Design and Development of a Nylon Based Actuator for use in a Soft Robotic Glove

Ruairí Coulter
School of Mechatronic Engineering
Dublin City University
Dublin, Ireland
ruairi.coulter2@mail.dcu.ie

K. R. Sanjaya Dinuwan Gunawardhana
School of Electronic Engineering
Dublin City University
Dublin, Ireland
sanjaya.gunawardhana2@mail.dcu.ie

Shirley Coyle
School of Electronic Engineering
Dublin City University
Dublin, Ireland
shirley.coyle@dcu.ie

***Abstract*—This research develops a nylon-based actuator for a soft robotic glove to assist users with impaired hand strength, such as stroke or arthritis patients. Traditional soft robotic gloves are bulky or, in the case of pneumatic systems, limited by power source requirements. This study aims to create a lightweight solution using twist and coiled polymers (TCP), specifically nylon fishing wire, to assist finger movement through thermal contraction. A prototype glove integrating the artificial muscle and a heating element was designed to aid finger movement, with a heat-resistant glove ensuring safety. Braided nylon wire muscles showed promising tensile and contraction test results, demonstrating flexibility and strength, with an optimal activation temperature of 100°C. Controlled by an Arduino Uno, the heating element effectively activated the artificial muscles for finger movement. This work presents a significant step towards creating more accessible and effective soft robotic gloves, potentially benefiting individuals with hand mobility issues in therapeutic and everyday contexts.**

Keywords—Artificial Muscles, Actuation, Twist and Coil Polymer, Soft Robotics, Wearable Technology

I. Introduction

The development of soft robotic gloves has gained significant attention due to their potential in assisting individuals with impaired hand strength, such as those recovering from stroke or living with arthritis. However, current designs are often hindered by bulkiness or reliance on external power sources, such as pneumatic systems, which limit their portability and practicality in everyday use[1]. To address these challenges, this research focuses on creating a lightweight, textile-based actuator using twist and coiled polymers (TCP), specifically nylon fishing wire, which is widely available to facilitate finger movement through the thermal contraction of the material.

There are several existing gloves and technologies currently used in robotic gloves, using both hard and soft robotics. The most fundamental examples are mechanically based exoskeletons, such as the glove developed by Vanteddu et al., constructed from hard plastic[2]. While effective in enabling movement, the glove's external mechanisms are bulky and unwieldy, making it unsuitable for long-term daily use. In contrast, more advanced soft robotic gloves like the AirExGlove employ pneumatic actuation, filling tubes on the backs of the fingers with pressurized air to initiate movement[3]. However, the reliance on a compressed air source limits its practicality in real-world scenarios, where portability and ease of use are critical.

Another notable example is the NOHAS glove, which uses a servo motor and cable-driven mechanism to flex the fingers[4]. Although this design improves portability, the hardware is concentrated around the wrist, creating challenges for users with limited arm strength. Furthermore, the servo-dependent actuation makes the entire system vulnerable to mechanical failure, impacting reliability in therapeutic settings.

Despite these advances, there remains a pressing need for more lightweight, power-efficient designs that do not compromise performance or ease of use. In comparison to existing models, one of the most advanced designs in the field is the iGrab glove, developed by Saharan et al., which utilizes coiled nylon muscles to actuate finger movement[5]. The iGrab represents a sophisticated application of twist and coil effects with the presence of temperature, leveraging thermally responsive nylon lines to replicate the natural flexion of human fingers. The coiled nylon muscles, first popularized by Haines et al. [6], undergo a heat-induced contraction when an electrical current is applied, generating the force necessary to pull tendons that control finger movement. In experimental trials, the iGrab achieved full finger flexion within 2 seconds, with the muscles pulsed using a 1.8 A current for 25 seconds at a 7% duty cycle. Despite the impressive performance, the design is not without its drawbacks. The reliance on an extensive pulley system to guide the nylon muscles introduces considerable bulk to the framework, compromising the glove's portability. Moreover, the substantial heat generated by the coiled muscles requires significant thermal insulation, particularly along the inner arm, to prevent burns during operation. This, coupled with the need for continuous power input to maintain actuation, makes the iGrab glove less practical for extended use in real-world applications where minimalistic and energy-efficient solutions are paramount.

