HIGH SCHOOL EDITION
Journal of Student Research

Volume 14 Issue 1 (2025)

Material Evaluation and Selection Criteria for 3D Printing

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ABSTRACT

3D printing has emerged as the primary additive manufacturing technology, widely utilized across industries in the past decade for its design flexibility, material efficiency, and rapid prototyping. FDM (Fused Deposition Modeling) stands out among 3D printing techniques for its use of reliable polymeric filaments, offering advantages like lightweight and cost-effectiveness. Despite the advantages of FDM, the abundance of filament materials in the market poses challenges in material selection to 3D printer users, that is which should be selected, and what should be the criteria to base. This research project is targeted to establish material selection criteria for 3D printing, demonstrates that filament material selection should be driven by the function of the printing object. The project endeavors to evaluate the properties of four major filaments available in the market, choosing a biomimetic hand as the final printing object. We identify suitable materials to be used to print each part of the biometric hand. Through experiments, we tested tensile creep, wear resistance, chemical solvent resistance and density of printing from the four filaments. We select Polylactic Acid (PLA) to make the 14 phalanges bones due to its high wear resistance and compromise well on other properties; select Polyethylene Terephthalate Glycol (PETG) to make the 5 metacarpal bones mostly due to its high creep performance; select Thermoplastic Polyurethane (TPU) to make the 8 pieces carpal bones. Acrylonitrile Butadiene Styrene (ABS) is ruled out due to low chemical resistance, and not suitable for biochemistry environments. Filament selection in 3D printing should consider material's property which can best benefit the object's function and duration, sometimes may compromise.

Introduction

Three-dimensional (3D) printing technology, also known as additive manufacturing (AM), is the process of building objects layer by layer in three dimensions. This technique has grown quickly over the past decade and is widely applied in different fields, including engineering, construction, medicine, aerospace, etc., with the advantages not only on material and machine cost saving, component lightweight, but also flexible complex customer design.

Fused deposition modeling (FDM) outweighs other techniques due to its simple processing, lightweight, rapid prototyping, and economical customized applications. FDM printer uses thermoplastics filaments which are fed into an extruder and subsequently melted by the heater. The molten material is then extruded through a nozzle to develop a multi-layer platform in the form of the desired shape. FDM can work with a wide range of reliable polymer filaments, which offers users more choices in terms of price and quality. Below are major four filament types:

- Acrylonitrile Butadiene Styrene (ABS),
- Polylactic Acid (PLA),
- Polyethylene Terephthalate Glycol (PETG),
- Thermoplastic Polyurethane (TPU)

Each of these 4 polymer materials has its own physical and mechanical properties, some properties are public from their manufacturers. When the material goes through molten, then cools down to form the object, the process can cause property changes, and the final properties are what 3D printer users care about and need to know.

Given different materials have varied properties, 3D printer user's face a question: when they plan to make an object with a FDM printer, what material should they choose? The material selection should be driven by the performing function of the object. In this project, we are going to make a biomimetic hand. A bionic hand needs to work in a biochemical environment, each part of a hand has different function emphasis, such as how specific parts require higher structural integrity while other parts require more flexibility. These are the keys we need to consider when selecting filament material to make it. In this project, we are going to test the above four material's post printing properties, then determine which material is suitable for the hand's different parts and use the selected material to make the hand.

Material's properties can be evaluated from the following few basic aspects:

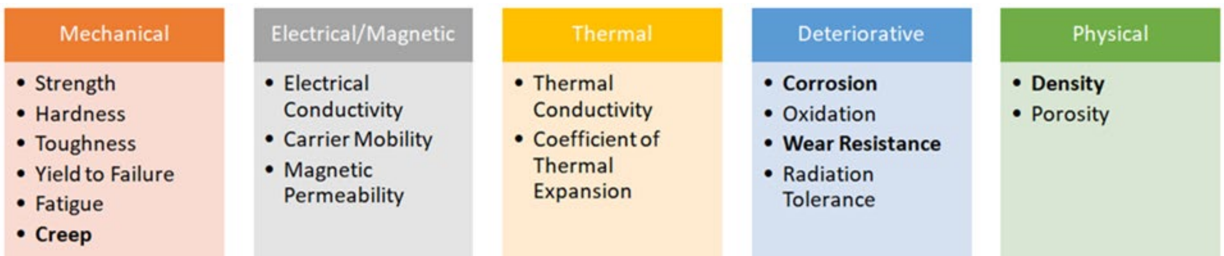


Figure 1. Basic aspects of material properties

In this research project, we evaluate the following few properties of the four filament polymers.

