Measurement and numerical analysis of the artificial muscles made of fishing line

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Abstract

This paper presents results of experimental and computational analysis of the artificial muscle (in form of coiled spring) made of nylon fishing line. By experimental measurement, the elasticity modules of chosen untwisted and twisted fishing line as well the spring constant of the coiled spring are found. The prestressing force in the twisted line and the coiled spring is measured as well. The measured parameters are put into the analytical and Finite Element Method (FEM) computational model of the coiled spring to calculate the elongation that results from the applied mechanical load. Linear and non-linear numerical elastostatic analysis is performed. An expression is established for analytical calculation for the thermoelastic stroke of the muscle. A good agreement of the measured and calculated results is obtained. Contrary to analytical methods, FEM enables modeling and simulating complex mechanical structures that occur in biomechanical and mechatronic applications of the artificial muscles in a form of nylon springs. Copyright © 2017 VBRI Press.

Keywords: Artificial muscle, actuators and sensors, fishing line, computational modeling, simulation.

Introduction

Like actuators and sensors, artificial muscles are needed for diverse applications, ranging from humanoid robots, prosthetic limbs, and exoskeletons, to comfort-adjusting clothing and miniature actuators for micro fluidic "laboratories on a chip". There are several material options for making them and each has specific properties and features [**1**-**2**]. One option is the low-cost high-strength polyethylene and the nylon fibers, most commonly used in fishing line [**3**]. The polymer fibers are twisted to make them chiral, which enables them to function as torsional and tensile muscle. A tensile stroke is greatly amplified by inserting such a large amount of twist that some twist converted to fiber coiling. By completely coiling, tensile contractions exceeding the maximum in vivo stroke of human skeletal muscles are obtained. Immediately after coiling adjacent coils are in contact, limiting contraction during actuation, and must be separated by increasing load or reducing twist. When adjacent coils contact, due to insufficient applied load or excessive twist, the muscle-direction thermal expansion becomes positive. When adjacent coils do not contact due to applied load, the muscle-direction thermal expansion is negative and the muscle performs mechanical work [**3**].

Previously, many papers have dealt with experimental and analytical analysis of thermo-elastic behavior of the artificial muscles and their applications in praxis. In [**4**], a new polymer artificial muscle based healing-demand composite was prepared and characterized. In [**5**], thermal energy was electromechanically harvested as electric energy using thermally powered torsional and tensile artificial muscle made from fishing line and sewing thread. In [**6**], the results of thermo-mechanical characterization conducted on a specific type of twisted polymeric fibre is presented. In [**7**], the state of the art macroscopic artificial muscles based on electromechanical reactions, which drive conformational (basic molecular motors) and macroscopic (swelling/shrinking) movements in conducting polymers is reviewed. In [**8**], the artificial muscles made of twisted Nylon 6.6 fibers are presented and are cold-drawn. A computationally efficient phenomenological thermo-mechanical constitutive model is developed in which several physical properties of the artificial muscles are incorporated to minimize the trial-and-error numerical curve fitting processes. In [**9**], the mechanical behavior of nylon coil actuators is studied by testing elastic modulus and by investigating tensile stroke as a function of temperature. In [**10**], a new biomimetic structure of nylon actuator is presented that imitates the human pinnate muscle in structure, ability to vary stiffness and the ability to increase force by recruiting additional fibers. In [**11**], the technical details on the manufacturing process of sample actuators and on the design and operation of the test bench is provided. Preliminary experimental results are reported. In [**12**], the design and experimental analysis of novel artificial muscles is provided, for powering a biomimetic robotic hand. In [**13**], structural-scale crack healing of artificial muscle reinforced ionomer composite is investigated. In [**14**], a multi-scale modeling framework for the thermo-mechanical actuation responses by a top-down strategy is established. Comparison between modeling results and experimental results exhibited excellent agreement. In [**15**], a new type of motion guidance system is proposed that simulates the way of motion that the human body moves as driven by muscle contractions. The main features of the above cited references are that mostly the analytical or phenomenological approaches are used in the computational analyses.

