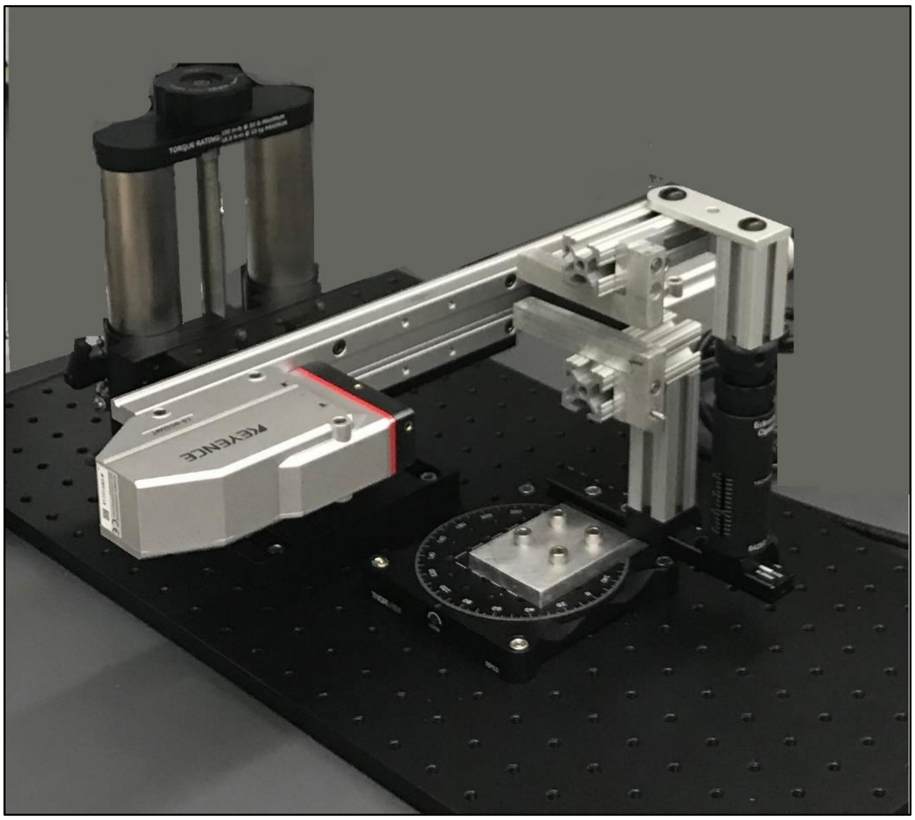
Final Report

Non-Contact Dimensional Measurement of Soft Biological Samples

PSU BME 2
Team Chicken Tenders



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Executive Summary

Measurement of the mechanical properties of biological tissues requires knowledge of the sample dimensions (e.g., cross-sectional area). Because soft hydrated biological materials (e.g., tendons) are extremely compliant, dimensional measurement techniques that contact the sample deform the tissue and provide inaccurate results. An existing non-contact laser-based device provides results that are inaccurate for very small (< 0.5 mm) samples.

Team Chicken Tenders developed a non-contact sensor that measures the cross-sectional area of biological samples smaller than 0.5 cm, for use in Dr. Spenser Szczesny's Biomedical Engineering Lab. The purpose of the device is to measure the major and minor diameters of an embryonic chicken tendon for use in research on understanding the elasticity of tendons.

The objective for this project was to develop a device and associated software to accurately measure the dimensions of biological tissues without contacting the sample. With the help of a graduate student in Dr. Szczesny's lab, Ben Peterson, three major customer needs were identified to develop the final product. The overall system would need to accurately and reliably measure tendons smaller than 0.5 mm, maintain tendon hydration during measurement, and incorporate current lab grips. The final product that was developed was able to hold the custom-built grips into its system and operate in a timely fashion to keep the tendon hydrated. In addition, the system was able to accurately measure tendons with a maximum error of 0.38% and standard deviation of ±1.38 μm.

With the approval from Dr. Szczesny for a budget increase, the device was developed with a total cost of $11,821.80. It was completed within the 15-week period that was allotted for the semester. The final product was presented at the Design Showcase and brought back to Dr. Szczesny's lab for immediate use.

Table of Contents

1.0 Introduction

Team Chicken Tenders developed a non-contact sensor that measures the cross-sectional area of biological samples smaller than 0.5 cm, for use in Dr. Spenser Szczesny's Biomedical Engineering Lab. The purpose of the device is to measure the major and minor diameters of an embryonic chicken tendon for use in research on understanding the elasticity of tendons.

Embryonic tendons are compliant, semi-translucent tissues with ovular cross-sections that range in size from 50-300 um in diameter. Therefore, to aid in their research, Dr. Szczesny's lab required a device that: (1) accurately measures tendons smaller than 0.5 cm without deforming the sample, (2) keeps the sample hydrated, and (3) incorporates custom build tendon grips for holding the sample during testing.

Based on these needs, Team Chicken Tenders developed four design concepts. Two of the designs incorporate commercially available optical hardware (Keyence LS-9030M Optical Micrometer and the Basler Ace acA4024-29um Area Scan camera) into a custom-built system. The overall system will be able to hold the specimen and provide speed and consistency in the measurement process. The Keyence hardware is a non-contact dimensional measurement device that uses a laser to measure the outer diameter of various objects. Meanwhile, the Basler camera is a high-resolution camera able to identify objects down to 7 µm. Other concepts such as developing a laminar flow channel with an incorporated imaging system, or a radar-based distance sensor were considered. The laminar flow channel could keep the specimen hydrated and stationary without need for grips while the radar distance sensors could detect the dimensions of tendons regardless of translucency.

The Keyence LS-9030M laser hardware best satisfied the engineering specifications. The hardware would be mounted to a translating stage that interfaces with a desktop through associated software, which translates the input from the sensor into major and minor diameter values.

2.0 Manufacturing Process

Within the Design Specification Report (DSR), Team Chicken Tenders presented a design that was built around the Basler Ace acA4024-29um camera. However, due to trouble finding a lens with the proper resolving power, the idea was dropped in favor of the Keyence system presented in the Statement of Work Report. This design change is feasible as the underlying structure works for both designs. The only changes in the manufacturing process plan is how the laser itself is secured. A CAD model shown in Figure 1 shows the previous design and the current iteration.

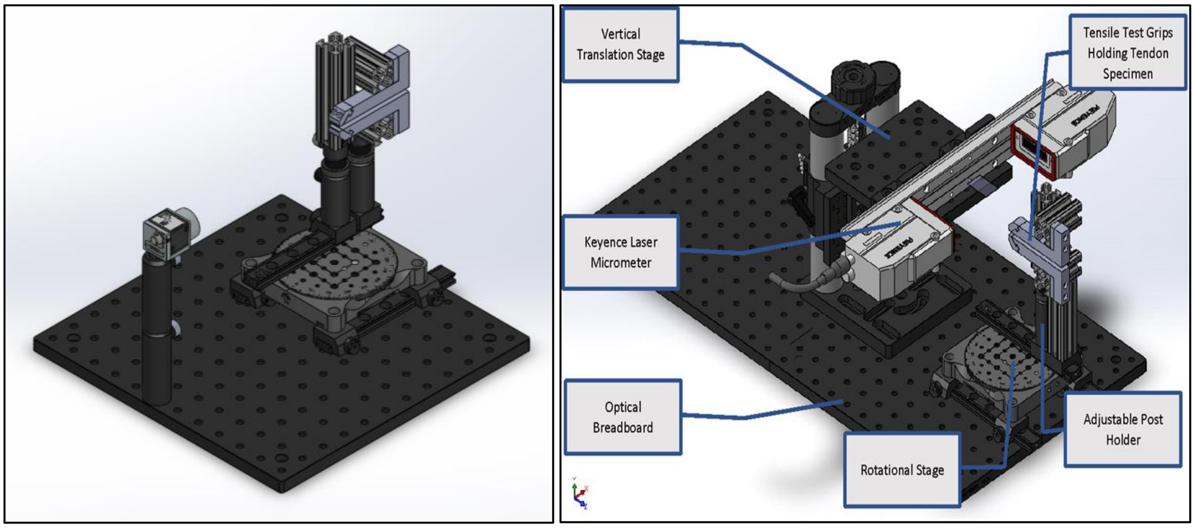

Figure 1. The previous design reported for the DSR (left); current design for final product (right)

The manufacturing process for the final product was a mixture of assembling off-the-shelf components, modifying certain purchased pieces, and manufacturing custom pieces from stock metal. The design was based around equipment purchased from Thorlabs, whose products were built with ¼" tapped holes. This provided a straightforward assembly process for the equipment and adaptability for other lab applications in the future. Table 1 contains the Bill of Materials of the equipment and hardware purchased. The final cost of the materials was reduced from the base cost of the components by $2000 due to a discount provided by Keyence at the time of purchase.

