Design, numerical and experimental investigation of linear XY compliant mechanisms for precision motion applications

Sandesh Solepatil[1*], Narendra Deore[2], Vikas Dive[1],
Amol Mali[1], Aniket Kolekar[1], Ganesh Jadhav[1]

[1] Department of Mechanical Engineering, D Y Patil International University, Akurdi, Pune, Maharashtra, 411044, India
[2] Department of Mechanical Engineering, Pimpri Chinchwad College of Engineering, Pune, Maharashtra, 411044, India
* Corresponding author's e-mail: sandeshpatil310@gmail.com

ABSTRACT

Compliant mechanisms have gained significant importance in precision engineering due to their ability to achieve smooth and accurate motion through elastic deformation without conventional joints. This study presents the design, numerical analysis, and experimental validation of linear and linear XY compliant mechanisms intended for precision motion applications, particularly in biomedical scanning systems. Various compliant mechanism configurations are developed using parallel beam arrangements with different geometric parameters such as beam thickness and effective beam length, resulting in 1.5-turn and 2-turn mechanisms. Numerical investigations are carried out using finite element analysis to evaluate displacement, stress, and stiffness characteristics under varying actuation forces. PLA material is considered to study the influence of material properties on performance. The results indicate that PLA exhibits significantly higher compliance and achieves the required range of motion (2–4 mm) with substantially lower actuation forces compared to metallic materials. A maximum displacement of up to 12.37 mm is achieved with optimized geometric parameters while maintaining stresses within permissible limits. Experimental validation of the selected PLA-based XY compliant mechanism shows good agreement with numerical results, with a maximum deviation of 1.13%. The study demonstrates that properly designed PLA-based compliant mechanisms are highly suitable for low-force, high-precision applications such as biomedical scanning and micro-positioning systems.

Keywords: compliant mechanism, linear XY motion stage, finite element analysis, PLA material, precision positioning, biomedical scanning applications.

INTRODUCTION

Precision motion mechanisms play a crucial role in modern engineering applications such as micro- and nano-manufacturing, biomedical scanning, optical instrumentation, and precision positioning systems. Conventional rigid-body mechanisms, which rely on multiple joints and sliding elements, often suffer from drawbacks such as friction, backlash, wear, and assembly errors, thereby limiting their accuracy and repeatability in high-precision applications [1,2]. To overcome these limitations, compliant mechanisms also known as flexural mechanisms have emerged as an effective alternative. Compliant mechanisms achieve motion through the elastic deformation of flexible members rather than through relative motion between rigid parts. This inherent feature provides several advantages, including smooth and continuous motion, high resolution, compact design, reduced part count, and improved reliability [3–5]. Due to these advantages, compliant mechanisms have found widespread application in precision engineering fields such as atomic force microscopy, micro-electromechanical systems (MEMS), biomedical devices, and precision

scanning stages [6,7]. Among various compliant mechanism configurations, linear and planar XY compliant mechanisms are of particular interest because they enable precise translational motion along orthogonal directions. Such mechanisms are extensively used in precision positioning systems where controlled linear displacement with minimal parasitic motion is required [8]. The performance of a compliant mechanism is strongly influenced by geometric parameters such as beam length, thickness, and configuration, as well as by material properties, which collectively determine stiffness, stress distribution, and achievable range of motion [9,10]. Several researchers have investigated parallel-beam compliant mechanisms and flexure-based motion stages to achieve high accuracy and decoupled motion. Shaw et al. [11] provided a comprehensive foundation for the analysis and synthesis of compliant mechanisms, while Shino et al [12] highlighted their advantages in precision engineering applications. Studies have shown that increasing beam length or introducing curved and folded beam geometries significantly enhances compliance and displacement capability without compromising structural integrity [13,14]. However, such design modifications must be carefully optimized to avoid excessive stress concentrations and material failure [15,16].

Material selection is another critical factor in compliant mechanism design. While metallic materials such as steel and aluminium offer high strength, they often require relatively large actuation forces to achieve the desired displacement [17–18]. Recently, polymer-based materials such as polylactic acid (PLA) have attracted attention due to their low stiffness, lightweight nature, ease of fabrication using additive manufacturing, and suitability for low-force actuation systems [19–21]. These properties make PLA particularly attractive for biomedical and micro-positioning applications, where low actuation force and moderate displacement ranges are desired [22–24]. Despite substantial progress, challenges remain in achieving large strokes with minimal parasitic motion, developing systematic design procedures that balance geometric and material considerations, and integrating compliant mechanisms with high-performance actuators and control systems for practical deployment in industrial and biomedical applications.

In recent years, compliant mechanisms have received significant attention as precision motion stages in engineering and scientific applications

due to their low friction, high repeatability, monolithic designs, and elimination of traditional joints. A comprehensive review by Ding et al. outlines the key advances in piezo-actuated compliant micro-positioning stages, emphasizing modern flexure designs, kineto-static modeling, material selection, actuator integration, and functional attributes such as motion amplification and self-guiding mechanisms. This review identifies emerging trends in compliant micro-positioning and the challenges in design synthesis and fabrication methods suitable for high-precision applications such as micro-robotics and automation systems [25]. Recent work also highlights the rapid development of compliant precision positioning and manipulating mechanisms, focusing on innovative flexure structures, structural optimization, and multi-DOF motion capabilities. For example, Zhang *et al.* (2023) summarize the design of compliant positioning and manipulation mechanisms, underscoring the combined modeling, sensing, and control requirements needed to enhance dynamic performance and motion accuracy[26].

On the application side, new compliant positioning stages have been developed by Grandhe and Bandopadyay for automated microscopy and biomedical scanning, demonstrating improved precision and reduced mechanical complexity through compliant designs [27]. These studies illustrate growing interest in XY traverse stages that leverage compliant flexures to guarantee smooth motion and positional accuracy suitable for biological imaging and micro-assembly tasks. Recent original research continues to expand the design space of compliant mechanisms. A 2025 study by Wang proposes a novel parallel compliant stage with input–output decoupling, which improves motion control and stiffness characteristics in multi-axis applications and reflects the trend toward more complex compliant architectures tailored for precision engineering platforms [28]. In addition to structural design innovations, significant progress has been made in modular and customizable flexure-based micro-positioning stages that facilitate assembly, integration, and simulation for various application requirements. Liao *et al.* (2022) present a design methodology for flexure-based modular stages that simplifies assembly while enabling precise motion control through structural optimization and simulation methods [29]. Across these recent studies, several common research directions

emerge: Advanced modeling and optimization techniques, including kineto-static analysis, topology optimization, and integrated simulation frameworks; Material and fabrication innovations, especially with additive manufacturing, that expand the design freedom while addressing anisotropic behavior and performance variability, Integration of actuation and sensing, particularly piezoelectric actuation with feedback control, to realize real-world applications in microscopy, biomedical devices, and precision manufacturing; and Deeper focus on multi-DOF compliant mechanisms with decoupled motion and minimized parasitic effects [30–32]

This study addresses these challenges by presenting the design, numerical analysis, and experimental validation of linear and linear XY compliant mechanisms tailored for precision motion applications, focusing on beam geometry variation and material comparison to achieve controlled micrometer-scale displacements.

