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# The Relationship between Force and Length Change with Temperature Changes in the Synthetic Muscle of Complex Nylons

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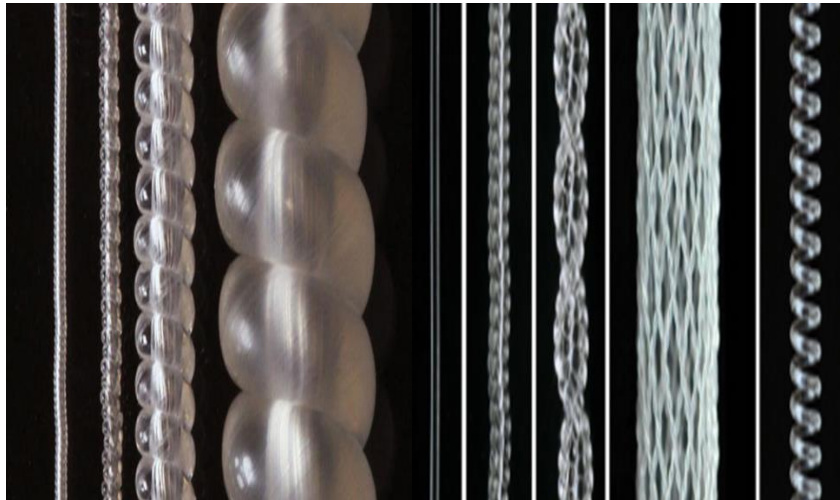
## Abstract

Artificial muscle benefits from outstanding properties and is widely used in numerous industries. The new type of this muscle is made of nylon and provides more advantages than the previous ones. The mechanism is such that by giving heat, it causes a change in the length of the muscle. The study analyzes the muscle and calculates the changes in length and force by giving heat, and the relationship between changes in length and force with temperature changes is determined. For this purpose, three diameters are considered and their efficiency is compared.

**Keywords:** Nylon Artificial Muscles, Length Changes, Force Changes, Biomechanics.

## 1. Introduction

Muscles can be divided into two types, biological and artificial. Biological muscles can withstand a wide range of pressures and forces and are inherently adaptable to the environment and are optimal dampers. The stimulation of this type of muscle is very fast and often unlimited [1]. However, artificial muscle (AM) is a term used for all materials and instruments that are capable of reversing, stretching, and rotating around a component based on an external stimulus. Due to their high flexibility, versatility, and power-to-weight ratio compared to rigid actuators, these muscles have technology with high potential for replacement in current systems. Artificial muscles come in many forms; including artificial pneumatic muscles, artificial muscles with sponge hydrogel, artificial muscles with carbon nanotubes, artificial muscles with carbon nanotube threads, and artificial muscles made of nylon. This study considers the nylon one (Figure 1).



**Figure 1. Artificial muscles made of the nylon yarn**

Nylon-coil synthetic muscles are created by the interlocking of polymer fibers. These polymer fibers, with their subsequent rotations, form a heavy twisted band, producing a muscle that contracts when heated and returns to its original size when cooled. This is while the force required by these muscles is created by temperature changes. These types of muscles behave like actuators, so it called nylon-coil actuators (NCA).

NCA is a new type of operator that has advantages over conventional operators such as electric motors or pneumatic systems such as easy construction, less space occupied than other operators, as well as cost-effectiveness of production. These muscles are energized by temperature changes that can be caused by electrical, light absorption, or chemical reactions of fuels. The twisting of the polymer fibers turns them into a twisting muscle that contrasts dramatically with increasing temperature. When it cools, however, it returns to its initial state. If the initial twist of the fibers is in the opposite direction, these fibers expand when heated and the process occurs upside down [2].

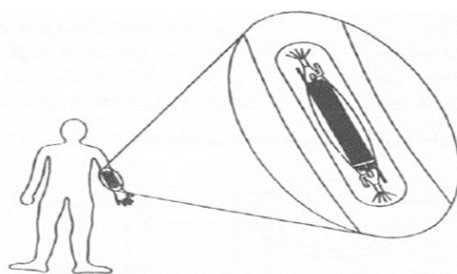
The warm-up muscle twists and turns as it warms up to produce the necessary force, and when it cools down, it relaxes and relaxes. In this way, they are activated by changing the temperature [3].

Nylon filaments do not lose their efficiency after 100,000 cycles of resizing and have the ability to contract and expand 17 times per second. However, the mechanical strength of these muscles is 100 times greater than that of human muscles of similar length and weight. The artificial muscles produced have a power of 7.1 horsepower per kilogram, which is equal to the mechanical power of the jet engine. Twisting the polymer fibers creates AM that can spin a heavy rotor at more than 10,000 rpm. Compared to human muscles, which have a %20 contractility, artificial muscles can contract up to %50 of their length and contract and expand millions of times in heavy mechanical operations. Produced in a relatively simple process using nylon, the synthetic muscles respond to heat by changing thickness and length.

Artificial muscles have countless uses. Many advanced humanoid robots, prosthetic surgeries, and skeletons are limited by motors and hydraulic systems. Therefore, due to their size and weight, these systems have limited skills, power generation and activity capability. Artificial muscles can be used for robots and exoskeletons. Another function that scientists have come up with is to use the exterior of cars to change themselves aerodynamically. In general, using this new technology in advanced vehicles, while reducing fuel consumption and noise pollution, can also positively affect their speed [4-7]