- Density as physics aspect
- Wear resistance as deteriorative aspect
- Tensile creep as mechanical aspect
- Solvent resistance (Acetone):

We design a test experiment to evaluate these properties from printing samples, and then rank the four materials based on their test result. Also consider material cost is a factor, make compromise selection for each part of the final printing object, which is the biomimetic hand.

We use the Prusa i3 MK3S+ model as the printer, regular setting, nozzle temperature 225 °C, bed temperature 80 °C, and nozzle speed 50m/s. Fusion 360 CAD tool and PrusaSlicer to do the sample design in this project.

Figure 2. The 3D printer used in this project, Prusa i3 MK3S+ model.

Experiments Design and Data Collection

Density Test

Each filament manufacturer has density publicly posted. FDM 3D printer fed the polymer filament into an extruder and a heater subsequently melted it. The molten material is then extruded through a nozzle to develop a multi-layer platform in the form of the desired shape. This temperature up-down and layer by layer process could bring in air and humidity, and cause material density change.

Our test procedure is as follows: We print 3 cm x 3 cm x 2 cm cubes, 4 samples of each material, measure volume and weight, and then calculate density. Repeat the same procedure under popular 15% infill setting and 100% infill setting, then compare density of 15% infill setup and 100% infill setup, with manufacturer posted density.

Table 1. Density test records and results

	TPU (15% infill)						TPU (100% infill)					
trail	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)
1	2.96	2.96	1.98	17.3	9	0.5	2.98	2.99	4.78	42.6	49	1.2
2	2.97	2.98	1.98	17.5	9	0.5	3.01	3.00	4.80	43.3	49	1.1
3	2.96	2.97	1.98	17.4	9	0.5	3.00	3.00	4.80	43.2	49	1.1
4	2.97	2.97	1.97	17.4	9	0.5	2.98	3.00	4.78	42.7	49	1.1
Average	2.97	2.97	1.98	17.4	9	0.5	2.99	2.99	4.78	42.7	49	1.1
	PLA (15% infill)						PLA (100% infill)					
	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)
1	2.98	3.00	1.99	17.8	8	0.4	2.98	2.98	5.00	44.4	53	1.2
2	2.98	2.99	2.00	17.8	8	0.4	2.98	2.99	5.00	44.6	53	1.2
3	2.99	2.99	2.00	17.9	8	0.4	2.98	2.98	4.99	44.3	53	1.2
4	2.99	2.98	2.02	18.0	8	0.4	2.97	2.99	4.99	44.3	53	1.2
Average	2.99	2.99	2.01	17.9	8	0.4	2.98	2.99	4.99	44.4	53	1.2
	PETG (15%)						PETG (100%)					
	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)
1	2.97	2.99	1.99	17.7	8	0.5	2.97	2.99	4.98	44.2	53	1.2
2	2.97	2.98	1.99	17.6	8	0.5	2.97	2.99	4.99	44.3	53	1.2
3	2.97	2.98	1.99	17.6	8	0.5	2.98	2.98	4.99	44.3	53	1.2
4	2.97	2.99	2.00	17.8	8	0.5	2.97	2.98	4.99	44.2	53	1.2
Average	2.97	2.99	1.99	17.6	8	0.5	2.97	2.99	4.99	44.3	53	1.2

	ABS (15%)						ABS (100%)					
	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)	L(cm)	W(cm)	D(cm)	Volumn	Weight(g)	Density(g/cm^3)
1	2.97	2.98	1.99	17.6	7	0.4	2.97	2.98	2.01	17.8	18	1.0
2	2.96	2.96	1.99	17.4	7	0.4	2.96	2.95	1.98	17.3	18	1.0
3	2.97	2.98	1.99	17.6	7	0.4	2.97	2.98	1.99	17.6	17	1.0
4	2.96	2.97	1.99	17.5	7	0.4	2.98	2.97	2.00	17.7	18	1.0
Average	2.97	2.97	1.99	17.5	7	0.4	2.97	2.97	1.99	17.6	18	1.0

Average testing result by material, and compare with manufacture density, as shown in Table 2, trend as Fig. 2.

