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(Research Article)

Effectiveness of different 3D printing filaments in fabricating compliant mechanisms: Mechanical properties, durability, recyclability, and cost

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Abstract

This study evaluates the effectiveness of different 3D printing filaments for compliant mechanisms, with a focus on cost, mechanical performance, and recyclability. Specifically, the research investigates the coefficient of stiffness of an ortho-planar spring, the rotational range of a cross axis flexural pivot, and the number of cycles a compliant bistable switch can endure. Using a 3D printer, filaments PLA, PLA+, PETG, ABS, and TPU were tested to determine their suitability for compliant mechanisms. Results indicate significant variation in durability and mechanical performance among materials, informing optimal choices for practical home-printed compliant mechanisms.

Keywords: Compliant Mechanisms; Bi-stable switch; Ortho-planar springs; Cross axis flexural hinge; 3D Printing; Filaments

1. Introduction

Compliant mechanisms are flexible structures that transfer force and motion through elastic deformation. As noted, "compliant mechanisms can achieve complex motions without traditional joints, which reduces wear and maintenance" [1]. This ability makes them particularly suitable for 3D printing, as they can be produced more easily and economically than traditional mechanisms. However, selecting the appropriate filament is crucial for optimal performance, as different materials vary significantly in terms of flexibility, strength, and sustainability

Aim

The aim of this study is to identify the most effective filament for home printing compliant mechanisms based on criteria such as durability, cost, ease of printing, and recyclability.

Objective

The objective of this study is to measure the number of cycles each filament can endure, the spring constant of various materials, and their rotational flexibility.

1.1. Scope and Limitation of Study

The scope of this study is limited by the reliance on a third-party 3D printing service; the accuracy of the results may also improve with a sample size an order of magnitude larger.

This research focuses on three distinct compliant mechanism designs, each with unique characteristics that make them suitable for a range of engineering applications:

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1.2. Bistable Switch

A compliant switch featuring two stable positions, achieved through elastic deformation. This bistable behavior makes it effective in applications like latching or switching, where maintaining a state without continuous energy input is crucial. According to Howell [2], bistable mechanisms are valuable for reducing part count and providing reliable, energy-efficient functionality in devices like microswitches and snap-action components.

1.3. Cross-Axis Flexure Hinge

A mechanism that facilitates rotational movement through flexible segments rather than traditional bearings, minimizing friction and wear. Howell describes this type of flexure as an ideal solution for systems requiring precise, low-friction pivoting [2]. A Lego-compatible version is utilized in this research for convenience

1.4. Ortho-planar Spring

A flat spring designed to provide movement along a single axis while remaining in-plane, beneficial for compact systems with space constraints. Howell discusses the efficiency of ortho-planar springs for applications that require planar force response and predictable stiffness [2]. This mechanism's stiffness and range of motion are key criteria for evaluating material suitability in this study.

2. Literature Review

The unique design of compliant mechanisms promotes simpler, lighter, and more efficient systems, making them particularly appealing for applications in robotics, biomedical devices, and consumer products [3]. The integration of 3D printing technology has accelerated the development of compliant mechanisms by enabling rapid prototyping of complex geometries that are challenging to achieve through conventional manufacturing methods [4].

3D printing has transformed the production of compliant mechanisms, allowing for the creation of intricate designs with high precision, accessible to anyone with a 3D printer. Material selection is crucial, as different filaments exhibit varying mechanical properties, including elasticity and strength. While common materials like PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) are popular, comprehensive studies comparing the performance of various filaments in the context of compliant mechanisms are scarce [5]. This highlights a significant gap in the literature, indicating the need for systematic research to identify optimal filaments for one-off applications, ensuring users achieve desired performance and durability.

Furthermore, while existing studies often emphasize theoretical design, empirical research on how different 3D printing filaments affect compliant mechanisms' functionality remains limited [6]. As 3D printing gains popularity among hobbyists and small-scale manufacturers, understanding filament properties becomes essential. Addressing this gap will equip designers and makers with valuable insights, allowing for informed material choices in their 3D-printed compliant mechanisms.

3. Methodology

To evaluate the performance of different filaments, we conducted a series of tests on the 3D-printed compliant designs using five different filaments: PLA, PLA+, ABS, PETG, and TPU. The models were sourced from the BYU Compliant Mechanisms Research Group's open-source repository [7, 8, 9]. Each filament was tested using five individual samples, printed with identical dimensions and layer heights to ensure uniformity. The printing was outsourced to a third-party service, and each sample was printed with standard quality settings (0.2 mm layer height, 30% infill).

To ensure consistency, all samples were cycled under controlled conditions with room temperature maintained at 25°C. The number of cycles each filament could endure before failure was recorded for each sample, and the average cycle count was calculated. Additionally, any visible defects or signs of wear during the testing process were noted.

3.1. Bistable switch:

The bistable switches were manually cycled between their two stable positions to closely replicate real-world usage. Each cycle was defined as a complete activation from one stable state to the other, followed by a return to the original state. The cycling was done by hand, ensuring consistent force application across all samples. The test was carried out until the mechanism failed, which was defined as the point where the bistable switch could no longer return to its original stable state, exhibited significant deformation, or snapped.