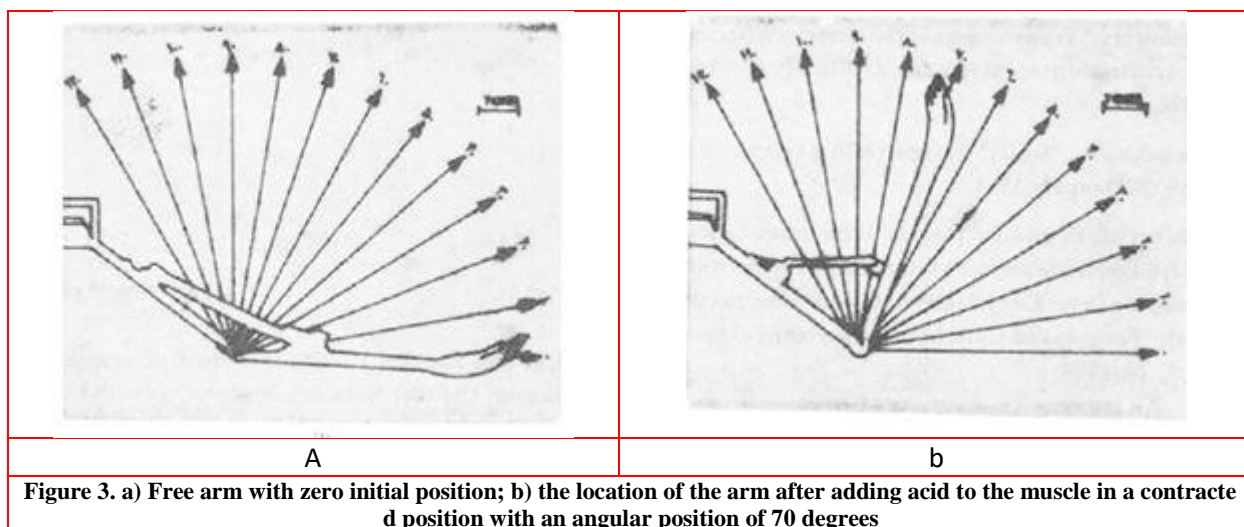


Moghaddari et al. (1995) investigated the use of polymer gels and artificial muscles. They described the role of gel stimuli in artificial muscles and how to prepare an AM from polyacrylonitrile fibers and compared the function of AM with natural muscle in the human body. The following figure illustrates an example of the use of artificial muscles in cybernetic hands.



**Figure 2. Synthetic muscle from polyacrylonitrile fibers**

Moghaddari et al. (1995) placed AM against two molar HCL currents and showed that the muscle reacts rapidly to this current and its volume and length decrease. However, the flow of NaOH demonstrates the opposite effect. The figure below illustrates the function of this experimental muscle as a simple stimulus in an artificial arm.

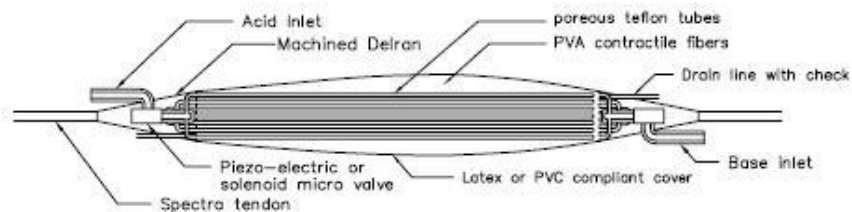


**Figure 3. a) Free arm with zero initial position; b) the location of the arm after adding acid to the muscle in a contracted position with an angular position of 70 degrees**

Given that one of the most important and common properties of gels in artificial muscles is the ability to change their volume, Li and Tanaka (1989) addressed this issue [8]. Rossi et al. Showed that gels can shrink or swell several times their original volume due to a small change in external conditions such as temperature [9]. Burke (1992) proposed a design for an AM using contractile

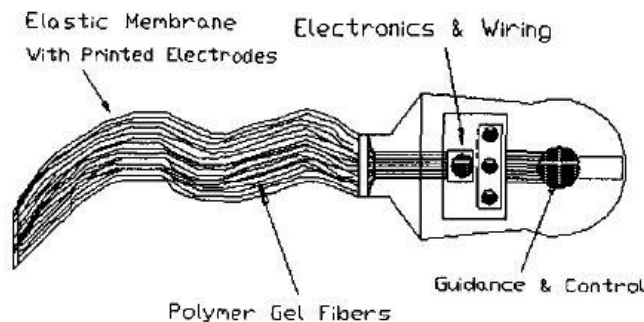


gels. In the proposed design, which is very similar to the skeletal muscle of the human body, two miniature valves are used to control acid or base flow. As a result, by changing the pH of the environment, the AM is controlled (Figure 4) [10].



**Figure 4. Artificial muscle using a type of contractile gel [10]**

In the figure below, Shahinpour illustrates another application of gel stimuli, which uses an electric field change to bend gel fibers. In the proposed model, creating consecutive and inverted bends in the fishtail causes it to move in the fluid (Figure 5) [11].



**Figure 5. Gel-like stimuli in artificial muscle [11]**

Heinz et al. showed that fishing lines can play the same role and effect in artificial muscles [12]. In their paper, Michael C. Yip et al. developed a thermomechanical and thermoelectric model of supercoiled polymer (SCP) actuators and tested the controllability. Furthermore, they used a stimulus in a robotic arm to demonstrate its applicability as a low-cost, high-performance robotic muscle [13]. Mir Vakili et al. used a simple electrical coating that is used as a means of heating an electrical stimulus to achieve relatively high energy [14].

This study is intended to model the NCA operators and calculate the relationship between force and heat, as well as the change in length and heat, using the Finite Element Method (FEM) and Abaqus [15-18]. Therefore, the relevant variables include changes in different temperatures, changes in length due to temperature changes, as well as the force exerted by the muscle.

The study aims to find the relationship between the change in length and the heat transferred to the AM made of nylon and find the relationship between the force exerted by the AM and the heat transferred. Furthermore, two basic assumptions are raised:

- The heat transfer propagated through the muscle is uniform.
- The rings created by the brain are interconnected and in complete contact with each other.



## 2. Methodology

Using the Finite Element Method (FEM) and Abaqus software, the relationship between length change by temperature change as well as temperature change with the applied force of the muscle is examined. For the study purpose, three different diameters are considered for nylon artificial muscles. However, for each diameter measure, temperature changes will be applied in five different intervals. First, we model the muscles using SolidWorks software (Figure 6). However, the muscles are made of nylon and their length is 10 cm. Given that for nylon AM so far only practical experiments have been performed to examine changes in length and only for an approximate diameter of 0.8 mm, therefore, simulation and analysis are performed at this diameter and the lower diameter, i.e. 0.6 mm, and the higher diameter, i.e. 1 mm, to compare the results with practical experiments. Upon modeling the muscles, the data was input to Abaqus for further analysis. Five constant temperatures, namely 30, 40, 50, 60, and 70 ° C was applied to each muscle to get the output of strain and force.