In this paper, the experimental measurements are done to specify the elasticity modulus of chosen untwisted and twisted fishing line as well as the spring constant of the coiled spring. The measured samples are obtained by our home-made device. The prestressing force in the twisted line and coiled spring is measured as well. The measured parameters are put into the analytical and Finite Element Method (FEM) computational models of the coiled spring for calculation of the spring elongation due to the applied mechanical load. Linear and non-linear elastostatic analysis is performed using the BEAM188 finite element (3D-beam finite element) of the commercial FEM code ANSYS [**16**]. An expression is established for analytical calculation of the thermoelastic stroke of the muscle. The calculated results are compared with the experimentally measured elongation of the artificial muscle caused by additional mechanical and thermal load. Finally, results of the FEM elastostatic analysis of the like von Mises structure actuator that is made of two springs are presented. The main purpose of the paper is modeling and simulation of the artificial muscles made of fishing line and obtained results comparing with the ones obtained by the measurements.

Experimental

The measured samples were produced using a home-designed and made device consisting of a supporting frame, DC stepper motor, motor controller and computer with relevant software. The device twists the fishing line until it coils and creates the required number of turns in the coiled spring. The control unit controls the rotation speed and number of engine rotations.

Mechanical properties of the analyzed samples were measured using testing machine shown in **Fig. 1**. The machine measures the force of tensile deformation in both the untwisted and twisted fishing line, as well as in the coiled spring (an artificial muscle). Translational movement of the upper grip is realised by rotational motion of the ball screw. The sample's elongation and corresponding tensile force are measured. Load cell sensor with measuring range up to 1 kN and with resolution of 0.2 N is used. The extension is determined from measured ball screw speed with the appropriate pitch. The accuracy of positioning is indicated to 0.001 mm. Elasticity modules (untwisted and twisted fishing line) and spring constant (coiled spring) are calculated from measured data. The same testing machine is used to determine the prestress force in the twisted line and in the coiled spring.

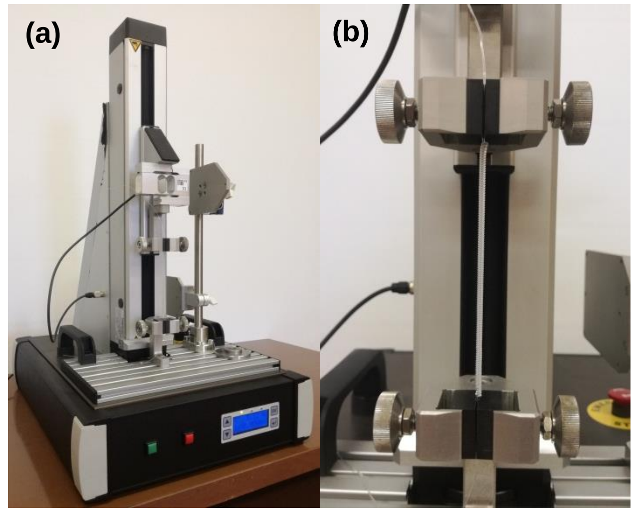

Fig. 1. (a) Testing machine for measuring mechanical properties (b) a sample of the coiled spring.

Thermo-mechanical elongation of the artificial muscle is provided using the experimental device shown schematically in the **Fig. 5(a)**. The home-made test machine for the measurements of the actuation stroke of the spring is composed from the metallic frame with adjustable clamps for the fixation of the spring. The spring is placed inside a thermally insulated PET tube to ensure constant temperature. The bottom of the spring is fixed at a tested weight. The spring is heated and cooled with water from the laboratory containers which has electronically stabilized hot and cold temperatures. After stabilizing water to the desired temperature, the charge (~ 50 ml) of the water is injected through the upper end of the device. Flowing water heats (or cools) the spring and continuously flows to the sink. Precision of the spring elongation measurement due to temperature changes and applied mechanical load of the string with the length of 100 mm is +/- 0.2 mm.

Mechanical properties of the untwisted and twisted fishing line measurement

In **Fig. 2(a)**, the fishing line (Sufix, Suple Link, Finland) is depicted in its initial state: L_0= 900 mm is the length; d_0 = 0.8 mm is the diameter. From the measurement, the material properties of the line are obtained: E_0 = 2400 MPa is the elasticity modulus; ν_0 = 0.35 is the Poisson ratio and G_0 = 909.1 MPa is the shear modulus. After hanging weight m = 0.7 kg, twist is inserted into these polymer fibers by introducing n_t = 330 turns (**Fig. 2**) which is the point at which some twists convert to the fiber coiling.