Origin of this work

The origin of this work stems from the growing demand for high-precision linear and planar XY motion systems in applications such as biomedical scanning, optical inspection, micromanufacturing, and micro-positioning devices. Conventional rigid-body mechanisms commonly used in such applications rely on bearings, sliders, and joints, which introduce friction, backlash, wear, assembly complexity, and maintenance issues. These limitations significantly degrade positioning accuracy and repeatability, particularly when low-force and small-displacement motion is required.

To overcome these drawbacks, the present research is motivated by the need to develop a joint-less, compact, and low-force precision motion mechanism using compliant mechanism principles. Compliant mechanisms achieve motion through elastic deformation, enabling smooth, continuous, and backlash-free motion with reduced part count and improved reliability. Based on this motivation, the study focuses on the design of linear and linear XY compliant mechanisms using parallel beam configurations, which are well known for providing symmetric motion, high directional compliance, and reduced parasitic displacement.

- The justification for the proposed mechanism design is threefold:

Selection of parallel beam configuration: Parallel beam flexure arrangements were selected because they offer decoupled translational motion, high stiffness in undesired directions, and predictable force–displacement behavior. This configuration is particularly suitable for precision XY stages where controlled linear motion along orthogonal axes is required.

- Use of multi-turn (1.5-Turn and 2-Turn) beam geometry:

The introduction of 1.5-turn and 2-turn beam geometries increases the effective beam length without increasing the overall footprint of the mechanism. This design choice is justified by the need to enhance compliance and achieve larger displacement ranges under low actuation forces. The comparative investigation of these two configurations allows systematic evaluation of the influence of effective beam length on displacement, stiffness, and stress behavior.

- Material selection and manufacturing considerations:

The mechanism is designed to be fabricated using additive manufacturing, enabling rapid prototyping and geometric flexibility. PLA was selected as the baseline material due to its low stiffness, ease of fabrication, and suitability for low-force actuation applications. This choice aligns with the intended biomedical and precision scanning applications, where lightweight structures and moderate displacement ranges are preferred.

METHODOLOGY

Precision scanning mechanisms incorporating compliant mechanisms are in current demand of modern technologies such as micro and nano manufacturing, characterization equipment's etc. There is a need to develop a compliant mechanism for a linear range of motion of 2 to 4 mm in the X and Y directions. A linear compliant mechanism in the X-direction is designed and developed for the given compliant values. After designing the linear compliant mechanism in the X-direction, a similar attempt is made to develop a combined X-Y-compliant mechanism. The developed combined X-Y compliant mechanism's performance behavior for varying loading conditions is numerically investigated using the commercial FEA tool Ansys. To achieve the maximum range of motion for a given loading condition, various

combinations of beams are used to develop compliant mechanisms in a linear direction. A systematic numerical analysis is carried out to evaluate the performance of compliant mechanisms with various arrangements of beams. By analyzing different combinations of the beams in a linear X-Y compliant mechanism, a suitable arrangement of beams is recommended for the combined linear and rotary compliant mechanism for the required range of motion.

Design of XY compliant mechanism based on geometric parameters
1. XY compliant mechanism with 1.5 turns (thickness of 0.5 mm, 1 mm and 2 mm)
2. XY compliant mechanism with 2 turns (thickness of 0.5 mm, 1 mm and 2 mm)

Numerical analysis of XY compliant mechanism with 1.5 turns

The numerical analysis of linear XY compliant mechanism with parallel beam arrangement is studied. The schematics of the linear XY compliant mechanisms are shown in Figure 1. The XY compliant mechanism is modified further by increasing the length of the beam, which resulted in 1.5 turns of the beam due to a change in the location of the joint (of the beam and the motion stage) at the center of the motion stage. Since the beam is connected at the center of the face of the motion stage, the actuating force is applied at the outer beam, as shown in Figure 1 which is further transmitted through the parallel beams. The overall dimensions of the compliant mechanism are 200 × 200 × 10 mm with a square motion stage size of 50 × 50 mm. To analyze the effect of the geometric parameters, the thickness of the beam varied to 0.5 mm, 1.0 mm, and 2.0 mm for the numerical analysis. The numerical analysis

is carried out for the XY compliant mechanism, having a beam thickness of 0.5 mm. The meshing of the mechanism's geometric model, as shown in Figure 2, features 64751 nodes and 36957 triangular elements. The position of the actuating force in the compliant mechanism is shown in Figure 3 (Table 1).

Table 1. Material properties for PLA material

Sr.No	Content	Values
1.	Youngs modulus	3450 MPa
3.	Ultimate Tensile strength	54.1 MPa
4.	Poissons ratio	0.39

Numerical analysis of linear XY compliant mechanism with PLA material

The numerical analysis for XY compliant mechanism with PLA material is carried out for the beam thickness of 0.5 mm. Actuating forces ranging from 0.1 N to 0.4 N is applied to evaluate displacement in the mechanism. At 0.1 N actuating force, the displacement achieved is 1.1451 mm, as shown in Figure 4. With an increased force of 0.4 N, the displacement achieved is 4.58 mm. The stiffness of the mechanism at 0.4 N is measured at 0.08 N/mm with PLA.

The beam thickness is increased from 0.5 mm to 1.00 mm and modified XY compliant mechanism performance is studied for the range of motion. Actuating forces ranging from 1.0 N to 3.0 N is applied for displacement evaluation. At 1.0 N actuating force, the displacement achieved is 1.9638 mm, as shown in Figure 5. With an increased force of 3.0 N, the displacement achieved is 5.8875 mm. The stiffness of the mechanism at 3.0 N is measured at 0.517 N/mm with PLA.
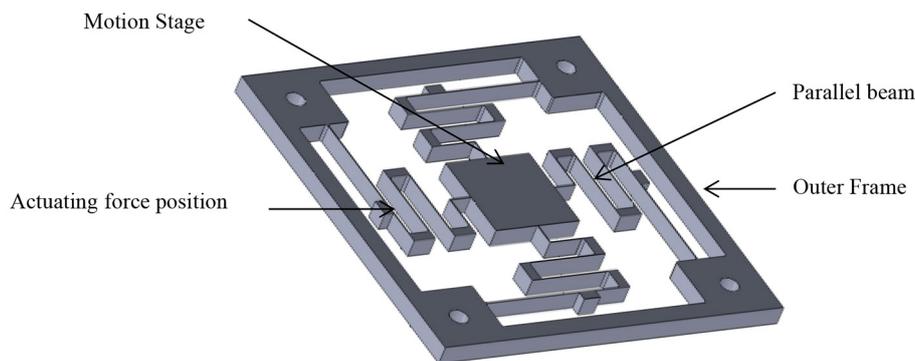

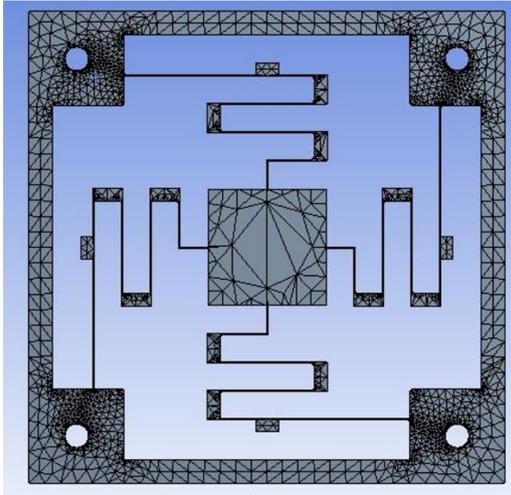
Figure 1. XY Compliant mechanism with 1.5 turns