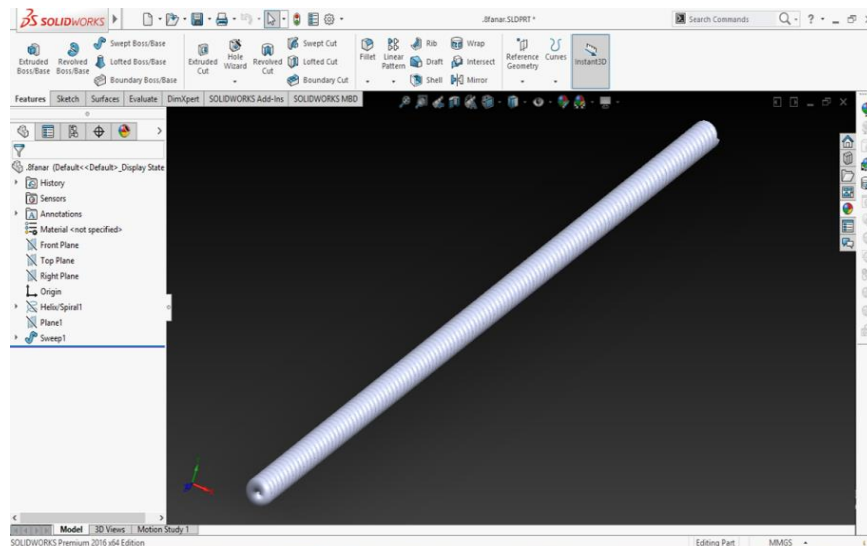


Figure 6. Spring model of nylon muscle in SolidWorks

Three-dimensional and free elements have been used to mesh the muscles. The following figure illustrates the meshing process of the muscles.

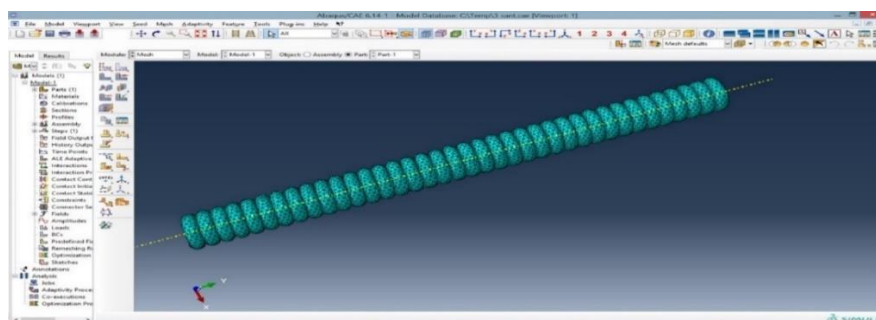


Figure 7. Muscle meshing output in Abaqus



### 3. Results and Discussion

The following figures show the strain contours for a diameter of 0.6 mm at each temperature.

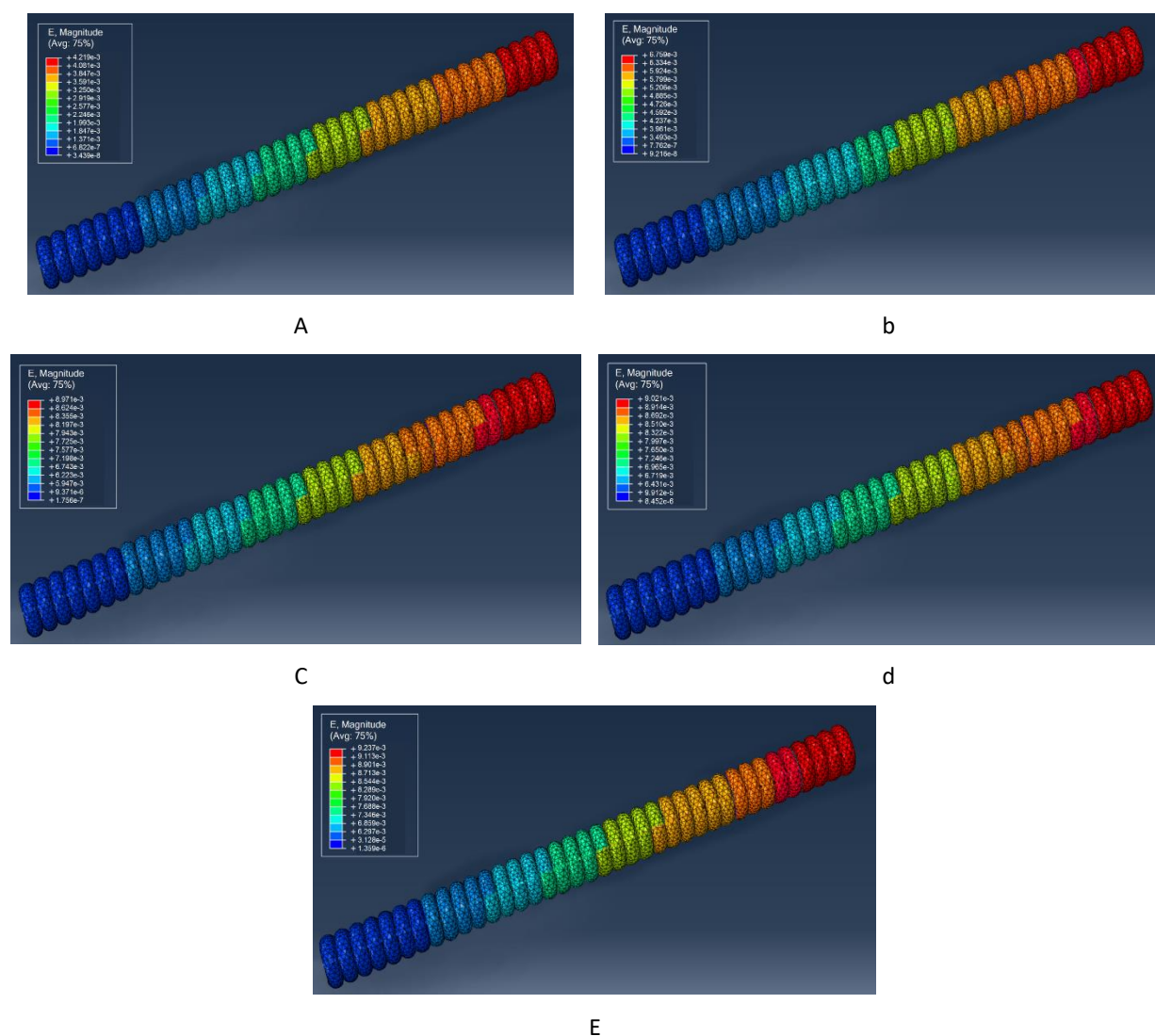


Figure 8. Muscle strain contour with a diameter of 0.6 mm; a) 30°C; b) 40°C; c) 50°C; d) 60°C and e) 70°C



Figure 9 illustrates the strain contours for a diameter of 0.8 mm at each temperature.

