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Advancements in Panoramic-DIC System for Vascular Imaging

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Ph.D. Research Rotation Report

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1 Introduction

1.1 The DIC Technique

Digital Image Correlation (DIC) has become an important imaging technique in biomechanics, known for its non-invasive, optical assessment capabilities.[1] It plays a crucial role in understanding soft tissue deformation by providing valuable insights into the mechanical behavior of tissues under stress.[2] In vascular imaging, DIC is able to simplify the complex mechanical behavior of blood vessels under various physiological and pathological conditions.[3] This technique has the ability to capture subtle changes in tissue structure under different states in biomechanical research.[4]

1.2 Limitations of the Traditional DIC Technique

Despite the advantages, traditional DIC systems have several limitations in biomechanical applications. For example, when studying arterial mechanics, these systems often struggle with the quasi-cylindrical nature of arteries, which may lead to restricted observational fields and make it difficult to capture the natural but irregular curvature of these vessels.[5,6] Besides, it is challenging to maintain the integrity of these samples *in vitro* to mimic the *in vivo* physiological state, as traditional DIC setups may not adequately replicate the dynamic environmental conditions.[7,8] These limitations have been evident in studies where accurate modeling of arterial behavior is critical but constrained by these traditional systems' inherent restrictions.

2 Background

2.1 The pDIC System

Advancements in the DIC technique have led to the development of panoramic-DIC (pDIC) systems, which are designed to overcome the limitations of traditional approaches.[7]

The pDIC system addresses the need for more comprehensive imaging of quasi-cylindrical samples by utilizing a sophisticated array of cameras and mirrors. It employs a concave conical mirror, transforming a conventional binocular stereo-DIC setup into an almost infinite-view system, through the use of multiple cameras that cover the full 360-degree surface of cylindrical samples.[9] This advancement provides a significant improvement in capturing full-field, three-dimensional deformations of biological tissues, enabling researchers to study vascular mechanics with unprecedented detail and accuracy.

As detailed in Genovese *et al.* (2021)[10] and Bersi *et al.* (2016, 2018)[6,11], this technique has shown promising results in providing comprehensive full-field, surface deformation data for arterial samples, ranging from murine to human scales.

2.2 The pDIC System in Dr. Bersi's Lab

Dr. Matthew Bersi, an Assistant Professor in the Department of Mechanical Engineering & Materials Science at Washington University in St. Louis, specializes in biomechanics and the development of innovative mechanical testing approaches for geometrically complex tissues. His research emphasizes the creation of new

methods for the mechanical characterization of soft tissues, contributing significantly to the field.

In Dr. Bersi's lab, there is a pDIC system with four cameras. Figure 1 shows the pDIC system in Dr. Bersi's lab.