Figure 2. Meshing of XY compliant mechanism with 1.5 turns for 0.5 mm beam thickness
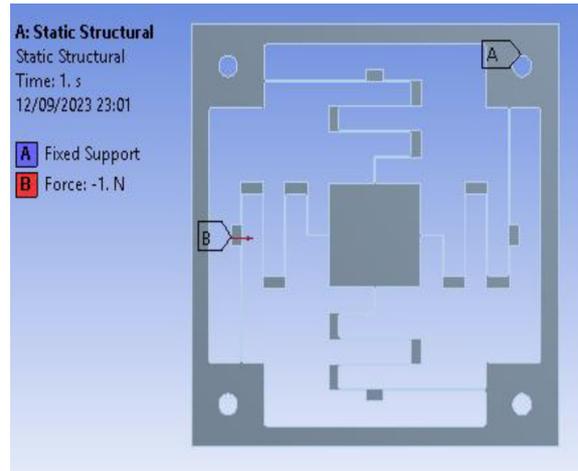

Figure 3. Position of actuating force for XY compliant mechanism with 1.5 turns using 0.5 mm beam thickness
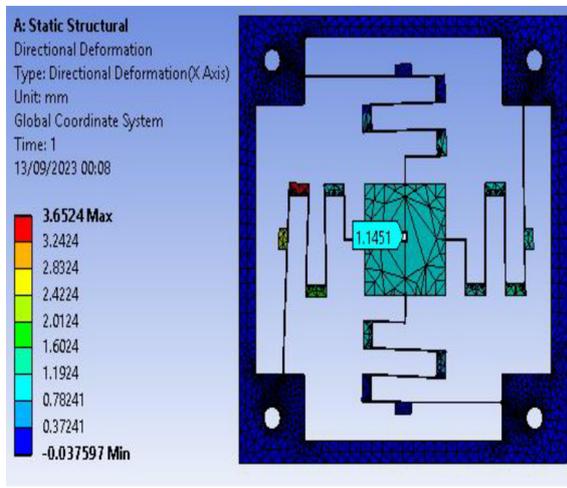

Figure 4. Displacement of XY compliant mechanism with 1.5 turns for 0.5 mm beam thickness at 0.1 N force using PLA
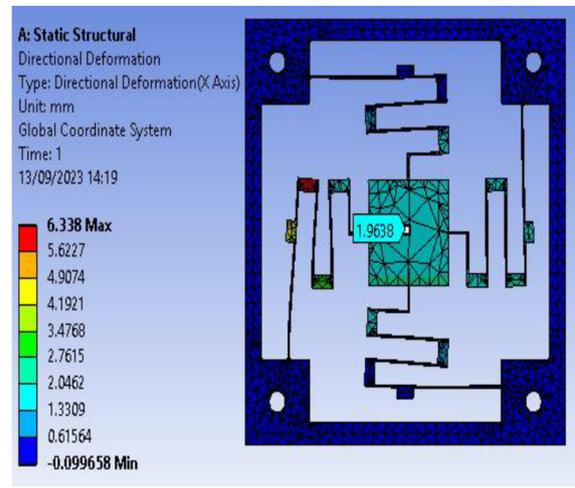

Figure 5. Displacement of XY compliant mechanism with 1.5 turns for 1 mm beam thickness at 1 N force using PLA

The thickness of the beam in a given compliant mechanism is increased to 2.0 mm. Actuating forces ranging from 1.0 N to 10 N is applied to evaluate displacement in the mechanism. At 1.0 N actuating force, the displacement achieved is 0.2568 mm, as shown in Figure 6. With an increased force of 10 N, the displacement obtained is 2.568 mm for the 2.0 mm beam thickness and the stiffness of the mechanism is measured at 3.89 N/mm with PLA.

The stress analysis is done for the linear XY compliant mechanism with 0.5 mm beam thickness. Actuating forces ranging from 0.1 N to 0.4 N are applied to find the stress in the mechanism for the PLA material. At 0.1 N actuating force, the induced equivalent stress was 4.072 MPa, as shown in Figure 7. For a higher actuating force of 0.4 N, the equivalent stress increased to 16.28 MPa for the 0.5 mm beam thickness.

The stress analysis is done for a similar mechanism by changing the thickness to 1.0 mm for a PLA material. Actuating forces ranging from 1.0 N to 3.0 N are used for stress evaluation. The equivalent stress induced at 1.0 N actuating force is 9.91 MPa, as shown in Figure 8. With an increased force of 3.0 N, the equivalent stress induced 29.75 MPa for the 1.0 mm beam thickness. For the mechanism with a 2.0 mm beam thickness, actuating forces ranging from 1.0 N to 10 N applied with the same material as PLA. Figure 9 shows the induced equivalent stress is 3.27 MPa at 1.0 N actuating force.
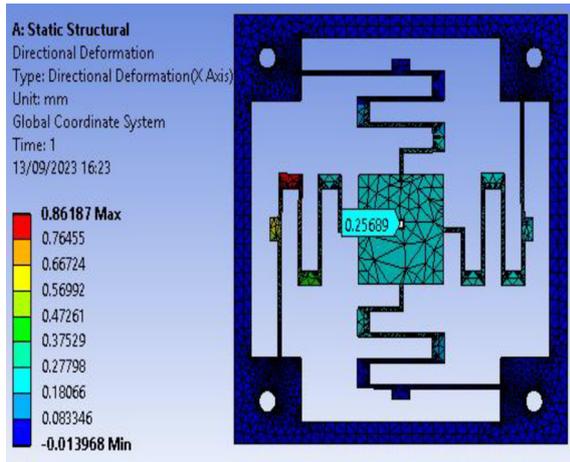
Figure 6. Displacement of XY compliant mechanism with 1.5 turns for 2 mm beam thickness at 1 N force using PLA
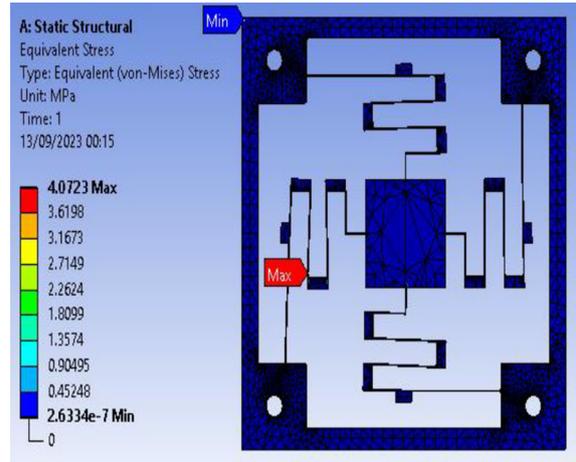

Figure 7. Equivalent stress of XY compliant mechanism with 1.5 turns for 0.5 mm beam thickness at 1 N force with PLA
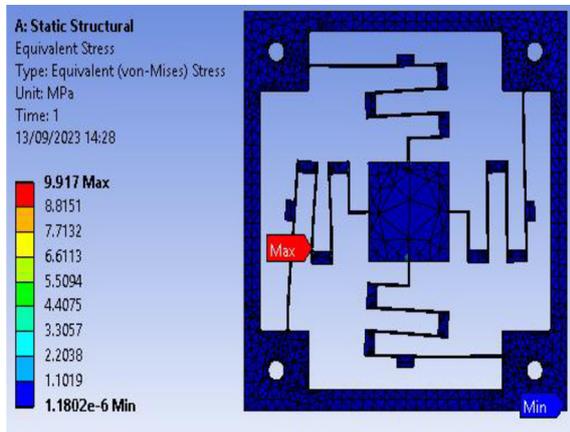