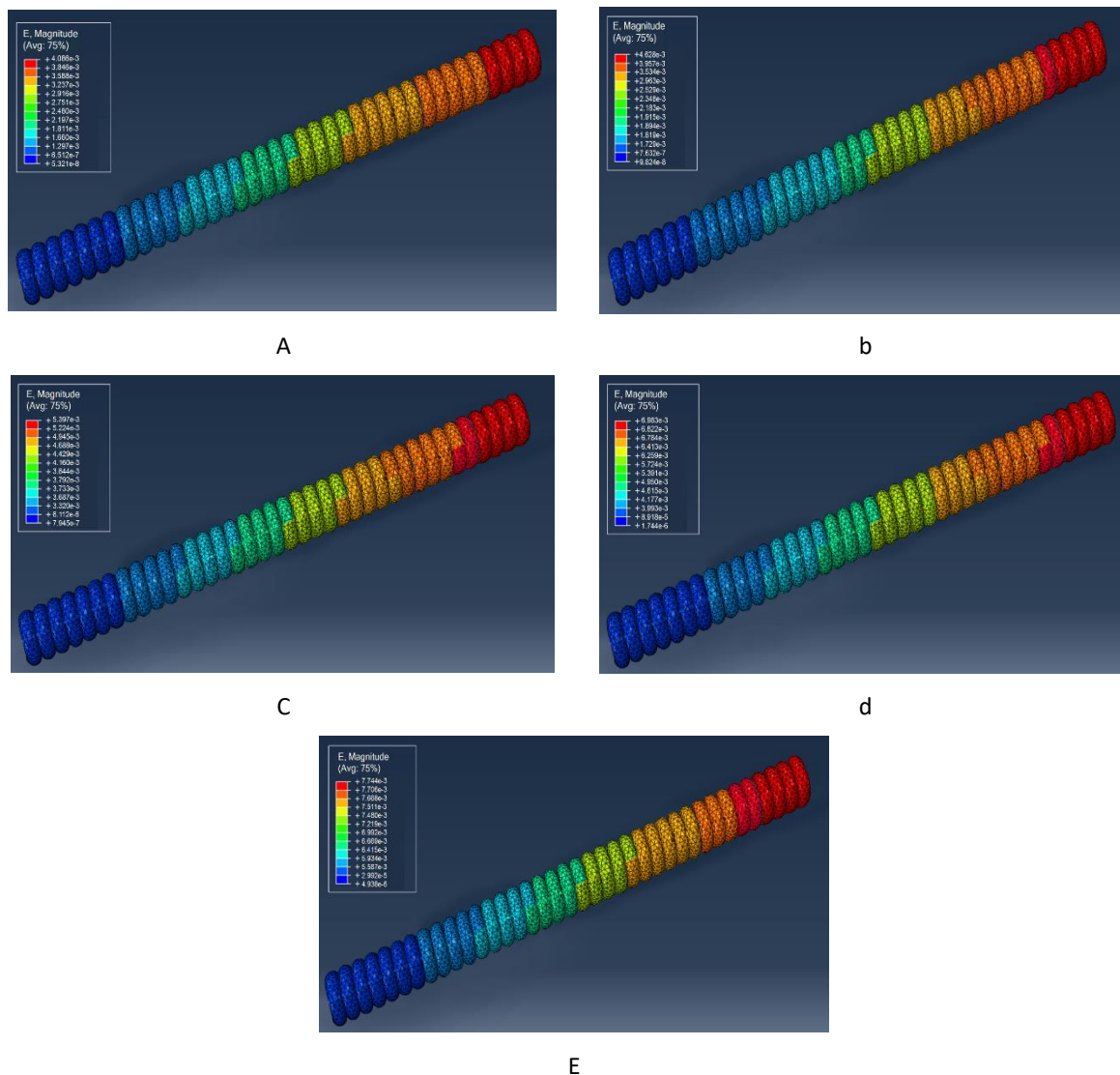


Figure 9. Muscle strain contour with a diameter of 0.8 mm; a) 30°C; b) 40°C; c) 50°C; d) 60°C and e) 70°C



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Finally, Figure 10 illustrates the strain contours for a diameter of 1 mm at each temperature.