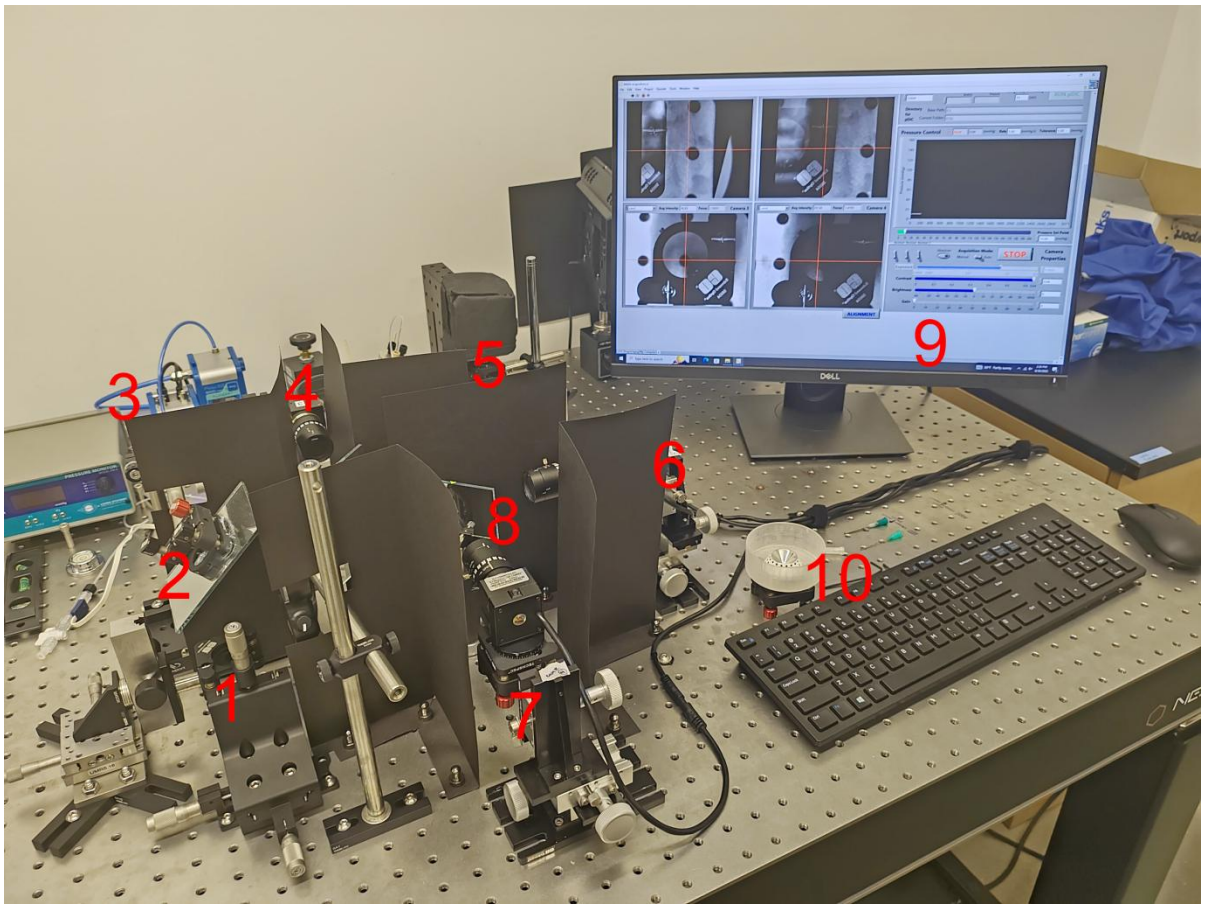

Figure 1. *The pDIC system in Dr. Bersi's lab at the beginning of the rotation. The system includes the stage target to place sample (1), a 45-degree reflective mirror (2), pressure transducer and control systems (3), four cameras from different perspectives (4-7), three one-way mirrors (8) to adjust the light pathways, the computer and software to help calibration and to capture the images (9), and a sample concave conical mirror to place the sample (10).*

2.3 The pDIC System Setup

Figure 2 shows the top view of the pDIC system setup in Dr. Bersi's lab. Figure 3 shows the concave conical mirror of the pDIC system.