Figure 8. Equivalent stress of XY compliant mechanism with 1.5 turns for 1mm beam thickness at 1N force with PLA
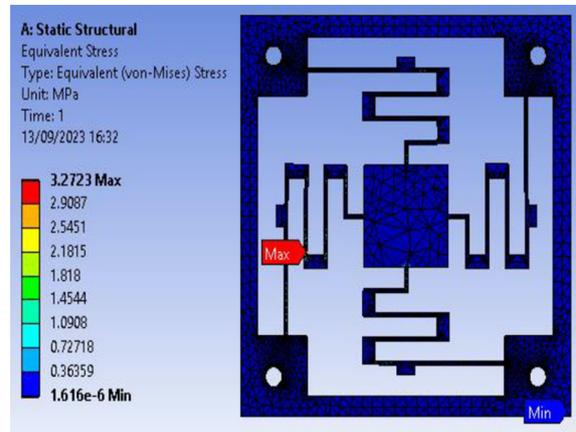

Figure 9. Equivalent stress of XY compliant mechanism with 1.5 turns for 2mm beam thickness at 1N force with PLA

With an increased force of 10 N, the equivalent stress obtained is 32.72 MPa for the 2.0 mm beam thickness.

The XY linear compliant mechanisms with PLA material give a suitable range of motion for less actuation force. Hence, this material is further tested for different actuating forces within the range of 0.1 N to 10 N, ensuring the testing of the material up to yield strength. The findings of the numerical analysis of linear XY compliant mechanism with PLA material is summarized in Table 2. The maximum displacement of 4.5857 mm occurred for 0.4 N actuating force applied on a compliant mechanism with 0.5 mm beam thickness. When the thickness is increased to 1.00 mm, the displacement of 5.8875 mm is achieved for an actuating force of 3.0 N. The displacement is further reduced to 2.568 mm at

an actuating force of 10 N when the thickness is increased to 2 mm.

From above numerical investigation it is observed that, for a given range of motion (2.00 mm to 4.00 mm) the PLA material requires less actuating force. Hence for biomedical scanning application the PLA material is considered for further modifications or developments of combined linear and rotary compliant mechanisms.

The numerical investigation of linear XY compliant mechanism is studied, and the findings are summarized in Table 3. For a linear 1.5 turns XY compliant mechanism with PLA material, the maximum stress induced is 16.28 MPa for an actuating force of 0.4 N for a 0.5 mm thickness beam. It resulted into the 4.58 mm displacement of motion stage. As thickness increased to 1.0 mm, a maximum stress

Table 2. Displacement for linear XY compliant mechanism with 1.5 turns

Force in N	Displacement in mm		
	1.5 Turns with 0.5 mm	1.5 Turns with 1 mm	1.5 Turns with 2 mm
0.1	1.1451	0.19638	0.02568
0.2	2.2902	0.3927	0.05136
0.3	3.4353	0.58875	0.07704
0.4	4.5857	0.78513	0.10272
1	---	1.9638	0.2568
2	---	3.9276	0.5136
3	---	5.8875	0.7704
4	---	---	1.0272
5	---	---	1.284
6	---	---	1.5408
7	---	---	1.7976
8	---	---	2.0544
9	---	---	2.3112
10	---	---	2.568

Figure 10. Force vs displacement for linear XY compliant mechanism with 1.5 turns with PLA material

of 29.75 MPa at an actuating force of 3.0 N is induced displacing the motion stage by 5.88 mm. For a thickness of 2.00 mm, the stress induced is 32.72 MPa at an actuating force of 10 N. It resulted in to a displacement of 2.56 mm of motion stage.

Displacement of XY compliant mechanism with 1.5 turns is shown in Figure 10. Maximum displacement of 4.58 mm is achieved with beam of 0.5 mm thickness at actuating force of 0.4 N. Displacement of 5.88 mm is achieved for beam of 1 mm thickness at actuating force of 3 N and displacement of 2.56 mm is achieved with 2 mm beam thickness at actuating force of 10 N.

Numerical analysis of linear XY compliant mechanism with PLA material using 2 turns

The XY compliant mechanism is modified further by increasing the length of the beam,
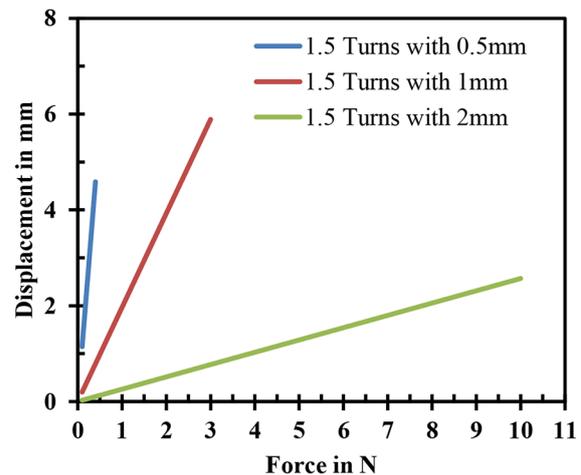
which resulted in 2 turns of the beam. Since the beam is connected at the offset of the motion stage, the actuating force is applied at centre of motion stage, as shown in Figure 11, which is further transmitted through the parallel beams. The overall dimensions of the compliant mechanism are 200 × 200 × 10 mm with a square motion stage size of 50 × 50 mm. To analyze the effect of the geometric parameters, the thickness of the beam varied to 0.5 mm, 1.0 mm, and 2.0 mm for the numerical analysis. PLA materials are used for displacement and stress analysis of mechanism. The numerical analysis is carried out for the XY compliant mechanism, having a beam thickness of 0.5 mm. The meshing of the mechanism's geometric model, as shown in Figure 12, features 66872 nodes and 37367 triangular elements.

The analysis is done with PLA material for displacement and stress analysis. The position of the actuating force in the compliant mechanism is shown in Figure 13. To analyze the displacement of the mechanism with a 0.5 mm beam thickness, actuating forces ranging from 0.1 N

Table 3. Displacement and stress values of XY compliant mechanism with 1.5 turns with different thickness

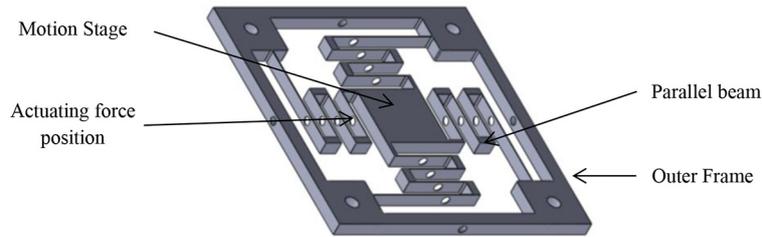| Thick ness (mm)	Materials					
	PLA					
	Force (N)		Displacement (mm)		Stress (MPa)	
	Min	Max	Min	Max	Min	Max
0.5	0.1	0.4	1.14	4.58	4.07	16.28
1	1	3	1.96	5.88	9.91	29.75
2	1	10	0.25	2.56	3.25	32.72