This research expands on the novel solution of employing braided nylon wire muscles, which rely on thermal contraction to actuate finger movement. When heated to an activation temperature of 100°C, these artificial muscles produce sufficient tensile force to facilitate hand movement.

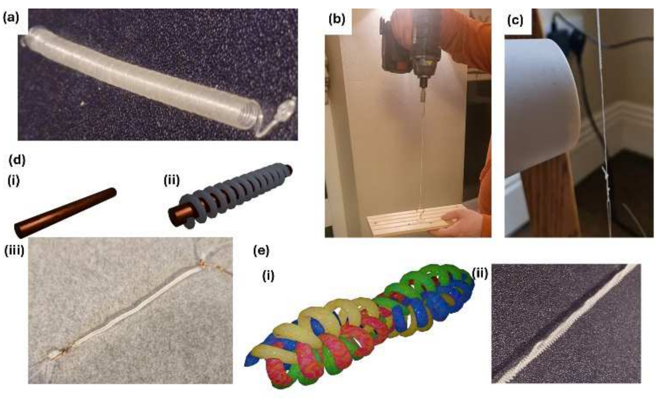

Figure 1: Coiling Methods, a) Wooden core used coil, b) Self-Coiled actuator, c) Melted Self-Coiled actuator, d) i) Copper core, Schematic(ii) and actual(iii) of copper core coiling method e) Schematic (colours used for distinguish 4 wires) (i) and actual (ii) images of braided actuator

This research is funded by Insight Research Ireland Centre for Data Analytics at Dublin City University (SFI/12/RC/2289_P2).

A prototype glove incorporating these muscles and a heating element, controlled via an Arduino Uno, was developed and rigorously tested for both tensile strength and contraction efficiency. This work aims to overcome the limitations of current robotic gloves by presenting a simpler, more lightweight alternative that offers comparable actuation without the complexity of pulley systems or excessive heat management requirements. By focusing on a design that avoids external power sources and reduces the need for intricate mechanical frameworks, the glove developed in this study represents a significant step forward in creating more accessible, user-friendly soft robotic devices for rehabilitation and daily use.

II. Technical Description

A. Artificial Muscles

In the initial design phase, nylon 6 was selected as the primary material for artificial muscles due to its advantageous thermal contraction properties and its prevalence in previous studies as a reliable actuator material[7]–[9]. Nylon 6 is also widely available and cost-effective, making it ideal for prototyping actuators in soft robotics. To ensure consistent actuation performance, wires of varying diameters were tested to optimize mechanical responsiveness.

Six coiling approaches were taken to investigate the efficacy of each approach. The six approaches were implemented as follows a) single wire around a wooden core, b) double-helix around another wire, c) self-coiled d) melted after self-coiling, e) coiled around a thin copper core and f) braided after coiling. The first initial proof-of-concept actuator (a) was created by coiling nylon wire around a 1.5 mm wooden core (Figure 1(a)), followed by heat treatment at 150°C for one hour. Once cooled, the wire was re-extended and reactivated with a targeted heat source, inducing contraction via thermal effects. The objective was to develop a compact yet robust coil suitable for the mechanical demands of soft robotic applications, improving upon previous designs.

A number of samples were prepared to assess the impact of core diameter on the actuator's mechanical properties. Nylon wires with diameters of 0.4 mm and 0.26 mm were coiled around a 1.5 mm wooden core and subsequently heat-treated. This stage aimed to evaluate how wire thickness and core size influenced tensile strength and elasticity.

In the next design iteration, a double-helix coiling technique was used, twisting two nylon wires together to form a dual-core actuator where each wire acted as the core for the other. This configuration aimed to enhance structural integrity while maintaining the flexibility needed for reliable actuation.

