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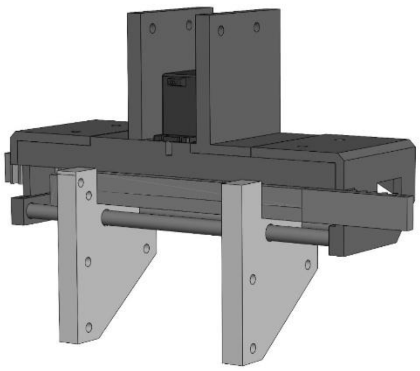

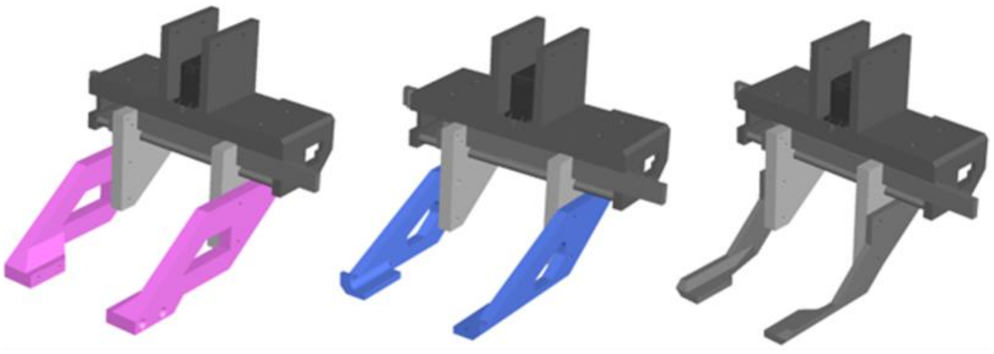

UPGRADING A 3D-PRINTED GRIPPER FOR ENHANCED ROBOTIC HANDLIN

41739 - EXPERIMENTAL PLASTIC AND METAL PROCESSING TECHNOLOGY

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Introduction

Dalsa describes itself as a space for interdisciplinary projects to explore and develop new technologies within the life science industry, with a vision to be a leading facility in the development and implementation of future automation technology in life-science, R&D, and manufacturing (Dalsa frontpage, u.d.)

The field of bioengineering is crucial, but despite the availability of advanced, fully automated solutions, they remain largely accessible only to large commercial organizations that can afford significant investments. For academic institutions, the high cost of purchasing, implementing, and maintaining automated equipment limits accessibility, forcing reliance on manual labor. This not only reduces efficiency but also introduces issues like human errors or fatigue. (Gabor, 2024)

To address these challenges, a previous master's thesis project, “Advancing Laboratory Automation in Life Sciences through Robotic Design and Implementation” by Karol Gabor, focused on developing a cost-effective robot arm. This project aimed to automate lab procedures by developing an accessible system that relies on automation rather than manual labor. Specifically, the project proposed a robotic arm designed to automate the process of transporting sample plates from and to lab machines. The goal was to create a modular and cost-effective arm that could be easily adapted and duplicated for different environments and equipment, by making the whole project open-source and utilizing 3D printing.

An essential component of this robot system is its end-effector, or gripper system, which is responsible for picking up and holding sample plates, While the previous project successfully developed a 3D printed robot capable of transporting plates, the gripper design has some limitations- It lacks the stiffness and grip precision required to reliably hold specific target samples.

Therefore, the task of this project is to redesign and fabricate an improved gripper for enhanced robotic handling. This involves analyzing the limitations of the current design, developing a new 3D printed gripper with enhanced stiffness and holding capability, and validating its performance through testing on the robotic arm.

Problem formulation

An analysis of the existing gripper, developed in the previous project, identified several key limitations and problems:

Not 3D printable: The original gripper was identified as being made of a metal sheet. One of the project's goals was to create a fully 3D printable robotic arm for ease of replication and modularity. The goal for the new gripper is therefore to be 3D printed.

Stiffness: A critical issue of the original gripper is the lack of sufficient stiffness and grip precision. Instead of securely grasping sample plates with adequate force, the existing claws would bend and “give”. This might also be a problem in 3D printed structures, as plastics typically exhibit lower stiffness compared to materials like metal, necessitating careful design optimization to achieve the required rigidity.

Extending: The current design only grasps samples from a single direction. A specific user requirement for the improved design was the ability to grab samples from multiple directions, accommodating the diverse loading and unloading mechanisms of various laboratory machines.

One-way gripping: The original gripper could only grab samples from a single direction. A specific user requirement for the improved design was the ability to grab samples from multiple directions, accommodating the diverse loading and unloading mechanisms of various laboratory machines.

Loading on 3D printed Gears: The existing setup places a large force on the 3D printed gears and gear rack, which means the rack bends. While 3D printing offers benefits for rapid prototyping and cost reduction, the printed gears have inherent limitations regarding loading-bearing capacity and functional reliability.

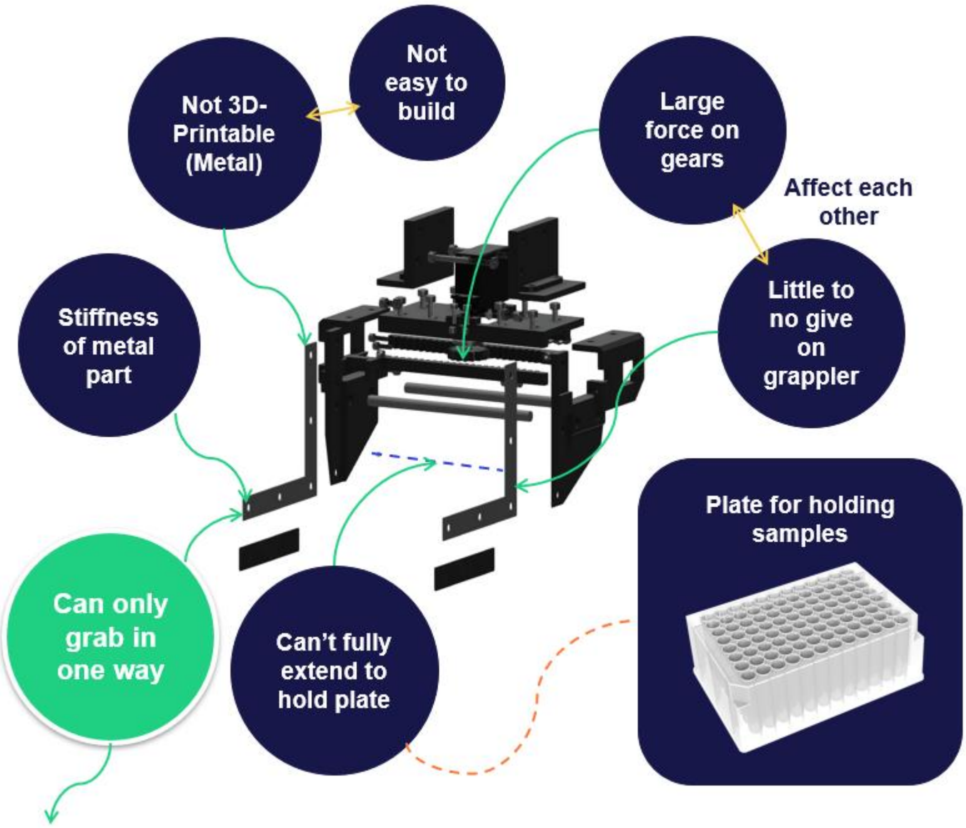


Figure 1: Identified problem with the existing gripper system.

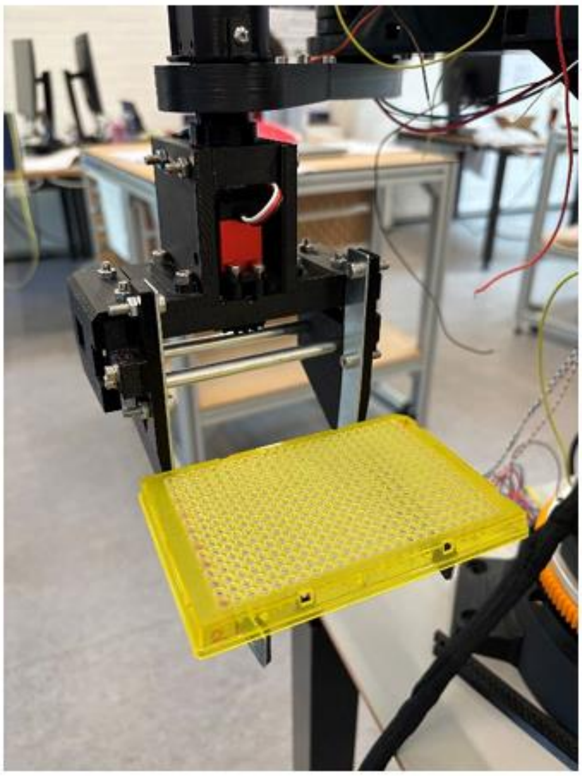


Figure 2: Existing gripper handling sample plate

Based on the identified problem and requirements for the gripper system, the following problem formulation has been formulated:

This 3-week project focuses on redesigning and fabricating an improved gripper for an existing robotic arm developed in a previous student project. The current gripper lacks the stiffness and grip precision required to reliably hold a specific target sample. The goal is to analyze the limitations of the current design, develop a new 3D-printable gripper with enhanced stiffness and holding capability, and validate its performance through testing on the robotic platform.

Product Design Requirements

To redesign the gripper system, a set of requirements was formulated based on the identified problems with the existing gripper as well as additional wishes from users in the DALSA lab.

The sample plates:

The following picture is an example of a sample plate. All plates are the same length and depth, but usually different heights.

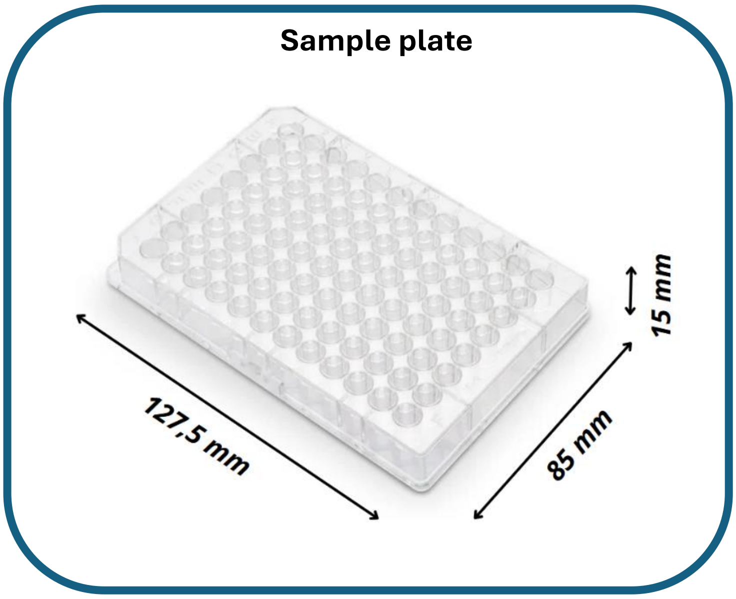


Figure 3: Example of sample plate.

Key product design requirements for the new gripper system:

Plate dimensions: The gripper must be designed to handle sample plates in dimensions 8,5 cm x 12,5 cm, but varying heights. This means that the gripping mechanism must accommodate different plate heights and weights while maintaining a secure hold.

Gripper Scenarios/ Interaction Methods: The gripper must support diverse methods of plate handling, which have been identified in the DALSA lab.

From the top: For many machines, the gripper needs to grab and place plates from the top. This requires the robot arm to be positioned above the plate, with the gripper engaging the plate from its sides.

From the sides: For certain machines and especially for the plate hotels, the gripper must be able to grasp the plate from the side while the robot arm is positioned horizontally. This enables the robot to position the plate from the side and place it into the hotel.

From the bottom: When retrieving plates from sample hotels, the gripper needs to pull the samples out, likely from the bottom, and then grab the sides of the plate.

Suction cups: The design must also account for the fact that some machines handle plates from the top using suction cups. This implies the gripper design should not obstruct the top surface of the plate, or it should be able to interact with plates that have been handled this way.

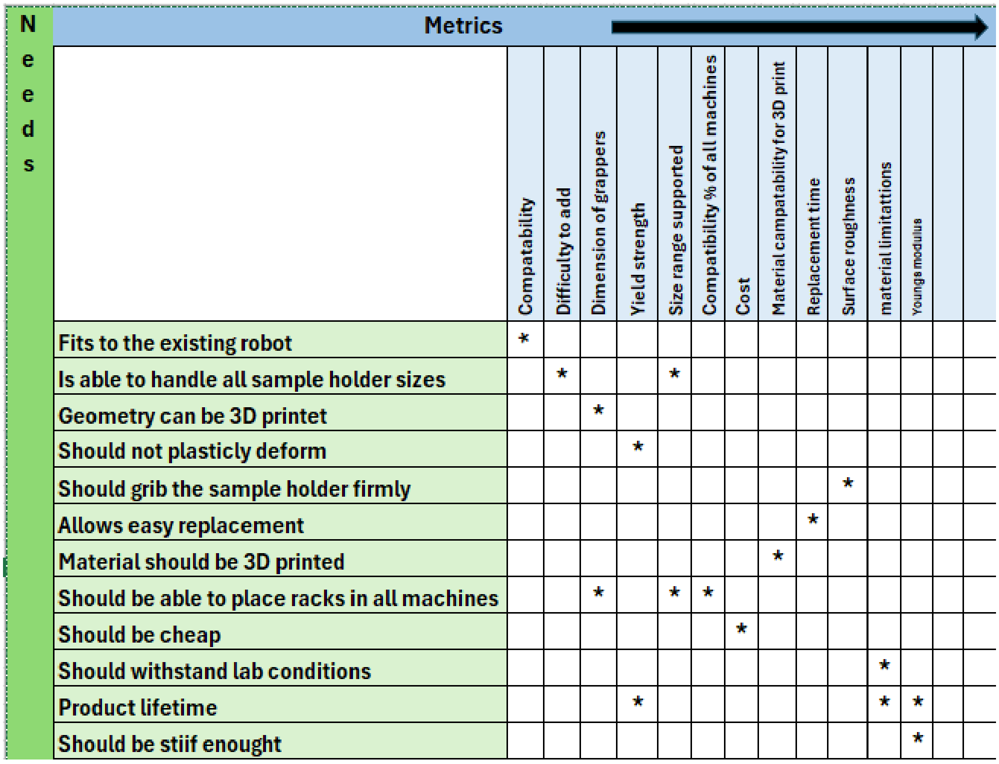
Figure 4: The different grip scenarios

Needs/metrics Matrix

Based on the problems identified with the existing gripper as well as the different gripper scenarios, a needs/metric matrix was made. The needs identified are:

- The solution should fit the existing robot without too much redesign.
- The solution should be able to handle all sample sizes and grab from both the short and long sides.
- The geometry of the solution should be 3d printable
- The material chosen should allow for 3D printing
- The gripper should not plastically deform when force is applied.
- The gripper should be stiff enough as to “give” or elastically deform when force is applied
- It should grab the sample firmly without slipping, requiring a sufficient friction coefficient
- The solution should allow for easy replacement - design for disassembly
- The solution should be able to accommodate several gripper scenarios / different machines
- The solution should be cheap
- The material should be able to withstand lab conditions and cleaning
- The product lifetime should be at least 3 years
- These needs were then used to create a needs/metrics matrix, where each need was matched with a corresponding metric, creating a way to measure the success of each need.