Figure 11. XY compliant mechanism with 2 turns of 0.5 mm thickness
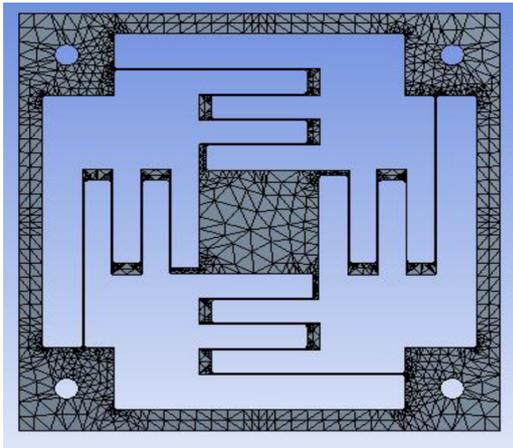
Figure 12. Meshing of XY compliant mechanism with 2 turns for 0.5 mm beam thickness

is determined based on the yield strength of the material. At 0.1 N actuating force, the displacement achieved is 2.42 mm, as shown in Figure 14. With an increased force of 0.5 N, the displacement achieved is 12.12 mm for the 0.5 mm beam thickness. The stiffness of the mechanism at 0.5 N is measured at 0.041 N/mm with PLA.

Similar analysis is carried out for 1 mm beam thickness. Actuating forces ranging from 1 N to 3 N is applied for displacement evaluation. At 1 N actuating force, the displacement achieved is 4.12 mm, as shown in Figure 15. With an increased force of 3 N, the displacement achieved is 12.37 mm for the 1.0 mm beam thickness. The stiffness of the mechanism at 3 N is measured at 0.24 N/mm with PLA.

The thickness of the beam in a given compliant mechanism is increased to 2.0 mm. Actuating forces ranging from 1.0 N to 10 N is applied to evaluate displacement in the mechanism. At 1.0 N actuating force, the displacement achieved is 0.7595 mm, as shown in Figure 16. With an increased force of 10 N, the displacement obtained is 7.595 mm for the 2.0 mm beam thickness and the stiffness of the mechanism is measured at 1.31
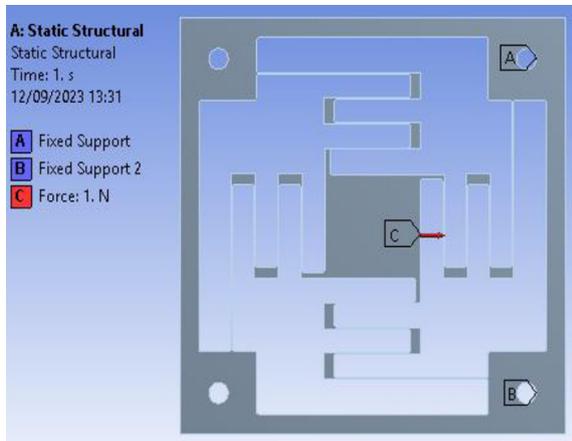
to 10 N is applied. The displacement is shown in Figure 14. Increasing the actuating force to 8.0 N, the displacement achieved is 3.5813 mm for the 0.5 mm beam thickness. When applied to the beam, the mechanism showed a stiffness of 2.233 N/mm at 8 N actuation.

Actuating forces ranging from 0.1 N to 0.5 N is applied to evaluate displacement in the mechanism, using PLA as the material. The force range

Figure 13. For XY compliant mechanism with 2 turns using 0.5 mm beam thickness
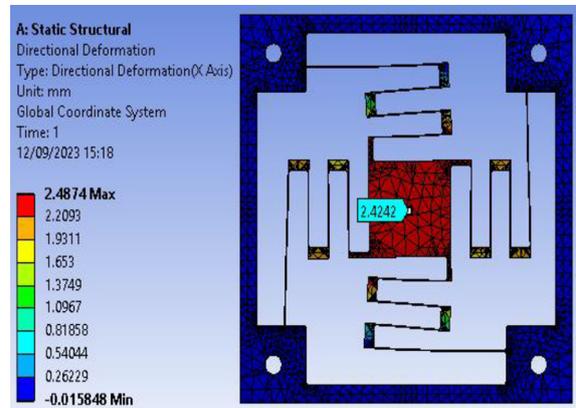

Figure 14. Displacement of XY compliant mechanism with 2 turns or 0.5 mm beam thickness at 0.1 N force using PLA
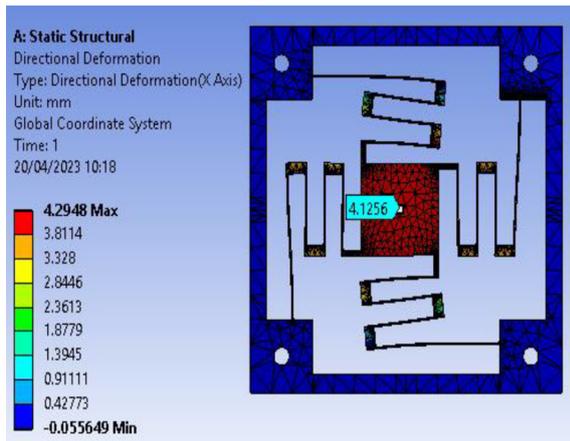
Figure 15. Displacement of XY compliant mechanism with 2 turns for 1 mm beam thickness at 1 N force using PLA
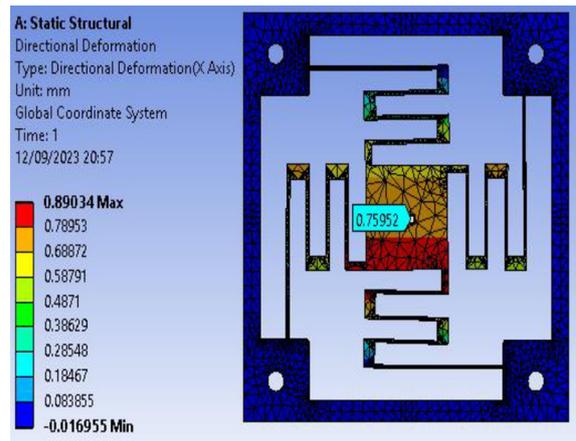

Figure 16. Displacement of XY compliant mechanism with 2 turns for 2 mm beam thickness at 1 N force using PLA

N/mm with PLA. The stress analysis is done for the linear XY compliant mechanism with 0.5 mm beam thickness. Actuating forces ranging from 0.1 N to 0.5 N are applied to find the stress in the mechanism for the PLA material. At 0.1 N actuating force, the induced equivalent stress is 3.04 MPa, as shown in Figure 17 For a higher actuating force of 0.5 N, the equivalent stress increased to 15.23 MPa for the 0.5 mm beam thickness.

The stress analysis is done for a similar mechanism by changing the thickness to 1.0 mm for a PLA material. Actuating forces ranging from 1 N to 3 N are used for stress evaluation. The equivalent stress induced at 1 N actuating force is 11.11 MPa, as shown in Figure 18. With an increased force of 3 N, the equivalent stress induced 33.33 MPa for the 1.0 mm beam thickness. For the mechanism with a 2.0 mm beam thickness, actuating forces ranging from 1.0 N to 10 N are applied with the same material as PLA. Figure 19 shows the induced equivalent stress is 3.32 MPa at 1.0 N actuating force. With an increased force of 3.0 N, the equivalent stress obtained is 33.2 MPa for the 2.0 mm beam thickness.