Table 1. Bill of Materials

Company	Item #	Item Description	Quantity	Price	Total	Lead Time
Thorlabs	RP03	Ø4.3" Manual Rotation Stage	1	$259.92	$259.92	Today
Edmund Optics	#84-353	101.6mm Length, ¼"-20 Thread, Adjustable Post Holder	2	$125.00	$250.00	Today
Thorlabs	RLA0600	Dovetail Optical Rail, 6", Imperial	3	$45.72	$137.16	Today
Thorlabs	RC1	Dovetail Rail Carrier, 1.00" x 1.00" (25.4 mm x 25.4 mm), 1/4" (M6) Counterbore	6	$26.94	$161.64	Today
Thorlabs	MB1224	Aluminum Breadboard 12" x 224" x 1/2", 1/4"-20 Taps	1	$272.95	$272.95	Today
Thorlabs	MB4	Aluminum Breadboard 4" x 6" x 1/2", 1/4"-20 Taps	1	$44.13	$44.13	Today
Thorlabs	TR2	Ø1/2" Optical Post, SS, 8-32 Setscrew, 1/4"-20 Tap, L = 2"	1	$5.35	$5.35	Today

Thorlabs	TR3	Ø1/2" Optical Post, SS, 8-32 Setscrew, 1/4"-20 Tap, L = 3"	1	$5.58	$5.58	Today
Thorlabs	AP90	Right-Angle Mounting Plate, ¼"-20 Compatible	1	$86.30	$86.30	Today
Thorlabs	AB90	Right-Angle Bracket with Counterbored Slots	2	$27.85	$55.70	today
Thorlabs	CL5A	Table Clamp, L-Shape, Rounded Lip	2	$4.28	$8.56	today
Thorlabs	VAP4	4" Travel Vertical Translation Stage, 8-32 and 1/4"-20 Taps	1	$740.17	$740.17	today
McMaster-Carr	92311A153	18-8 Stainless Steel Cup-Point Set Screw (pkg of 50)	1	$5.94	$5.94	2-3 days
McMaster-Carr	94758A102	18-8 Stainless Steel Flange Nuts	4	$3.46	$13.84	today
McMaster-Carr	47065T101	T-Slotted Framing and Fittings https://www.mcmaster.com/47065T101	1	$10.57	$10.57	Today
McMaster-Carr	47065T142	Plated Steel End-Feed Fastener, 1/4"-20 Thread for T-Slotted Framing	2	$2.30	$4.60	Today
McMaster-Carr	47065T255	T-Slotted Framing Silver Straight Surface Bracket, 2" Long for 1" High Rail	5	$6.07	$30.35	Today
Keyence	LS-9030M	1D Optical Micrometer	1	$6,500.00	$6,500.00	2-3 days
Keyence	LS-9501	Controller, NPN type	1	$3,700.00	$3,700.00	2-3 days
Keyence	CA-U4#	24V DC Switching Power Supply	1	$280.00	$280.00	2-3 days
Keyence	OP-66844	USB Cable for vision system, 2m	1	$20.00	$20.00	2-3 days
Keyence	LS-H2	LS Navigator 2 Software	1	$1,000	$1,000	2-3 days
Keyence	CB-B3	Sensor Cable	1	$500.00	$500.00	2-3 days
Keyence		Discount			-$2,000.00	
				Total	$11,821.80	

2.1 Vertical Stage Set-up

As shown in Figure 2, the entire structure is assembled on top of a 12" x 24" optical breadboard (MB1224). On one side of the breadboard, the vertical translating stage (VAP4) is screwed on using four ¼" screws. Using a right-angle bracket (AP90) that is attached to the front panel of the stage, an additional 4" x 6" optical breadboard (MB4) is mounted onto the bracket.

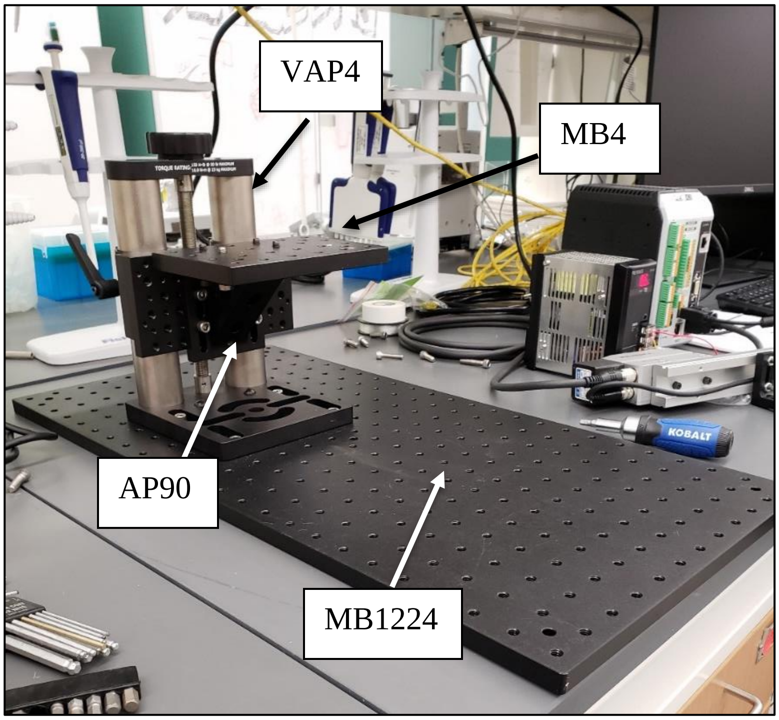

Figure 2. Set up of vertical stage

Prior to having the 4” x 6” breadboard screwed on, the plate needs to be modified. Since the laser will be mounted onto the 4” x 6” breadboard, the non-standard hole spacing on the laser mounting holes (4.33” distance) make it tough to properly secure the laser with the manufactured holes. Therefore, the breadboard needs to be modified by adding two additional ¼” tapped holes 4.33” from the left most set of holes. Figure 3 shows where the two holes where be tapped.

