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Structural analysis and material selection for biocompatible cantilever beam in soft robotic nanomanipulator

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Abstract

This paper investigates the selection of appropriate materials for cantilever beams in surgical robotic nanomanipulators. Cantilever beams play a crucial role in soft robotic surgery. Biocompatible materials, which have minimal adverse effects on biological systems, are commonly used for these beams. Using SOLIDWORKS software simulation, the study assesses the flexibility of cantilever beams made from different biocompatible materials. The analysis involves varying the applied force (0.001 µN to 0.004 µN), beam length (80 µm, 120 µm, and 160 µm), and beam thickness (0.4 µm, 0.6 µm, and 0.8 µm). Four materials—Alumina, Poly-Ether-Ether-Ketone (PEEK), Polyurethane (PUR), and Ti-6Al-4V—are evaluated. Simulation results highlight Polyurethane (PUR) as a suitable material for cantilever beams in nanomanipulators due to its favorable properties. These findings provide valuable insights for the design and advancement of efficient and reliable robotic nanomanipulators, advancing the field of soft robotic surgery.

Keywords
Cantilever beams, surgical robotic nano-manipulators, biocompatible materials, soft robotic surgery, simulation analysis.

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1 Introduction

The term "mechatronics" refers to the coordinated use of physical systems, information technology (IT), and sophisticated decision-making throughout the design, production, and use of industrial goods and processes [1]. In the mechatronic field, the robot is a crucial term. The Robotic Institute of America defines a robot as "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks," which is the definition that is currently most frequently used [2]. Today, robotic nano-manipulators are used in surgery applications. Nanomanipulator is a device created to control items at the nanoscale or a microscope attached to a virtual reality (VR) interface that enables the user to virtually teleport to the sample surface. Due to the numerous biological and material science applications of nanomanipulator, it has recently attracted a lot of interest. Nanomanipulator is demonstrated by the definition of material qualities, creation of electronic chipsets, testing of microelectronic circuits, teleoperation of operations, micro-injection, and manipulation of chromosomes and genes [3]. Nanomanipulator involves a variety of scenarios, but the most common ones are those that use scanning tunneling microscopy (STM), atomic force microscopy (AFM), and nanorobotic manipulator (NRM) [4]. The cantilever beam is one of the important parts of a robotic nanomanipulator in the field of soft robotic surgery applications. Minimally invasive surgery (MIS), particularly for abdominal procedures, has established itself as the industry standard [5]. A cantilever beam can be utilized as a part of the tool or instrument to manipulate tissues or carry out treatments at the microscopic level. Typically compatible materials are used in soft robotic cantilever beams because of their flexibility. Biocompatible materials are those that can interact with biological systems without harming them or producing unfavorable effects. These materials are employed in a variety of medical and healthcare applications. In Neurosurgery, minimally invasive techniques are employed for the biopsy operation (Fig. 1) which required precisely placing a device into a brain lesion. To access the tumor, the physician drills a hole in the skull and inserts a biopsy probe where a cantilever beam is used [6].

In Gynaecologic surgery, each Zeus system contains two physically separate subsystems known as "Surgeon-side" and "Patient-side" shown in (Fig. 2). The surgeon-side console consists of two handles for operating the robotic arms and a display for documenting the surgical operation. The surgeon console controls three robotic arms that are mounted above the operating table as a component of the patient-side subsystem. The biocompatible material is used as a cantilever beam in these robotic arms [7]. In minimally invasive surgery, by replacing and increasing human skills, minimally invasive surgery (MIS) can increase patient safety and the effectiveness of medical interventions [8]. The development of surgical instrumentation that can access the surgical target through numerous small entrances (Fig. 3) which employed the cantilever beam. The aforementioned applications show that the cantilever beam is widely used in medical applications. These cantilever beams are composed of biocompatible materials. There is a limited number of studies that focused on single biocompatible material as a cantilever beam independently. But the response of the cantilever beam depends on the type of material, the width, length, and applied force. Hence, optimization of the material and the effect of the influential parameters is important and such studies seem not to exist in the available literature. The objective of this study is to optimize the biocompatible materials and to investigate the effect of influential parameters on the response of the biocompatible materials in cantilever beam under specific conditions using the SOLIDWORKS simulation software.