In the state (**Fig. 2(b)**), L_t = 740 mm, d_t = 0.87 mm, E_t = 2100 MPa, G_t = 795.5 MPa and ν_t = 0.32, is the measured length, diameter, elasticity modulus, shear modulus and Poisson ratio at this limit state, respectively.

F_t = 6.9 N is the prestressing force at this limit state, which corresponds with the applied mass m = 0.7 kg and the gravity g = 9.81 ms^{-2}. The normal stress in the twisted line is $\sigma_t = \dfrac{F_t}{\pi d_t^2/4} = 11.6$ MPa. Compared to the initial state, the material properties and the length of the line decrease and the diameter of the line increases. The measured properties are needed for the computational analysis.

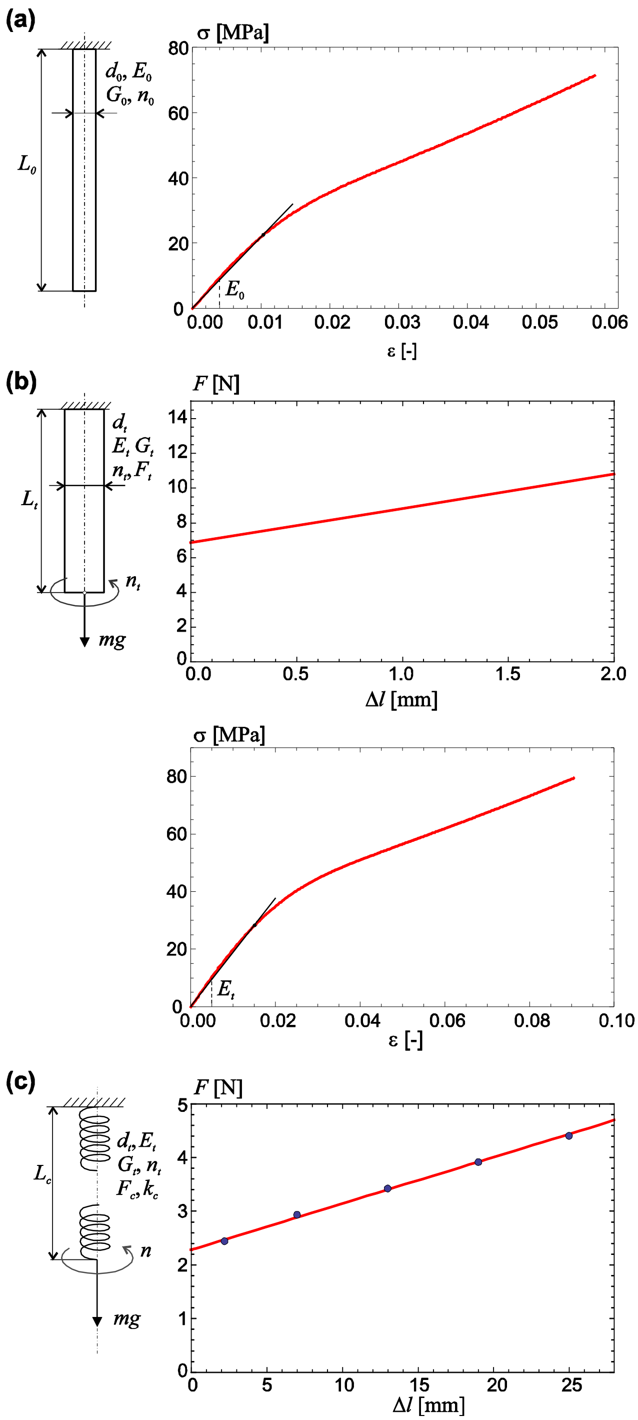

Fig. 2. (a) To measurement of the material properties of the fishing line, (b) to measurement of the material properties and prestress force of the twisted the fishing line, (c) to measurement of the spring constant and prestressing force of the partially unwound spring.

Mechanical properties measurement of the spring

By inserting additional twist the coiled spring with n = 155 turns is obtained (**Fig.2(c)**) with the length L_c = 135 mm and the mean radius R_c = 0.79 mm. The prestressing force in the spring was F_c = 5.5 N. After removing mass m, the spring is partially unwound to a steady state in which the prestressing force decreases to F_c = 2.3 N and the spring constant is k_c = 100 N/m. In that state the energy in the actuator is much lower, but the future handling of it is user friendlier. Changing of the material properties and the diameter of the twisted line after coiling is assumed as negligible. The above measured values are the mean values from the 5 times repeated measurements that are used in the further analysis of the spring.