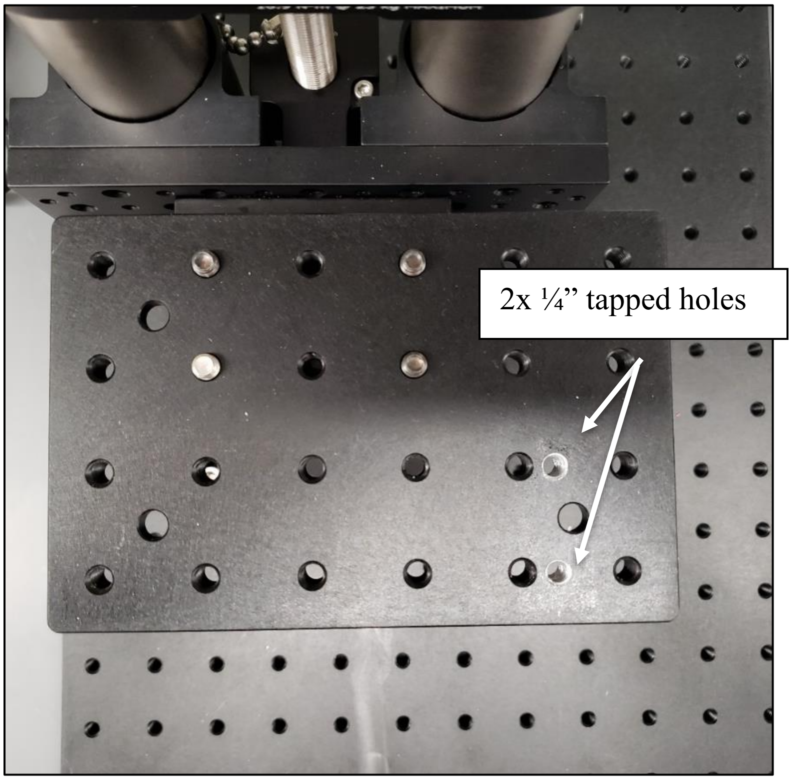

Figure 3. Tapped holes placed 110 mm away from left most holes

Once tapped, the breadboard can be attached to the AP90 right angle bracket using four ¼” screws.

Figure 4 shows how the laser will be attached to two ¼” and M4 slotted right angle brackets (AB90). Four ¼” screws will be used to mount the bracket to the breadboard and four M4 screws for the lasers built in through holes. M4 nuts will be attached to secure the M4 screws to the bracket itself.

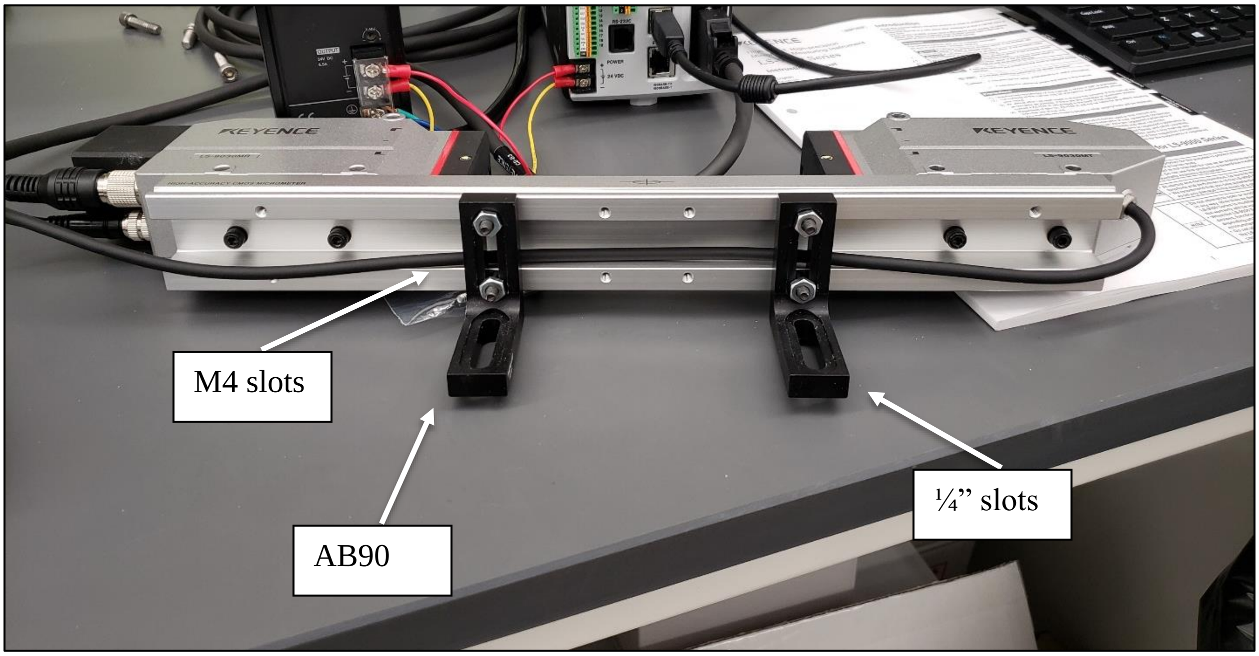

Figure 4. Laser and AB90 attachment

2.2 Rotating Base and Grip Fixtures

Figure 5 shows structure for holding the tendons. This structure revolves on a 4.3” manual rotating stage (RP03). The base will be screwed onto the 12” x 24” breadboard using four ¼” screws.

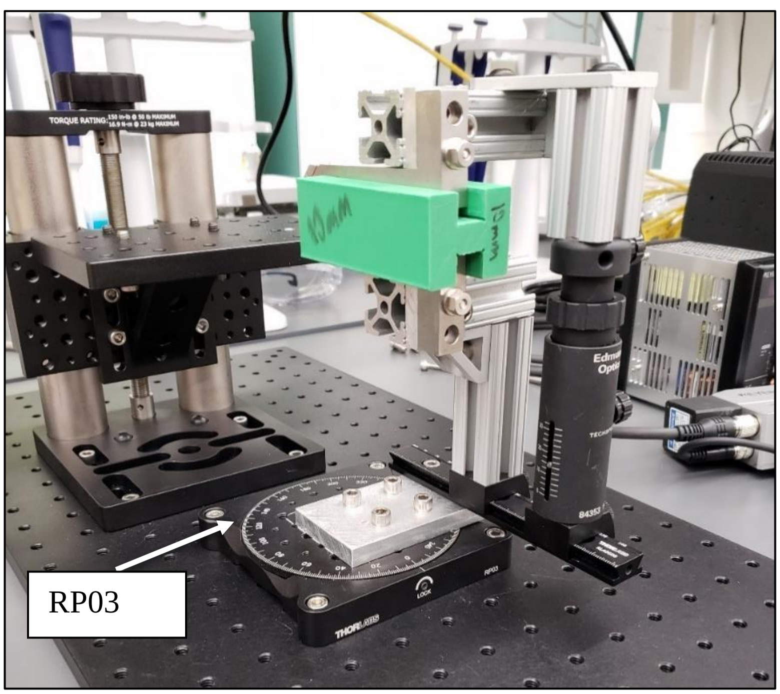

Figure 5. Structure for holding the tendon grip fixtures

The stage will be placed right under the laser where the center of the base is within the full width of the laser path, as shown in Figure 6.