2 Methodology

This section describes the selection of the material, assumption and boundary condition, and simulation setup for the cantilever beam.

2.1 Selection of the Materials

The author has selected four types of biocompatible materials like Alumina, PUR (Polyurethane), PEEK (Poly-Ether-Ether-Ketone), and Ti-6Al-4V (titanium alloys). The basis of selection is discussed as follows. Alumina-based bio-ceramic materials are considered one of the best materials to use in biomedical engineering because of their excellent biomechanical and biocompatibility properties [9]. The three main subcategories of bioceramics are bioinert, bioactive, and bioresorbable ceramics [10]. Alumina and zirconia, two bio-inert ceramics with high mechanical and chemical stability, exhibit a "contact osteogenesis" pattern when in touch with bone tissue [11–14]. PUR is a versatile elastomer that exhibits exceptional flexibility and resilience. It has superior impact resistance, low friction, and vibration damping qualities. These qualities make it ideally suited for soft robotic applications. PEEK is a high-performance thermoplastic that is renowned for its superior mechanical attributes, such as high strength, stiffness, and chemical resistance. It is used in soft biomedical engineering applications due to its advantageous mechanical properties [15] for soft robotic applications. Ti-6Al-4V is the alloying system titanium-aluminum vanadium type VT-6 (6Al-4V, Grade5, SAT-64, T-A6V, Ti-Al-V) with an average aluminum content of 6% and vanadium - 4% are the most widely used titanium alloys in additive industries [16] and soft robotic applications. The mechanical properties of the materials are listed in Table 1.

2.2 Boundary Condition and Assumption

The fixed end of the cantilever beam is fastened to hard support, which prevents motion in all directions. The force is applied to the cantilever beam's free end. The cantilever beam is unrestricted in its ability to bend and move in transitional directions means movements can include bending and deflection, other than axially. The forces were varied from 0.001 µN to 0.004 µN. Then the thickness and length were set up at three different values for each material: 80 µm, 120 µm, and 160 µm for length, and 0.4 µm, 0.6 µm, and 0.8 µm for thickness. However, the value of the width is kept fixed.

It has been assumed that the materials will react linearly and elastically. The cantilever beam is said to be made of homogeneous materials, each of whose characteristics is thought to remain constant throughout. The cantilever beams will only experience modest deflections, keeping the beam within its elastic range.

2.3 Simulation Setup

At first, the static Structural analysis has been chosen. Then 3D geometry of the cantilever beam has been developed using the sketching module employing the dimensions. After that, the material selection and settings of the material attributes have been fixed from the software database using the drop-down menu. The assumption and boundary condition has been set using the simulation module. The load, length, and thickness of the cantilever beam have been selected as the variable parameters during the simulation. The mesh is generated for the computational domain to discretize the geometry of the cantilever beam. Optimization of the mesh generation has been done using the trial and error method. The finite element analysis (FEA) was utilized to simulate the structural response of the beam under various loading scenarios.

Table 1: Properties of different bio-compatible materials.

Properties	**Alumina**	**PUR**	**PEEK**	**Ti-6Al-4V**
Elastic Modulus(N/m^2)	3.7×10^{11}	2.41×10^{9}	3.9×10^{9}	1.02×10^{11}
Poisson's Ratio	0.22	0.3897	0.4	0.31
Mass Density(kg/m^3)	3960	1260	1310	4428.784
Tensile Strength(N/m^2)	3×10^{8}	4×10^{7}	9.5×10^{7}	1.01×10^{9}
Thermal Expansion Coefficient(/ K)	7.4×10^{-6}	4×10^{-5}	3.6×10^{-3}	9×10^{-6}
Thermal Conductivity(W/m. k)	30	0.2681	0.24	6.9
Specific Heat(J/ kg. k)	850	1900	1850	586.04

Sources: SolidWorks software

3 Results and Discussion

This section describes the simulation results of the four types of materials obtained at different influential parameters.