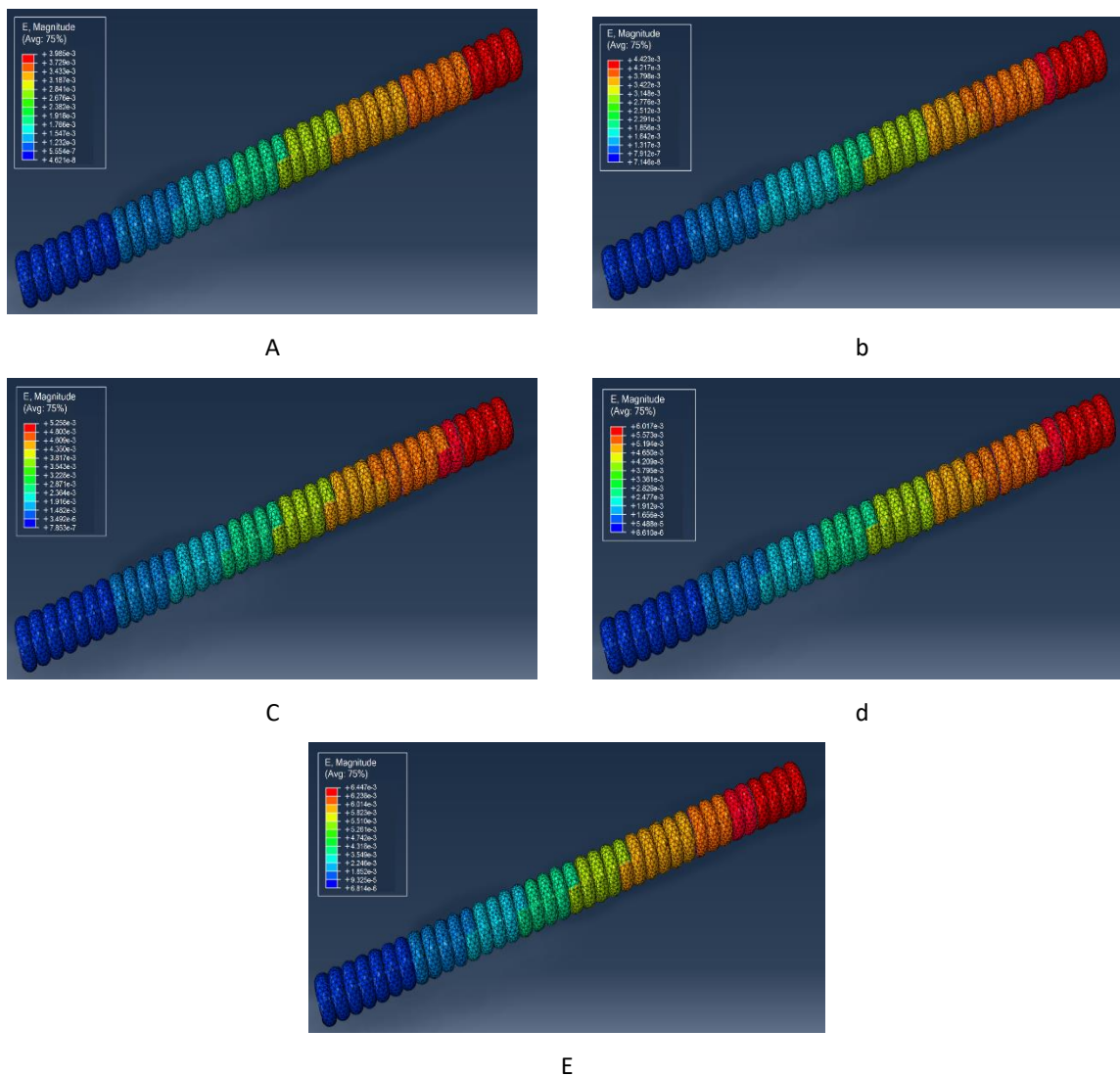


Figure 10. Muscle strain contour with a diameter of 1 mm; a) 30°C; b) 40°C; c) 50°C; d) 60°C and e) 70°C



As the strain contours, the output of the force contours is correspondingly obtained, which is exhibited as an example of a force contours for a diameter of 0.8 at a temperature of 50 ° in Figure 11.

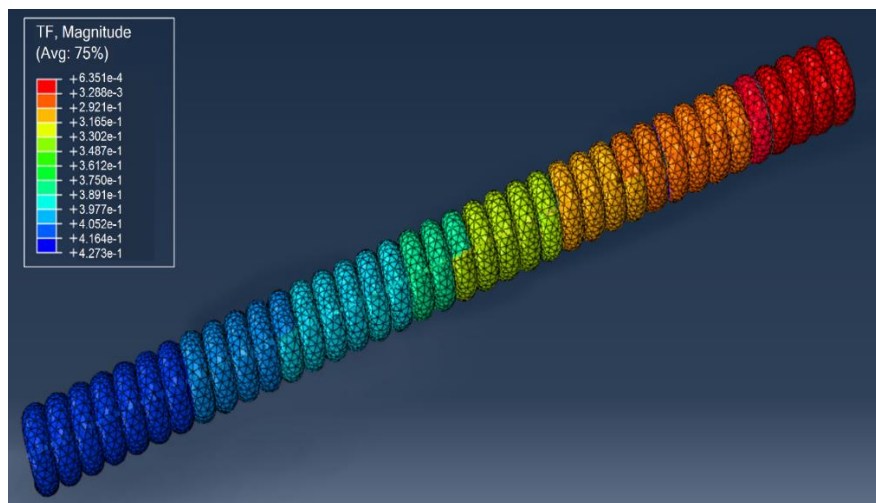
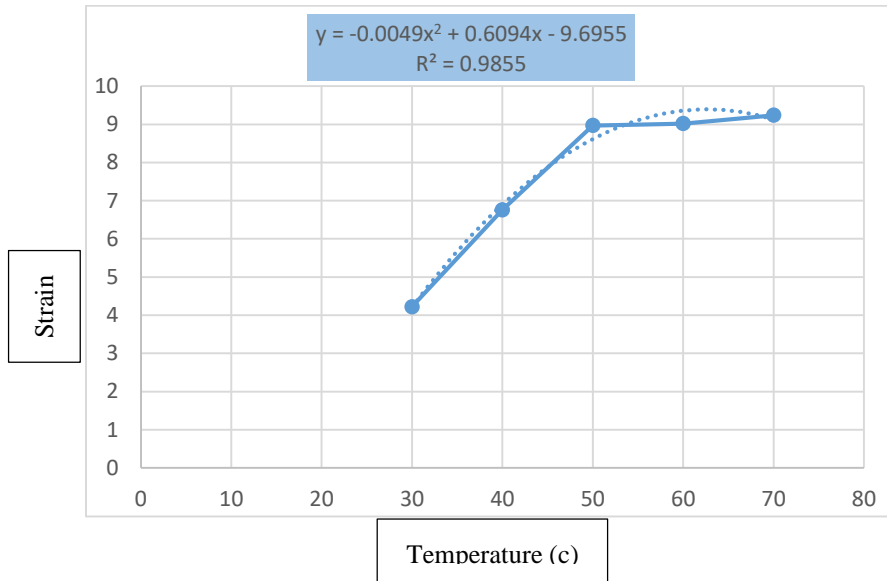


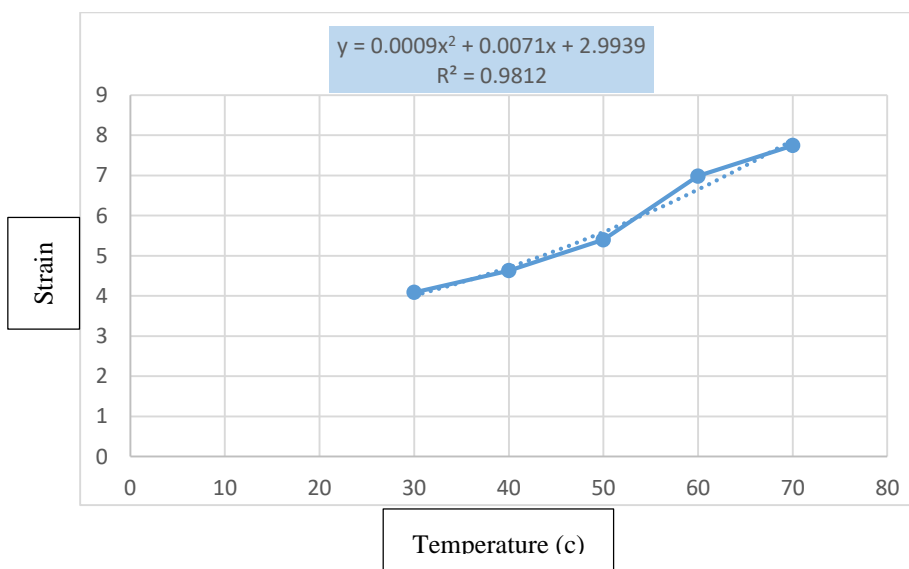
Figure 11. Muscle force contour with a diameter of 0.8 at a temperature of 50 ° C

In the following, the results of strain and force at five constant temperatures and three different diameters for nylon AM are compared. Furthermore, a comparison diagram is provided consistent with the results obtained from practical experiments for diameter 0.8 by Michael C. Yip et al.