Table 2. Density test result of material average vs. research density

	Measured Density (15% infill)	Measured Density (100% infill)	Manufacture Density	Change by 15% Pringting	Change by 100% Pringting
TPU	0.5	1.1	1.21	-57%	-6%
PLA	0.4	1.2	1.24	-64%	-4%
PETG	0.5	1.2	1.27	-64%	-6%
ABS	0.4	1.0	1.05	-62%	-4%

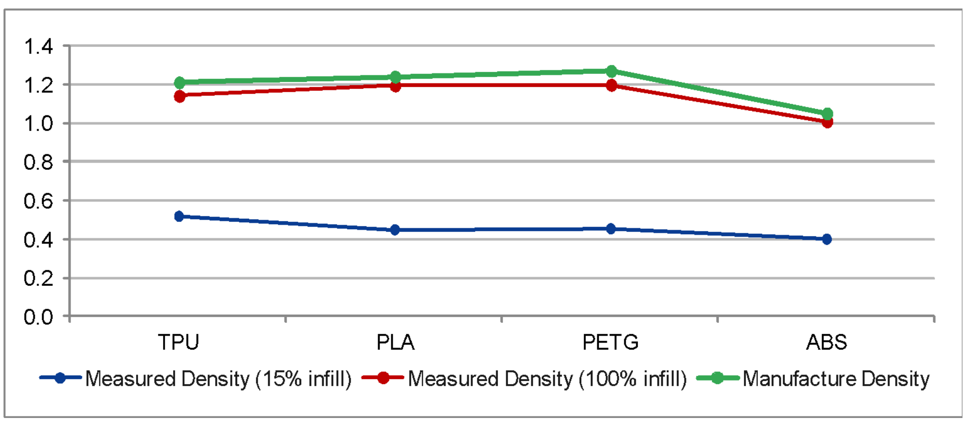


Figure 2. Density test result vs. researched density

We can see 3D printing does change material density, for 100% infill, density slightly drops, but no big difference across the four materials. That is because the layer-by-layer printing process can bring in air and humidity, which causes density reduction.

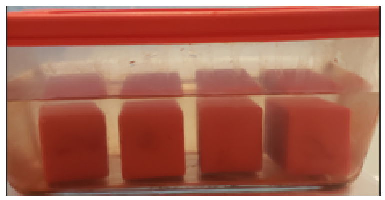
Solvent Test

Chemical reaction is an important property index for all materials. Since we are going to make a biomimetic hand in this project, we need to test the materials solvent resistance. Chemical solvent resistance is the degree to which the printed part retains its mechanical properties and shape when it comes in contact with chemicals or solvents. High solvent resistance is specially preferred in biomedical, biochemical environment. We chose acetone as the test solvent.

Our test procedure is as follows:

- We print 3 cm x 3 cm x 5 cm cubes, 4 samples for each material, with a popular 15% infill setting, measure pre-acetone weight and take pictures, then sink into acetone for 6 hours. After 6 hours, take the samples out, leave it overnight to try, observe surface peel, corner/edge and color change, take pictures and measure post-acetone weight.
  Since the 15% infill sample is lighter than the solvent, see Fig. 2 in 2.1 Density Test, a metal block is used to sink the sample down under the liquid.
- Repeat the same steps with 100% infill setting.
- We found ABS material has the worst acetone resistance during the test with 15% infill, the samples totally melted, so we did acetone vapor test for ABS 15% infill setup as a supplementary, instead of continuing doing100% infill setup in acetone liquid.

Acetone liquid test
with 15% infill sample
metals are used

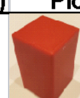
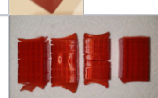
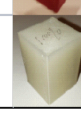
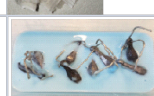


Acetone liquid test
with 100% infill sample

Acetone Vapor test
with 15% infill sample
a metal board in the middle of the container

Figure 3. Acetone solvent resistance testing

Table 3. Solvent resistance test with two infill setting, before and after 6 hours immersing

	15% Infill				100% Infill			
	Before Solvent		After Solvent		Before Solvent		After Solvent	
	Weight Avg. (g)	Picture	Weight Avg. (g)	Picture	Weight Avg.(g)	Picture	Weight Avg.(g)	Picture
PETG	18.75		19.75		53.00		54.00	
TPU	19.00		20.00		49.00		54.50	
PLA	19.00		22.00		53.00		56.00	
ABS	15.75		NA		**Because ABS 15% infill sample completly melted, so the below sovent vapor test is done next, not 100% infill solvent liquid test**			
					Before Vapor		**After Vapor**	
					16.00		17.25	

We can see PETG has the best solvent resistance, whereas ABS is the worst one, has zero tolerance.

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Tensile Creep Test

When a plastic component is subjected to a load, there will be a predictable deformation. If the load is sustained, the deformation will continue to increase with time without any increase in load. This deformation is commonly referred to as creep. It occurs at stresses below the yield strength. Low tensile creep is commonly preferred. We test tensile creep for the four materials to compare the material's tolerance under force.