3.1 Optimization of the Materials

Figure 4 shows the effect of applied force on the deflection of the materials. Overall, from this graph, we can easily figure out the deflection of cantilever beams made of different materials. The applied force ranged from 0.001µN to 0.004 µN. It is evident from the graph that deflection increases with increasing force. Polyurethane (PUR) exhibits the maximum deflection, while Alumina represents the minimum deflection. PEEK and Ti-6Al-4V show a moderate level of deflection. Thus, Polyurethane (PUR) demonstrates the greatest degree of flexibility compared to the other three materials (Alumina, PEEK, and Ti-6Al-4V). As displacement is a measure of material flexibility, it can be concluded that Polyurethane is the best material among the four.

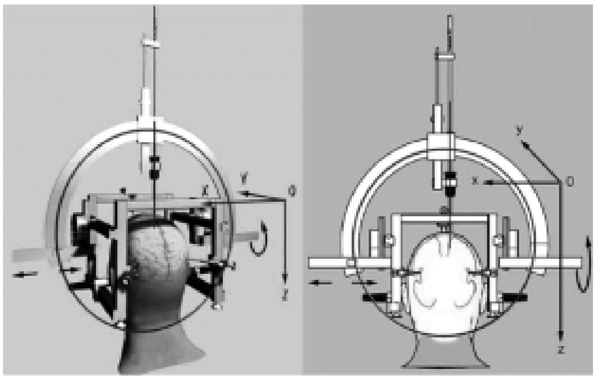

Figure 1: Application of surgical robot with Cantilever beam biopsy [2].

Figure 2: (A) Zeus surgical telemanipulator system. (B) Robotic instrument arms and Aesop endoscope arm (not sterile-draped) at the operating table [[17]].

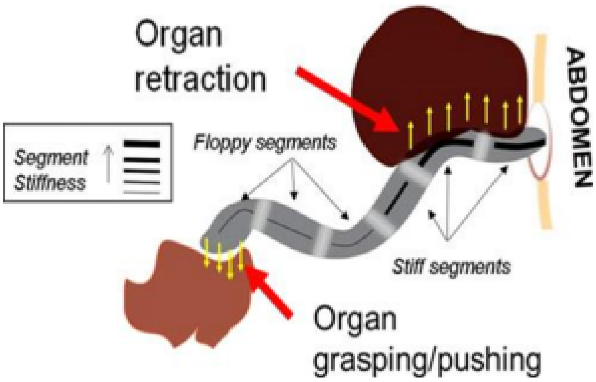

Figure 3: Envisaged surgical scenario with a manipulator [18].

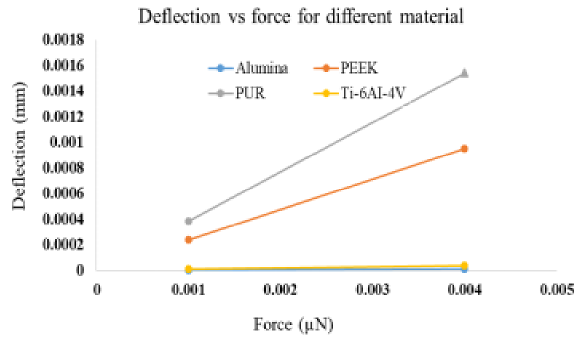

Figure 4: (Effect of applied force on the deflection of the material [L=80 µm, Width=10 µm, thick=0.6 µm].

3.2 Effect of Applied Force on PUR Deflection

Figures 5, 6, and 7 show the displacement of a cantilever beam made of Polyurethane material with three types of loads. The values of length, width, and thickness are kept fixed, while only the forces vary. It is observed that the beam deflection increases with increasing load.

3.3 Effect of Beam Length on PUR Deflection

Simulation results in Figures 8, 9, and 10 indicate that displacement/deflection increases with increasing beam length at the micrometer scale. The values of force, width, and thickness are kept fixed.