The XY linear compliant mechanisms with PLA material give a suitable range of motion for less actuation force. Hence, this material is further tested for different actuating forces within the range of 0.1 N to 10 N, ensuring the testing of the material up to yield strength. The findings of the numerical analysis of linear XY compliant mechanism with PLA material is summarized in Table 4. The maximum displacement of 12.12 mm occurred for 0.5 N actuating force applied on a compliant mechanism with 0.5 mm beam
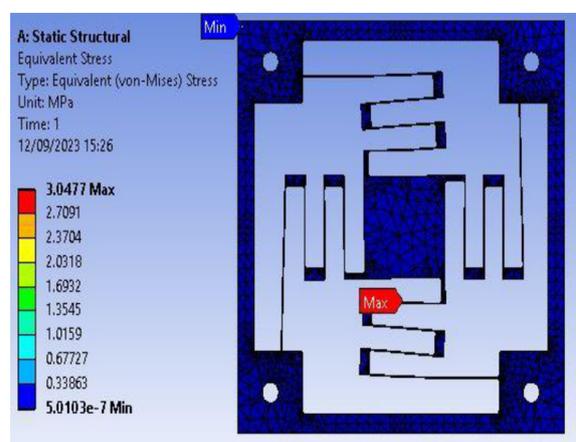

Figure 17. Equivalent stress of XY compliant mechanism with 2 turns for 0.5 mm beam thickness at 0.1 N force with PLA

thickness. When the thickness is increased to 1.00 mm, the displacement of 12.37 mm is achieved for an actuating force of 3.0 N. The displacement is further reduced to 7.5 mm at an actuating force of 10 N when the thickness is increased to 2 mm.

From above numerical investigation it is observed that, for a given range of motion (2.00 mm to 4.00 mm) the PLA material requires less actuating force. Hence for biomedical scanning application the PLA material is considered for further modifications or developments of combined linear and rotary compliant mechanisms.

The numerical investigation of linear XY compliant mechanism is studied, and the findings are summarized in Table 5 for a linear 1.5 turns XY compliant mechanism with PLA material, the maximum stress induced is 15.23 MPa for an
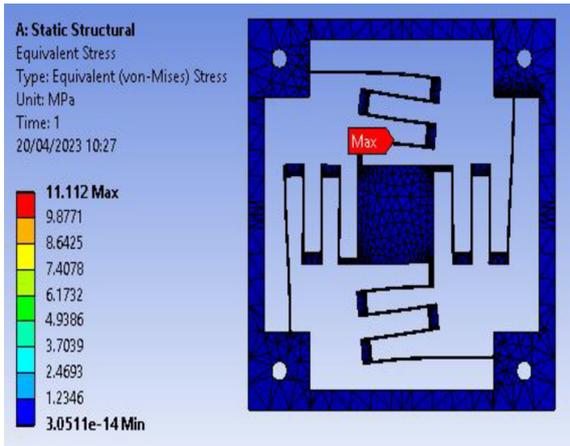
Figure 18. Equivalent stress of XY compliant mechanism with 2 turns
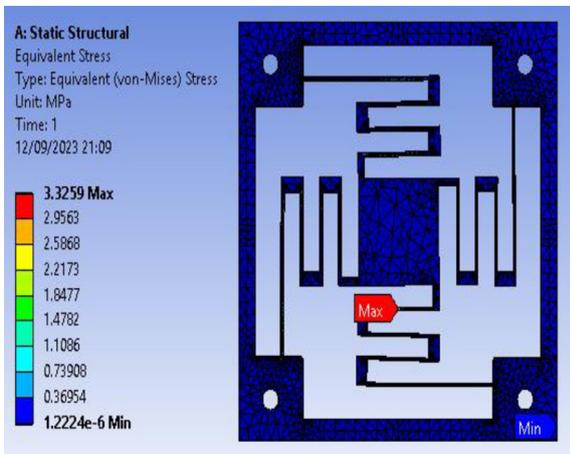for 1 mm bea thickness at 1 N force using PLA

Figure 19. Equivalent stress of XY compliant mechanism with 2 turns
for 2 mm beam thickness at 1 N force with PLA

actuating force of 0.5 N for a 0.5 mm thickness beam. It resulted into the 12.12 mm displacement of motion stage. As thickness increased to 1.0 mm, a maximum stress of 33.33 MPa at an actuating force of 3.0 N is induced displacing the motion stage by 12.37 mm. For a thickness of 2.00 mm, the stress induced is 33.2 MPa at an actuating force of 10 N. It resulted in to a displacement of 7.5 mm of motion stage.

Displacement of XY compliant mechanism with 2 turns is shown in Figure 20. Maximum displacement of 12.12 mm is achieved with beam of 0.5 mm thickness at actuating force of 0.5 N. Displacement of 12.37 mm is achieved for beam of 1 mm thickness at actuating force of 3 N and displacement of 7.5 mm is achieved with 2 mm beam thickness at actuating force of 10 N.

Table 4. Displacement for linear XY compliant mechanism with 2 turns

Force in N	Displacement in mm		
	2 Turns with 0.5 mm	2 Turns with 1 mm	2 Turns with 2 mm
0.1	2.4242	0.4125	0.07595
0.2	4.8484	0.825	0.1519
0.3	7.2726	1.2375	0.22785
0.4	9.6968	1.65	0.3038
0.5	12.126	2.0625	0.37975
1	- -	4.1256	0.7595
2	- -	8.2512	1.519
3	- -	12.3768	2.2785
4	- -	- -	3.038
5	- -	- -	3.7975
6	- -	- -	4.557
7	- -	- -	5.3165
8	- -	- -	6.076
9	- -	- -	6.8355
10	- -	- -	7.595

Experimental analysis of XY compliant mechanism with 2 turns

The experimental setup for a linear XY compliant mechanism, as shown in Figure 21, is developed with parallel beam positions with a thickness of 1 mm. PLA material is used for manufacturing. The linear compliant mechanism is proposed for biomedical scanning applications with a range of motion of 2 mm to 4 mm. In the numerical analysis, the maximum actuating force applied to the mechanism is 3 N due to the yield strength of the PLA. The experimental setup developed will be tested for the range of actuating forces 1 N to 8 N.