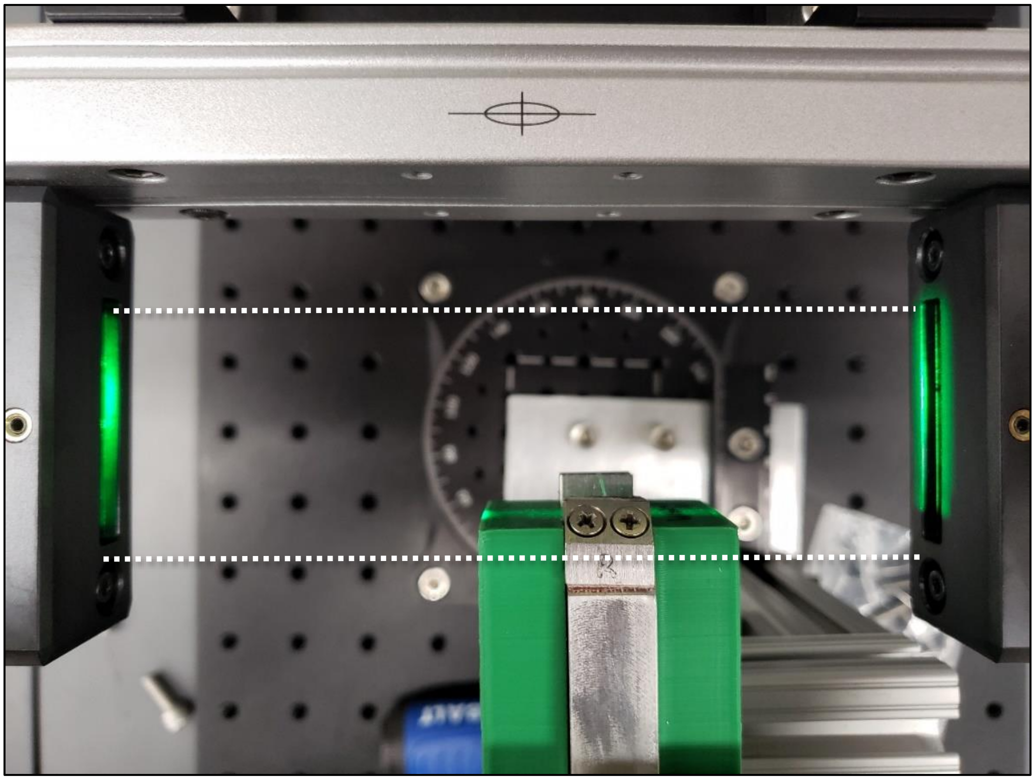

Figure 6. Tendon sample can be placed within the zones shown by the dashed lines

On top of the rotating base, a custom bracket was machined in order to provide an offset between the center of the rotating base and the optical rail (RLA0600) that will hold the grip fixtures. Figure 7 shows the manufactured piece on top of the stage.

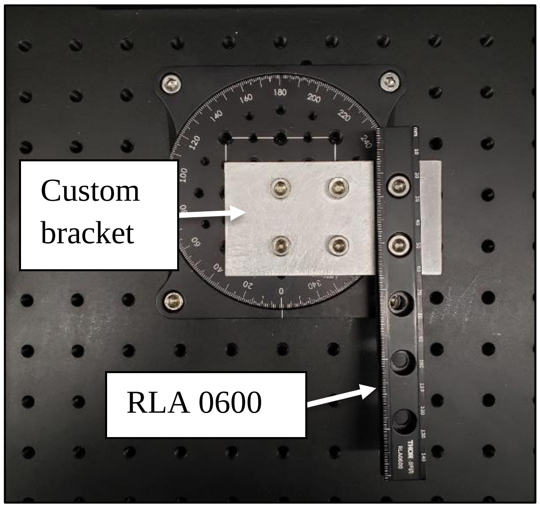

Figure 7. Custom built bracket

Once the piece is manufactured, it can be screwed onto the rotating base using four ¼" screws. A 6" optical rail (RLA 0600) is screwed to the other two tapped holes on the base. Two 1" x 1" dovetail rail carriers (RC1) will slide on top of the optical rail. Each rail will hold a fixture responsible for holding the grips. Figure 8 shows the fixture that will hold the bottom grip. 80/20 T-slot rods will be cut into two pieces: a 3" piece and a 2" piece. One end of the 3" piece was tapped for ¼" threading; this was done to screw the 80/20 onto the rail carrier. The two 80/20 pieces were secured to each other using an 80/20 right angle bracket.

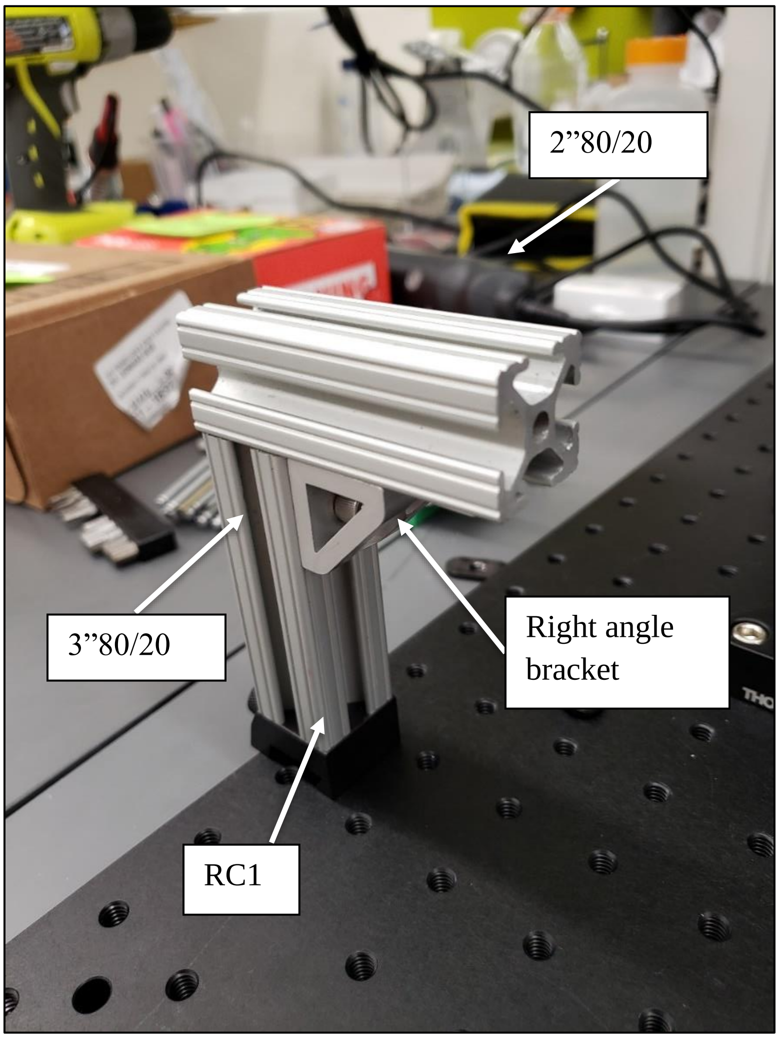

Figure 8. Fixture to hold bottom grip

Figure 9 shows the fixture that will hold the top grip. An Edmund Optics Adjustable Post Holder (84-353) was screwed to a rail carrier (RC1). Inside the holder, a post (TR2) was inserted and placed flush with the top. Similar to the bottom grip, another 2” and 2” piece of 80/20 was cut. The 2” piece was tapped with ¼” threading to be secured to the post (TR2) that was inserted in the holder. A spacing bracket was used to connect the 2” piece to the 2” piece.