Results and discussion

Elastostatic analysis of the single artificial muscle

Fig. 3 shows the coiled spring loaded by load $F = mg$, m is the mass of the applied load and g is the gravity. Further, $L_c = nd_t$ is the coiled spring length, n is the number of turns, d_t is the diameter of the twisted fiber and R_c is the mean radius of the coiled spring. The adjacent coils contact that means, the pitch of the spring is equal to the diameter of the twisted fiber d_t. An elongation ΔL_c of the pre-stressed spring is expressed as:

$$\Delta L_c = \frac{4R_c^3 n(F - F_c)}{G_t r_t^4} \quad (1)$$

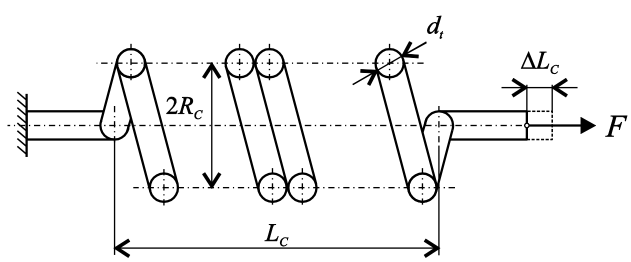

Fig. 3. To computational model of the coiled spring.

In (1), G_t is the shear modulus of the twisted fiber and F_c is the prestressing force in the coiled spring. Both parameters are obtained by the measurements presented in the previous chapter. The expression (1) is well known, and is derived from the principle of minimal potential energy which is valid for relatively small elongation of the spring.

The FEM model is also used for the coiled spring. Elastostatic linear and nonlinear analysis is performed using 31500 number of BEAM188 finite element with commercial software ANSYS [**16**] (there is insignificant difference in results between both approaches arised). A dependence of the spring elongation on the applied load is shown in **Table 1** and **Fig. 4**. In comparison to the measurement, the FEM solution gives more accurate results than the calculation by the analytical expression

(1). As expected, the spring starts extending upwards when the load exceeds the prestressing force.

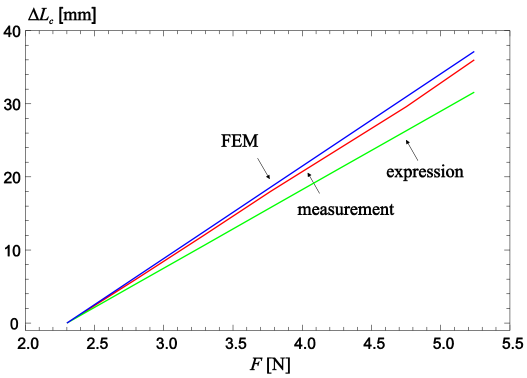

Fig. 4. Elongation of the coil.

Table 1. Results of the computational analysis and measurement.

	m [kg]	*F*[N]	measure ΔL_c [mm]	FEM ΔL_c [mm]	Δ [%]	exp.(1) ΔL_c [mm]	Δ [%]
1	-	2.3	0	0	-	0	-
2	0.05	2.7905	5.9	6.17	4.58	5.26	10.85
3	0.10	3.2810	11.9	12.35	3.78	10.53	11.51
4	0.15	3.7715	18.0	18.54	3.00	15.79	12.28
5	0.20	4.2620	23.8	24.74	3.95	21.06	11.51
6	0.25	4.7525	29.6	30.92	4.46	26.32	11.08
7	0.30	5.2430	35.5	37.12	4.56	31.59	11.01

Thermoelastic deformation of the single muscle

The device in **Fig. 5(a)** was built to measure the thermoelastic elongation of the spring. The partially unwound spring is incorporated into the plastic tube and heated by hot water. The reference temperature was 24 °C.

The thermoelastic elongated spring is measured done for two different hanged weights *m* (280 and 320 g) and two different temperature rises Δ*t* (6 and 13 °C). Obtained results are shown in **Table 2**.