A pneumatic system is designed to apply the actuating force at the motion stage and analyze the behavior of the compliant system. A pneumatic cylinder is used at an initial pressure of 0.1 bar to generate the requisite force of 1 N at the square motion stage. A dial gauge indicator measures the displacement at the square motion stage. A 4.08 mm of displacement is observed for 1 N actuating force. The actuating force is further increased by 1 N step and measures the displacements for the developed linear XY compliant mechanism. The said mechanism sustained the actuating force up to 3 N. However, the permanent deformation is observed beyond the 4 N actuating force. For an actuating force of 3 N, the mechanism shows a displacement of 12.22 mm at the square motion

Table 5. Displacement values of XY compliant mechanism with 2 turns with different thickness

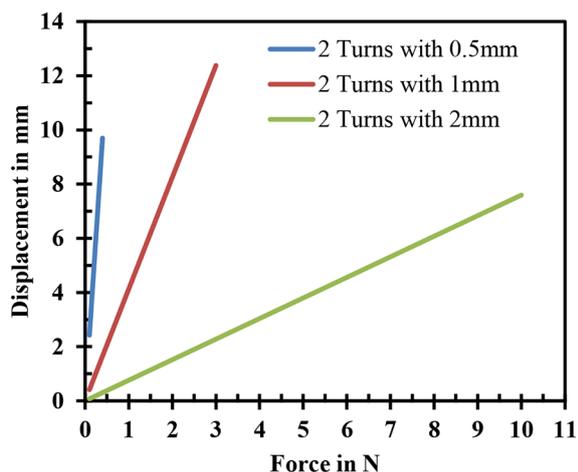| Thick ness (mm)	Materials					
	PLA					
	Force (N)		Displacement (mm)		Stress (MPa)	
	Min	Max	Min	Max	Min	Max
0.5	0.1	0.5	2.42	12.12	3.04	15.23
1	1	3	4.12	12.37	11.11	33.33
2	1	10	0.75	7.5	3.32	33.2

Figure 20. Force vs displacement for linear XY compliant mechanism with 2 turns

stage. The compliance value achieved for the linear XY compliant mechanism is 4.08 E-03 m/N.

The numerical results are validated using the experimental results discussed here. A linear XY compliant mechanism at 1 mm thickness is developed using PLA material and investigated by numerical and experimental methods. The displacements of 12.22 mm obtained from the numerical analysis are in good agreement with the displacement value of 12.37 mm obtained from the experimental method. The comparison of results is documented in Table 6 and graphically shown in Figure 22. The maximum percentage error for a given range of forces is 1.13 % in the linear XY direction.

The numerical and experimental investigation gives the confidence to analyze further modified combinations of compliant mechanisms with different arrangements of beams and other elements like notches. For the specified range of motion, 2 mm to 4 mm, the PLA material with a suitable combination of geometric parameters like length and thickness is recommended due to the less actuating force when compared with metals.

RESULT AND DISCUSSION

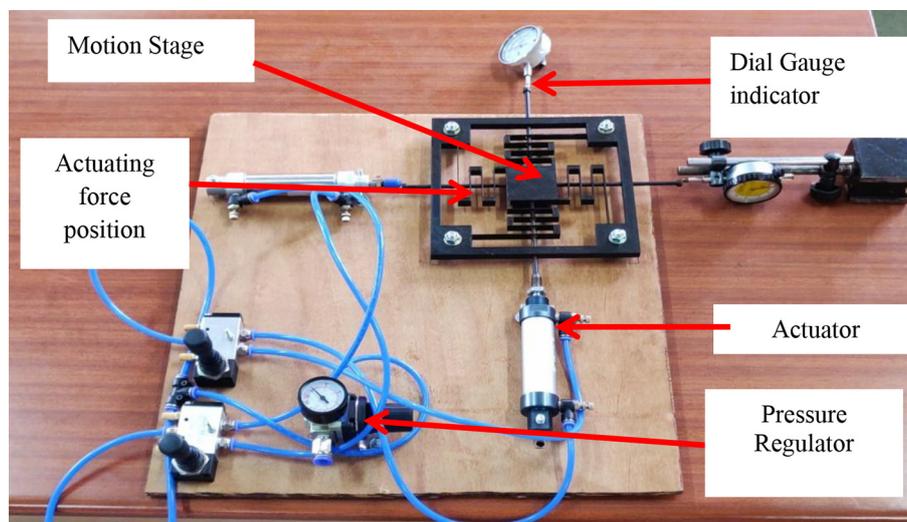The effects of beam thickness, effective beam length (number of turns), and material selection

Figure 21. Linear XY compliant mechanism

Table 6. Comparison of displacement by numerical method and experimental method

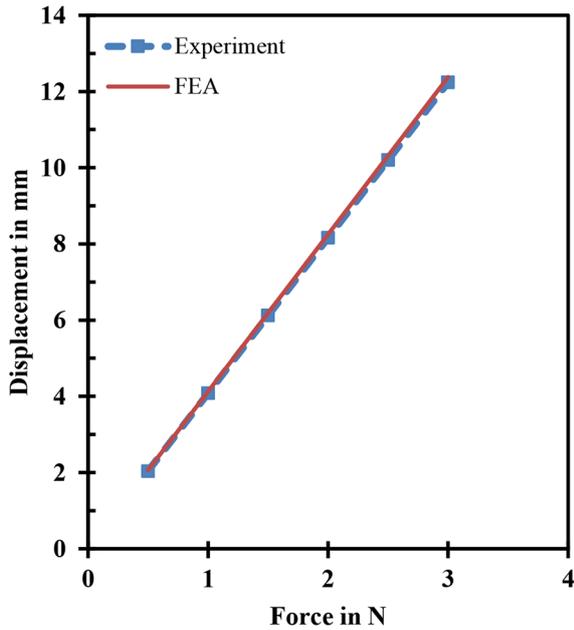| Force in N	Displacement in mm	
	Experiment	Numerical (FEA)
1	4.08	4.13
1.5	6.12	6.19
2	8.16	8.25
2.5	10.2	10.31
3	12.22	12.38

Figure 22. Force vs displacement for linear XY compliant mechanism with 2 turns using numerical and experimental method

on displacement, stress, and stiffness characteristics are systematically analyzed.

Effect of beam thickness on displacement

The beam thickness significantly influences the displacement characteristics of the compliant mechanisms. For both 1.5-turn and 2-turn XY configurations, a reduction in beam thickness results in increased flexibility and higher displacement for a given actuation force. For the 1.5-turn configuration using PLA material, the mechanism with a beam thickness of 0.5 mm achieved a displacement of 4.58 mm at an actuation force of 0.4 N. When the beam thickness was increased to 1.0 mm, a higher actuation force of 3.0 N was required to achieve a displacement of 5.88 mm. Further increasing the thickness to

2.0 mm significantly reduced the displacement to 2.56 mm, even at an actuation force of 10 N. This trend clearly demonstrates the inverse relationship between beam thickness and compliance. A similar trend was observed for the 2-turn configuration, where the mechanism with a 0.5 mm beam thickness achieved a maximum displacement of 12.12 mm at just 0.5 N actuation force, while the 2.0 mm thick beam required 10 N to achieve a displacement of 7.5 mm. These results highlight the critical role of beam thickness in tuning the displacement range and stiffness of compliant mechanisms.

Influence of beam geometry and number of turns

The effective beam length, represented by the number of turns in the compliant mechanism, has a pronounced effect on the achievable displacement. Increasing the number of turns from 1.5 to 2 effectively increases the beam length, thereby enhancing flexibility and compliance. For identical beam thickness and material, the 2-turn configuration consistently exhibited higher displacement compared to the 1.5-turn configuration. For example, with PLA material and 0.5 mm beam thickness, the displacement increased from 4.58 mm (1.5 turns at 0.4 N) to 12.12 mm (2 turns at 0.5 N). This substantial improvement demonstrates the effectiveness of geometric modification in achieving large stroke motion without introducing additional mechanical components. However, increasing the number of turns also increases the overall deformation of the structure, which may lead to higher parasitic motions and reduced stiffness in undesired directions. Therefore, an optimal balance between beam length and stiffness is essential, particularly for applications requiring controlled and repeatable motion

Impact of material

Material properties strongly affect the force – displacement and stress behavior of compliant mechanisms. For the 1.5-turn configuration with 0.5 mm beam thickness, PLA achieved 4.58 mm at just 0.4 N. Similar trends were observed for the 2-turn configuration, where PLA-based mechanisms exhibited substantially higher displacement under low actuation forces compared to metallic counterparts. Stress analysis showed that metallic materials experienced high stress levels close

to their yield limits under relatively small displacements. In contrast, PLA demonstrated lower induced stresses well within its elastic limit, even at large displacements. These findings clearly indicate that PLA is more suitable for low-force, high-displacement applications such as biomedical scanning systems.