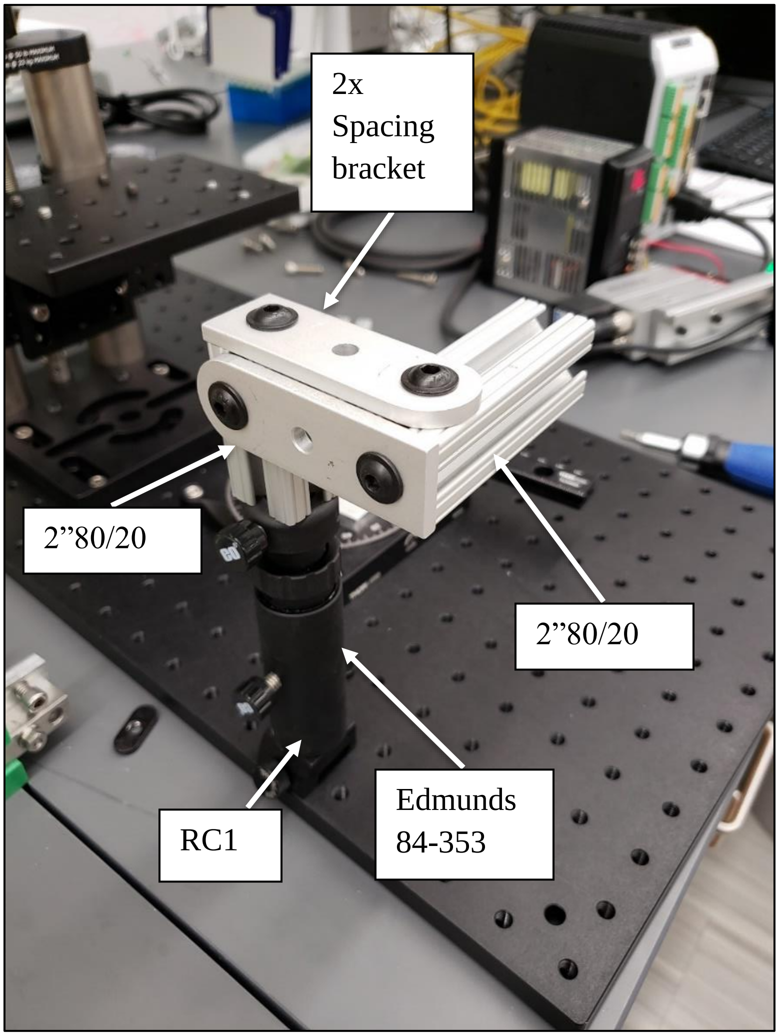

Figure 9. Fixture to hold top grip

In order to properly attach the tendon grips to the 80/20, two custom built brackets were built due to the non-standard spacing in the holes on the grips. Figure 10 shows the drawing that was used to manufacture the two brackets and the final product. These two pieces were attached to the 80/20 via screws from McMaster-Carr (470657101).

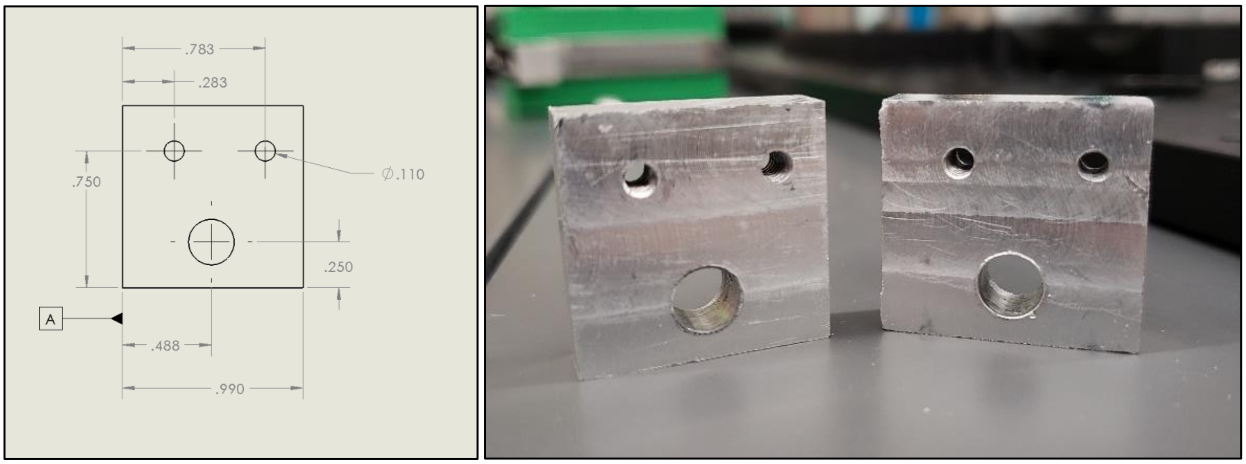

Figure 10. Print for bracket (left); final product (right)

2.3 Keyence Hardware and Software Set Up

Figure 11 shows how the Keyence LS-9030M was secured to the 4” x 6” breadboard.

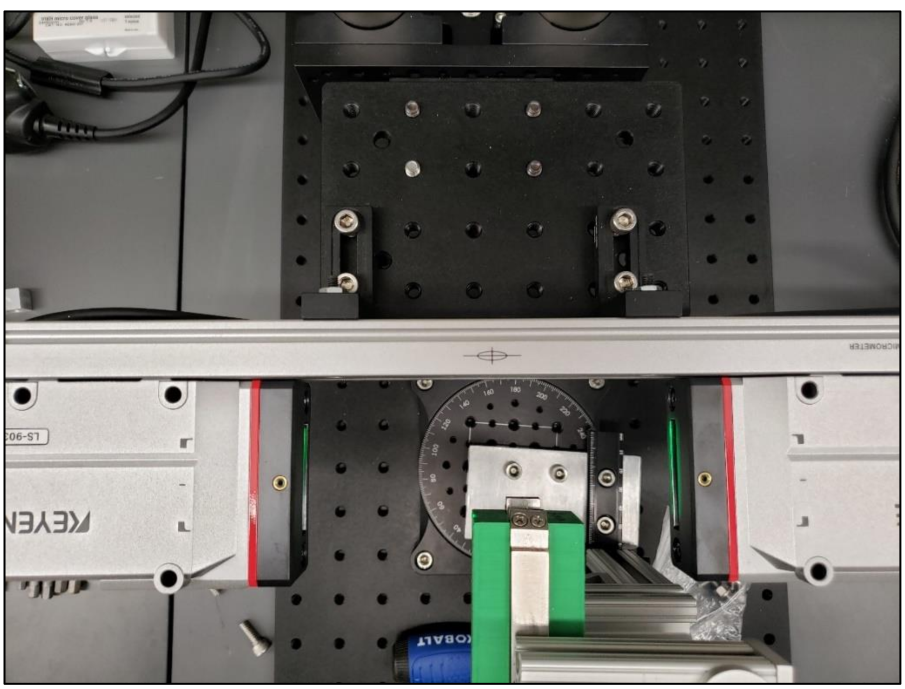

Figure 11. Laser attached to breadboard using ¼” screws

In order to attach the grips to the custom brackets, four 6/32” set screws were placed into the tapped holes and the grips were inserted. From there, a nut was placed onto the screw to tighten the fixture. Figure 12 shows this process.

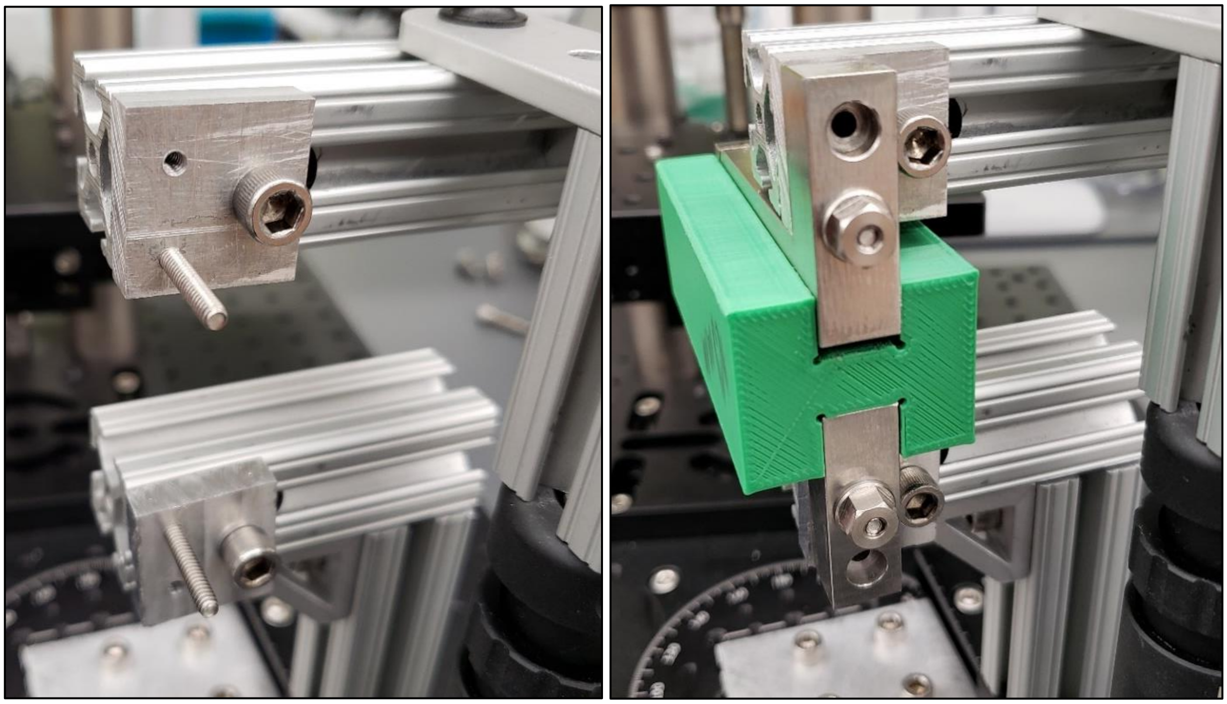

Figure 11. Process for attaching grips to custom brackets (left to right)

Once the grips are attached, the laser needs to be set up. This was done by following the instructions provided with the hardware. Figure 12 shows the overall setup for the Keyence hardware.

