.5% and a specific work capacity of 0.49 kJ kg−1, which is 63 times higher than that of typical mammalian skeletal muscles (7.7 J kg−1). The stroke (contraction) decreases when stress below 3.1 MPa is applied. In addition, applying high stress reduces the stroke due to the lower Young's modulus of the yarn in the contraction state and greater elastic elongation at higher loads in the initial state. This is illustrated in Fig 3.

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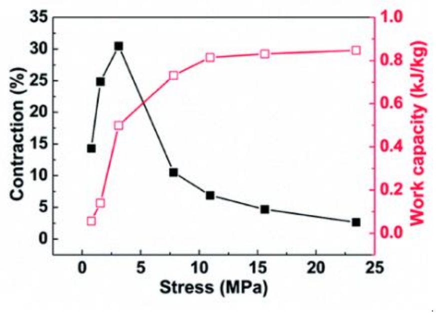

Fig 3 Stress dependency of contraction

The twist insertion also has an inverse relationship with the work capacity. A low twist insertion yarn coil provides a work capacity of 0.498 kJ/kg, whereas a high twist yarn gives a poor work capacity of 0.06kJ/kg. Figure 3 shows the relationship between the various parameters.

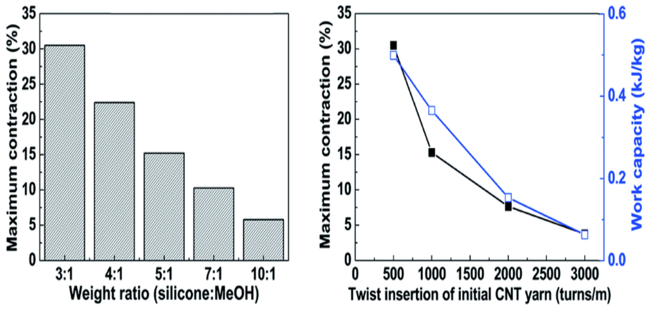

Fig 4 Optimization chart for the HCYM

3.1 Application of HCYM Actuator for Soft Prosthetics

Artificial muscles that can convert electrical, thermal or chemical energy into mechanical energy for tensile contraction, torsional rotation or bending, have received considerable attention for their promising applications in exoskeletons, prosthetics devices and microfluidics.

The practical implementation of this carbon nanotube elastomer actuator is presented by Jae-Hun Jeong *et al.*The HCYM unit was designed, as shown in Fig. 4[1], and applied to the lever arm. The lever arm was operated using commercial batteries (AAA, 6 V), that resulted in a lever arm that could be smoothly moved by the HCYM actuator. When a stress of 23.4 MPa was applied to the actuator, a 10 g weight attached at the end could be lifted and moved through ~1cm with and without an applied voltage of 6 V.

The HCYM can be a good choice for actuation in soft prosthetics. Moreover, owing to their simplicity and high performance, these yarn muscles can also be used for diverse applications such as robots, catheters for minimally invasive surgery, and microfluidic circuits.

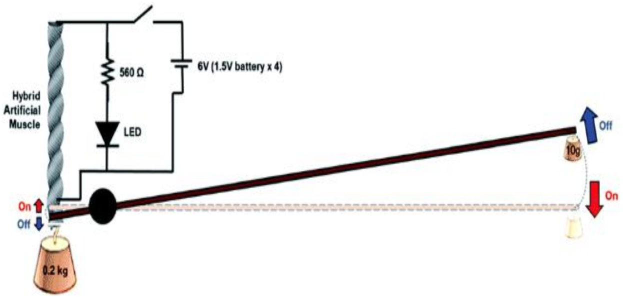

Fig 4 Schematic Circuit diagram for the actuation

A Major Challenge

A difficult challenge in the implementation of this actuator would be upscaling the single yarn structures to large actuators in which hundreds or thousands of such yarn muscles will operate in parallel with an atomic level of control[4]. If this challenge is overcome and successfully implemented, it would be a major milestone in the field of prosthetics.

IV. CONCLUSION

Soft actuators constitute an important step forward towards entirely soft robots and towards potential applications such as wearable, medical devices, exoskeletons and prosthetics. The most essential part of a soft robot is the actuator used to propel it[2]. While pneumatic and hydraulic actuators dominate the field, they are generally more suitable for applications, such as grippers due to the equipment needed to generate pressure for actuation. Phase change materials are an attractive alternative to conventional electromechanical actuators. They rely on the mechanical force produced by the rapid expansion that occurs at the phase transition temperature. Also, as soft robotic applications shift more towards autonomous operation and aim to match the characteristics of living systems more options for soft, powerful and scalable actuators are required. The HCYM actuator is one such option.

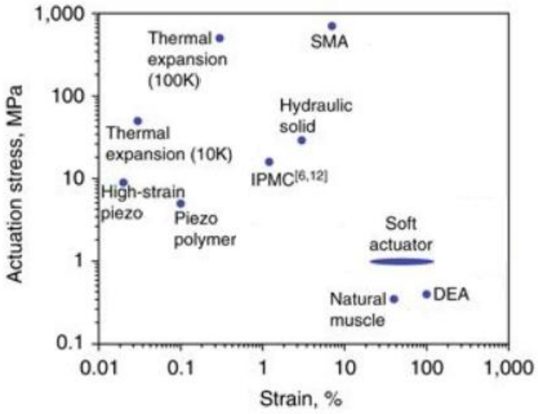

Fig 5 Stress-Strain Comparison chart for different actuators

To summarize, dielectric actuators need very high voltages, IPMC actuators generate limited force, SMAs need to be small or have very high currents, and piezoelectric generate almost no strain. For most applications, an actuator may need to generate high forces for long periods of time. This would require large electromechanical assemblies or centralized fluidic pumping systems to generate such force. For all the specified and established reasons, the carbon-nanotube elastomer actuator will prove a very good alternative for actuation and the main focus area being soft prosthetics or robotics

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