**Diagram 1. Maximum strain at the temperatures for muscle 0.6 mm in diameter**

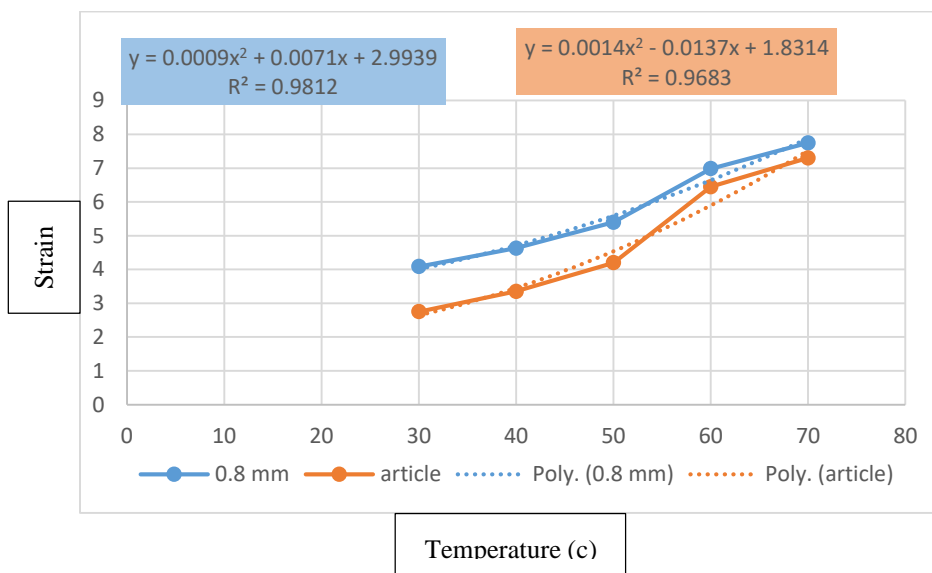
As the diagram displays, the maximum length change occurs at 70 ° C, which is equal to 109.237 mm. Considering the free length of the muscle, i.e. 100 mm, the maximum amount of strain in 0.6 diameters is 9.237. However, the upward trend of the Diagram illustrates that by increasing temperature, the amount of strain correspondingly increases. In other words, strain is directly related to temperature.



**Diagram 2. Maximum strain at the temperatures for a 0.8 mm diameter muscle**

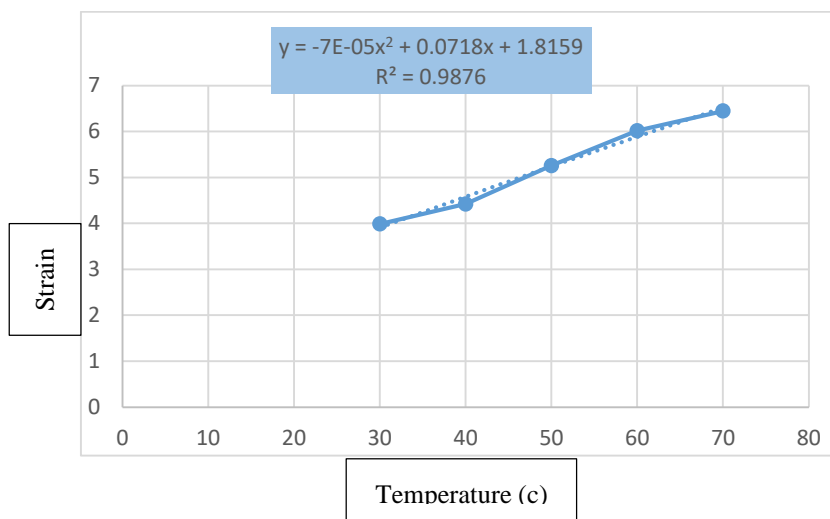


As the previous muscle, the maximum amount of strain occurs at the last temperature, which is equivalent to 7.744. In the diagram, the upward trend is similarly well-maintained. Here, the amount of strain obtained for a muscle with a diameter of 0.8 mm and the amount obtained in practical experiments are compared.



**Diagram 3. Comparison between the maximum amount of muscle strain with a diameter of 0.8 mm in the analysis mode by software and practical analysis**

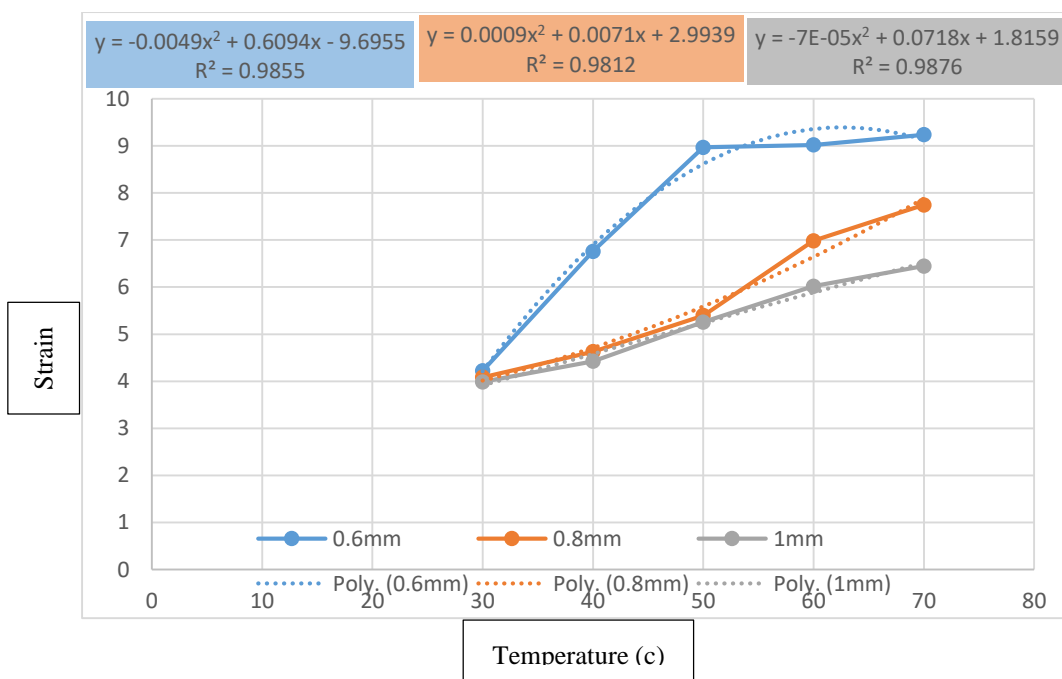
Diagram 3 displays that the values obtained by software analysis are slightly higher than the practical analysis. The reason for this difference can be because the software cannot provide the complete conditions in which the practical test was performed in that environment, and only by applying the boundary conditions can it be approached to that environment. Therefore, there is always some difference between theoretical and practical results.