Table 1: Needs, Metrics Matrix

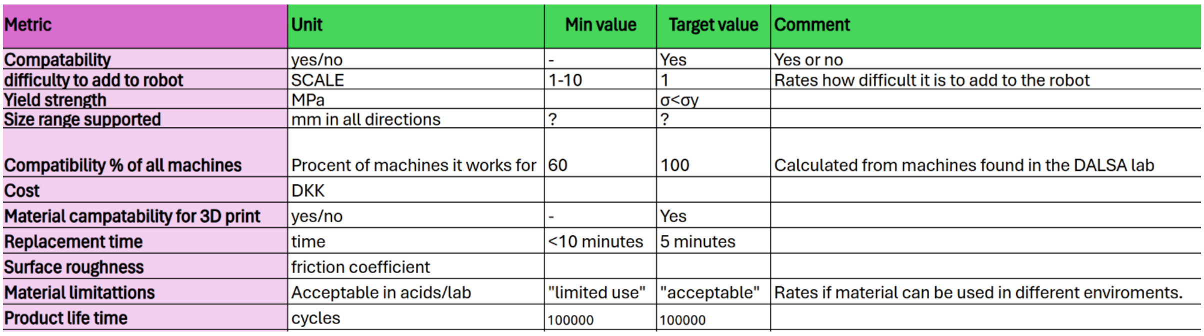


Needs	Compatability	Difficulty to add	Dimension of grappers	Yield strength	Size range supported	Compatibility % of all machines	Cost	Material campatability for 3D print	Replacement time	Surface roughness	material limitattions	Youngs modulus		
Fits to the existing robot	*													
Is able to handle all sample holder sizes		*			*									
Geometry can be 3D printet			*											
Should not plasticly deform				*										
Should grib the sample holder firmly										*				
Allows easy replacement									*					
Material should be 3D printed								*						
Should be able to place racks in all machines			*		*	*								
Should be cheap							*							
Should withstand lab conditions											*			
Product lifetime				*							*	*		
Should be stiif enought												*		

Specifications

Based on the metric, each need was given a unit, a minimum value, as well as a target value. Based on these specifications, the redesigned gripper system can be effectively measured through direct comparison as well as functional testing. Each metric provides a quantifiable target of characteristics that allow for clear evaluation.

Table 2: Specification table



Metric	**Unit**	**Min value**	**Target value**	**Comment**
Compatability	yes/no	-	Yes	Yes or no
difficulty to add to robot	SCALE	1-10	1	Rates how difficult it is to add to the robot
Yield strength	MPa		σ<σy	
Size range supported	mm in all directions	?	?	
Compatibility % of all machines	Procent of machines it works for	60	100	Calculated from machines found in the DALSA lab
Cost	DKK			
Material campatability for 3D print	yes/no	-	Yes	
Replacement time	time	<10 minutes	5 minutes	
Surface roughness	friction coefficient			
Material limitattions	Acceptable in acids/lab	"limited use"	"acceptable"	Rates if material can be used in different enviroments.
Product life time	cycles	100000	100000	

Material selection

For material selection, the program “Ansys Granta Edupack” was used to plot a performance index for the selected materials. As one of the project's requirements is a fully 3D printable solution, only plastics with the ability to be processed by 3D printing were considered.

A plot with Price on the y-axis and Volume per unit of stiffness on the x-axis was created. This index was chosen because the gripper solution needs to be as thin and stiff as possible while keeping the price as low as possible, to ensure that the solution can be replicated easily.

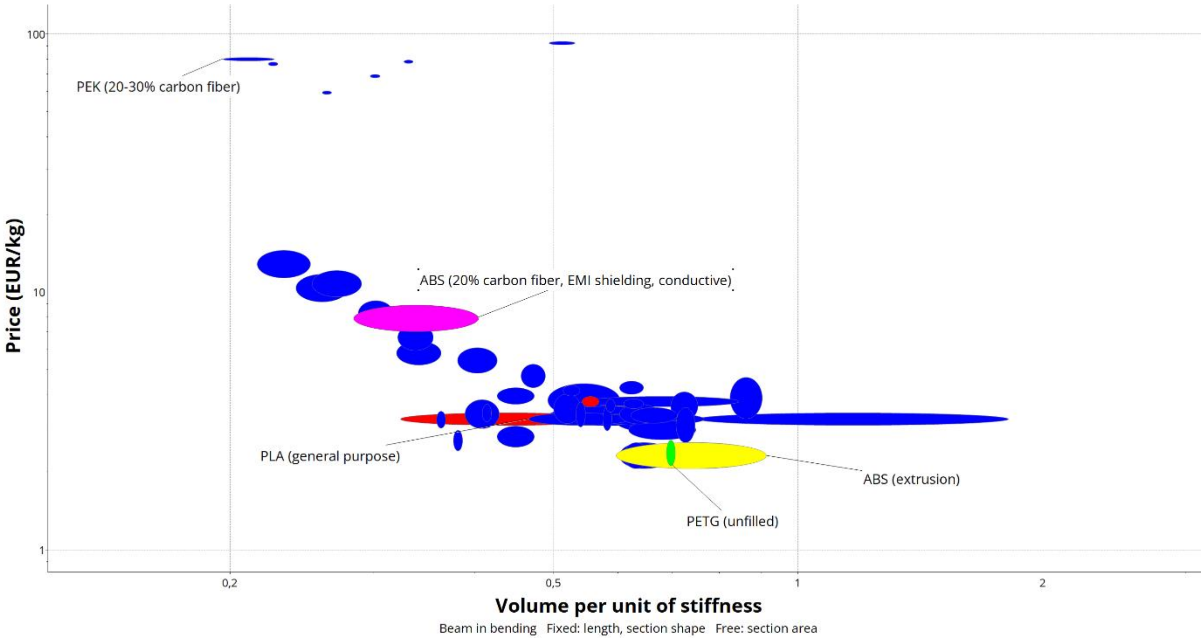


Figure 5: Material analysis in Granta Edupack.

PLA (Polylactic acid)

PLA is a biodegradable thermoplastic made from renewable resources. It is one of the most popular materials for 3D printing. It has a tensile strength of 50 to 70 MPa. PLA is easy to print, gives a good surface finish, and is low-priced. The main disadvantages of PLA are low heat resistance and poor chemical resistance.

PETG (Polyethylene Terephthalate Glycol)

PETG is a modified form of PET (used in plastic bottles), enhanced with glycol to prevent crystallization and make it more printable. The result is a tough, impact-resistant, and slightly flexible material that combines the properties of PLA and ABS. It has a tensile strength between 50 and 60 MPa, and it has good chemical resistance.

ABS (Acrylonitrile butadiene styrene)

ABS is a petroleum-based thermoplastic polymer known for its high strength, impact resistance, and durability. Its tensile strength ranges between 40 and 50 MPa, and it is easy to 3D print. The primary disadvantage of ABS is that it contracts when cooled, resulting in layer separation and warping.

PEK (Polyetherketone)

PEK is a semicrystalline high-performance thermoplastic known for exceptional mechanical strength, chemical and thermal resistance, and dimensional stability. Its tensile strength ranges from 100 to 120 MPa. PEK is 3D printable but requires industrial-grade equipment due to its extreme processing demand.

The graph indicates that the optimal material for a thin and stiff gripper is PEK with 20-30% carbon fiber. With this material, high stiffness can be achieved, allowing the design to be as thin as possible. However, it is also costly, and an industrial grade 3d printer would be needed. This would be a good option for further investigation, however, not for the current scope of this project.

Another option would be ABS with the addition of carbon fiber. ABS is an easy material to print, but without carbon fiber, it will not give sufficient stiffness. PETG is a suitable material due to its good chemical resistance; however, it is more challenging to print. The graph also reveals that PETG has lower stiffness than PLA.

PLA was chosen as the most suitable material for the 3D printers available for this specific project. PLA is easy to print, low in price, commonly used, and gives good stiffness. The orientation of 0° was used for 3D printing PLA, as it exhibits the highest tensile strength in this orientation. (Syaefudin, 2023)

Brainstorm

Based on the needs, brainstorming was conducted. Several ideas were found and evaluated.

The Ideas:

Snap fit solution:

The first idea explored using snap fits to attach different grippers to the robot arm. The gripper should therefore be interchangeable, allowing for customization. However, this idea focused most on the attachment of the gripper and the geometry of the gripper itself. This idea scores second-to-last as the complexity of the solution was too high, as attaching the gear as a snap fit would need very fine accuracy.

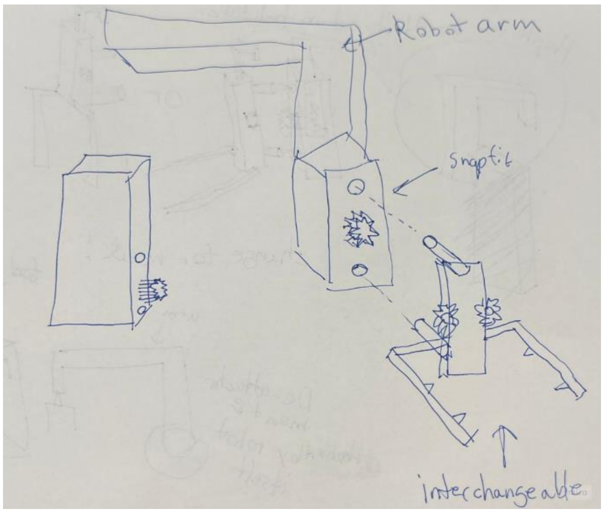


Figure 6: Idea 1

All in one solution

For this solution, several types of grippers are attached to the arm. Changing the gripper would, therefore, not be necessary. However, this would require lots of gears, and the arm would need to move more in the x,y, and z directions. This would also require a lot of additional coding for the arm to operate. Because of this, this solution scored the lowest on complexity, being too complex for the scope of the project.

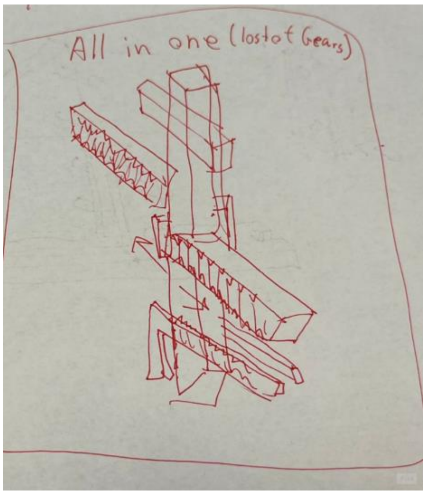


Figure 7: Idea 2

Universal base with snap-fit

The Idea behind this sketch is that the base of the gripper would be universal. The base has snap-fit holes. On the universal base, you could put different types of fingers to hold the plate. That is good, because then you can easily and quickly change gripper fingers. The problem here would be that 3d printed snap-fits are not stiff enough for the stability of the gripper.

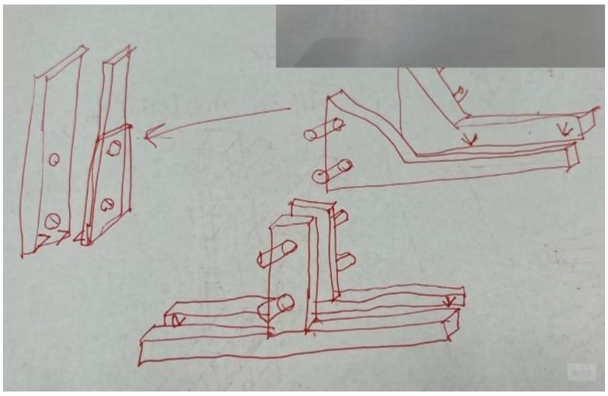


Figure 8: Idea 3

Attached with bolts

This idea presents a universal base for the gripper. With bolts and nuts, you can tighten different gripper fingers. The bots and nuts will make better connections than snap-fit. With that, you can have different gripper claws for different applications, and you can easily change them. We would apply rubber at the edge of the gripper's fingers for better grip and increased friction between the plates and fingers. This idea standardizes the gripper's base.

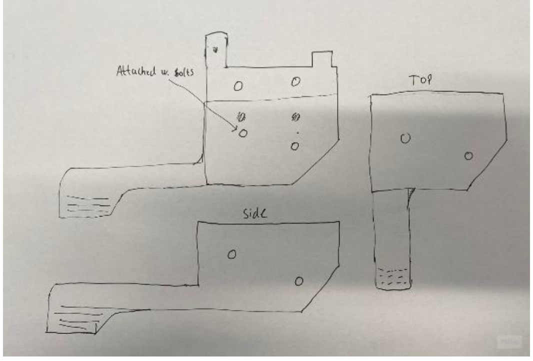


Figure 9: Idea 4

Gripper integrated into the claw mount:

This idea shows us the gripper claw in one piece with the base of the gripper. This will give the gripper more sturdiness. The downside is that when you have to change the grippers for another type of claw, you have to disassemble the whole gripper.