3.4 Effect of Beam Thickness on PUR Deflection

Figures 11, 12, and 13 depict the simulation of the cantilever beam with variable thickness. These figures show that the displacement of the beam decreases with increasing thickness. The values of force, length, and width are kept fixed.

3.5 Simulation Results in Terms of Magnitude

Figure 14 illustrates how the deflection of the beam changes with the applied force corresponding to the length. It is observed from the graph that as the force increases, the cantilever beam shows maximum deflection for the maximum length at 160µm, whereas for the minimum length at a length of 80µm, the cantilever beam shows the minimum deflection. Moreover, Figure 15 is a line graph that illustrates how the beam deflection decreases with increasing width. In this figure, it can be observed that for the maximum thickness of 0.8µm, the minimum deflection of the beam is observed, while for the minimum thickness of 0.4µm, the maximum deflection is found. These two graphs indicate that polyurethane beams with maximum possible lengths and minimum thickness exhibit greater deflection, indicating a higher level of flexibility that is expected for the surgical soft robotic application of a nanomanipulator.

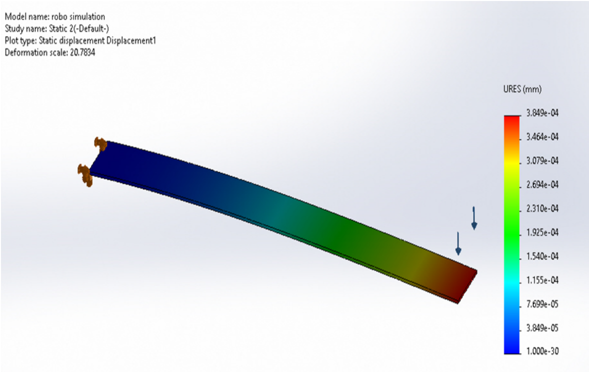

Figure 5: Graphical result of the cantilever beam made of Polyurethane (PUR); L= 80 µm, width= 10 µm, thickness = 0.6 µm [F=0.001µN].

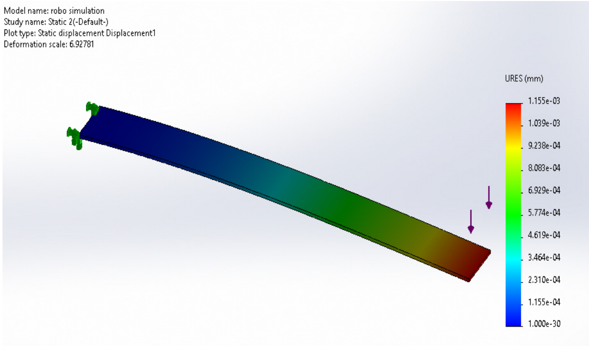

Figure 6: Graphical result of the cantilever beam made of Polyurethane (PUR); L= 80 µm, width= 10 µm, thickness = 0.6 µm [F=0.003µN].

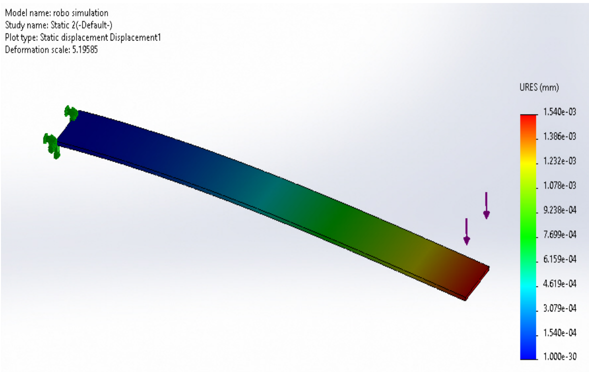

Figure 7: Graphical result of the cantilever beam made of Polyurethane (PUR); L= 80 µm, width= 10 µm, thickness = 0.6 µm [F=0.004µN].