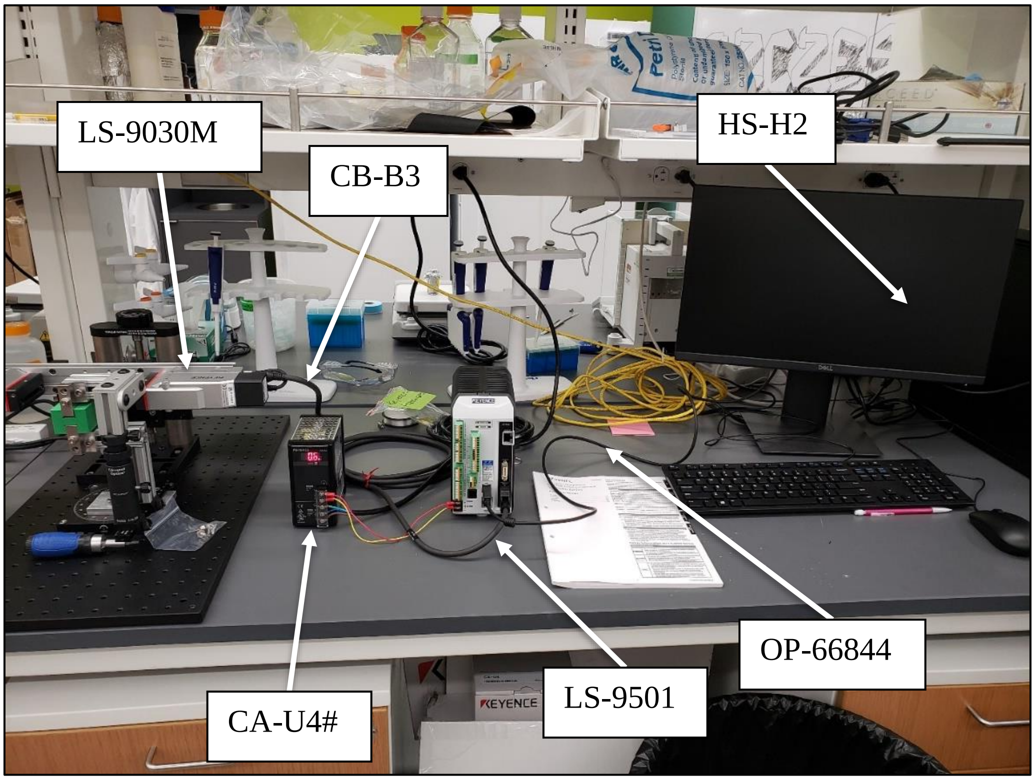

Figure 12. Overall system set up in the lab

The laser (LS-9030M) was attached to the controller (LS-9501) via a coaxial cable (CB-B3). This controller was attached to an external DC power supply (CA-U4#) and to a computer via USB (OP-66844). Keyence has provided software (HS-H2) that can be installed and run once set up.

After successfully setting up the system, a validation test was conducted to see whether the system meets the requirements of the customer and the specifications for the equipment from the manufacturer themselves.

3.0 Test Results and Discussion

The system was tested according to the most important customer needs addressed in the introduction of this report. The target values and results from this test are shown in Table 2. The main focus of the testing was to ensure that the system operated with the degree of accuracy and precision required by the research performed in Dr. Szczesny's lab, as well as operating fast enough for the measurements to be acquired before the tendon sample dehydrates from exposure to the atmosphere. The data produced by this testing has been provided to Dr. Szczesny via email. It will not be included in this report due to the extensive amount of data collected.

Table 2. Testing targets and results

Specification	Target Value	Tested Value
Accuracy of measurement for objects of known diameter	< 0.5% error	Maximum error of 0.38%
Reliability of measurement for tendon samples	< 5 µm deviation	1.28 µm deviation (n=42)
Speed of average operation to keep sample Hydrated	< 5 min	3 min 24 sec ± 52 sec (n=15)
Speed of post-processing to calculate cross-sectional area	< 5 min	4 min 38 sec ± 11 sec (n=15)

The test to determine the system's accuracy for objects of known diameter was performed using gauge pins secured to the system as shown in Figure 13. These gauge pins have a known size that is specified by an ASME standard and verified by digital dial calipers before the test was performed. To provide an encompassing range of measurements, gauge pins of size 1, 14, and 60 were chosen for testing. Each pin was measured multiple times using the laser to obtain an average measurement over the length of the pin. This average measurement was then compared to the known value of the diameter of the pin to find a % error value for the laser measurement. The largest error for the three pins was found to be 0.38% for the smallest pin, size 60. This error was beneath the target maximum of 0.5% error specified by Dr. Szczesny and can be explained in part by the lack of precision from calipers relative to the laser system as well as variations in diameter along the length of the gauge pin.

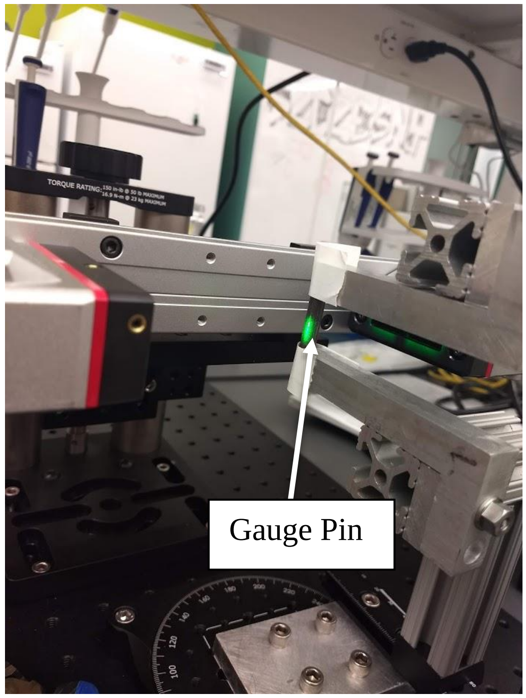

Figure 13. Testing setup using gauge pins to find the accuracy of the system.

In order to find the reliability of measurement for tendon samples, the system was used to measure a rat-tail tendon sample provided by the lab. This specimen is representative of the embryonic chicken tendons that is the main focus of the system, but somewhat larger and slightly less translucent. Multiple measurements were taken along the length of the tendon specimen to find the variability of measurements taken with the laser. The largest deviation found through testing was 1.28 μm for the minor diameter of the specimen. Some variability was expected due to the inconsistent nature of biological samples, and this result met the specification of a deviation less than 5 μm that was set by Dr. Szczesny.

The speed of operation for the laser system was tested to minimize the tendon's exposure to the dry atmosphere in the lab which should keep the tendon from becoming too dehydrated during testing. From discussion, the maximum operation time was specified as 5 minutes to secure the tendon, take measurements for both major and minor diameters, and remove the tendon. In performing this process 15 times, the operation time was found to be 3 min 24 sec ± 52 sec, which successfully meets the specification. The large amount of variance likely arises from the lack of training by the user. Through multiple tests, the user should have improved times as the user will become more familiar with the process of operating the system.