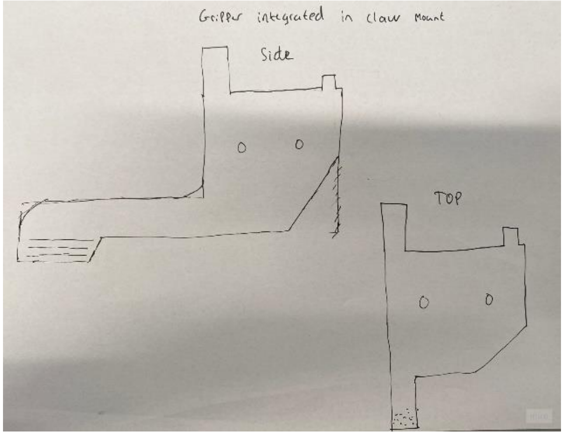


Figure 10: Idea 5

360

This gripper would be redesigned. It would be able to turn 360°. It would be able to pick the plates from the top and the side. And it would give us stability and accuracy, which is essential for robots.

The downside of this gripper is that it is quite complex. We would need to change the motor and 3D print complex parts.

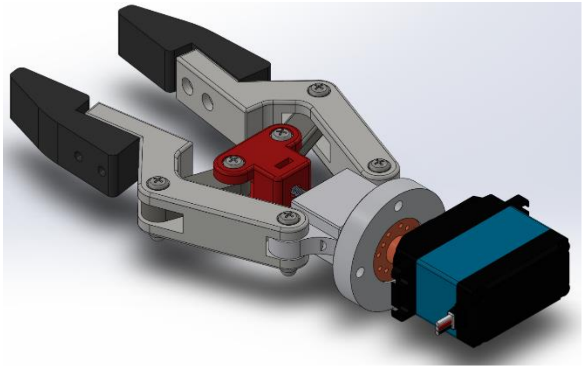


Figure 11: Idea 6

Rating:

When evaluating the ideas, a scoring system was utilized, assigning a score from 1-5 in four key categories. These categories were crucial for determining the feasibility and effectiveness of proposed solutions for the robotic arm.

The four main criteria were:

- Easy replacement: Is the solution easy to add to the robot? Would it be easy to replace or interchange parts?
- Complexity: Are there several parts to be manufactured? Is geometry complex? The simpler, the easier!
- Cost: Would the solution be costly? Or cheap to manufacture?
- Universal positioning: Would the solution accommodate the requirement for several gripping scenarios?

Table 3: Scoring table for assessing different gripper ideas

No.	**Idea**	**Easy Replacement (1 is bad, 5 is good)**	**Complexity (parts, Geometry) (1 is bad, 5 is good)**	**Cost (1 is bad, 5 is good)**	**Universal positioning (1 is bad, 5 is good)**	**TOTAL**
1	Snap-fit solution	4	2	3	5	14
2	All in one solution	4	1	2	5	12
3	Universal base with snap-fit	4	4	3	5	16
4	Attached with bolts	4	4	5	5	18

5	Gripper integrated into the claw mount	4	5	4	5	18
6	360	4	1	4	3	12

First iteration prototype

Following our idea generation phase, we began developing and testing physical prototypes to evaluate mechanical performance and compatibility. This section presents the first iteration of our gripper and base design, focusing on material choice, structural challenges, and initial functionality.

Grippers

Based on idea five from the brainstorming (see Table 3) and based upon research made on existing types of grippers., the first gripper was designed with inspiration from the original gripper mounted on the robot arm. The idea behind this approach was to evaluate how the same mechanical concept would perform when produced by 3D printing plastic instead of metal. To ensure compatibility with the existing base system, the Gipper was mounted directly onto the rods, integrating it into the claw mount. The thickness of the gripper was set to 10mm. This value was chosen based on the dimensions of the original 3d printed components and served as a starting point for evaluating stiffness. The idea was to test the mechanical performance of the 10mm profile under loads and adjust the thickness accordingly in future iterations, based on the observed stiffness and deflection.

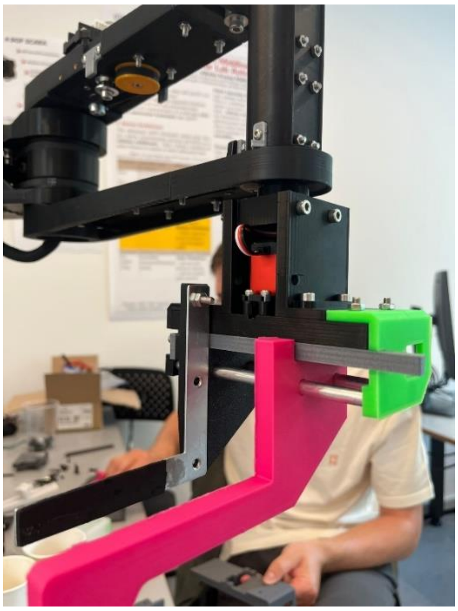


Figure 12: 1st. iteration gripper mounted on the

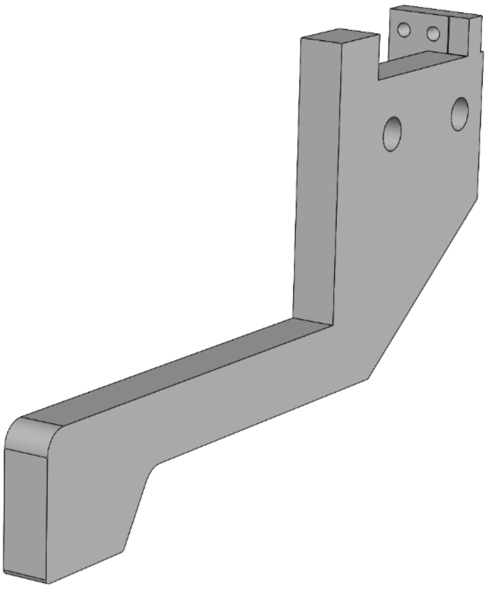


Figure 13: CAD file of the 1st. iteration gripper

original base system.

The first iteration of the 3D printed gripper faced several challenges, including issues with stiffness and its physical dimension, which could be a problem in laboratory settings. To account for the lack of thickness in the plastic material, the gripper was made very thick to ensure no bending when picking up the sample plate. However, this made it almost too bulky and could potentially cause problems in the laboratory environment, where space and fit are important.

It was suggested that we try designing a gripper with four points of contact instead of two, as this would improve stability when picking up a sample plate with uneven weight distribution.

Base

To address the extension-related issues identified, a new, longer base was printed. It was also decided to add a universal base to make the change of grippers quicker and easier without having to disassemble the entire base. This idea was based on suggestion no. 4 from the brainstorming session (see Table 3). Implementing the universal base would require an iteration and redesign of the gripper mount to ensure a proper fit.

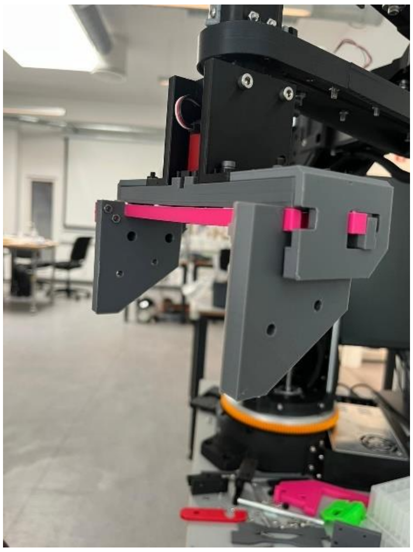


Figure 14: The first iteration of the base with the extended system

While creating an extended base seemed like a straightforward solution, it introduced several new problems that affected both the precision and mechanical performance of the gripper.

Warpage:

Warpage was observed in several locations, likely caused by the printer settings or the increased length of the printed parts. This was particularly problematic for components like the rack gear, where stability is critical to ensure proper function. A possible solution for future iterations would be ribs to reduce deformation.

Printed rods vs. metal rods:

The original included metal rods. However, to simplify the first iteration, these were replaced with 3D printed rods. Due to the limited precision of FDM printing, the rods required extensive post-treatment to ensure a smooth and round surface. And even after the surface treatment of the rods, the plastic rods were not smooth enough and lacked sufficient stiffness.

Insufficient stiffness:

The new base lacked stiffness. With the larger and longer design, rigidity was compromised, as the thickness of the base was not increased to match the extended dimensions. This became a problem during use, as an unstable base can lead to imprecise, unsafe, or unreliable handling. Improving the structural integrity of the base would therefore the essential in future iterations.

Limitations and improvements (after 1 iteration)

Based on the results of the first iteration prototype as well as the issues identified in" Product Design Requirements", it was decided to divide the original requirements along with the new insights into two categories: Need to have and Nice to have. This distinction served as a guide for the next iteration by clearly prioritizing core functionality over secondary features.

Need to Have	Nice to have
- A new, stiffer base able to extend the full length of the sample plate - Easy to add and change grippers - Defines maximum dimensions to ensure the gripper fits within the "hotel." - Moderate stiffness to prevent bending when transporting samples - Able to grab sample plates from multiple angles - Able to fully extend to hold the sample plate	- Fully 3d printable design - Improved gear mechanism to ensure proper closing

- Contact the sample plate at four points for improved transport stability	

2nd iteration

Based on the first iteration as well as requirements, a 2nd iteration base and grippers were designed and printed.

2nd iteration base:

For the second iteration, it was decided – due to limited programming skills and time constraints – to continue using he original motor and core mechanical setup. The focus was instead placed on improving the gripper mechanism itself. However, to allow the gripper to properly extend and grab the sample plate from both the long and short sides, several modifications to the base design were necessary.

The first iteration prototype lacked sufficient stiffness; both the spur and the gear racks were somewhat unstable. To address this, the following changes were implemented.

- Extended and reinforced several structural parts
- Increased gear thickness to improve mechanical stability
- Introduced a support beam and a one-part design for added rigidity
- Added angle supports along the sides
- Integrated mounting hole to attach different grippers and cutouts for the thickened gears

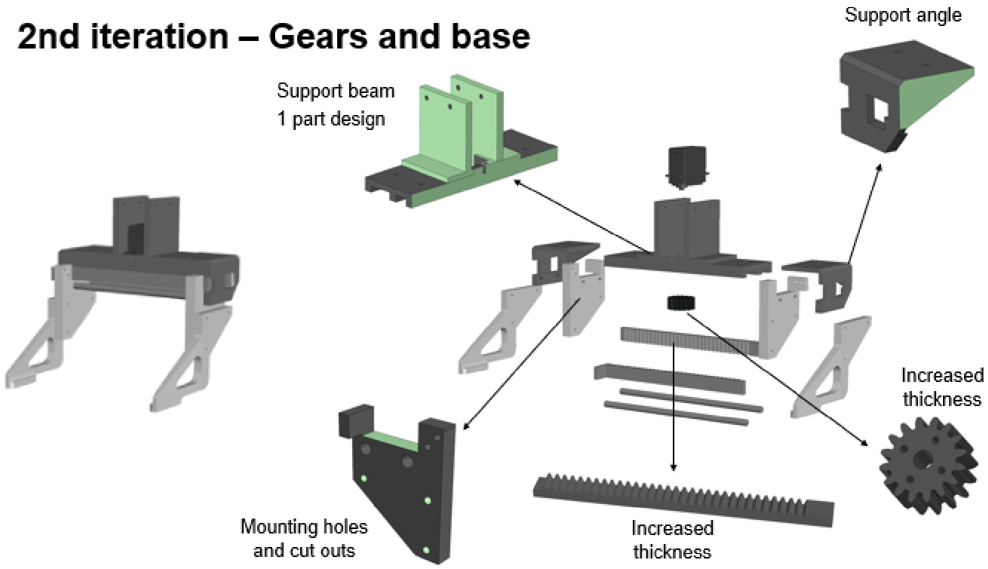


Figure 15: 2and iteration - Gears and base.

Despite the changes, testing revealed that the base still had a significant amount of “give” when force was applied. The flexibility of the plastic used meant that even with stiffer grippers, the overall structure could still deform. This highlighted the need for an even more stable base in the final iteration.

2nd iteration grippers:

The second iteration of the grippers focuses on structural improvements to address the deflection and instability issues observed in the first design. A key modification was the addition of a support beam to enhance rigidity and the load-bearing performance (see ***Error! Reference source not found.*** for all designs made in the 2nd iteration).

Two gripper designs were tested:

Gripper 2.3: Shorter and slimmer design

- More compact and easier to fit within tight spaces
- Less stiff compared to the longer version, but lighter.

Gripper 2.4: Longer and stiffer design

- Increased length and additional support
- Required a thicker profile to maintain stiffness

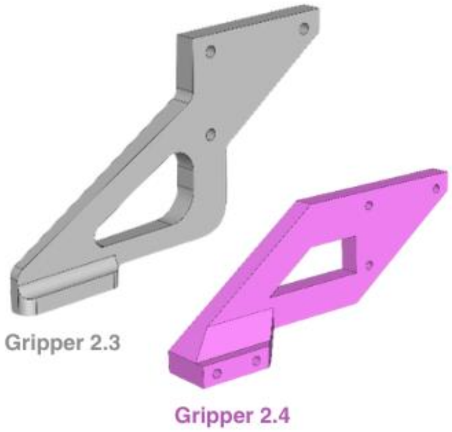


Figure 16: The two 2nd iteration grippers, 2.3 and 2.4

Test and comparison of the two grippers:

The two grippers were tested in the lab, to find if they would successfully fit in the different machines and be able to place a sample plate in different machines. For most machines, the gripper both succeeded in securely gripping the plates, but two main areas of problem as found, which will be explained below.