Table 1 Number of Cycles to Failure for Various Filaments in Bistable Compliant Switches

Filament	Cycles for Sample 1	Cycles for Sample 2	Cycles for Sample 3	Cycles for Sample 4	Cycles for Sample 5
PLA	13	5	18	6	21
PLA+	25	12	41	32	28
PETG	246	210	321	250	232
TPU*	N/A	N/A	N/A	N/A	N/A
ABS	62	69	51	48	73

*TPU did not exhibit bi-stable behaviour, no snapping action observed

3.2. Ortho-planar Spring

To evaluate the stiffness of the ortho-planar spring, the spring will be securely attached to two clamps, ensuring it is held horizontally in a fixed position. Slotted masses will be incrementally added to the center of the spring, allowing for controlled adjustments to the load applied. For each added mass, the resulting displacement of the spring will be recorded using a meter rule, measuring the vertical displacement from its original resting position. This process will be repeated for a series of masses to obtain a range of displacement data. A scatter plot will be constructed using all 5 samples to illustrate the relationship between the added mass and the measured displacement. Subsequently, a line of best fit will be drawn through the plotted data points for each filament type tested. From the resulting linear relationship, the spring constant (k) has been calculated using Hooke's Law.

$$F = -k \cdot x \qquad (1)$$

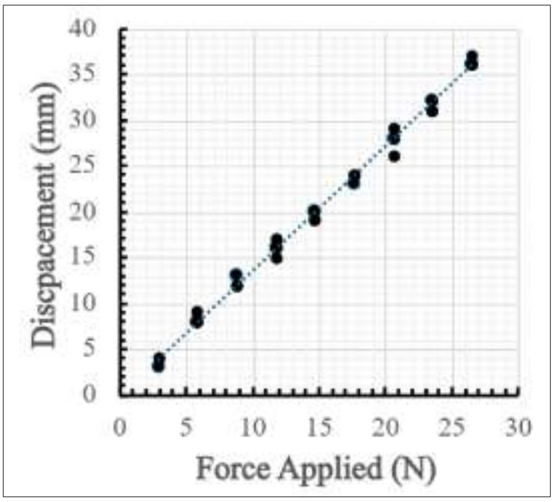

Figure 1 Scatter plot for PLA

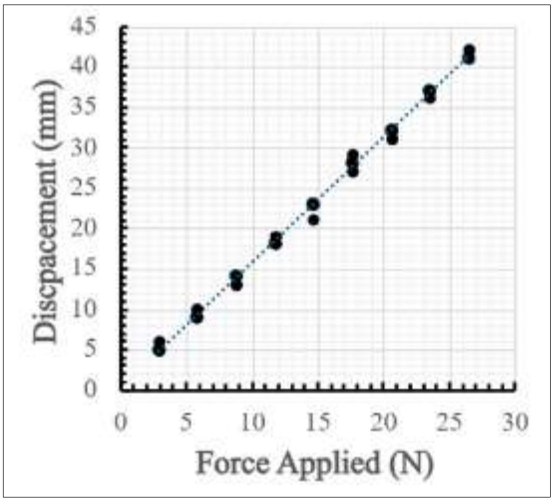

Figure 2 Scatter plot for PLA+

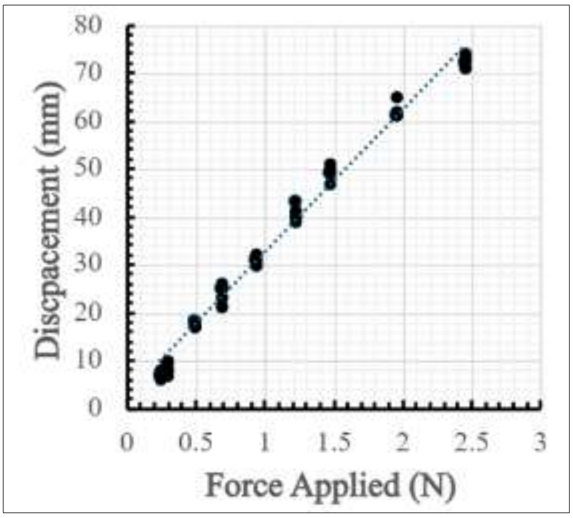

Figure 3 Scatter plot for TPU

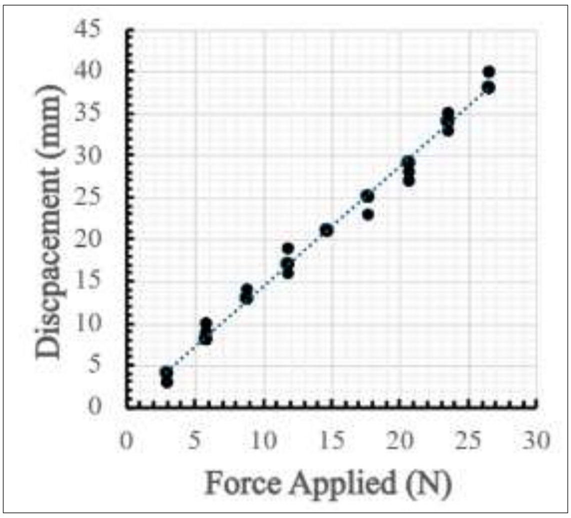

Figure 4 Scatter plot for PETG

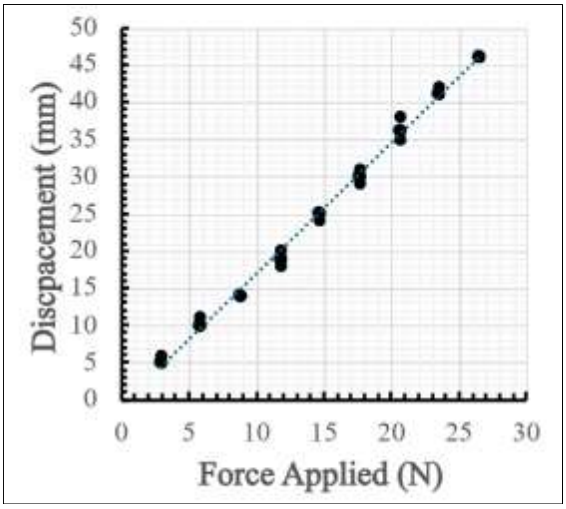

Figure 5 Scatter plot for ABS

3.3. Cross-axis Flexural Pivot

The cross-axis flexural pivot will be mounted securely to ensure rotation occurs in a controlled plane. We will apply a manual rotational force to the pivot, recording the process with a video. The pivot will be rotated until it can no longer bend or until it snaps.

The recorded video will then be analyzed frame by frame to identify the highest point of rotation. Using a digital protractor tool, the angle will be measured by referencing a horizontal line. The phone used to record the video will be positioned parallel to the cross-axis flexural pivot to maintain consistent reference points. This process will be repeated for each filament type, and the maximum rotational angle will be documented for comparison for each sample.

Table 2 Maximum angle of rotation for Various Filaments in Flexural Pivot

Filament	Measured in degrees (°)				
	Angle for Sample 1	**Angle for Sample 2**	**Angle for Sample 3**	**Angle for Sample 4**	**Angle for Sample 5**
PLA	123	114	120	118	120
PLA+	96	94	89	102	91
PETG	82	87	78	80	88
TPU	255	269	262	278	272
ABS	72	73	69	72	70

4. Results