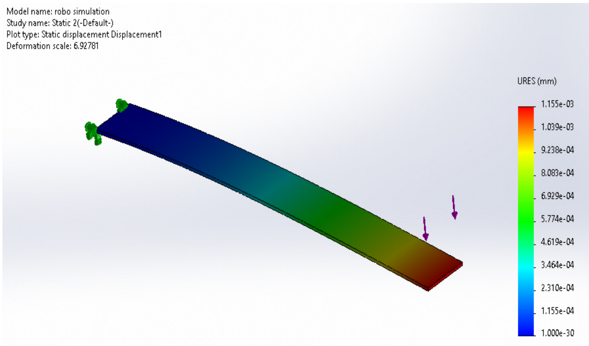

Figure 8: Graphical result of the cantilever beam made of PUR at F=0.001µN, width=10 µm, thickness=0.6 µm [L=80 µm].

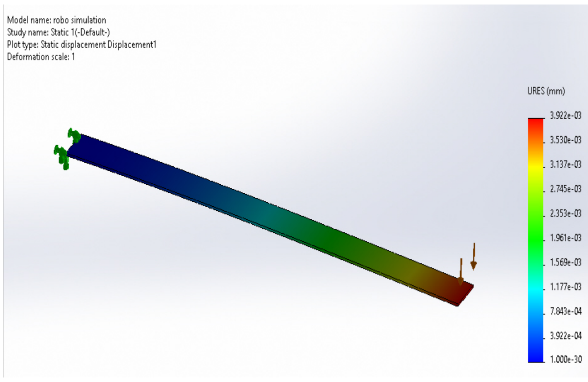

Figure 9: Graphical result of the cantilever beam made of PUR at F=0.001µN, width=10 µm, thickness=0.6 µm [L=120 µm].

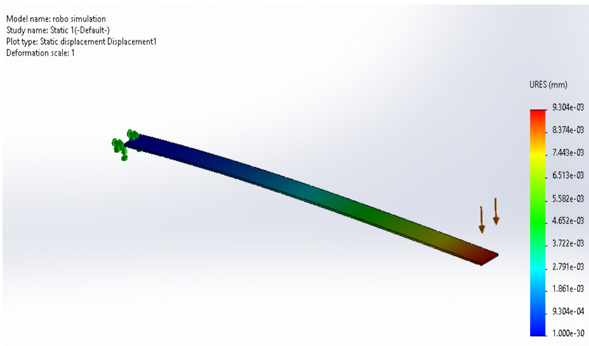

Figure 10: Graphical result of the cantilever beam made of PUR at F=0.001µN, width=10 µm, thickness=0.6 µm [L=160 µm].

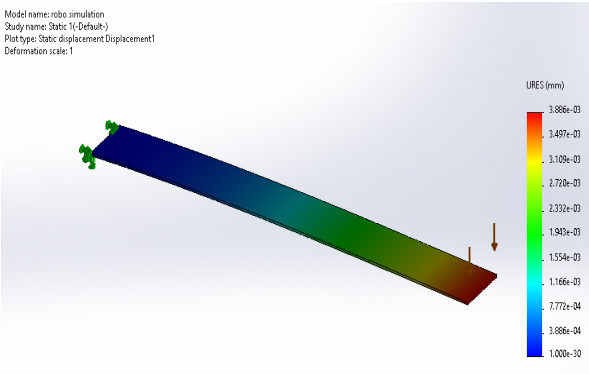

Figure 11: Graphical result of the cantilever beam made of PUR at F=0.001µN, L=80 µm, Width=10 µm [Thickness=0.4µm].

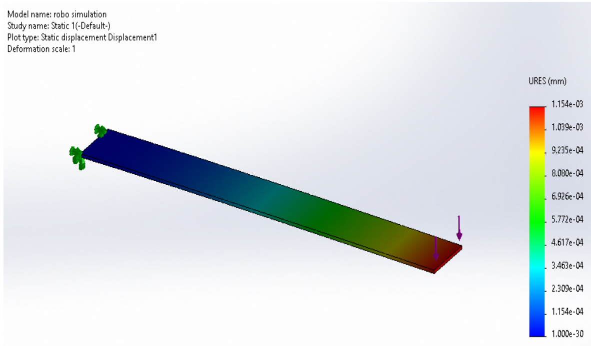

Figure 12: Graphical result of the cantilever beam made of PUR at F=0.001µN, L=80 µm, Width=10µm [Thickness=0.6µm].