Machine 1:

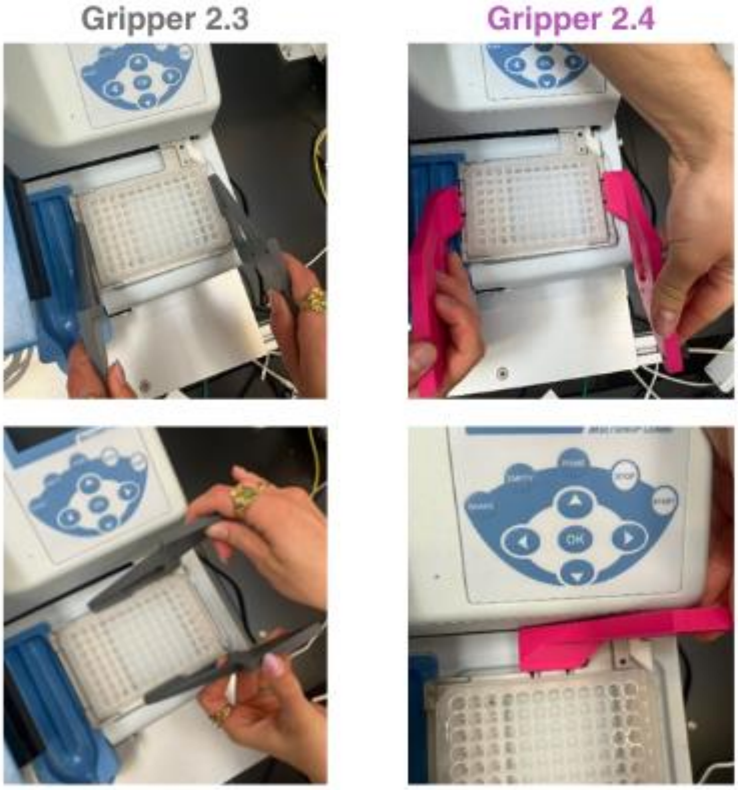


Figure 17: Different grippers in use cases.

For the first machine, gripper 2.3 fit and functioned well, with sufficient clearance on both sides, to securely grab the sample plate. In contrast, gripper 2.4 was too thick at the tip, and did not have enough clearance to securely grasp the plate from the machine. It would require at least 10-15mm of clearance to operate properly.

Machine 4 – Sample plate hotel:


Gripper 2.3

Gripper 2.4

Figure 18: Different grippers in use cases.

For the hotel, the performance of the grippers also varied. It was observed that gripper 2.3 had tips that did not protrude enough to ensure proper placement. Additionally, the support beam interfered with the insertion process, preventing the gripper from pushing the plate fully into the hotel. Gripper 2.4 was longer, which allowed it to successfully place the plate into the hotel without alignment issues.

In a different version of the sample hotel, both grippers encountered difficulty extracting the plate from its slot. This revealed a general limitation in the design:

- Neither gripper could effectively pull the plate out horizontally from the enclosed holder
- A proposed solution is to incorporate small hooks or extensions at the top of the grippers, allowing the robot to pull the plate toward itself before gripping the sides.

Both 2nd iteration grippers had strengths and weaknesses in different machine contexts. Gripper 2.3 provided greater stability and grip strength, but its size limited compatibility. Gripper 2.4 offered better maneuverability but lacked sufficient reach in some situations. As a result, a final iteration was developed, aiming to combine the advantages of both designs. Based on this, as well as the force analysis (see **Error! Reference source not found.**), a final iteration was made.

Final iteration

Based on the previous iterations and learnings, a final iteration of both the base and the grippers was developed for the project. The goal of this version was to use the final iterations for experimental testing as well as to compare and contrast.

Final iteration base

For the final iteration of the base, the 2nd iteration was used, but metal rods were attached instead of the 3d printed ones. This was an attempt to make the whole base sturdier, as well as making the opening and closing mechanism smoother.

Final iteration gripper:

Below are the three final iterations presented. These will be further analyzed and investigated through physical tests and simulations.

Gripper 2.4

This gripper is previously described in the above section. The gripper has 4 contact points when it grabs a sample plate; therefore, this was interesting to test. The thickness of the base of the gripper is 10 mm, making this the thickest gripper and the one that uses the most material, with a weight of 47 g.

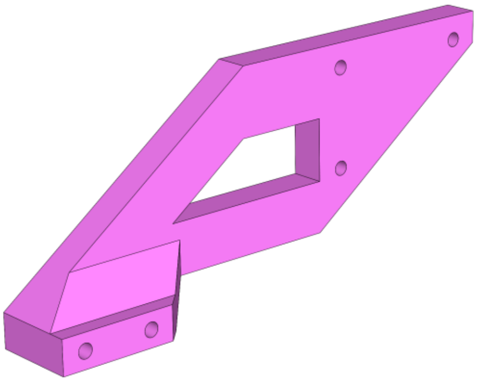


Figure 19: Gripper 2.4.

Gripper 3.1

Gripper 3.1 is an improved version of gripper 2.1, with longer reach and improved stiffness due to improved geometry. Further, a hook at the tip of the gripper was added for the purpose of being able to pull out plates, e.g., a sample plate hotel, where space on the side and at the top is limited. The thickness of the base of the gripper is reduced compared to 2.2, with a thickness of 8 mm and a weight of 34 g.

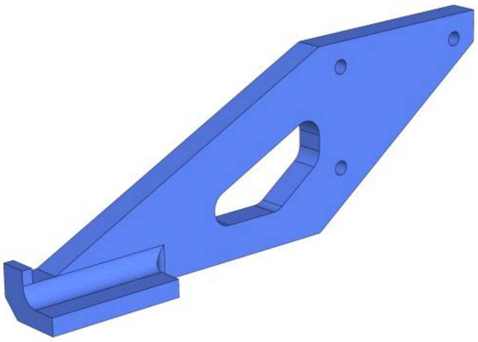


Figure20: Gripper 3.1.

Gripper 3.2

Gripper 3.2 was an attempt to make a design using less material, by minimizing the thickness and removing the structural beam as in 3.1. The thickness of the base of the gripper is 5 mm, and it has a weight of 21g.

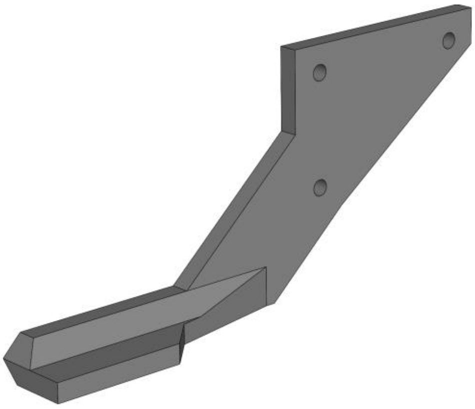


Figure 21: Gripper 3.2.

Machine capabilities

As part of our evaluation metric, we assessed the compatibility of each gripper design with various lab machines (see appendix 4). Our target was to achieve at least 60% compatibility, with higher compatibility considered even more desirable.

We tested gripper versions 2.3 through 3.2 in the lab and summarized the results in the table below:

Table 4: Compatibility of grippers with different lab machines and plates.

	Mantice	Plate hotel	Perkin Elmer	Suction cup holder	Plate rack	Sealing machine	BioTek plate washer	Multi drop	Compatibilty %
Gripper 2.3	**Yes**	No	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**	**75%**
Gripper 2.4	**Yes**	No	No	**Yes**	**Yes**	**Yes**	No	No	**50%**
Gripper 3.1	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**100%**
Gripper 3.2	**Yes**	No	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**87,5%**

Gripper 3.1 achieved the highest compatibility score at 100%. This was primarily due to the addition of a hook feature, which enabled it to pull plates out of the plate hotel. However, it's important to note that compatibility with the plate hotel assumes a specific programmed motion for placing and retrieving plates (see Figure XX).

Figure 22: Motion for placing and taking plates from plate hotels with gripper 3.1 iteration

Gripper 2.4 encountered significant issues due to its thickness, which caused it to collide with the sides of some machines. Gripper 2.3 performed reasonably well but had limitations: its short arms couldn't reach into the plate hotel effectively, and it lacked a central grip point on the plates for maximum stability.

Gripper 3.2 showed promising compatibility but lacked the hook feature required for plate hotel interaction (also shown in Figure XX). Additionally, it exhibited displacement issues under force, which will be discussed in a later chapter.

Experimental plan with an overview in table form

To evaluate the performance and stability (stiffness) of the different gripper designs, an experimental plan was developed. Three grippers were tested to determine which design would provide the most reliable grip under various loading conditions.

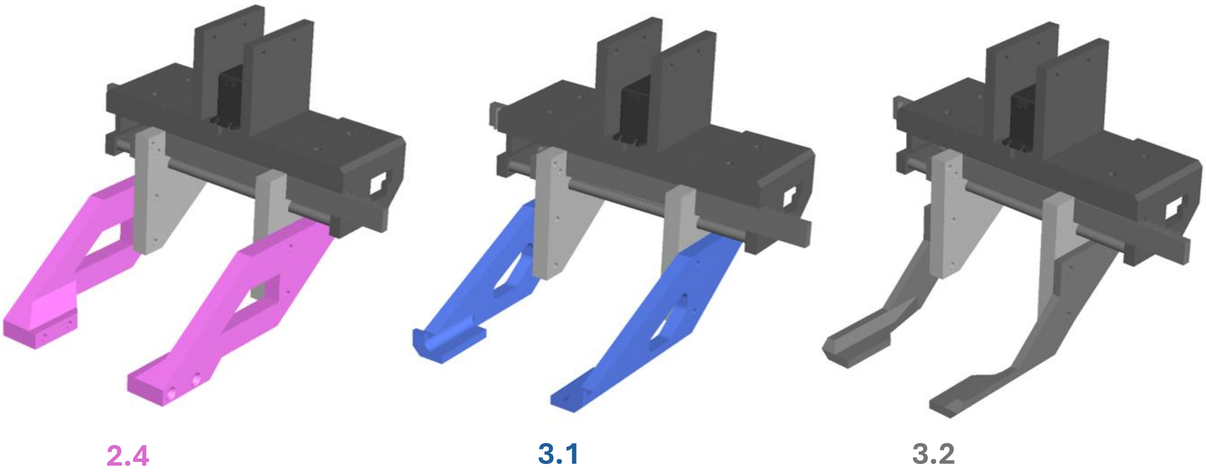


Figure 23: Three chosen iterations of grippers (2.2, 3.1, 3.2) for further investigation and test.

Sample plates

Two different sample plates were used to represent the standard lab conditions.

Plate A: 96-well, round bottom assay, height 1,5 mm, well volume: 500µL. (Round bottom assay plate, 2025)

Plate B: 24-well, deep well plate, height: 4,5 mm, well volume: 10mL. (Deep well plate, 2025)

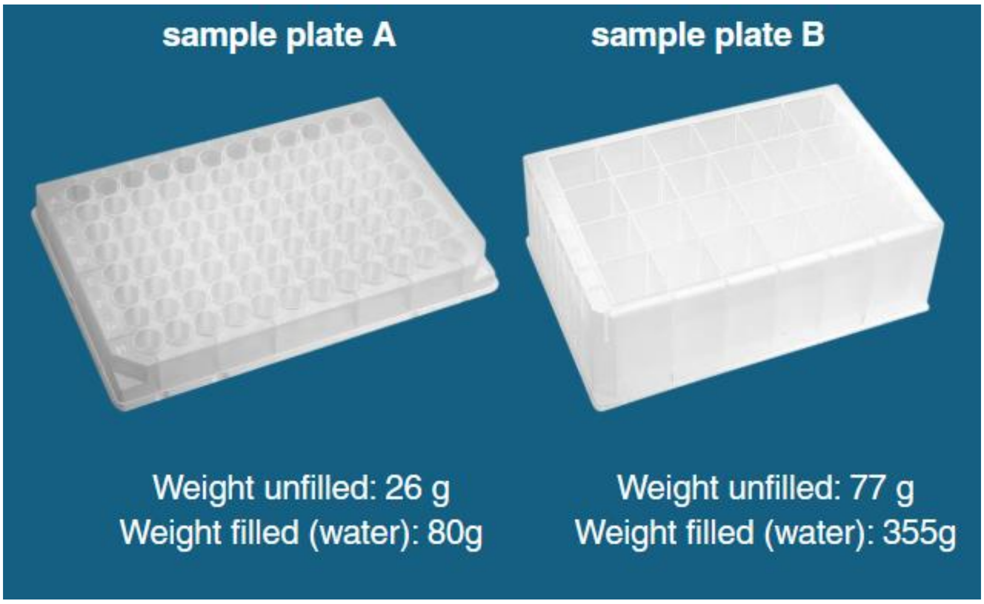


Figure 24: Sample plates used for test.

Test overview

Test Scenario	Succes-criteria
Hold plate without load	Able to hold for >30 seconds, 3 times
Hold plate with full load (weight applied to center)	Able to hold for >30 seconds, 3 times
Hold plate with ½ load applied end	Able to hold for >30 seconds, 3 time
Hold plate with ¼ load in each corner	Able to hold for >30 seconds, 3 times
Deflection test (weight applied at tip of each gripper)	Minimal deflection, no permanent deformation
Machine compatibility test	Above 70%
Force analysis	Maximum deflection of 1mm

Figure 25: Overview of experimental setup

Description of experimental procedure

Gripping test

Due to limitations with the robot's programming, the gripping tests were carried out manually. Each gripper design was mounted into the same base, which in turn was attached to the robotic arm. Manual force was used to close the gripper around the sample plate. Although the motor was not powered during testing, the passive clamping force generated was sufficient to securely hold the plates under test conditions.

The following test sequence was performed for each gripper and each plate type (A and B)

1. Grip the empty plate to assess fit and grip
2. Apply the maximum load (equivalent to a water-filled plate) in the center
3. Apply half the maximum weight at either end of the plate to simulate uneven loading (h1 and h2)
4. Apply a quarter of the total weight in each corner (to simulate uneven leads) (c1, c2, c3, and c4)

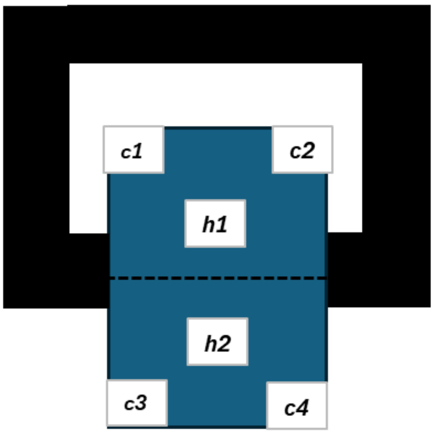


Figure 26: Illustration of where weight was distributed on the sample plate

Deflection test

A test was performed to measure the deflection of the entire gripper system (base and grippers). The test system is illustrated in figure xx.