Table 2. Thermoelastic elongation of the spring.

m	280 g			320 g		
Δt [°C]	Δl_{ct} [mm] analytic	Δl_{ct} [mm] measure	Δ [%]	Δl_{ct} [mm] analytic	Δl_{ct} [mm] measure	Δ [%]
1	0.32	-	-	0.30	-	-
5	1.59	-	-	1.54	-	-
6	1.91	2.0	4.50	1.84	1.75	5.14
10	3.20	-	-	3.08	-	-
13	4.14	4.3	3.72	4.00	3.8	5.26

For the analytical solution, the simplified mechanical model for elongation of one coil extended length is proposed (**Fig. 5(b)**). Stretched length of one thread of one coil is depicted in three states:

1) Initial state (red line) - the coils are in contact with the pitch of the coil equal to the twisted line diameter d_t;
2) After the mechanical loading $F = mg$ - green line with mechanical stroke δ_{sc} and the length $\Delta l_c = 2\pi R_c$ (we assume that the stretched length of one coil changes due to mechanical load negligibly);
3) After thermal loading by temperature rise Δt (blue line) - due to negative thermal expansion coefficient α_t the coil length is shortened by the value $\Delta l_{ct} = \alpha_t l_c \Delta t$ and the thermal stroke is $\delta_{st} = \Delta l_{ct} / \sin\beta$. The angle $\beta = \arcsin((\delta_{sc} + d_t)/l_c)$. A total spring thermal stroke is $\delta_s = n\delta_{st}$ with *n* turns.

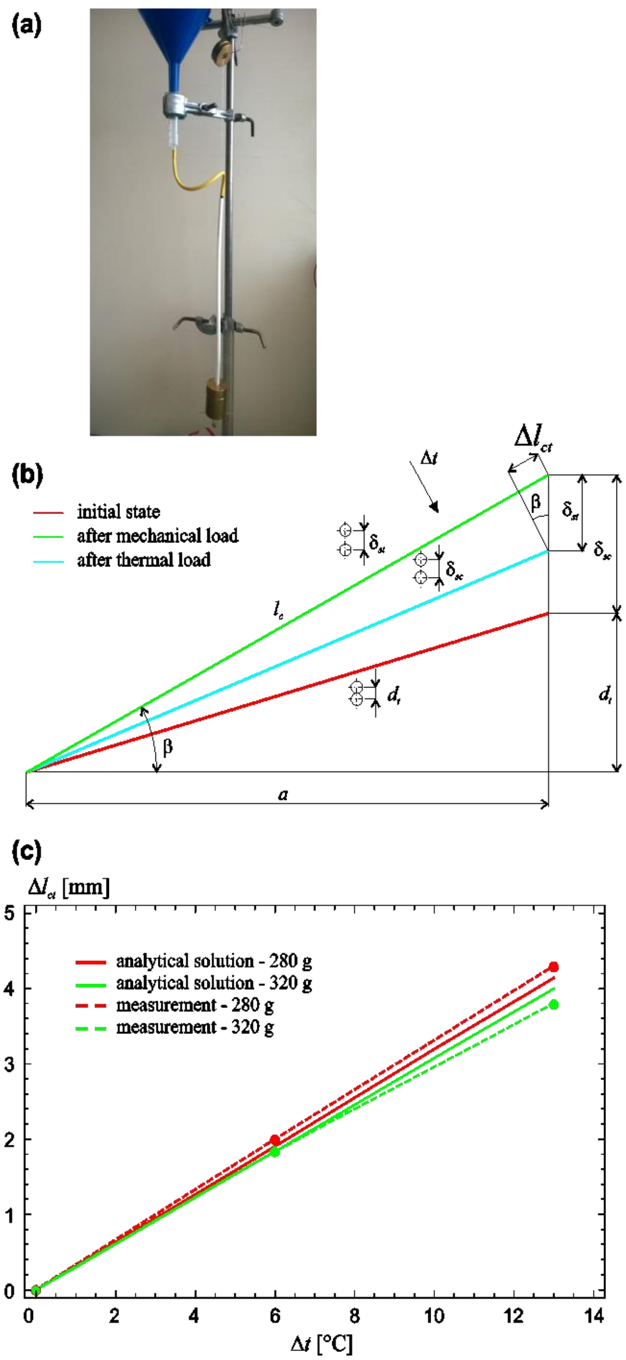

Fig. 5. The measurement and calculation of the thermoelastic elongation of the spring:(a) device for the measurement, (b) the simplified mechanical model for analytical solution, (c) comparison of the analytical solution and the measurement.