A self-coiled configuration (Figure 1(b)), inspired by artificial muscle research in robotics and prosthetics, was also tested. This coil required precise control to prevent breakage under excessive tension and was formed by attaching one end of the nylon to a stationary weight and using a drill to induce twisting. In an attempt to improve flexibility, this coil was heated above standard activation temperatures to soften the material slightly (Figure 1(c)), though this method risked reducing tensile strength, which was noted during previous testing.

It was observed that reducing the core diameter increased strength at the expense of elasticity. To balance these properties, a new coil was created by winding 0.4 mm thickness nylon around a 0.5 mm copper core (Figure 1(d)). The copper's high thermal conductivity facilitated more efficient and uniform contraction, improving performance during thermal actuation.

Building on literature that suggests braiding can further enhance tensile strength in artificial actuators[6], a braided structure was constructed using four copper-core wires with the copper removed. The braid, shown in Figure 1(e), aimed to maximize tensile strength while maintaining sufficient elasticity for application in soft robotics.

Each actuator variant then underwent mechanical testing. An in-house rig assessed tensile strength by applying incremental weights, with a heat gun providing consistent thermal activation across samples. For precise measurement, untreated, self-coiled, and braided samples were further tested on a Zwick Tensile Testing Machine, which measured maximum tensile capacity under controlled force application.

Differential Thermal Analysis (DTA) was used to assess optimal temperature ranges for actuation. By measuring exothermic and endothermic responses, DTA provided comparative data between untreated and copper-core coiled wires, identifying the thermal points for peak contraction. Finally, contraction testing on the Zwick Tensile Testing Machine provided a comparative evaluation of contraction forces at 90°C to 120°C with a constant gauge length of 50 mm. This test focused exclusively on the braided wire, recording contraction efficacy in response to thermal input for validation in soft robotic applications.

B. Actuation Methods

The actuation mechanism for the nylon-based artificial muscles, as outlined in the literature, involves either applying an electrical current through the wire or placing an external heat source near it. Both methods induce thermal contraction, which enables the wire to contract and facilitate finger movement. However, each method carries potential safety risks that require appropriate precautions.

However, copper's high thermal conductivity and rapid heat dissipation suggested it was unsuitable as a sustained heat source. A resistive heating element was therefore selected as an alternative. Initially, a series of five 1 kΩ resistors connected to a voltage source was tested, but calculations revealed that this method required over 11 minutes to reach the target temperature, making it impractical for real-time actuation.

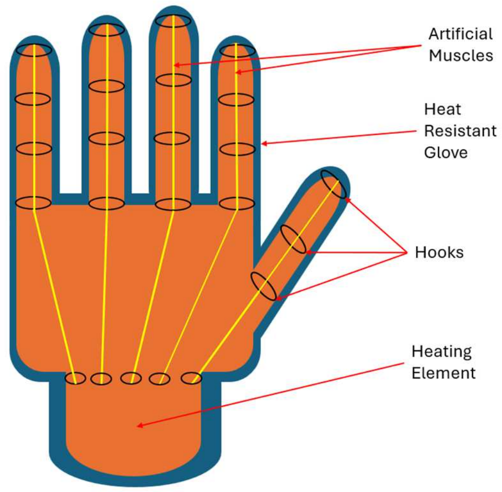

Figure 2: Glove prototype design

The final heat source tested was a silicone heating mat, which was selected for its capacity to reach a maximum temperature of 200°C, exceeding operational requirements. The heat mat was connected to a series of DC batteries to increase the output voltage, and the temperature was carefully monitored using a thermocouple. By adjusting the voltage, the heat mat was gradually brought to the desired temperature, ensuring controlled, responsive actuation for the nylon-based artificial muscles.