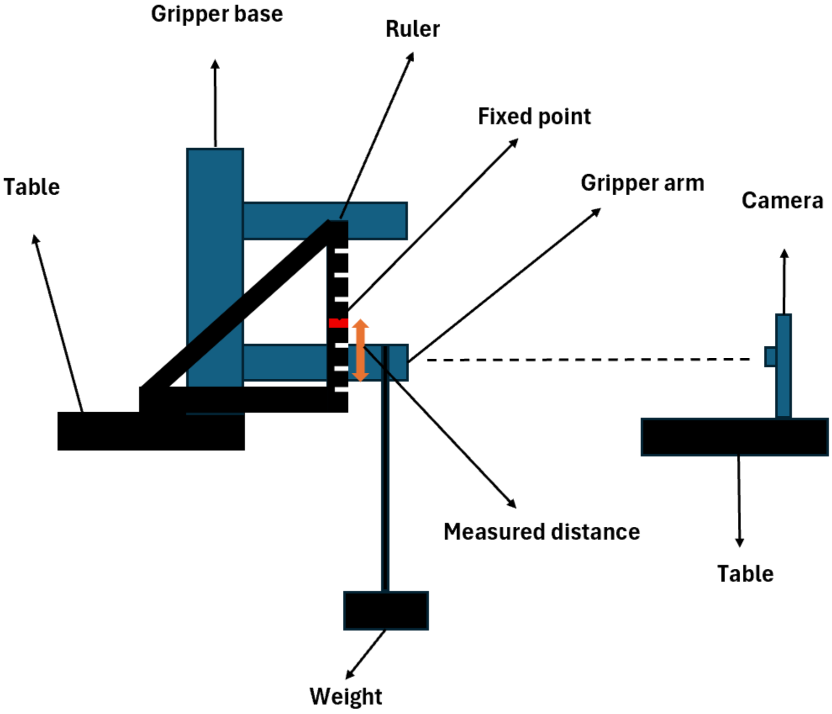


Figure 27: Deflection test setup of the entire gripper system.

The gripper system was clamped to a table, to make sure it was securely attached. A ruler was placed behind the system. On the ruler, a fixed point was set for later image analysis. A phone was securely placed in front to take a picture of the system (see picture of test setup, appendix 1). Weight was applied to one gripper; a picture was taken, and the deflection could be measured in the image analysis software Fiji (ImageJ).

The following test sequence was performed for each gripper:

1. A control picture before the weight is applied.
2. Pictures with different weights are applied, 100 g, 200 g, ..., 1000 g.
3. Image analysis in software Fiji (ImageJ).
    a. The control picture taken at step 1 is used to set the scale and to measure the control distance from the fixed point on the ruler to the bottom of the gripper arm.
    b. The scale is then set on the pictures of the system, where different weights are applied, and the distance from the fixed point and the bottom of the gripper is measured.
    c. The measured distance is then subtracted by the control distance to find the total deflection at a given point.

In this test case, the experiment was not repeated. It is, however, recommended to repeat the test to estimate the margin of error.

Results

In the following section, the results from the two experimental tests and the three grippers are compared in their performance.

Gripping test

Gripper 3.1:

This gripper demonstrated the overall best performance.

- With sample plate A, it passed all tests, except when a load was applied to the front half of the plate (h2)
- With sample plate B, it failed to hold the plate when weight was applied to either end (h1 and h2) or in the front corners (c3 and c4)

These results suggest that while the blue gripper provided the best grip effect, it lacked sufficient force transmission towards the front.

Test gripper 3.1								
	Without weights	80 g	40 g, h1	40 g, h2	20 g, c1	20 g, c2	20 g, c3	20 g, c4
Sample plate A	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
	Without weights	355 g	177 g, h1	177g, h2	88 g, c1	88 g, c2	88 g, c3	88 g, c4
Sample plate B	🟩	🟩	🟥	🟥	🟩	🟩	🟥	🟥

Figure 28: Grip test results for gripper 3.1 (pass/fail)

Gripper 2.4

This design used four screws as contact points, but it consistently underperformed, likely due to the “give” of the base which caused the grippers to deflect too much, making only 2 of the 4 contacts points grabbing the sample plate.

- The gripper only succeeded in holding sample plate A with no load and an evenly distributed maximum load.
- In all other tests, especially with uneven or heavier loads, the gripper failed to maintain a secure hold.
- The gripper scratched the sample plates and could potentially poke a hole if the force applied was sufficient.

This shows that a point-based gripping system without surface contact may not be reliable for varying plate types and weight loads.

Test gripper 2.4								
	Without weights	80 g	40 g, h1	40 g, h2	20 g, c1	20 g, c2	20 g, c3	20 g, c4
Sample plate A	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥
	Without weights	355 g	177 g, h1	177g,2	88 g, c1	88 g, c2	88 g, c3	88 g, c4
Sample plate B	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Figure 29: Grip test results for gripper 2.2 (pass/fail)

Gripper 3.2

The grey showed a similar performance profile to the blue gripper, but a slightly reduced capacity.

- It was capable of securely holding sample plate B without any load, and when weight was applied to the backend corners (c1 and c2)
- However, when the same weight was applied to the front corners, the plate would tilt.
- When larger loads were applied, it would also fail to maintain a firm grip.

Test gripper 3.3								
	Without weights	80 g	40 g, h1	40 g, h2	20 g, c1	20 g, c2	20 g, c3	20 g, c4
Sample plate A	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
	Without weights	355 g	177 g, h1	177g,2	88 g, c1	88 g, c2	88 g, c3	88 g, c4
Sample plate B	🟩	🟥	🟥	🟥	🟩	🟩	🟥	🟥

Figure 30: Grip test results for gripper 3.2 (pass/fail)

A shared weakness

All three grippers demonstrated a common weakness. The front half of the plate (h2) was consistently the most unstable area under testing for both sample plates (A and B). This is likely due to the force distribution as well as the deflection of the whole gripper system. Because the gripping force originates high up, near the mounting point between the base and the gripper, there is a loss of force transmission towards the tip of the gripper. Combined with the flexibility of the base, this results in a non-uniform force distribution, with significantly more pressure applied at the rear contact points than at the front. This mismatch is especially problematic under asymmetric load conditions, where the plate's weight is not evenly distributed.

Deflection test

Figure 12 presents the total deflection of the complete assembly under varying applied weights for three different grippers. The x-axis represents the deflection ranging from 0 to 8 mm, while the y-axis shows the applied weight ranging from 0 to 1200 g. The complete dataset can be found in appendix 2.

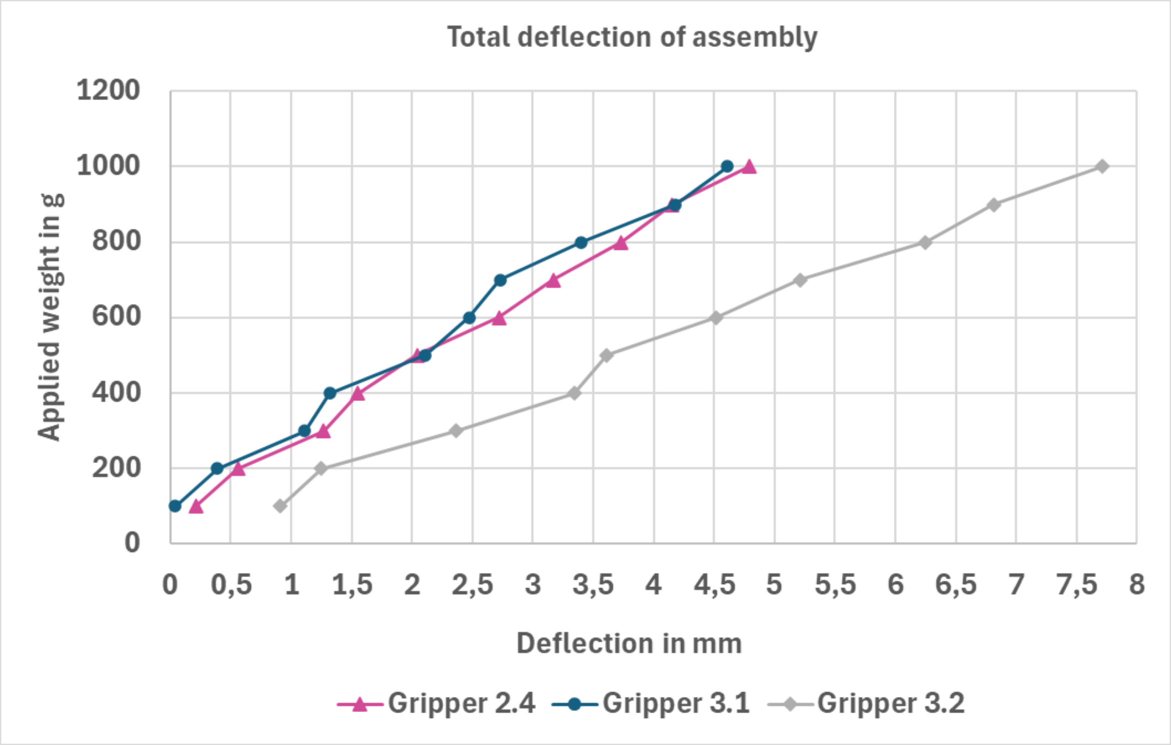


Figure 31: Result from a test of the total deflection of the assembly with the 3 different grippers.

In general, across all test cases, there is a trend suggesting a linear relationship between the applied weight and deflection.

Gripper 3.1

For the assembly with gripper 3.1 we see the lowest amount of deflection under applied load with a maximal deflection of 4,6 mm at 1000 g.

Gripper 2.4

The curve for the assembly with gripper 2.4 closely follows the curve of gripper 1, but with an average deflection of 0,2 mm higher under the applied loads.

Gripper 3.2

The assembly with gripper 3.2 is where the most deflection occurs. With a deflection of approximately 1 mm with an applied weight of 100 g and a maximum deflection of 7,7 mm at 1000 g.

The test in general shows that there is substantial deflection under applied loads and that the deflection not only occurs on the grippers but from the whole base and assembly. In the next section the actual deflection that comes from the grippers will be investigated.

Description of theoretical/numerical analysis (Force analysis)

During our design iterations, multiple force analyses were conducted to determine the optimal geometry of the plastic gripper. This was important to ensure that the gripper remained stiff with minimal deflection when gripping a plate, while also being thin enough to fit into various machines such as those used in hotels.

To define the applied force in our SolidWorks simulations at the gripper's contact points, a calculation was needed to estimate how much force is required to lift a sample plate. The friction coefficient of rubber on impact-resistant polystyrene was used as a reference, as it is the closest material found to PLA. For soft rubber, which was used in the contact areas of the gripper, the friction coefficient ranges from 1.6 to 1.87. (See Figure 32)

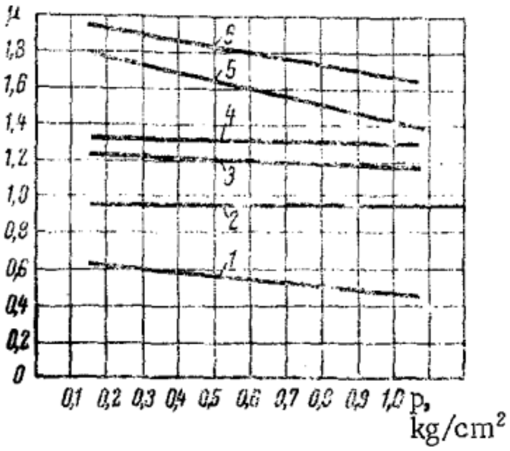


Figure 32: Friction coefficient of soft rubber with respect to the plastics: 1) polytetrafluoroethylene, 2) rigid polyvinyl chloride, 3) polyethylene P4020-C, K, 4) polyethylene P2010-T, 5) polymethylmethacrylate, 6) impact-resistant polystyrene. (D.S.)

We selected the lower friction coefficient value of 1.6 for our calculations to ensure a conservative estimate for safety and reliability. To estimate the gripping force required from each side of the gripper, we used the following formulas:

$$F = \frac{m \cdot g}{\mu} \; and \; F_{each\ gripper} = \frac{F}{2}$$

For sample plate A

For sample plate A, the filled weight is 80 grams, which corresponds to 0.080 kilograms. The gravitational force acting on the plate is:

$$0{,}080\ kg * 9{,}8\ \frac{m}{s^2} = 0{,}7840\ N$$

Using a friction coefficient of 1.6, the required total normal force is:

$$\frac{0{,}7840\ N}{1.6} = 0{,}49\ N$$

Dividing the force between the two grippers:

$$\frac{0{,}49\ N}{2} = 0{,}245\ N$$

For sample plate B

For sample plate B, the filled weight is 355 grams, or 0.355 kilograms. The gravitational force is:

$$0{,}3550\ kg \cdot 9{,}8\ \frac{m}{s^2} = 3{,}479\ N$$

The required total normal force is:

$$F = \frac{3{,}479\ N}{1{,}6} = 2{,}174\ N$$

Dividing between both grippers: $\frac{2{,}174\ N}{2} = 1{,}087\ N$

This analysis shows that to lift a filled sample plate A, each gripper must apply a normal force of approximately **0,25 N**, while for the heavier sample plate B, each gripper must apply approximately **1,08 N**. These values were used to define the boundary conditions in the SolidWorks simulations.

Payload Limitation and Practical Gripping Capacity

According to the referenced master's thesis, the robot system was able to handle a total payload of 750 grams with the old gripper arm already attached. The old gripper assembly, including its base, had a combined weight of 330 grams. The new and improved base with two grippers attached weighs 407 grams.

This means the available payload in the new setup is calculated as:

$$750\ g + 330\ g - 407\ g = 673\ g$$

Under the new design, the gripper must therefore be able to safely lift and hold items weighing up to **673 grams**. Based on our earlier friction analysis, this is entirely achievable with the updated configuration. To verify this, we calculated the required gripping force using the following steps:

$$0{,}673\ kg \cdot 9{,}8\ \frac{m}{s^2} = 6{,}595\ N$$

$$F = \frac{6{,}595\ N}{1{,}6} = 4{,}122\ N$$

$$\frac{4{,}122\ N}{2} = 2{,}061\ N$$

To ensure reliability and accommodate potential variation in surface conditions, manufacturing tolerances, or material fatigue, we applied a safety factor in our SolidWorks simulations. With a safety factor of approximately 3, this results in a required maximum design force of around **6 N per gripper**.