The post-processing time was specified by the sponsor to ensure that the system could still be used to complete research in a timely manner despite the increase in complexity from the system currently used in the lab. The post processing time included the time needed to export the diameter measurement data from the Keyence software to an Excel template used to calculate the elliptical cross-sectional area. The resulting time for this test was 4 min 38 sec ± 11 sec which meets the specified range of less than 5 minutes. The process was almost entirely restricted by the processing time needed for the computer to export the data to Excel.

4.0 Customer Needs Self-Assessment (Design Criteria Satisfaction)

The customer needs that influenced the final design are shown in Table 3. These needs have changed slightly from the ones previously proposed in the statement of work (SOW). The initial design proposed relied on a camera and image processing software, which would have resulted in a less expensive system. In discussion with the sponsor, the increased accuracy of the laser system was determined to be more important. With the approval to expand the project budget, the need to stay within budget was removed from the customer needs. Additionally, the need of keeping the tendon hydrated was taken into consideration with the final design by reducing the operating time, as previously discussed. Since the sponsor approved of this decision, the need for quick operation that was listed in the SOW was redundant and removed from the list of needs used to evaluate the final design.

This design decision to solve the dehydration issue by reducing operating time was successful in regard to meeting the time constraints recommended by the sponsor, but may have not fully solved the issue as intended. During the testing process, the laser returned steadily decreasing measurements for the tendon sample. This trend indicates that the sample was contracting due to dehydration at a rate that could affect the calculations for cross-sectional area of the sample. In further discussion of this issue, the sponsor indicated that they would observe the issue and address it using an external humidification system, if needed. Other than this factor, the final system meets and exceeds the other customer needs considered in this project.

The deliverables addressed in the SOW report were also changed for the final design due to the transition from a camera system to a laser micrometer system. The image processing system was no longer needed and was replaced with the Keyence software used to control the laser and output data. In addition, the 3D printed Alpha prototype was replaced with a full CAD model of the laser system after the sudden change in designs. This prototype still served to outline the mechanical relationships between different parts of the system and plan the pieces that needed to be purchase for the final design. Other than these two changes, all agreed deliverables, including the alpha prototype, design specification report, and final product were provided to the sponsor.

Table 3. List of customer needs used in development of the final design.

Customer Need	**Level of importance 1-5**	**Weight**
System accurately and reliably measures tendon diameter on the scale of 0.5 mm	5	25%
Tendon remains hydrated during measurement	5	25%
System incorporates current lab grips	4	20%

System operates safely	2	10%
System is durable in everyday use	2	10%
System is easy to use	2	10%

5.0 Project Management Summary

5.1 Project Schedule

The 3D printed alpha prototype was completed October 14th. Feedback was collected and changes were made to the design. The finalized Solidworks model was presented to the sponsor on October 31st as a beta prototype following the shift in designs from the camera system to the laser system. Final design changes were discussed, and the final iteration was built and presented in class on December 10th.

It was expected that the final device would be assembled, and the poster would be completed by November 21st. The timeline changed due to the shift in design concpets. It came to light that the camera would not satisfy customer needs. At this point, the team cancelled the Basler camera purchase and ordered the Keyence Laser on November 22nd.

The changes forced the timelines for assembly, testing, and final poster submission to be pushed back. The Keyence laser had a four-day lead time and arrived at Dr. Szczesny's lab during the Thanksgiving holiday. Assembly was conducted on December 2nd, testing on the December 3rd and the final poster was submitted on December 5th. In retrospect, requesting specification sheets instead of trusting the word of representatives would have allowed the team to avoid this delay.

The last milestone was to present the final project presentation on December 10th. Regardless of the delay, the team met this final deadline and presented the final design to the class on December 10th and at the Design Showcase on December 12th. The Gantt Chart for the project is attached in Appendix A.

5.2 Economic Analyses - Budget and Vendor Purchase Information

The overall budget, shown in Table 4, for the overall project and the specific components being purchased to create the non-contact measurement device. The bulk of expenses is included in the hardware required by the Keyence Optical Micrometer. All hardware and materials purchased are detailed in the Bill of Materials located in Section 2. As described in section 2, the overall budget for the project was less than the base price of the components due to a discount that was provided by Keyence at the time of purchase.

Table 4. Overall budget

Travel	$0
Equipment Usage Time	$0
Hardware - Keyence Optical Micrometer including $2000 discount	$10,017.50
Materials – Excluding Keyence Hardware	$1,804.30
Poster	$64.24
Total Expenses	$11,886.04

5.3 Risk Plan and Safety

Throughout the course of this project, the team learned about some possible risks that were not considered in the first few weeks. These are the last two risks listed in Table 5. In November, due to the complexity of the project, Dr. Szczesny questioned which system would be better between the camera and the laser due to some conflicting information provided about the camera system hardware that was initially selected for the DSR. Upon further investigation, the camera system would not provide the necessary level of accuracy and reliability for the project. This is the last risk listed in Table 5. Since there was not a lens available that could provide the right resolving power, the Basler order had to be cancelled and an order was placed to the Keyence laser, which delayed the project as mentioned in section 5.1

Despite these setbacks, the team completed all the project deliverables by their respective deadlines, and the sponsor was satisfied with the final product. However, this risk could have been avoided with more extensive research into the specifications of selected parts instead of relying on the expertise of representatives from the supplier.

Table 5. Final Risk Plan

Risk	Level	Actions to Minimize	Fall-Back Strategy
Injury to team member during manufacturing process	Moderate	Follow all Learning Factory safety rules Ask questions when unsure about how machinery works	Have another team member take over the work if necessary
System does not give accurate measurements	High	Test early and often Demo parts before purchasing Consult Dr. Szczesny before purchasing	Design the set up so that a new measuring device can be incorporated in the future
Delays in order placement or delivery	Moderate	- Inform Dr. Szczesny of all prototyping deadlines Order parts earlier than needed	Ask Dr. Szczesny if there is anything they can provide in the meantime
Researching Graduate student not satisfied	Low	Understand the customer's needs Keep frequent contact with customer	Discuss ways to fix the problem in the future
Specimen becomes dehydrated during measurement process	Moderate	Incorporate a hydration technique in the design Design the system to be simple and fast so that the specimen is not out of hydration for too long	Discuss possible tissue rehydration methods with Dr. Szczesny
Design is too complex/ expensive so the sponsor decides to switch to another concept	High	Keep a log of all details when creating each design so that if we need to switch we still have all of the necessary details	- Contact vendors and ask if they have any suggestions or try to negotiate with them
Products customer representatives give inaccurate information	High	Do own research to assure that they are correct before placing any orders	- Work on other parts of the project in the meantime while waiting for specific products

6.0 Conclusions and Recommendations

The objective for this project was to develop a device and associated software to accurately measure the dimensions of biological tissues without contacting the sample. With the help of a graduate student in Dr. Szczesny's lab, Ben Peterson, three major customer needs were identified to develop the final design. The overall system would need to accurately and reliably measure tendons smaller than 0.5 mm, maintain tendon hydration during measurement, and incorporate current lab grips. The final product that was developed was able to hold the custom-built grips into its system and operate in a timely fashion to keep the tendon hydrated. In addition, the system was able to accurately measure tendons with a maximum error of 0.38% and standard deviation of ±1.38 μm. All the major needs were met, and the system can successfully measure the dimensions of small biological samples.

While the system is complete and functional, there are areas of improvement that can certainly be made. The primary area that can be improved is the method for inserting the grips. Currently, a combination of set screws and flange nuts are used to secure the grips on. However, screwing the nut into the set screw every time a measurement needs to be taken can add up a lot of time. To improve this, a better solution of inserting the grips needs to be further explored. In addition, the hydration of the sample was not completely ideal. An external humidification system would help solve this issue, as discussed previously.

Appendix A: Gantt Chart

Appendix A contained the Gantt Chart discussed in Section 5.1.