C. Controller

Muscle actuation was managed by an Arduino Uno microcontroller integrated with a MOS module breaker. The Arduino controlled the MOS module via a push-button. When pressed, the button activated the muscle, keeping it in a contracted state until pressed again, at which point the muscle relaxed upon cooling. This output was connected to the MOS module's input, allowing the Arduino to control the heat mat while keeping within safe voltage limits. Pressing the button again interrupted the current, allowing the muscle to cool and relax.

D. Prototype

The prototype was a glove designed to flex the fingers toward the palm, similar to the iGrab and NOHAS gloves. The artificial muscle was attached at the fingertip and wrist, with a heating element placed beneath the coiled muscle to actuate movement via thermal contraction. This approach aimed to optimize glove space and minimize material usage. A sketch of the glove design is shown in Figure 2. To test the prototype glove, a silicone finger model was used to simulate the resistance of a human finger.

The prototype was assembled using a heat-resistant curling iron glove. The artificial muscle, consisting of the braided wire described in the "Artificial Muscles" section, was attached to the silicone finger model by securing it at the fingertip and wrist. The heating element, a heat mat controlled by the Arduino Uno and MOS module (as outlined in the 'Controller' section), was evaluated for its effectiveness in actuating finger movement.

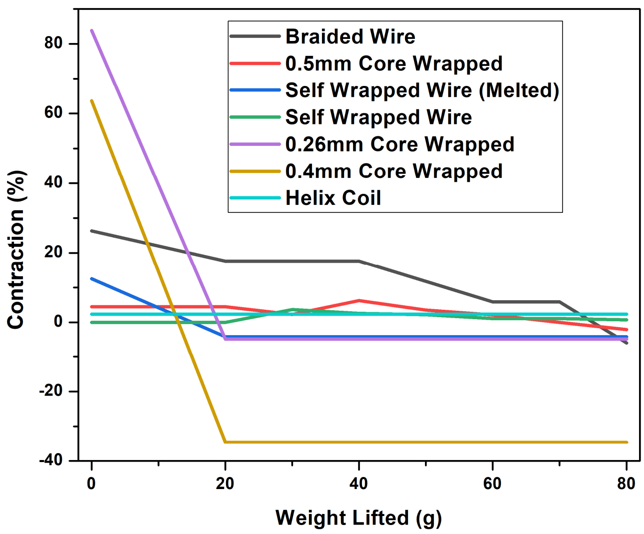

Figure 3: Contraction of muscles with varying weights

III. Results

A. Artificial Muscles

A suitable coiling approach was chosen for the artificial muscle based on the results of weight testing. The braided wire demonstrated the highest percentage of contraction relative to its length under various applied weights, as shown in Figure 3.The results of the tensile test, indicate that the braided wire is capable of expanding up to 600% of its original length before failure (Figure 4).

An experimental test-rig was set up applying a force from 0.25 to 0.5 N. The artificial muscle achieved a maximum contraction of 10.80 mm. Subsequently, the contractive force exerted by the wire was evaluated using a constant gauge length approach, rather than a fixed force. This method allowed for the determination of the maximum force generated by the artificial muscle, enabling a more accurate understanding of its contractile capacity. As illustrated in Figure 5, the braided wire generates ~0.1 N of contractive force when activated by heat.

Additionally, the nylon wires were DTA tested to find the optimal heating point. This analysis was conducted on both untreated and heat-treated nylon samples. The DTA testing did not reveal any exothermic or endothermic reactions. It moved in a straight line, and did not change at any temperature in the desired range of 95-110°C prototype. During the construction of the prototype glove, the braided artificial muscle was secured to both the fingertip and the wrist using wire. The prototype was subsequently tested for functionality, successfully demonstrating its ability to actuate movement in the silicone finger model, as illustrated in Figure 7.

IV. Discussion

A. Artificial Muscles

In the weight testing of coiled wires, it was observed that wires coiled and heat-treated around larger wooden cores exhibited high flexibility but lacked sufficient strength. This outcome suggests that larger cores may compromise the mechanical durability required for artificial muscle applications, indicating that smaller core sizes produce stronger actuators. The 0.26 mm wire extended even with 20 g from the reference point for measuring contraction and thereafter no contraction observed with heat.