Force analysis results

In this chapter, we present the simulations conducted during the development of our gripper design, specifically for all Iteration 2 models and the final Iteration 3 model. These simulations were essential in guiding the evolution of the gripper geometry and ensuring that the final design met the mechanical and dimensional requirements for use in various medical machines designed for handling plastic sample plates.

The project began with Iteration 1, where we created a simple physical prototype based on our initial concept and idea generation process. This version was 3D printed without any simulation or numerical analysis. The purpose was to quickly explore form, scale, and physical interaction with the sample plates. While this gave us valuable hands-on feedback, it lacked the mechanical validation needed for further development.

2nd Iterations

During the second iteration, we began integrating simulation into our design process. At this stage, we focused purely on structural performance without applying any safety factor. Each simulation was run with a 2 N force applied to a single gripper arm to analyse how different geometries performed under realistic gripping conditions.

Below are the results from the simulations:

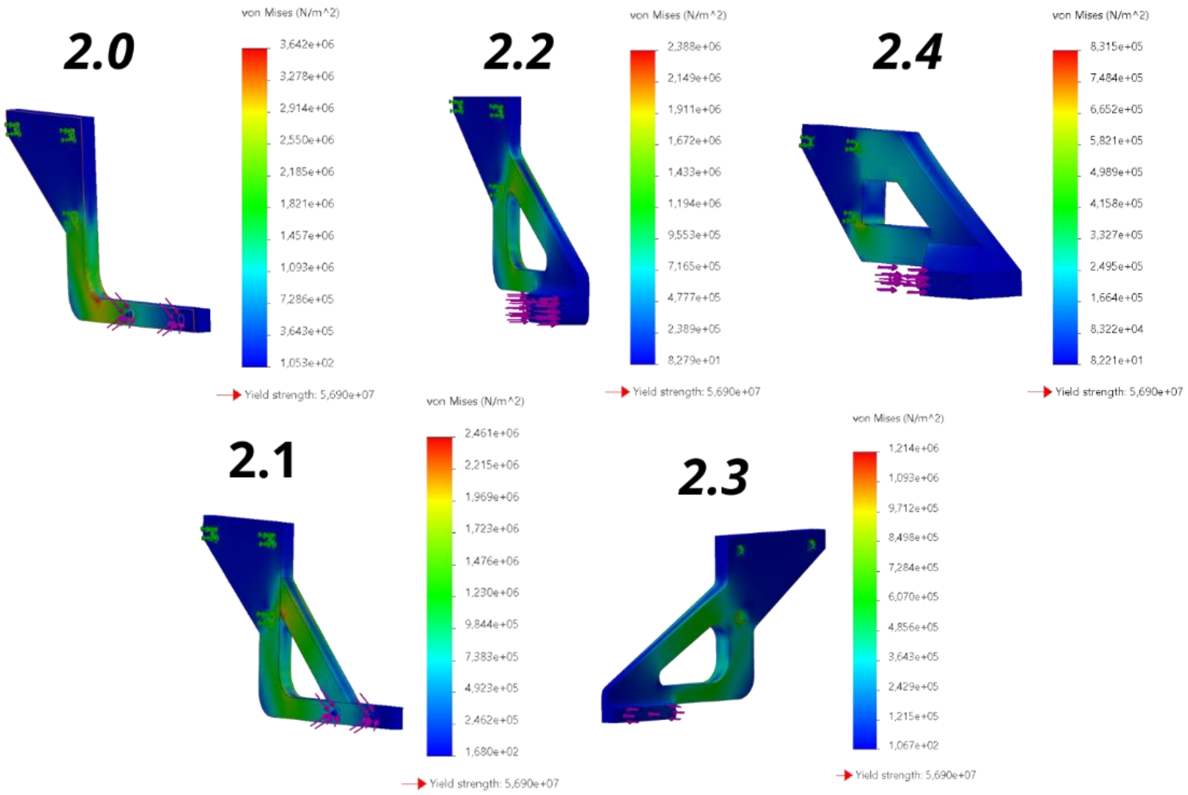


Figure 33: Stress simulations of all second iterations in SolidWorks, with a 6 N force applied at the contact points of a single gripper.

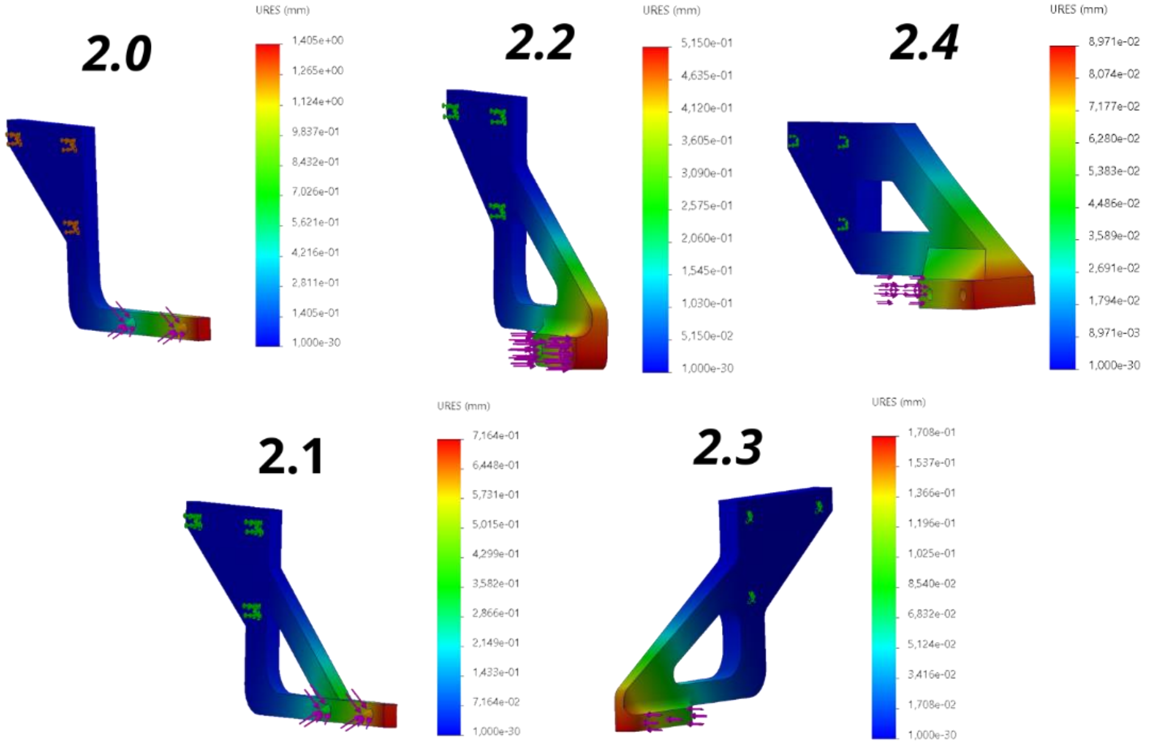


Figure 34: Displacement simulations of all second iterations in SolidWorks, with a 6 N force applied at the contact points of a single gripper 35

From the results of the displacement and stress simulations, we observed clear differences between each sub-version of the second iteration (see Figure 33 and **Error! Reference source not found.** 23). The initial version, Iteration 2.0, experienced very high deformation, with a maximum displacement of approximately 1.4 mm. Such a level of flex would likely compromise the gripper's ability to hold and place medical plates. Additionally, high stress concentrations were found at sharp internal corners, indicating potential failure points under repeated loading.

In response, Iteration 2.1 introduced a supporting beam to improve stiffness. This modification reduced the displacement to around 0.7 mm, effectively halving the previous result. However, stress concentrations at the corners remained a concern.

For Iteration 2.2, we made two key design changes: the length of the gripper was shortened to reduce tip flexibility, and fillets were added to all critical corners to minimize sharp stress transitions. This led to a more stable design with improved deformation.

Building on this, Iteration 2.3 implemented a tapered profile by maintaining a thicker base while gradually thinning toward the gripping tips. This adjustment significantly improved performance, bringing the maximum displacement down from 0.5 mm to just 0.1 mm. This improvement was likely due to both the reduced mass at the ends and more efficient load distribution. The fillets from Iteration 2.2 were retained to continue relieving stress in critical areas.

While Iteration 2.3 was functionally successful, it was still limited in reach and needed better compatibility with the plate-machines in the lab. Therefore, Iteration 2.4 focused on combining high stiffness with extended reach by increasing the overall thickness to 10 mm and elongating the arm. This change further reduced the displacement to 0.09 mm, meeting the structural performance targets while allowing access to plate storage systems such as the medical hotels.

However, during physical testing in the lab, we discovered that the increased thickness created new issues. The gripper was now too thick to fit into several machines and could no longer grip plates from both the long and short sides. These limitations highlighted the need for further refinement in Iteration 3, with a focus on balancing stiffness, reach, and geometric compatibility.

It is also worth noting that in all second iteration simulations, the maximum von Mises stress observed was approximately $2.4 \cdot 10^6 \frac{N}{m^2}$, which is significantly below the yield strength of the PLA-like material used, set at $5.69 \cdot 10^7 \frac{N}{m^2},$. This confirms that, structurally, none of the designs approached the material's failure limit under the simulated load of 6 N, and all geometries stayed well within the elastic range of the material.

Final Iterations

The third iteration was developed to solve the issues identified in iteration 2.4, specifically the need to reduce thickness to fit into lab machines while ensuring the gripper remained long enough to reach into the plate hotels. For these simulations, a safety factor of 3 was introduced to ensure the design could handle extreme loading conditions without permanent deformation.

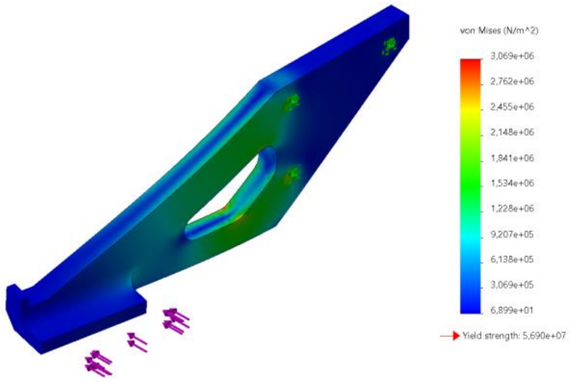


*Figure 36: Stress simulation of **Iteration 3.1** in SolidWorks, with a 6 N force applied at the contact points of a single gripper.*

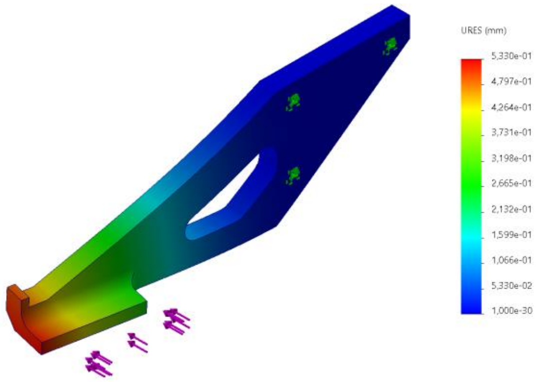


*Figure 37: Displacement simulation of **Iteration 3.1** in SolidWorks, with a 6 N force applied at the contact points of a single gripper.*

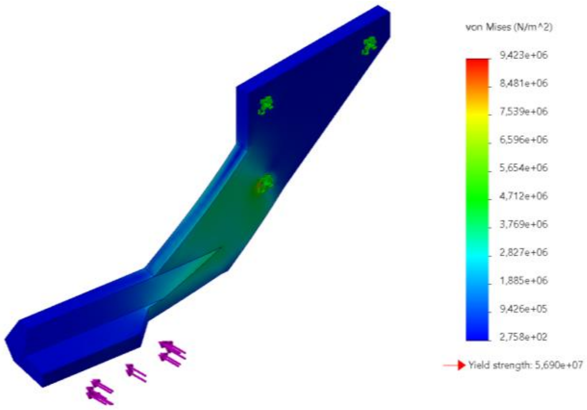


*Figure 38: Stress simulation of **Iteration 3.2** in SolidWorks, with a 6 N force applied at the contact points of a single gripper.*

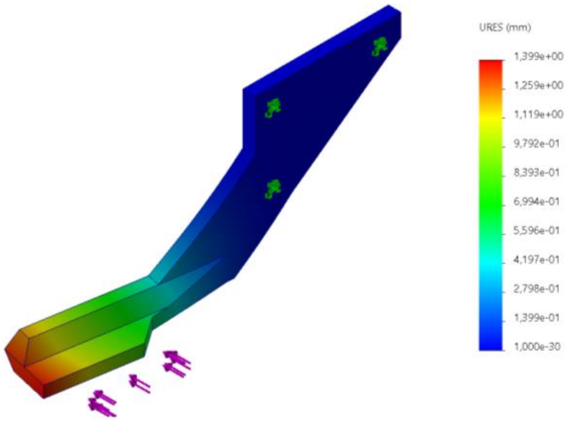


*Figure 39: Displacement simulation of **Iteration 3.2** in SolidWorks, with a 6 N force applied at the contact points of a single gripper.*

For Iteration 3.1, we designed a version capable of handling all expected scenarios. The arm was extended in length, and a supporting beam was added for stiffness and placed so it would not interfere with plate hotel placement. Based on earlier tests, we also added a small hook at the tip to help pull out plates without depending entirely on gripper thickness.

Further testing in the lab revealed that we could grip plates near their end, insert them halfway into the hotel, and then use a programmed motion to push them in completely (see figure XX). With this insight, we retained an 8 mm thickness and achieved a maximum deformation of 0.5 mm (see figure XX), with no significant stress concentration (see figure XX). In contrast, iteration 2.4 was too thick at 10 mm and had a 30 mm wide tip, making it incompatible with both the hotels and other placement systems. Iteration 3.1 reduced the tip width to 20 mm and the thickness to 8 mm, solving both problems.

To explore the limits of thinness, we developed one final version: Iteration 3.2. The goal was to test if a 5 mm thick gripper without a support beam could still function. Although we saw no immediate need for the beam during our lab observations, we were concerned it might interfere with machine edges in future use cases. We added various tapered features to reinforce the geometry.