**Diagram 4. The maximum amount of strain at any temperature for a muscle with a diameter of 1 mm**

The maximum strain obtained in this diameter is at a temperature of 70 ° C and is equal to 6.447.

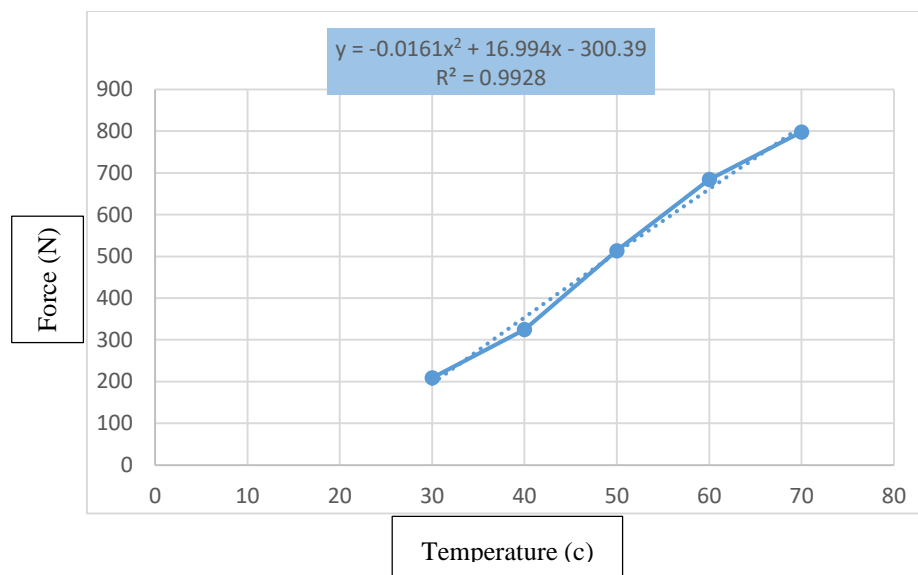
The strain diagrams are compared in three diameters in Diagram 5.



**Diagram 5. Comparison between the maximum amount of strain in three diameters of 0.6, 0.8, and 1 mm**



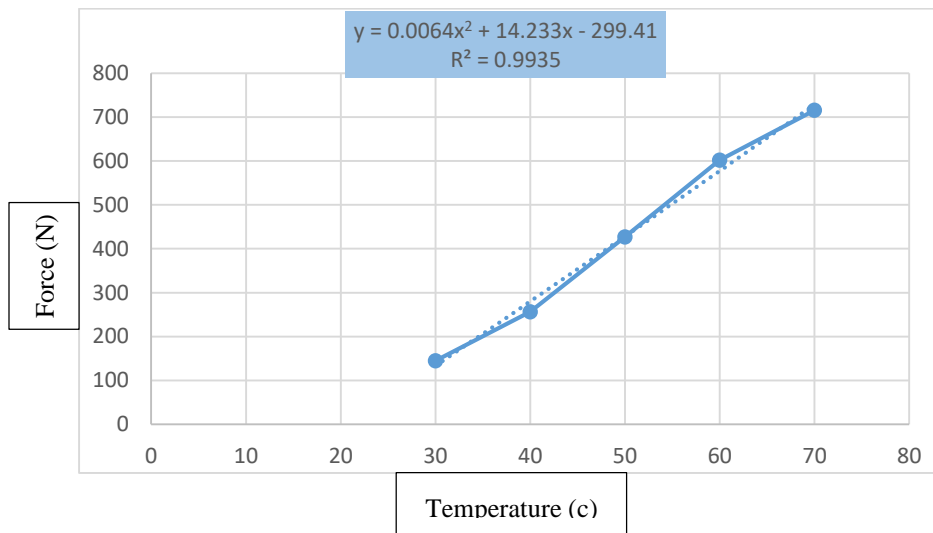
In all three Diagrams, the strain for different diameters illustrates that the graph is ascending: the changes in length and finally the strain is directly related to changes in temperature. However, as the results of the analysis show (the numbers given for each diameter that represented the highest amount of strain) we conclude that at the smallest diameter of 0.6 mm, we have the largest change in length and strain. In other words, the change in length is inversely related to the diameter of the muscle. The maximum amount of force in a muscle with a diameter of 0.6 mm is 798.2 m at a temperature of 70 °C, which is displayed in Diagram 6.



**Diagram 6. The maximum amount of force per temperature for a muscle with a diameter of 0.6 mm**

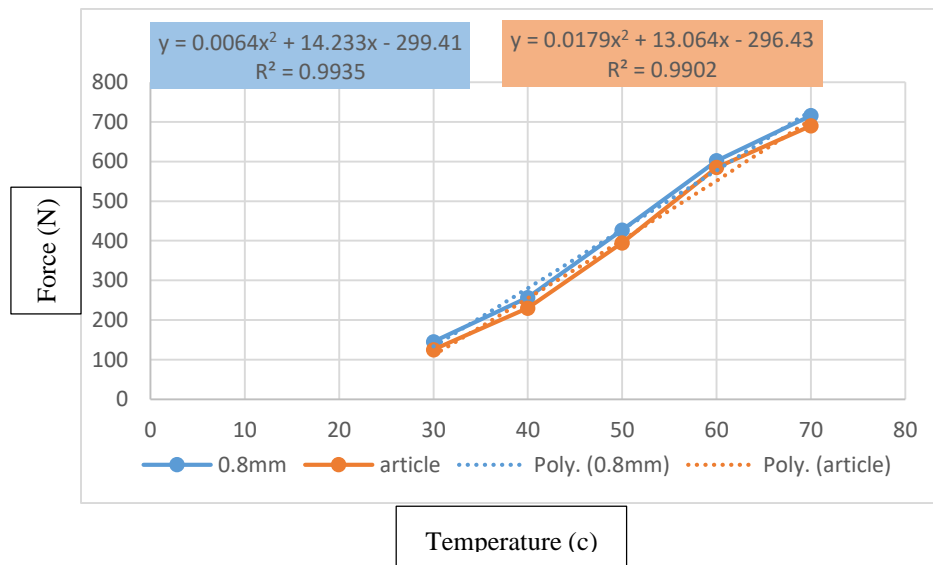


The maximum force for muscle 0.8 mm in diameter is 715.9 mN, at a temperature of 70 ° C (Diagram 7).