Our test procedure is as follows:

- Use 3D printer to make:
  A test holder: this holder is used through the whole tensile creep test.
  Test bar of 2 cm x 2.5 mm x 20 cm: 3 test bars of each material

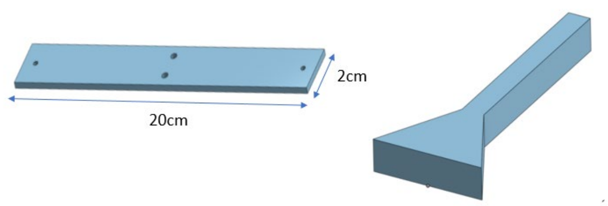


Figure 4. Test sample bar and support holder

- Hock up test structure as Fig. 5. Fix the center point; 2 lbs weight is hung on each side; keep this loading state for 6 hours.
- After 6 hours, unload the weight, measure h1 and h2, and take the average of h1 and h2 as the deformation, or creep.

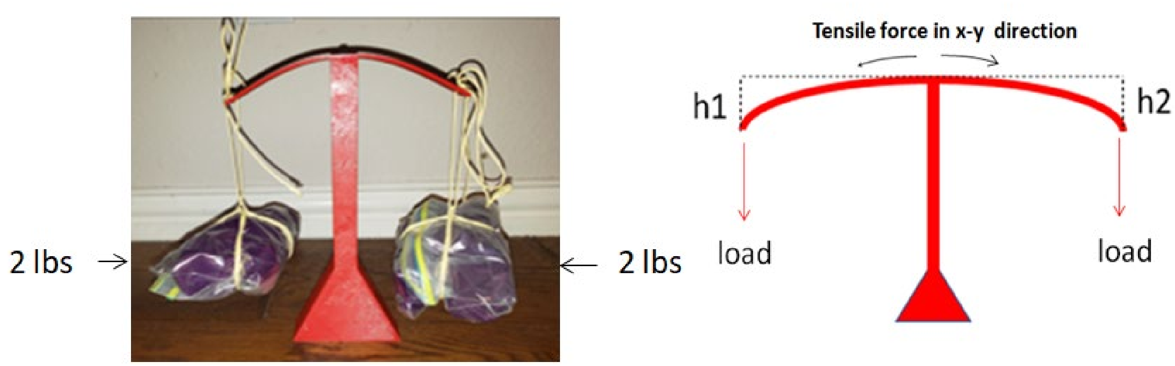
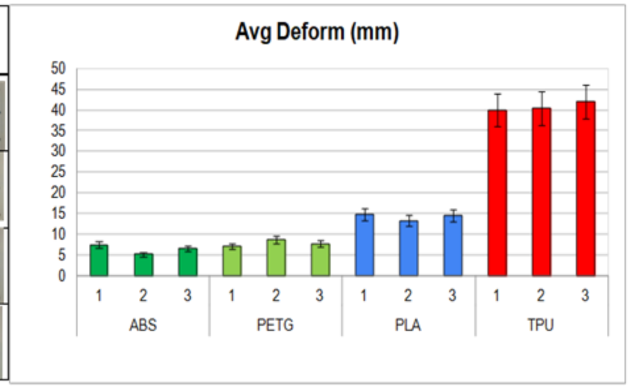


Figure 5. Creep testing

Table 4. Creep test data

Material	Trail #	Right(mm) h2	Left(mm) h1	Avg Deform (mm)	Avg. (mm)	Picture
ABS	1	7.5	7.5	7.5	6.4	
	2	4.5	6.0	5.3		
	3	7.0	6.0	6.5		
PETG	1	7.0	7.3	7.2	7.9	
	2	9.5	8.0	8.8		
	3	8.5	7.0	7.8		
PLA	1	15	14.5	14.8	14.2	
	2	13	13.5	13.3		
	3	15	14.0	14.5		
TPU	1	41.0	39.0	40.0	40.8	
	2	41.0	40.0	40.5		
	3	41.0	43.0	42.0		



We can see ABS deform the least and TPU is the highest under the same circumstance. Although TPU had the highest deformation, it still does not reach its yield strength, and does not break.

Wear Resistance Test

Wear can be defined as the damage or removal of material that a solid surface has undergone due to sliding, rolling, or impacting against another solid surface. Typically, wear is undesirable as it can lead to increased friction, and ultimately to material failure or loss of functionality. Wear resistance refers to a material's ability to resist material loss by some mechanical action. High wear resistance material is commonly preferred. The most common way to test wear resistance is to rub two surfaces against one another, then inspect the surface for damage or change in mass.