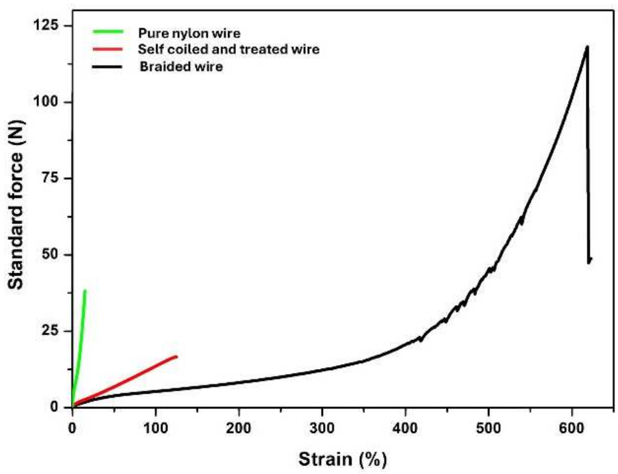

Figure 4: Tensile test results of pure nylon wire, self-coiled and treated nylon wire and braided nylon wire.

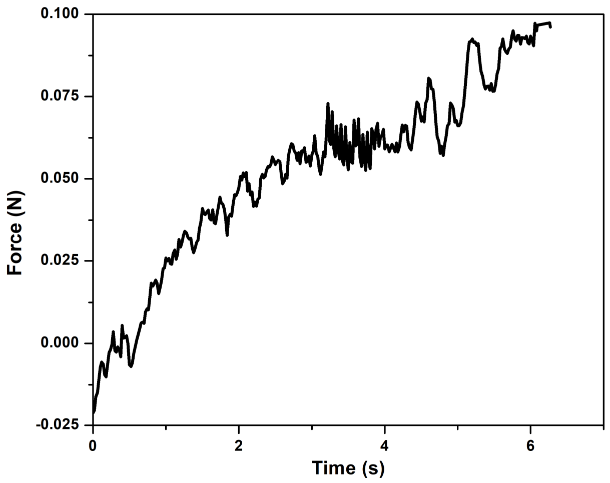

Figure 5: Contractive force measured on braided muscle

The double-helix configuration, while strong, lacked elasticity, which hindered its ability to contract effectively and limited the range of movement. Although the self-coiled wire is well-documented in the literature[10], [11], its performance here was suboptimal, displaying limited contraction under applied weights. The melted variant of the self-coiled wire performed comparatively lower results, with further diminished contraction capacity.

In contrast, the copper-core coiled wire demonstrated the most consistent performance across all weight levels, making it a preferred candidate for further development. This wire was subsequently braided to enhance its structural integrity and contraction ability. Upon testing, the braided wire outperformed all previously tested configurations, achieving superior contraction rates under applied loads.

Tensile testing revealed that heat-treated wires exhibited improved elasticity due to the re-crystallization of the nylon material, which allowed them to stretch and return to their original length upon heating. However, this increased elasticity was associated with reduced tensile strength. The heat-treated wires displayed a larger plastic deformation region compared to untreated wires, with the self-coiled wire, despite having a notable plastic region, being too rigid for substantial elongation. In contrast, braided wires demonstrated an extended plastic region before failure, allowing them to endure greater forces. The peaks in the tensile testing results for the braided wires correspond to the sequential snapping of individual filaments within the braid, which, despite partial strand failure, maintained functionality due to the redundancy of remaining filaments, providing resilience to the artificial muscle (Figure 4).

The maximum contractive force generated by the artificial muscle was recorded at ~0.1 N, a modest but sufficient force to actuate finger movement in the prototype (Figure 5). This force could potentially be increased with a longer wire length; the test wire was limited to 50 mm, and extending this length is expected to enhance contractive force.