**Diagram 7. The maximum amount of force per temperature for a muscle with a diameter of 0.8 mm**

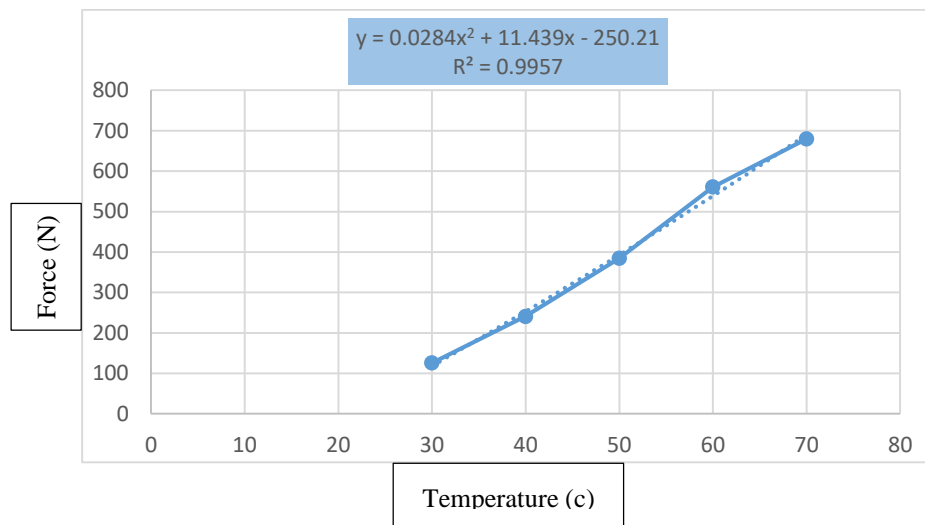
Diagram 8 compares the force on a muscle with a diameter of 0.8 mm in the state of practical experimentation and theoretical analysis, and the values of force in the theory are greater than in the state of practice.



**Diagram 8. Comparison between the maximum amount of force in a muscle with a diameter of 0.8 mm in the analysis made by software and practical analysis**

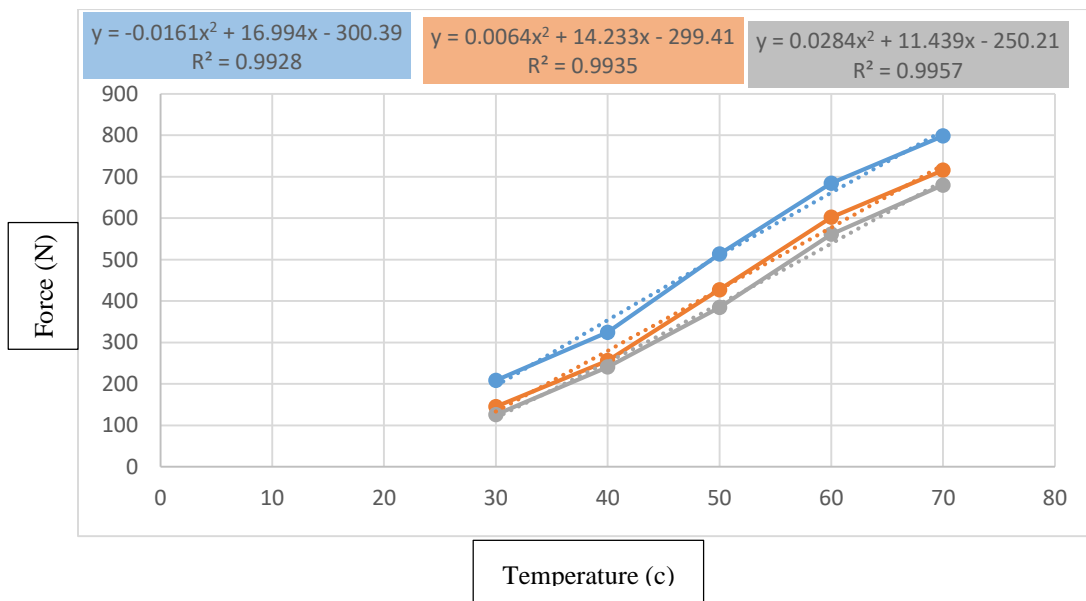


As Diagram 9 displays, the maximum force for a muscle with a diameter of 1 mm is 679.8 mN at a temperature of 70 ° C.



**Diagram 9.** The maximum amount of force at the temperatures for a muscle with a diameter of 1 mm

Finally, Diagram 10, compares the forces in all three diameters.



**Diagram 10.** Comparison between the maximum amount of force in three diameters of 0.6, 0.8, and 1 mm





As the results show, all the three force Diagrams are ascending, indicating that force changes are directly related to temperature changes. However, in the order of the diagrams, we conclude that the smallest diameter provides the most force changes. In other words, the change in force is directly related to the change in length (strain) and temperature but is inversely related to the diameter of the muscle.

#### 4. Conclusion Remarks

- Length changes were calculated according to temperature changes during the presented diagrams and the relationship between them was suggested for later uses;
- Force changes with temperature were correspondingly calculated and the results were presented in graphs and appropriate formulas;
- Changes in length and strength in terms of temperature changes in the synthetic muscles of complex nylons with a diameter of 0.8 mm were modeled using the software. Upon comparing with the practical results of other projects, it was found that the modeling is in good agreement with the practical results;
- For artificial muscles with diameters of 0.6 and 1 mm, modeling was performed and the relationship between changes in length and force in terms of temperature was proposed as a graph and formula for later uses in dynamic and control design.

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