Our test procedure is as follows:

- Use 3D printer to make:
  A disk: this disk is used to hold the weight above the test sample.
  A handle: it will be hooked up to the test sample, and the tester holds the handle to move the test sample forward and backwards over a sandpaper.
  Three test sample cones for each material.
  The disk and handle are used through the whole wear resistance test.

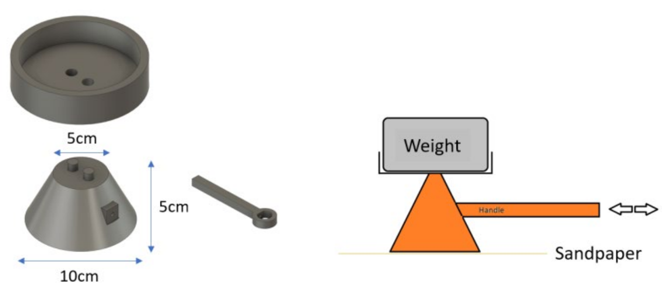


Figure 6. Assembly of wear testing mechanism

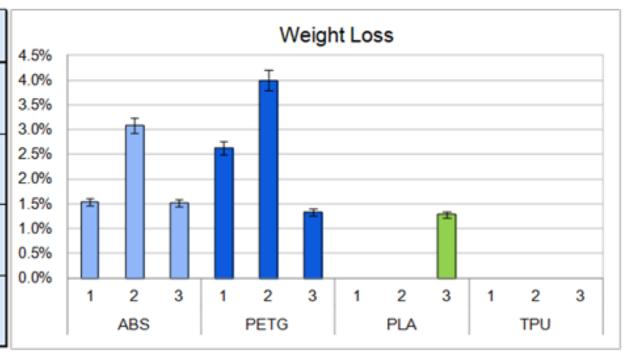
- Hock up test structure as the picture.

Figure 7. Fully assembled wear testing mechanism

- The weight, which is a can of 2.5 lb. in this test, was put on the disk.
- Pull the handle back and forth on a 400 grit sandpaper for 150 strokes.
- Measure the sample weight before and after the 150 strokes, debris caused by wearing were blown off before measuring post 150 strokes weight.
- Record the weight loss.
- A new 400 grit sandpaper of the same length was switched on when each new trail test started.
- Pull and push through the hole at the end of the handle to minimize force impact on vertical direction.
- Strokes are executed with similar frequency, about 0.6 to 0.7 seconds per stroke.

Table 5. Wear resistance test data

Material	Trail #	Before(g)	After(g)	Weight Loss	Averae	Score
ABS	1	65	64	1.5%	2.3%	1.2
	2	65	63	3.1%		
	3	66	65	1.5%		
PETG	1	76	74	2.6%	2.7%	1.0
	2	75	72	4.0%		
	3	75	74	1.3%		
PLA	1	77	77	0.0%	0.33%	9.0
	2	77	77	0.0%		
	3	78	77	1.3%		
TPU	1	81	81	0.0%	0.0%	10
	2	81	81	0.0%		
	3	81	81	0.0%		



TPU has the best wear resistance and PETG is the worst.

Data Analysis and Results

Property Comparison

To easily compare the four material's properties from the test result, we assign the test result with a rank score.

We assign the best performance as score 10. For creep test and wear resistance, since the lower number indicates the higher performance, so score 10 is assigned to best performance , and other lower scores were calculated with reverse proportion.

Solvent resistance result is qualitative, not numerical, so assigning points to those qualitative performance first, higher points is given to bigger change, that also means, the lowest point indicates the best solvent resistance. PETG has the best solvent resistance, it was given a score of 10, the other score was calculated with reverse proportion.

Table 6. Solvent damage grading rubric

Chemical Solvent

	1.Corner/Edge		2.Color		3.Surface Peel		4.Weight Change		Total Points	Score
	Change	Point	Change	Point	Change	Point	Change	Point		
PETG	Little round	1	No visible change	0	No peel	0	1.8%	1	**2**	**10**
TPU	No visible change	0	Faded	1	15%: layered 100%: slight peel	1	11%	3	5	**4.0**
PLA	No visible change	0	Faded	1	15%: shredde 100%: worse peel	2	5.6%	2	5	**4.0**
ABS	Melted at 15%	na	Melted at 15%	na	Melted at 15%	na	na	na	na	**0**

Table 7. Scoring of materials after the creep test and wear test

Tensile Creep:

Material	Trail #	Avg Deform (mm)	Avg. (mm)	Score
ABS	1	7.5	6.4	10
	2	5.3		
	3	6.5		
PETG	1	7.2	7.9	8.2
	2	8.8		
	3	7.8		
PLA	1	14.8	14.2	4.5
	2	13.3		
	3	14.5		
TPU	1	40	40.8	1.6
	2	40.5		
	3	42		

Wear Resistance:

Material	Trail #	Weigh Loss	Average	Score
ABS	1	2%	2.3%	1.2
	2	3%		
	3	2%		
PETG	1	3%	2.70%	1.0
	2	4%		
	3	1%		
PLA	1	0%	0.33%	9.0
	2	0%		
	3	1%		
TPU	1	0%	0.0%	10
	2	0%		
	3	0%		

When we select material to be used, there is another factor, which is cost/price, needs to be considered too. We print a same size sample 3 cm x 3 cm x 2 cm for each material, use a price calculation tool from Prusa manufacture, prices of the same sample size of the four materials are listed as the below. Since lower price is always preferred, as we assign the lowest price as score 10. Other price scores are calculated with reverse proportion.

Table 8. Cost of filament to print a 3x2x2cm cube

	Sample Object Price $	Score
ABS	0.14	10
PLA	0.18	7.8
PETG	0.19	7.4
TPU	0.27	5.2

Since density change is about the same cross each filament, so we only consider four criteria when we select. Now we put all four materials' ranking scores on four properties together in a radio's chart to compare:

	PLA	PETG	ABS	TPU
Wear Resistance	9.0	1.0	1.2	10
Tensile Creep	4.5	8.2	10	1.6
Solvent Resistance	4.0	10	0	4.0
Cost	7.8	7.4	10	5.2

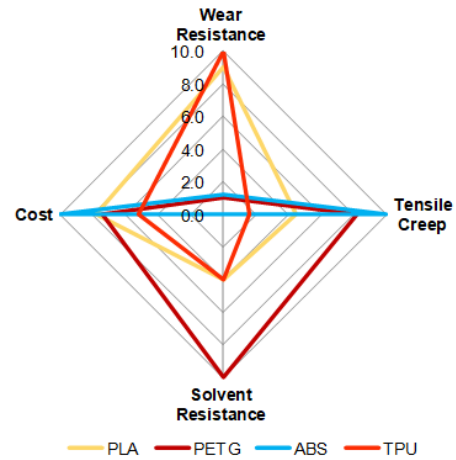


Figure 8. Radio chart of ranking scores of four filaments

We can see each filament material has its own advantage over others.

Material Selection

Our final object in this project is making a biomimetic hand, then what is the best material selection for each part of the hand? Fundamentally, a bionic hand needs to work in a biochemical environment, so low chemical reaction and high solvent resistance is #1 requirement. Based on our solvent test in section 2.2, we know that ABS can melt in acetone liquid, and can even have surface melt in acetone vapor, so ABS is ruled out first in this project selection.

	PLA	PETG	ABS	TPU
Wear Resistance	9.0	1.0	1.2	10
Tensile Creep	5.0	8.2	10	2.0
Solvent Resistance	4.0	10	0.0	4.0
Cost	7.8	7.4	10	5.2

To select from the other three materials, we summarize a hand's bone parts and their major function, function determines the criteria for material selection. Then the final selection is listed in the following table.
A human is composed by 27 bone pieces and has the following function:

Table 9. All bones in the biometric hand and their function

Bones	Pieces	Description	Function
Phalanges	14	DP 1-5 Finger tips MP 2-5 Middle phalanx PP 1-5 Proximal phapanx, connect to palm	Grab things, always in touch with objects, high wear resistance is required, tensile resistance is also needed.
Metacarpal	5	MC 1-5 Palm	hold weight, high tensile resistance is top preferred
Carpal	8	Parts of wrist	play a jointing function, be flexible and still can tolerance force

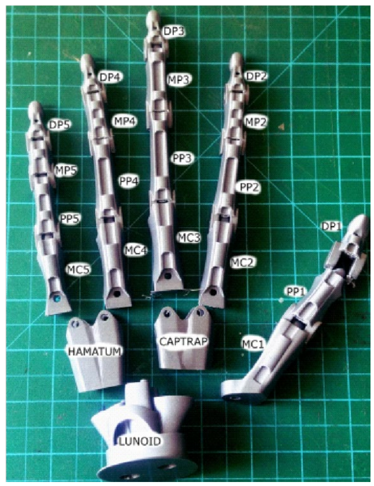


Figure 9. Diagram of all 3D printed parts in the biometric hand

To meet each part's function, filament material is selected as the below table:

Table 10. All parts in the biometric hand and material selection consideration

Bones	Pieces	Consideration	Proposed Material
Phalanges	14	Need to consider high wear score, so select between PLA(9) and TPU(10). While PLA's wear has score only 1 lower than TPU, but higher score on both creep and cost than TPU, and high tensile creep is also needed for fingers. So select PLA as an result of overall consideration.	PLA
Metacarpal	5	Palm's major function is holding weight. Need to select higher creep score, PETG is the next highest beside ABS, also has good solvent resistance, so PETG is the choice for metacarpal.	PETG
Carpal	8	These joins connect hand and arm, need to have good tolerance for bending, also can tolerant some force. TPU can deform remarkable under same circumstance, but still does not break. So TPU is the choice for carpal bones, TPU also has best wear and good acetone score.	TPU
Total bones	27		

After making a selection decision, then designing the hand in Fusion 360 software tool, the 3D printer executed the job based on software design. The Fusion design for hand parts are as the following figures:

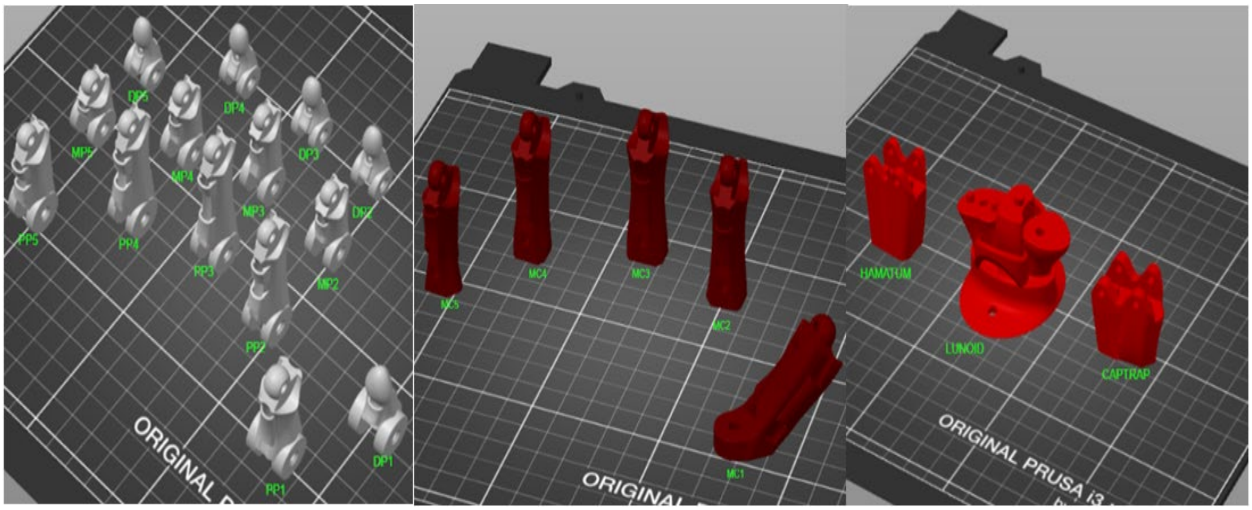


Figure 10. All parts of biometric hand loaded in Prusa Slicer

Then, using the 3D FDM printer as Fig.1, connect all above parts, the final biomimetic hand is made as the below:

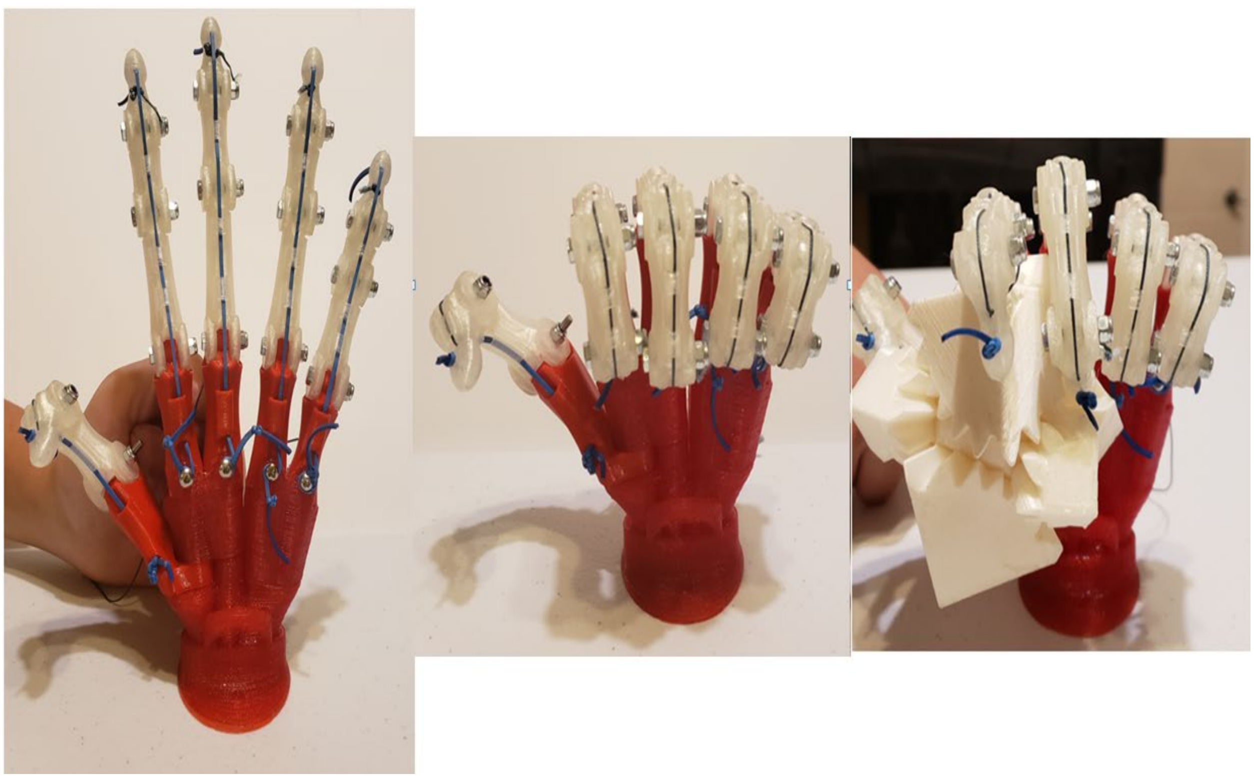


Figure 11. Full hand assembly with mechanical ability demonstration

Compare the material cost with the cases assuming no selection:

Table 11. Material cost comparing.

				Material Cost Compare ($)		
Bones	**Selected Material**	**Pieces**	**Material Cost ($)**	a. Estimated Cost using all PLA ($)	b. Estimated Cost using all TEPG ($)	c. Estimated Cost using all TPU ($)
Phalanges	PLA	14	**1.05**	1.05	1.08	1.58
Metacarpal	PETG	5	**0.84**	0.8	0.84	1.19
Carpal	TPU	8	**1.19**	0.79	0.84	1.19
Total		27	3.08	2.64	2.76	3.96

Since TPU is a comparably higher price material, and we select TPU to make the Carpal bone, so our cost is not the lowest, but the selection is a result of compromised consideration of material property, object function, object environment and cost. Selecting a function suitable material can grant the user longer duration time, it is a cost saving actually.

Conclusion and Discussion

Filament material selection needs to be driven by the print object's function and its working environment, not randomly selected, or picking the lowest cost. Correctly selecting filament material considering the object's function and environment can improve the object's function, increasing the benefit which the FDM printer brings to the user.

In this project, we tested and compared density, chemical resistance, tensile creep and wearing resistance of PLA, PETG, ABS, and TPU.. Since our prototype is a biomimetic hand, considering each part of the hand's work function and the hand's environment, ABS material has very low solvent resistance, and can't work in a biochemical environment, so we ruled it out first. Then we select PLA as the finger's material mostly due to its high wear resistance and overall well properties; we select PETG as the palm material due to its high tensile creep performance; select TPU as the carpal/waist material due to its high tolerance of bending. We demonstrated that the built biometric hand is able to replicate the dexterity of a human hand to the best of its ability given its physical limits. Through our experiment and demonstration we verified that scientific material selection can make the printing object working correctly with enhanced performance.

Acknowledgment

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

1. https://www.additivemanufacturing.media/articles/finding-value-with-design-for-additive-manufacturing
by Timothy W. Simpson

2. https://blog.prusa3d.com/3d-printing-price-calculator_38905/
by Prusa Research

3. https://help.prusa3d.com/materials?_gl=1*gxuctr*_ga*MTg5Mzg1NDkzNC4xNjkxNjcxMjA4*_ga_3HK7B7RT5V*MTY5MTY3MTIwOC4xLjAuMTY5MTY3MTIwOS42MC4wLjA.
by Prusa Research

4. https://www.instructables.com/3D-Printed-Bionic-Hand-Skeleton/
by Hendo J