DTA analysis did not identify a precise optimal heating temperature, it did reveal an approximate 20% reduction in wire mass above 110°C, suggesting the presence of absorbed moisture or a volatile component (Figure 6). This mass loss could indicate initial decomposition, although no significant changes occurred within the operational range of 90–110°C.

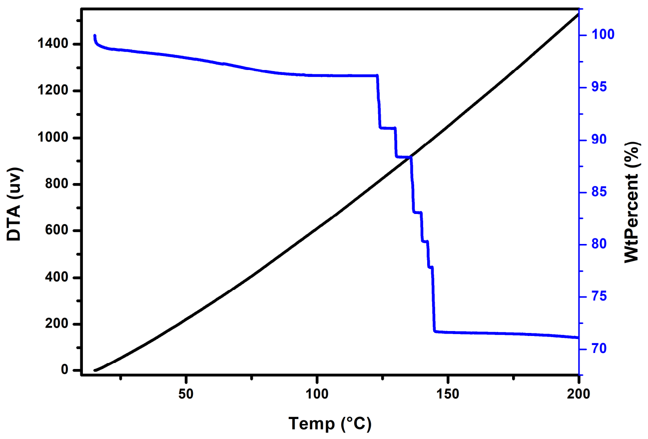

Figure 6: DTA testing of heat-treated wire

The optimal actuation temperature was selected as 100°C, providing adequate activation without risking material degradation due to overheating. The literature indicates an activation range of 95-110°C [5], corroborated by this experiment, which confirmed that temperatures below 90 °C are insufficient for actuation, while temperatures closer to the upper limit induce excessive stress and wire expansion, a phenomenon clarified by DTA testing.

B. Actuation Method

A silicone heat mat was selected as a more efficient heating element. The heat mat was able to reach the necessary temperature by connecting three 9 V batteries in series, achieving a temperature of 100°C. While the heat mat successfully actuated the wire in the prototype, the average actuation time was approximately 70 seconds.

C. Final design

In assembling the prototype glove, one significant challenge was securely attaching the artificial muscle without compromising the structural integrity of the glove. Piercing the glove to insert hooks was deemed unsafe, so an alternative method was implemented. A wire was wrapped around the tip of the finger, then connected to the muscle and secured to another wire encircling the wrist of the glove. As previously mentioned, a silicone finger model was used during testing to simulate human finger resistance, which successfully demonstrated the glove's ability to actuate finger movement.

The glove selected for the prototype was a heat-resistant hair straightening glove, capable of withstanding temperatures up to 180°C. This made it suitable for insulating against the heat mat, which operates at temperatures just over half that threshold.

Figure 7: Prototype glove with artificial muscle relaxed (left), and contracted (right)

V. CONCLUSION

In conclusion, a suitable actuator was identified for the soft robotic glove, offering a lightweight and compact solution for assisting users in gripping tasks by providing additional force and guided finger movement. This actuator's portability, due to minimal wiring and a compact power source, enables versatile usage across various settings, activated easily through a programmed push-button interface.

While promising, the actuator did not meet the expected performance benchmarks set forth in the literature, with observed force outputs falling below the targeted 5 N. Experimental tests indicated the actuator's challenges in contracting under forces exceeding 1 N, suggesting further enhancement is necessary for optimal performance. However, among the tested configurations, the braided wire showed notable strength and elasticity, equalling self-coiled variants from prior studies at ~20% [6], with shorter lengths, and demonstrating a pathway for future optimization.

To enhance the glove's functionality, several design improvements are recommended. Integrating a fingertip pressure sensor could facilitate precise grip strength adjustments, an essential feature for varied user needs. Additionally, an insulated layer around the heat mat and artificial muscles could retain heat more effectively, improving actuation efficiency and providing added safety for handling objects. Incorporating joint guides, as used in existing soft robotic hand designs, would further bolster grip strength by improving the torque exerted at the fingers. Finally, replacing the current heat mat with a larger, finger-length heating element would ensure even, faster heating along the actuator, leading to more consistent and reliable actuation. These enhancements, coupled with the observed potential of the braided wire actuator, establish a strong foundation for the next phase of the soft robotic glove's development.