		Name	Duration	Start	Finish
1		**Concept Generation**	**12 days?**	**9/7/19 8:00 AM**	**9/24/19 5:00 PM**
2		Week 2 Process Report	3 days?	9/10/19 8:00 AM	9/12/19 5:00 PM
3		Create Predicted Expens...	3 days?	9/10/19 8:00 AM	9/12/19 5:00 PM
4		Define Needs and Specifi...	3 days?	9/10/19 8:00 AM	9/12/19 5:00 PM
5		Grant Chart Draft 1	3 days?	9/10/19 8:00 AM	9/12/19 5:00 PM
6		Team Contact	4 days	9/7/19 8:00 AM	9/12/19 5:00 PM
7		Week 3 Progress Report	4 days	9/12/19 8:00 AM	9/17/19 5:00 PM
8		Assess Camera Option	4 days	9/14/19 8:00 AM	9/19/19 5:00 PM
9		Concept Generation PPT	8 days	9/10/19 8:00 AM	9/19/19 5:00 PM
10		Final Concept Selected	11 days?	9/10/19 8:00 AM	9/24/19 5:00 PM
11		**Week 4 Progress Report**	**5 days?**	**9/20/19 8:00 AM**	**9/26/19 5:00 PM**
12		Rate Ideas based on Specs	4 days?	9/23/19 8:00 AM	9/26/19 5:00 PM
13		Deliverable Agreement	5 days	9/20/19 8:00 AM	9/26/19 5:00 PM
14		**Week 5 Progress Report**	**5 days?**	**9/27/19 8:00 AM**	**10/3/19 5:00 PM**
15		SOW Report 1	5 days?	9/27/19 8:00 AM	10/3/19 5:00 PM
16		Concept Generation and...	3 days?	9/27/19 8:00 AM	10/1/19 5:00 PM
17		**Week 6 Progress Report**	**5 days?**	**10/4/19 8:00 AM**	**10/10/19 5:00 PM**
18		Update Gantt Chart	3 days?	10/8/19 8:00 AM	10/10/19 5:00 PM
19		SOW Presentation	3 days?	10/4/19 8:00 AM	10/8/19 5:00 PM
20		**Week 7 Progress Preort**	**5 days?**	**10/11/19 8:00 AM**	**10/17/19 5:00 PM**
21		Alpha Prototype present...	3 days?	10/11/19 8:00 AM	10/15/19 5:00 PM
22		Peer Evaluation	2 days?	10/11/19 8:00 AM	10/14/19 5:00 PM
23		Collect Alpha Protoype F...	3 days?	10/15/19 8:00 AM	10/17/19 5:00 PM
24		Update Expense Report	4 days?	10/14/19 8:00 AM	10/17/19 5:00 PM
25		Build Alpha Prototype	14 days?	9/25/19 8:00 AM	10/14/19 5:00 PM
26		Week 8 Progress Report	5 days?	10/18/19 8:00 AM	10/24/19 5:00 PM
27		Team Status Presentation	3 days?	10/18/19 8:00 AM	10/22/19 5:00 PM
28		**Week 9 Progress Report**	**15 days?**	**10/25/19 8:00 AM**	**11/14/19 5:00 PM**
29		Beta Prototype feedback	3 days?	10/29/19 8:00 AM	10/31/19 5:00 PM
30		DSR Exec Summary	5 days?	10/25/19 8:00 AM	10/31/19 5:00 PM
31		update expense report	1 day?	10/25/19 8:00 AM	10/25/19 5:00 PM
32		Order Camera	15 days	10/25/19 8:00 AM	11/14/19 5:00 PM
33		Build Beta protocal	8 days	10/18/19 8:00 AM	10/29/19 5:00 PM
34		Research Parts and Order	53 days	9/10/19 8:00 AM	11/21/19 5:00 PM
35		**Build final Design**	**60 days?**	**9/10/19 8:00 AM**	**12/2/19 5:00 PM**

Figure A.1: Gantt chart schedule

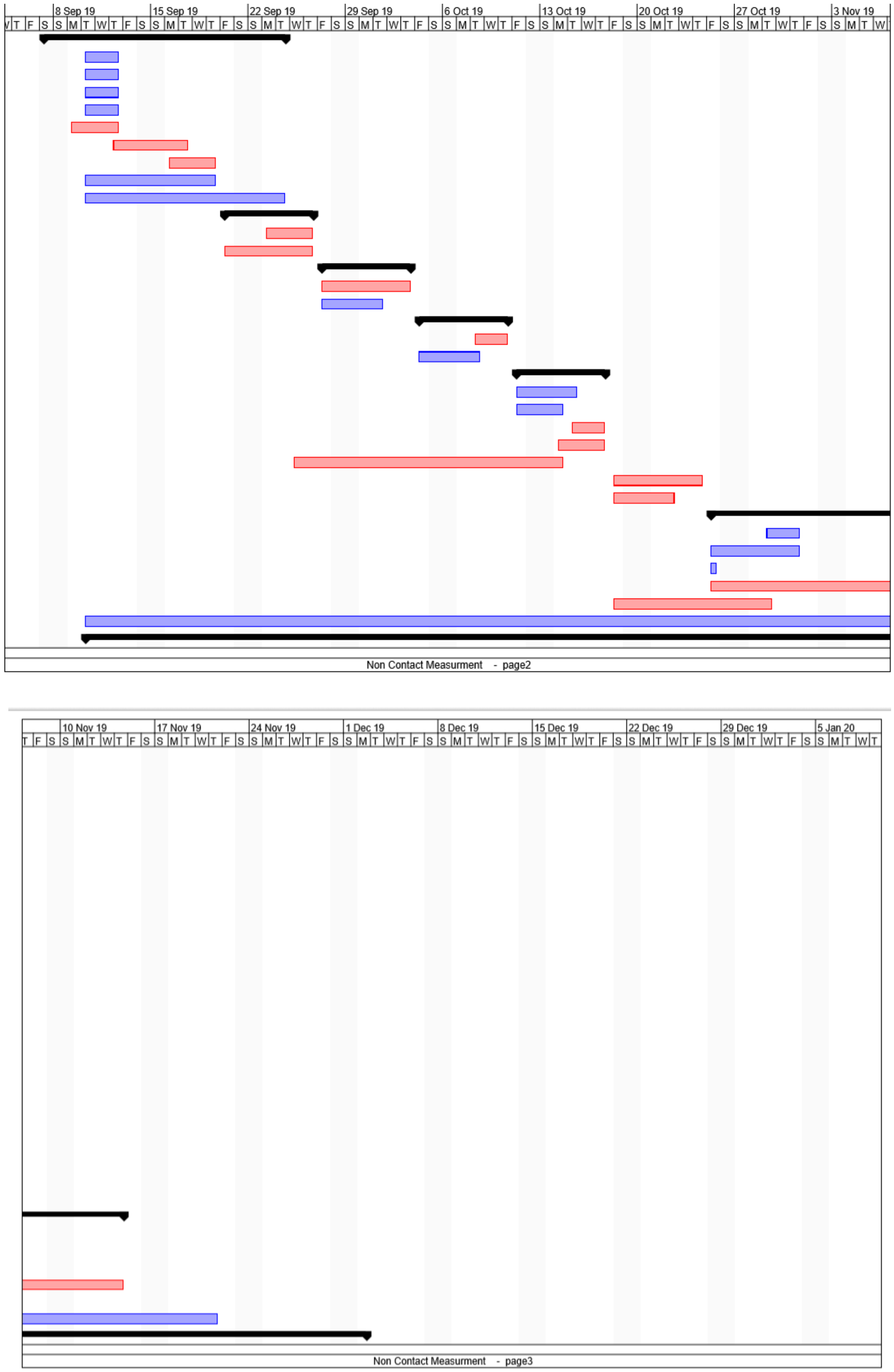

Figure A.2: Gantt chart schedule