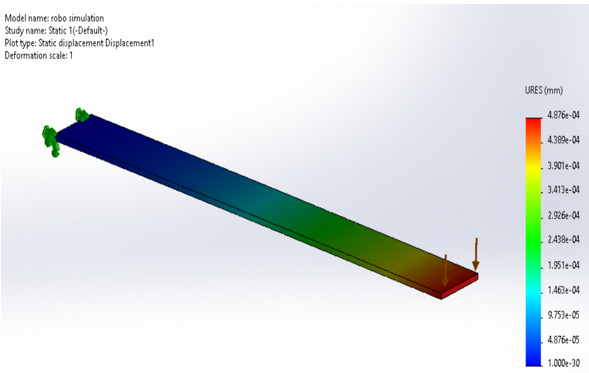

Figure 13: Graphical result of the cantilever beam made of PUR at F=0.001µN, L=80 µm, Width=10 µm [Thickness=0.8µm].

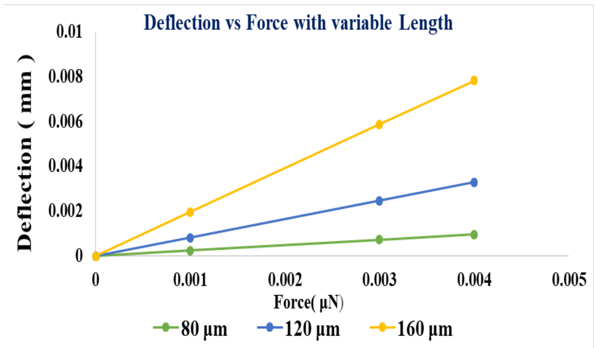

Figure 14: PUR deflection as a function of applied force corresponding to the length.

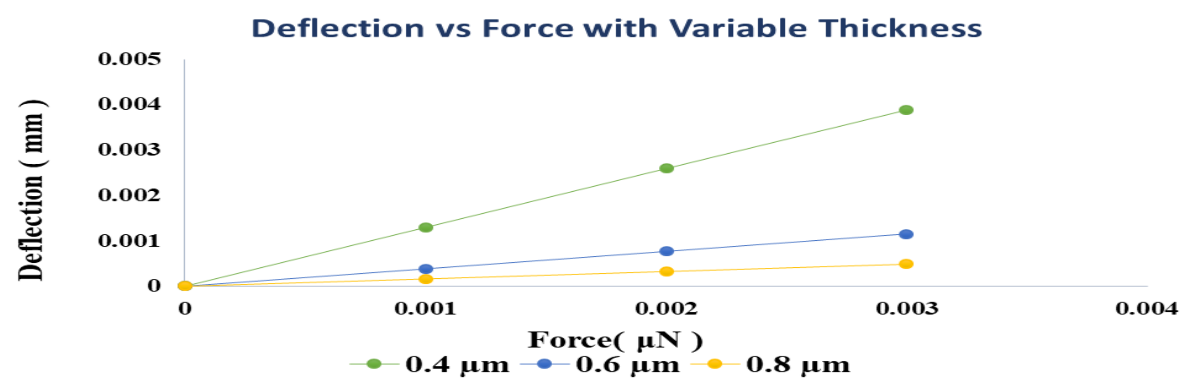

Figure 15: PUR deflection as a function of applied force corresponding to the thickness.

4 Conclusion

Polyurethane cantilever beams show great potential as a nanomanipulator in the fields of robotics and biology because it shows highest flexibility. Polyurethane is a flexible material with respect to biocompatibility and resilience to wear and tear. The polyurethane manipulator can provide the necessary dexterity and flexibility while working with biological systems at the molecular and cellular level. It could function more subtly inside the human body. A surgeon may work more precisely with less tissue injury using a nanomanipulator utilizing its high level of precision control. Polyurethane lessens the likelihood of an adverse response when used with human body parts. As a biocompatible material complies with scientific standards, polyurethane can be utilized in surgical procedures involving delicate human body parts.

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