Stress distribution and structural integrity

Stress distribution in the compliant mechanisms was primarily concentrated near the fixed ends of the beams and at beam–motion stage junctions. For PLA-based 1.5-turn mechanisms with 0.5 mm beam thickness, the maximum equivalent stress increased from 4.07 MPa at 0.1 N to 16.28 MPa at 0.4 N, remaining well below the ultimate tensile strength of PLA. For thicker beams and higher actuation forces, stress levels increased proportionally but did not exceed the allowable limits for the selected operating conditions. In the 2-turn configuration, even though higher displacements were observed, the maximum induced stress for PLA remained below 33.33 MPa, ensuring elastic behavior without permanent deformation within the tested force range.

Stiffness characteristics

The stiffness of the compliant mechanisms was calculated as the ratio of applied force to the resulting displacement. Results showed that stiffness increases with beam thickness and decreases with increasing beam length. For PLA-based 1.5-turn mechanisms, stiffness varied from 0.08 N/mm for 0.5 mm beam thickness to 3.89 N/mm for 2.0 mm beam thickness. In the 2-turn configuration, stiffness values were even lower due to increased beam flexibility, enabling large displacements with minimal actuation force. These characteristics are particularly advantageous for biomedical and precision scanning applications where low-force actuation is preferred.

Experimental validation and discussion

Experimental testing of the selected PLA-based linear XY compliant mechanism with 1 mm beam thickness validated the numerical predictions. At an actuation force of 1 N, the experimental displacement was measured as 4.08 mm, closely matching the numerical value of 4.13 mm. At 3 N, the experimental displacement

reached 12.22 mm compared to the numerically predicted 12.38 mm. The maximum percentage error between experimental and numerical results was limited to 1.13%, indicating excellent agreement and validating the accuracy of the finite element modeling approach. Minor deviations can be attributed to manufacturing tolerances, material anisotropy inherent in additive manufacturing, and experimental measurement uncertainties. For applications requiring controlled linear displacement in the range of 2–4 mm, such as biomedical scanning systems, the results indicate that a PLA-based XY compliant mechanism with optimized beam thickness and geometry provides an ideal balance between displacement capability, stiffness, and structural safety. The ability to achieve the desired motion with low actuation force reduces power consumption and simplifies actuator selection, making the proposed mechanism highly practical for real-world precision applications.

CONCLUSIONS

Based on the numerical and experimental investigations conducted in this study, the performance characteristics of linear and linear XY compliant mechanisms developed using parallel beam configurations have been systematically evaluated. The results clearly indicate that the displacement response of the compliant mechanisms is predominantly governed by beam thickness and effective beam length. A reduction in beam thickness leads to a significant increase in compliance and displacement, whereas an increase in thickness enhances stiffness at the expense of reduced motion. Similarly, extending the effective beam length through higher turn configurations substantially improves displacement capability. Among the investigated configurations, the 2-turn XY compliant mechanism consistently exhibited higher displacement than the 1.5-turn configuration under identical geometric and material conditions, demonstrating the effectiveness of geometric modification in achieving large-stroke motion. Material selection was found to be a critical factor influencing actuation force requirements and stress levels. Comparative analysis revealed that PLA-based compliant mechanisms achieved the desired displacement range with considerably lower actuation forces compared to metals. In particular, displacements

exceeding 4 mm were obtained under actuation forces below 1 N for PLA, whereas metallic mechanisms required significantly higher forces to produce comparable motion. Stress analysis confirmed that the PLA-based compliant mechanisms operated well within their elastic limits for the investigated loading conditions, ensuring structural integrity and reliable performance. Furthermore, stiffness analysis revealed an inverse relationship between stiffness and displacement, with thinner beams and higher turn configurations exhibiting lower stiffness and enabling large displacements under minimal actuation forces. These characteristics are especially advantageous for biomedical scanning and precision positioning applications, where smooth motion and low-force actuation are essential.

Experimental validation of the selected PLA-based linear XY compliant mechanism showed excellent agreement with numerical predictions, with a maximum deviation of only 1.13%, thereby validating the accuracy and reliability of the finite element modeling approach. Overall, the study demonstrates that an optimally designed PLA-based linear XY compliant mechanism, with appropriate geometric parameters, can effectively achieve controlled displacements in the range of 2–4 mm using low actuation forces. The findings provide practical design guidelines for the development and optimization of compliant mechanisms tailored for precision motion applications, particularly in biomedical and micro-positioning systems.

The present study establishes a validated design and analysis framework for PLA-based linear and linear XY compliant mechanisms intended for low-force precision motion applications. Building upon this foundation, several promising directions for future research can be identified to further enhance the applicability and performance of the proposed mechanisms.

Firstly, the proposed methodology can be extended to other widely used 3D-printing materials, such as PET-G, ABS, TPU, and fiber-reinforced polymer composites. These materials exhibit distinct mechanical characteristics compared to PLA, particularly in terms of Young's modulus, yield strength, damping capacity, and thermal stability. PET-G, with moderate stiffness and improved ductility, is expected to provide higher allowable strain and improved fatigue resistance, potentially enabling larger operational ranges without permanent deformation.

ABS, owing to its higher toughness and impact resistance, may offer improved durability under cyclic loading, albeit at the cost of higher actuation forces due to increased stiffness. Comparative numerical and experimental investigations across these materials would enable systematic evaluation of stiffness variation, required actuation force, stress distribution, and long-term reliability, leading to material-specific design guidelines for compliant mechanisms.

Secondly, future work will focus on the integration of suitable actuation systems, such as piezoelectric actuators and voice-coil motors, with the proposed compliant mechanisms. Piezoelectric actuators can provide high-resolution motion suitable for micro- and nano-positioning, while voice-coil actuators can enable larger strokes with smooth force control. The compatibility of these actuators with different compliant mechanism geometries and materials will be investigated to optimize overall system performance.

Furthermore, the development of closed-loop control systems constitutes an important extension of the present work. The integration of displacement sensors such as LVDTs, optical encoders, or capacitive sensors will allow accurate measurement of stage displacement in real time. Sensor feedback can be utilized to compensate for nonlinearities, material hysteresis, and manufacturing-induced uncertainties, thereby improving positioning accuracy and repeatability.

Finally, the implementation of real-time feedback control strategies will enable the transformation of the proposed compliant mechanism into a fully functional precision motion system. Advanced control algorithms can be employed to achieve high bandwidth, minimize parasitic motion, and ensure stable operation under varying load conditions. Such developments will significantly broaden the applicability of the proposed mechanisms in biomedical scanning, optical instrumentation, micro-manufacturing, and precision positioning systems.

Overall, these future research directions provide a clear pathway for extending the present work from a mechanically validated compliant mechanism to an integrated, intelligent precision motion platform tailored for next-generation engineering and biomedical applications.

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