The cost per kilogram of each filament was obtained by averaging market prices from various online 3D printing material suppliers. Prices were standardized based on bulk purchase rates to ensure consistency across filament types. For the purposes of this study, the cost per kilogram was calculated rather than per printed object to account for variability in the sizes of different printed parts.

Recyclability for each filament was evaluated based on the widely used resin identification code (RIC), which classifies materials from Type 1 to Type 7 [10]. Each filament's recyclability was assigned a type based on industry standards and environmental guidelines. Filaments with lower type numbers (e.g., PETG, classified as Type 1) offer easier recycling pathways, making them more suitable for sustainable 3D printing. Conversely, filaments with higher type numbers (e.g., TPU and ABS, classified as Type 7) are less recyclable, often requiring specialized facilities.

Table 3 Comparison of Durability, Cost, and Recyclability of 3D Printed Designs

Filament	Spring Constant (Nm^{-1})	Mean number of cycles till failure	Maximum Angle of Rotation (°)	Cost per kg (USD)	Recyclability (Type)
PLA	736	13	119	16.90	6
PLA+	640	28	94	17.30	6
PETG	701	251	71	20.00	1
TPU	43	N/A	267	29.37	7
ABS	588	60	71	21.99	7

5. Conclusion

5.1. Bi-stable switch

The observed cycle counts for the bistable switch exhibited substantial variation across samples within the same filament type, indicating that the lifespan may be influenced by print quality, an external factor not controlled within this study. Of the filaments tested, PETG demonstrated the highest cycle durability, making it the most suitable material for applications requiring snapping mechanisms. Additionally, PETG offers the advantages of recyclability and moderate cost, positioning it as a viable choice for sustainable design.

5.2. Ortho-planar Spring

The spring constant varied significantly among filament types, with PLA showing the highest stiffness, followed by PETG and ABS. TPU, with its notably low spring constant, demonstrated considerable flexibility. This variation suggests that PLA is best suited for applications requiring higher rigidity, while TPU is more appropriate for flexible designs.

5.3. Cross-axis Flexural Pivot

The maximum angle of rotation varied across filaments, with TPU displaying the greatest rotational range due to its flexibility, while PLA and PLA+ showed more limited rotation before deformation. PETG and ABS provided moderate rotation angles, balancing flexibility and strength. These results indicate that TPU is ideal for applications requiring extensive rotation, whereas PLA and PLA+ are better suited for designs prioritizing rigidity.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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