The thermoelastic analysis of the measured spring was done by the analytical model (described above) with thermal expansion coefficient $\alpha_t = 0.000075[1/°C]$. The mechanical stroke was calculated by expression (1), and it is 4.79 mm for the mass *m* = 0.280 kg and 9.0 for the mass *m* = 0.320 kg. These results are compared to the results from the measurement and are shown in **Table 2.** Graphical dependence is shown in **Fig 5(c)**. As shown in the table, a good agreement of experimental and analytical results is obtained.

Elastostatic analysis of von mises muscle structure

The von Mises truss system (built of two straight trusses) is often used in the design of thermo-elastic actuators and sensors. Because of excellent properties of the artificial muscle the straight trusses are replaced by two springs in our model (**Fig. 6(a)**). The geometric and mechanical parameters are the same as in **Fig. 2(c)**. The system is loaded by force F = 0.981 N. Dependence of the vertical displacement Δy on the angle θ is found. A very fine mesh of 63 000 Beam188 finite elements is used in geometric non-linear FEM analysis. As shown in **Fig. 6(b)**, a very strong (nonlinear) dependence is obtained. As expected, the displacement significantly increases with the angle θ. The results suggest potential use of similar systems in designing different types of inexpensive actuators and sensors.

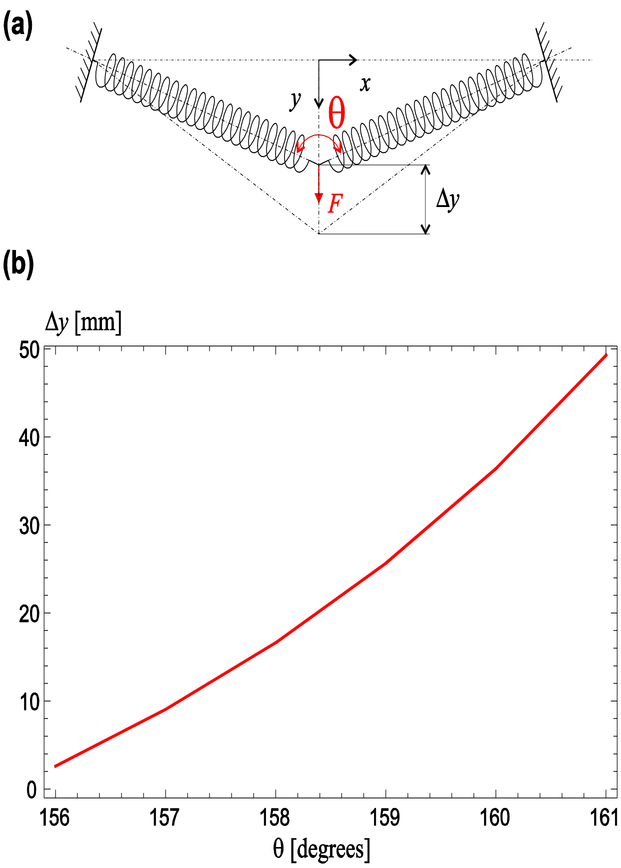

Fig. 6. (a) The Von Mises actuator made of fishing line springs, (b) dependence of the vertical displacement Δy on the angle θ.

Conclusion

This paper uses experimental measurements to specify the mechanical properties of untwisted and twisted fishing line, and the spring constant of a coiled spring (artificial muscle). The prestressing force in the twisted line and coiled spring is also measured. The measured parameters are than input into the analytical and Finite Element Method (FEM) computational models. Linear and nonlinear elastostatic analysis is performed using the BEAM188 finite element- software ANSYS [16]. An analytical approach is also used for calculating the elastic and thermoelastic elongation of the artificial muscle, as well. The results are compared with the measured muscle elongation caused by mechanical and thermal load. A good agreement of the measured and calculated results is obtained. As expected, the FEM elastostatic analysis results of the actuator, constructed as the von Mises truss system (made of two springs), show a strong dependence of its deformation on the angle between both springs. Contrary to analytical methods, FEM enables modeling and simulation of complex mechanical structures that occur in biomechanical and mechatronic applications. The computational modeling and simulation of the systems made of advanced materials help us in designing of artificial sensors and actuators (artificial muscles) in bio-mechatronics and in other areas of engineering.

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