Simulation results for Iteration 3.2 showed a relatively high deformation of 1.4 mm (see figure XX), about three times more than 3.1. However, no stress values exceeded the yield strength of the material (see figure XX), confirming that the design remained structurally sound.

Comparing with previous gripper

Finally, compared to the gripper that was on the machine when we started the project, we assumed that the original gripper was made of galvanized steel with a thickness of 1.5 mm. By measuring the force applied at different levels, we found that at 20

Newtons, the old, galvanized steel gripper exceeded its yield strength and began to deform plastically (see figure XX).

When performing the same test on our Gripper 3.1, which has a thickness of 8 mm, we found that it did not exceed its yield limit. Additionally, the displacement was only 1 mm, compared to 4 mm for the metal gripper. This clearly shows that our plastic gripper outperforms the old one in terms of both stiffness and yield strength.

However, it is important to note that our design is significantly thicker than the original metal gripper, which is a trade-off in terms of material usage and form factor.

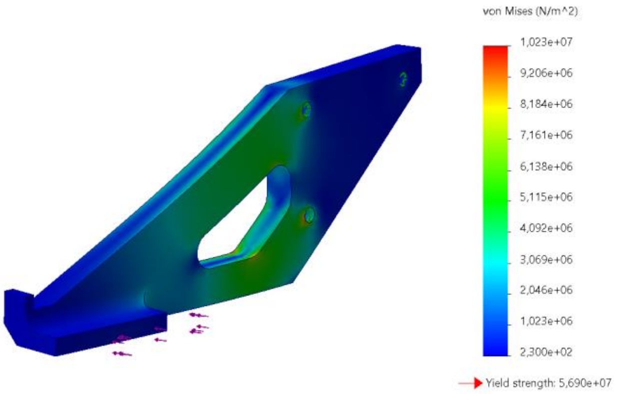


*Figure 40: Stress simulation of **Iteration 3.1** in SolidWorks, with a 20 N force applied at the contact points of a single gripper.*

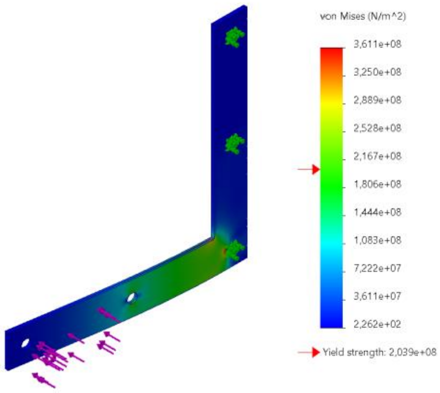


*Figure 41: Stress simulation of **old gripper** in SolidWorks, with a 20 N force applied at the contact points of a single gripper*

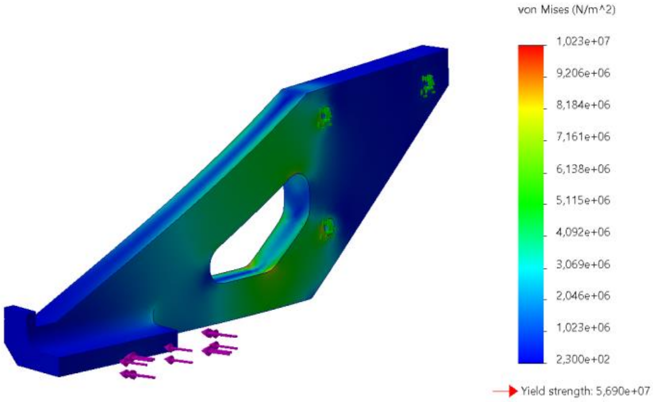


*Figure 42: Displacement simulation of **Iteration 3.1** in SolidWorks, with a 20 N force applied at the contact points of a single gripper*

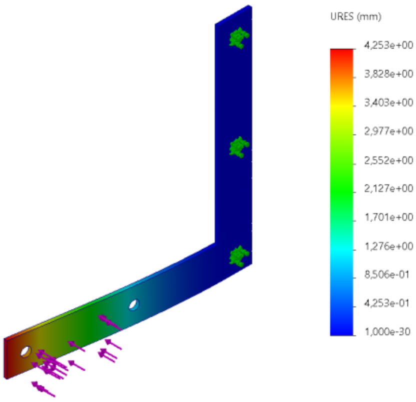


*Figure 43: Displacement simulation of **old gripper** in SolidWorks, with a 20 N force applied at the contact points of a single gripper*

Comparison with experimental results

When comparing our physical test results to the simulation outcomes, a significant difference in deflection becomes evident (see figure xx). Simulations performed using the same load values applied in the physical tests showed much lower deflection, suggesting that the observed displacement in the real setup is not coming from the grippers alone.

Ideally, we would have performed physical tests on the grippers in isolation to better compare with the simulation data, which was based on the gripper alone (not the full assembly including gears and base). However, due to time constraints, we only tested the full assembled setup and compared that to the gripper-only simulations.

Our observations indicate that the excessive deflection seen in the physical tests is largely caused by movement and flexibility within the base assembly itself (see data appendix 3).

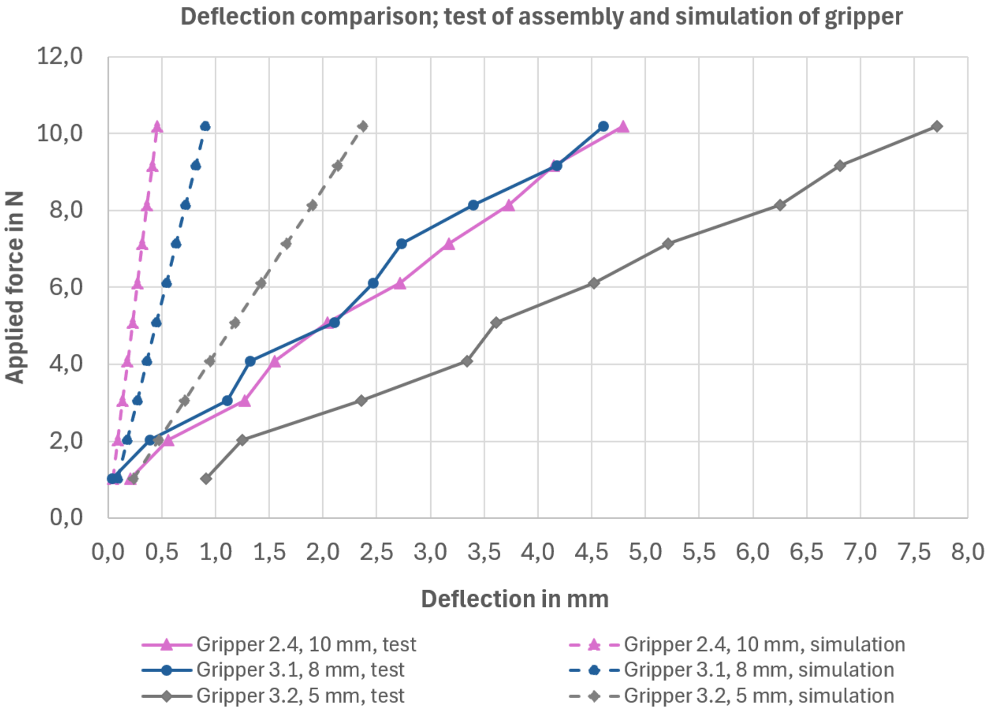


Figure 44: Comparison of deflection between physical tests and SolidWorks simulations for three gripper designs under increasing applied force.

We therefore believe the main reasons for the increased real-world deflection are:

- **Low assembly tolerance:** Due to sanding and 3D printing imprecision, the base has several small gaps that contribute to overall movement in the system.
- **Insufficient structural design for 3D printing:** Some parts, such as the gears and base walls, may be too thin or flexible and require design improvements to better resist deformation underload.

Lifetime

The lifetime for gripper 3.1 was determined under a cyclic fatigue test simulation under constant amplitude events with defined cycles. The simulation is Zero Based (LR=0) meaning that the load varies from zero to a maximum value. Since it wasn’t possible to find reliable fatigue test data (e.g. S/N, Wöhler curve) for PLA, stress amplitude at specific cycles was obtained for PP (Ticona GmbH, 2004, s. 6) as input data for the simulation. Since there are major differences between the mechanical properties of PLA and PP, the results of the test can only serve as a guideline. Since the gripper arm is only submitted to a limited force of 6 N, there is no damage after 1.000.000 cycles (see figure xx). 1.000.000 cycles are considered the minimum lifetime, since this approximately corresponds to daily operation of 1000 sample plates over 3 years.

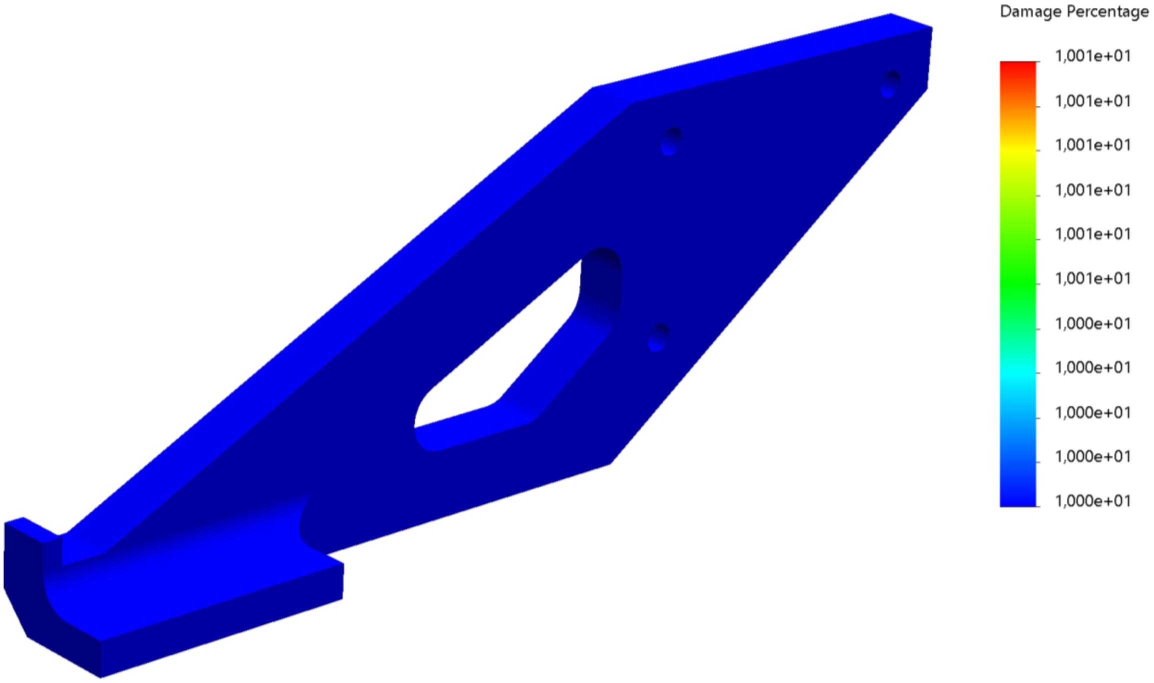
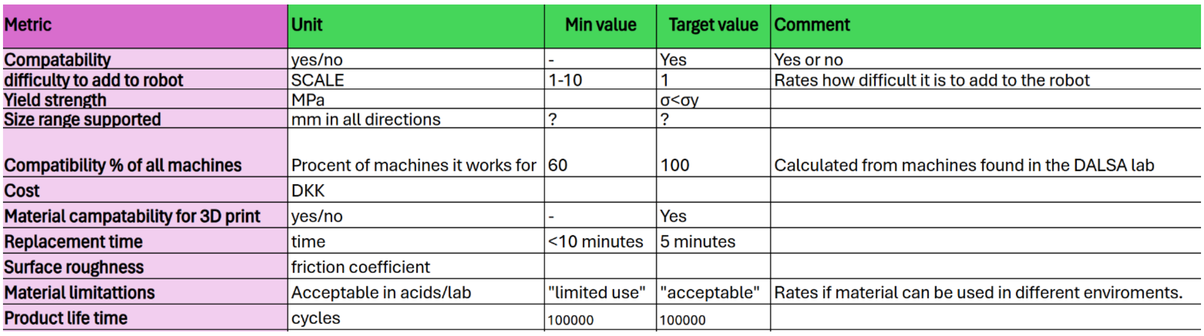


Figure 45: Fatigue simulation at 1.000.000 cycles.

Even though the simulations suggest there is no damage, it is however considered that some damage will occur, due to e.g. operation and cleaning (which potentially can contain dissolving chemicals). Furthermore, the actual gripping zone will have softer material with higher friction coefficient e.g. rubber that will be worn quicker and should be replaced regularly to secure proper gripping.

In conclusion comparable and reliable test data is needed to make valid assumptions regarding fatigue of the actual gripper based on simulations. Therefore, this would have to be investigated further to make any valid conclusions. These results, however, serve as an indicator that the assumption: that the low force applied to the gripper will not result in major fatigue damage over the minimum lifetime set to 3 years.

Evaluation of metric



Metric	**Unit**	**Min value**	**Target value**	**Comment**
Compatability	yes/no	-	Yes	Yes or no
difficulty to add to robot	SCALE	1-10	1	Rates how difficult it is to add to the robot
Yield strength	MPa		σ<σy	
Size range supported	mm in all directions	?	?	
Compatibility % of all machines	Procent of machines it works for	60	100	Calculated from machines found in the DALSA lab
Cost	DKK			
Material campatability for 3D print	yes/no	-	Yes	
Replacement time	time	<10 minutes	5 minutes	
Surface roughness	friction coefficient			
Material limitattions	Acceptable in acids/lab	"limited use"	"acceptable"	Rates if material can be used in different enviroments.
Product life time	cycles	100000	100000	

Table 5: Metrics

The gripper is compatible with the existing 3D printed robot arm. The gripper attaches to the robot arm with two bolts and two nuts. The gripper arms are easily attachable with 3 bolts and 3 nuts on each arm and it takes 5 minutes to attach and detach them. The force analysis shows that arms of the gripper are designed in a way that when the force is applied, arms of the gripper do not exceed the yield strength of the material. The whole gripper is made out of 3D printable material with the exception of 2 metal rods. PLA is the material that it was used for 3D printing. Gripper 2.4 is compatible with 50% of the machines in the lab. Gripper 3.2 has a compatibility of 87,5%. That means that this gripper can fit into every machine except Plate hotels. Gripper 3.1 is the best gripper, and it is compatible with every machine in the lab. The gripper lifetime is expected to be 1.000.000 cycles. That means the grippers lifetime is 3 years.