ACKNOWLEDGMENT

The authors acknowledge the funding and support given by Insight Research Ireland Centre for Data Analytics in Dublin City University (SFI/12/RC/2289_P2). Furthermore, authors acknowledge Christopher Crouch for the technical support and guidance given in the characterisation of samples for tensile testing. Moreover, authors acknowledge support given by Owen Clarkin for thermal characterization.

REFERENCES

[1] K. Nishikawa, K. Hirata, and M. Takaiwa, "Development of Self-Powered Prosthetic Finger with Pneumatic Passive Joints for Distal Interphalangeal Joint Amputees," J. Robot. Mechatronics, vol. 36, no. 5, pp. 1221–1234, Oct. 2024, doi: 10.20965/JRM.2024.P1221.

[2] T. Vanteddu and P. Ben-Tzvi, "Stable Grasp Control with a Robotic Exoskeleton Glove," J. Mech. Robot., vol. 12, no. 6, Dec. 2020, doi: 10.1115/1.4047724.

[3] A. Stilli et al., "AirExGlove-A novel pneumatic exoskeleton glove for adaptive hand rehabilitation in post-stroke patients," in 2018 IEEE International Conference on Soft Robotics, RoboSoft 2018, Jul. 2018, pp. 579–584. doi: 10.1109/ROBOSOFT.2018.8405388.

[4] E. R. Selvaraj Mercyshalinie, A. Ghadge, N. Ifejika, and Y. Tadesse, "NOHAS: A Novel Orthotic Hand Actuated by Servo Motors and Mobile App for Stroke Rehabilitation," Robotics, vol. 12, no. 6, p. 169, Dec. 2023, doi: 10.3390/robotics12060169.

[5] L. Saharan, M. J. De Andrade, W. Saleem, R. H. Baughman, and Y. Tadesse, "IGrab: Hand orthosis powered by twisted and coiled polymer muscles," Smart Mater. Struct., vol. 26, no. 10, p. 105048, Sep. 2017, doi: 10.1088/1361-665X/aa8929.

[6] C. S. Haines et al., "Artificial muscles from fishing line and sewing thread," Science (80-.)., vol. 343, no. 6173, pp. 868–872, Feb. 2014, doi: 10.1126/science.1246906.

[7] A. Cherubini, G. Moretti, R. Vertechy, and M. Fontana, "Experimental characterization of thermally-activated artificial muscles based on coiled nylon fishing lines," AIP Adv., vol. 5, no. 6, Jun. 2015, doi: 10.1063/1.4923315.

[8] Y. W. Huang, W. S. Lee, F. Yang, and S. Lee, "Tensile deformation of artificial muscles: Annealed nylon 6 lines," Polymer (Guildf)., vol. 177, pp. 49–56, Aug. 2019, doi: 10.1016/j.polymer.2019.05.070.

[9] G. Liu, Y. Zhang, J. Di, and Z. Wu, "Research on thermal actuation performance of twisted and coiled nylon artificial muscles based on yarn mechanics," Smart Mater. Struct., vol. 32, no. 1, p. 015002, Dec. 2023, doi: 10.1088/1361-665X/aca455.

[10] L. Wu, M. Jung De Andrade, L. K. Saharan, R. S. Rome, R. H. Baughman, and Y. Tadesse, "Compact and low-cost humanoid hand powered by nylon artificial muscles," Bioinspiration and Biomimetics, vol. 12, no. 2, p. 026004, Feb. 2017, doi: 10.1088/1748-3190/aa52f8.

[11] L. Saharan, L. Wu, and Y. Tadesse, "Modeling and Simulation of Robotic Finger Powered by Nylon Artificial Muscles," J. Mech. Robot., vol. 12, no. 1, Feb. 2020, doi: 10.1115/1.4044740.