Proposals for future work

Of the three selected prototypes the most suitable for the application is gripper 3.1. The gripper stays within the setup minimum and target values from the metric. Furthermore, the design is compatible with 100% of the machines from the DALSA lab. The gripper further has a limited deflection of 0,53 mm at the max calculated gripping force with a safety factor of 3. It is however observed that the deflection may derive from the base and not the actual gripper.

A further Finite element analysis of the whole assembly would give a good indication of where the deflection is highest and where the base would need to be thickened just as we did with the simulations for the gripper. This was tried but with the different files the assembly in SolidWorks did not work to make a final mesh. So, with limited time we did not achieve a simulation of everything assembled.

Also, it would be worth looking into a more precise 3D printer with stronger 3D printed material such as carbon fiber reinforced material.

In the rapid prototype process, the base seemed to be a significant challenge during the iteration of the gripper. While the original scope of the project focused on redesigning the gripper. While the original scope of the project focused on redesigning the gripper itself, it quickly became evident that the performance of the gripper was heavily influenced by the base. A considerable amount of time was therefore spent attempting to improve the base to support the new gripper designs. However, due to the limited timeframe and the defined scope of the course, a fully stable and optimized base was not achieved.

It is strongly recommended to further investigate and improve the mechanical design of the base in future work, as this aspect was not fully addressed within the timeframe of the course. If the current mechanical concept is chosen, switching to standard metal gears and gear racks would be recommended. This would likely improve tolerance, increase stiffness, and allow for a thinner design. Enhancing the overall stiffness of the base – either through material upgrades or structural reinforcement – would significantly contribute to a better and more consistent gripper performance.

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Introduction .... **Error! Bookmark not defined.**

Problem formulation .... **Error! Bookmark not defined.**

Product Design Requirements .... **Error! Bookmark not defined.**

Material selection .... **Error! Bookmark not defined.**

Brainstorm .... **Error! Bookmark not defined.**

First iteration prototype .... **Error! Bookmark not defined.**

  Grippers .... **Error! Bookmark not defined.**

  Base .... **Error! Bookmark not defined.**

Limitations and improvements (after 1 iteration) .... **Error! Bookmark not defined.**

2nd iteration 17

Final iteration .... **Error! Bookmark not defined.**

Final iteration gripper: .... **Error! Bookmark not defined.**

Machine capabilities .... **Error! Bookmark not defined.**

Experimental plan with an overview in table form .... **Error! Bookmark not defined.**

Description of experimental procedure ....**Error! Bookmark not defined.**

Results...**Error! Bookmark not defined.**

Description of theoretical/numerical analysis (Force analysis)...... **Error! Bookmark not defined.**

  For sample plate A...**Error! Bookmark not defined.**

  For sample plate B...**Error! Bookmark not defined.**

  Payload Limitation and Practical Gripping Capacity .....**Error! Bookmark not defined.**

Force analysis results ....**Error! Bookmark not defined.**

  2nd Iterations..**Error! Bookmark not defined.**

  Final Iterations 34

    Comparing with previous gripper............................**Error! Bookmark not defined.**

Comparison with experimental results ....**Error! Bookmark not defined.**

  Lifetime ....**Error! Bookmark not defined.**

Evaluation of metric ....**Error! Bookmark not defined.**

Proposals for future work ....**Error! Bookmark not defined.**

Appendix..**Error! Bookmark not defined.**

Appendix

Appendix 1: Test setup 1 pictures

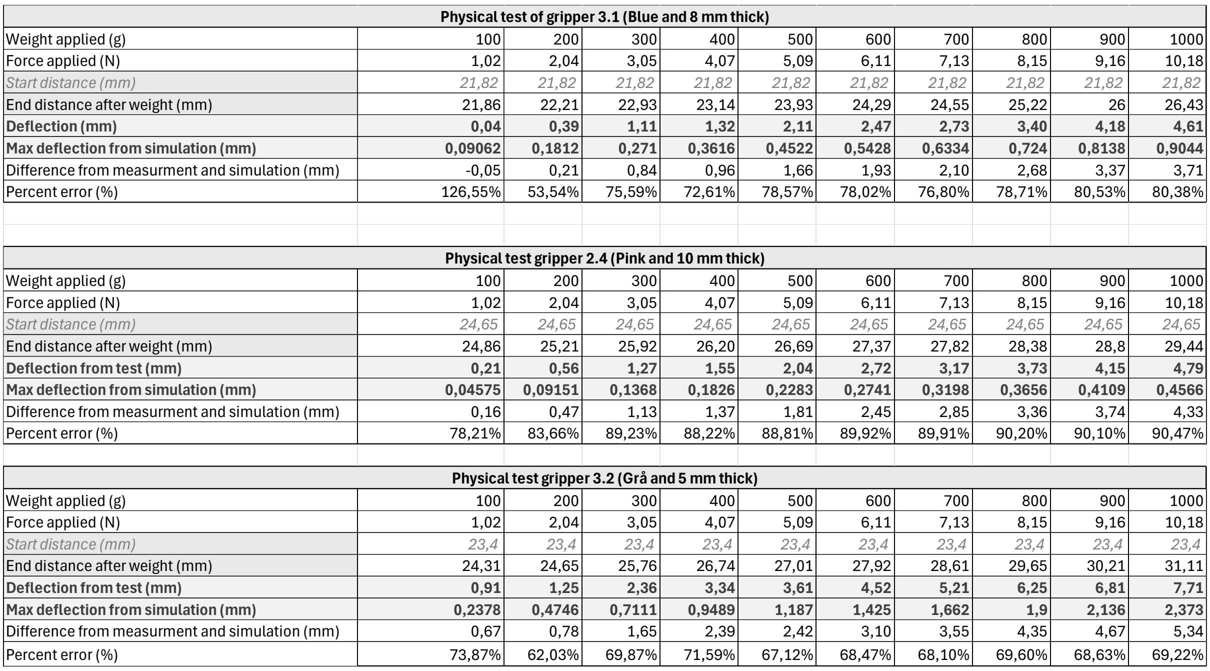
Appendix 2: Data test 2, total deflection of assembly

Test gripper 3.1											
	Without weights	100 g	200 g	300 g	400 g	500 g	600 g	700 g	800 g	900 g	1000 g
Distance from fixed point to bottom of gripper	21,82	21,86	22,21	22,93	23,14	23,93	24,29	24,55	25,22	26	26,43
		0,04	0,39	1,11	1,32	2,11	2,47	2,73	3,40	4,18	4,61

Test gripper 2.4											
	Without weights	100 g	200 g	300 g	400 g	500 g	600 g	700 g	800 g	900 g	1000 g
Distance from fixed point to bottom of gripper	24,65	24,86	25,21	25,92	26,20	26,69	27,37	27,82	28,38	28,8	29,44
		0,21	0,56	1,27	1,55	2,04	2,72	3,17	3,73	4,15	4,79

Test gripper 3.2											
	Without weights	100 g	200 g	300 g	400 g	500 g	600 g	700 g	800 g	900 g	1000 g
Distance from fixed point to bottom of gripper	23,4	24,31	24,65	25,76	26,74	27,01	27,92	28,61	29,65	30,21	31,11
		0,91	1,25	2,36	3,34	3,61	4,52	5,21	6,25	6,81	7,71

Appendix 3: Data from simulations and the comparison graph



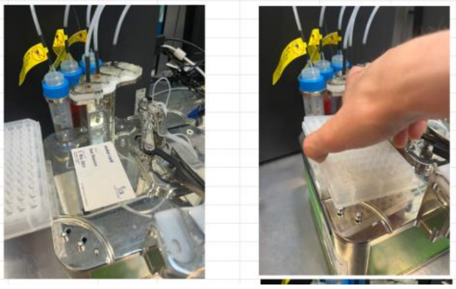
Physical test of gripper 3.1 (Blue and 8 mm thick)										
Weight applied (g)	100	200	300	400	500	600	700	800	900	1000
Force applied (N)	1,02	2,04	3,05	4,07	5,09	6,11	7,13	8,15	9,16	10,18
Start distance (mm)	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*	*21,82*
End distance after weight (mm)	21,86	22,21	22,93	23,14	23,93	24,29	24,55	25,22	26	26,43
Deflection (mm)	**0,04**	**0,39**	**1,11**	**1,32**	**2,11**	**2,47**	**2,73**	**3,40**	**4,18**	**4,61**
Max deflection from simulation (mm)	**0,09062**	**0,1812**	**0,271**	**0,3616**	**0,4522**	**0,5428**	**0,6334**	**0,724**	**0,8138**	**0,9044**
Difference from measurment and simulation (mm)	-0,05	0,21	0,84	0,96	1,66	1,93	2,10	2,68	3,37	3,71
Percent error (%)	126,55%	53,54%	75,59%	72,61%	78,57%	78,02%	76,80%	78,71%	80,53%	80,38%

Physical test gripper 2.4 (Pink and 10 mm thick)										
Weight applied (g)	100	200	300	400	500	600	700	800	900	1000
Force applied (N)	1,02	2,04	3,05	4,07	5,09	6,11	7,13	8,15	9,16	10,18
Start distance (mm)	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*	*24,65*
End distance after weight (mm)	24,86	25,21	25,92	26,20	26,69	27,37	27,82	28,38	28,8	29,44
Deflection from test (mm)	**0,21**	**0,56**	**1,27**	**1,55**	**2,04**	**2,72**	**3,17**	**3,73**	**4,15**	**4,79**
Max deflection from simulation (mm)	**0,04575**	**0,09151**	**0,1368**	**0,1826**	**0,2283**	**0,2741**	**0,3198**	**0,3656**	**0,4109**	**0,4566**
Difference from measurment and simulation (mm)	0,16	0,47	1,13	1,37	1,81	2,45	2,85	3,36	3,74	4,33
Percent error (%)	78,21%	83,66%	89,23%	88,22%	88,81%	89,92%	89,91%	90,20%	90,10%	90,47%

Physical test gripper 3.2 (Grå and 5 mm thick)										
Weight applied (g)	100	200	300	400	500	600	700	800	900	1000
Force applied (N)	1,02	2,04	3,05	4,07	5,09	6,11	7,13	8,15	9,16	10,18
Start distance (mm)	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*	*23,4*
End distance after weight (mm)	24,31	24,65	25,76	26,74	27,01	27,92	28,61	29,65	30,21	31,11
Deflection from test (mm)	**0,91**	**1,25**	**2,36**	**3,34**	**3,61**	**4,52**	**5,21**	**6,25**	**6,81**	**7,71**
Max deflection from simulation (mm)	**0,2378**	**0,4746**	**0,7111**	**0,9489**	**1,187**	**1,425**	**1,662**	**1,9**	**2,136**	**2,373**
Difference from measurment and simulation (mm)	0,67	0,78	1,65	2,39	2,42	3,10	3,55	4,35	4,67	5,34
Percent error (%)	73,87%	62,03%	69,87%	71,59%	67,12%	68,47%	68,10%	69,60%	68,63%	69,22%

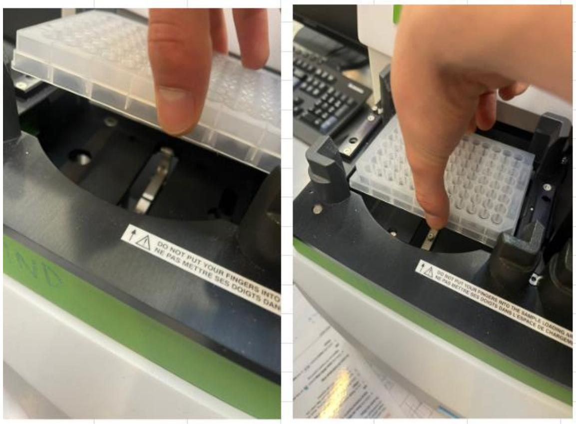
Appendix 4: Lab Machines

Machine 1: Mantice

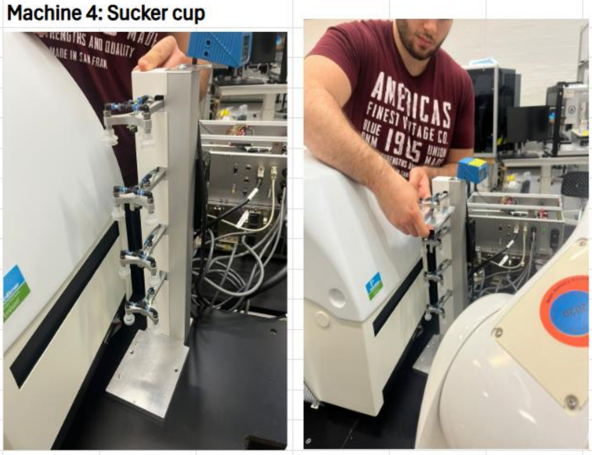


Machine 2: Plat hotel

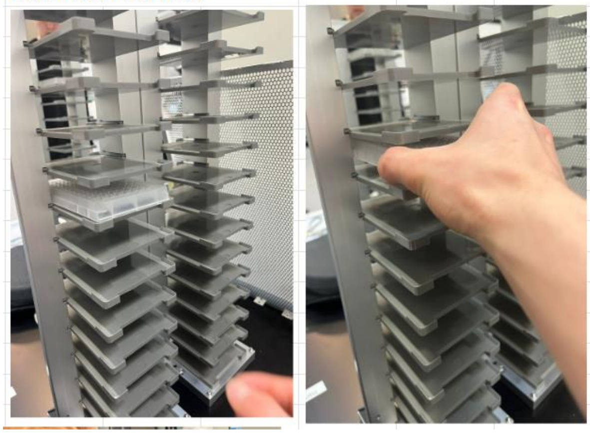
Machine 3: PerkinElmer



Machine 4: Sucker cup



Machine 5: Plate Rack



Machine 6: Sealing Machine

Machine 7 Biotek

Multidrop