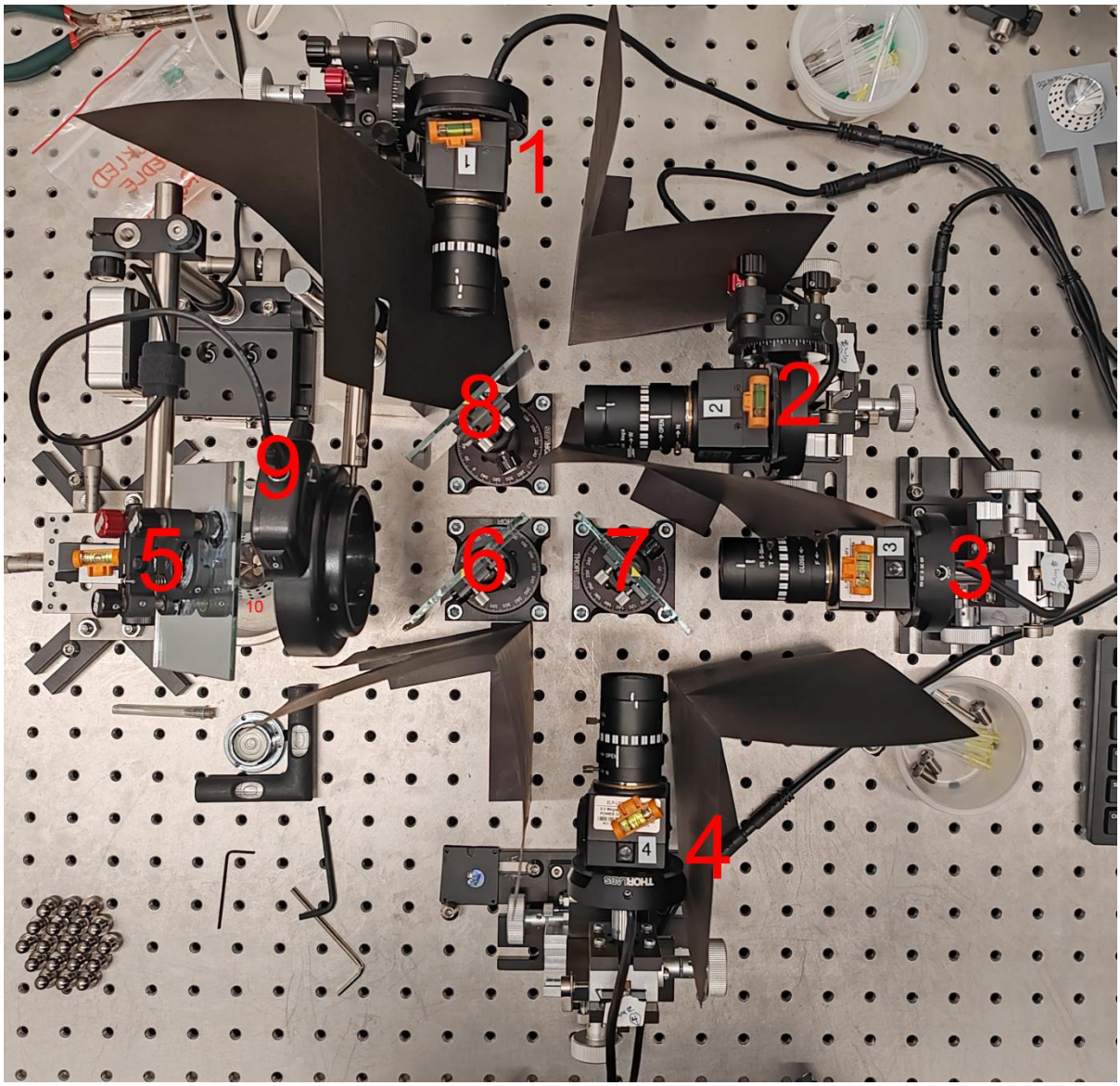

Figure 2. *The top view of the pDIC system in Dr. Bersi's lab at the end of the rotation. The system includes four cameras from different perspectives (1-4), a 45-degree reflective mirror (5), three one-way mirrors (6-8), the light source for the sample (9), and a concave conical mirror to place the sample (10). The camera and mirror numbers are used from now on throughout this report.*

The setup in Figure 2 shows how four cameras work together to capture images from different views of the sample in the concave conical mirror plate 10.

The view of the sample is first reflected by mirror 5. While camera 3 can capture the direct image passing through mirrors 6 and 7, the view of camera 3 is then used as a reference for calibration and correlation comparison. Camera 4 captures the image passing through mirror 6 and reflected by mirror 7. Camera 1 captures the image reflected by mirror 6 and passes through mirror 8. Finally, camera 2 captures the image reflected by mirrors 6 and 8.

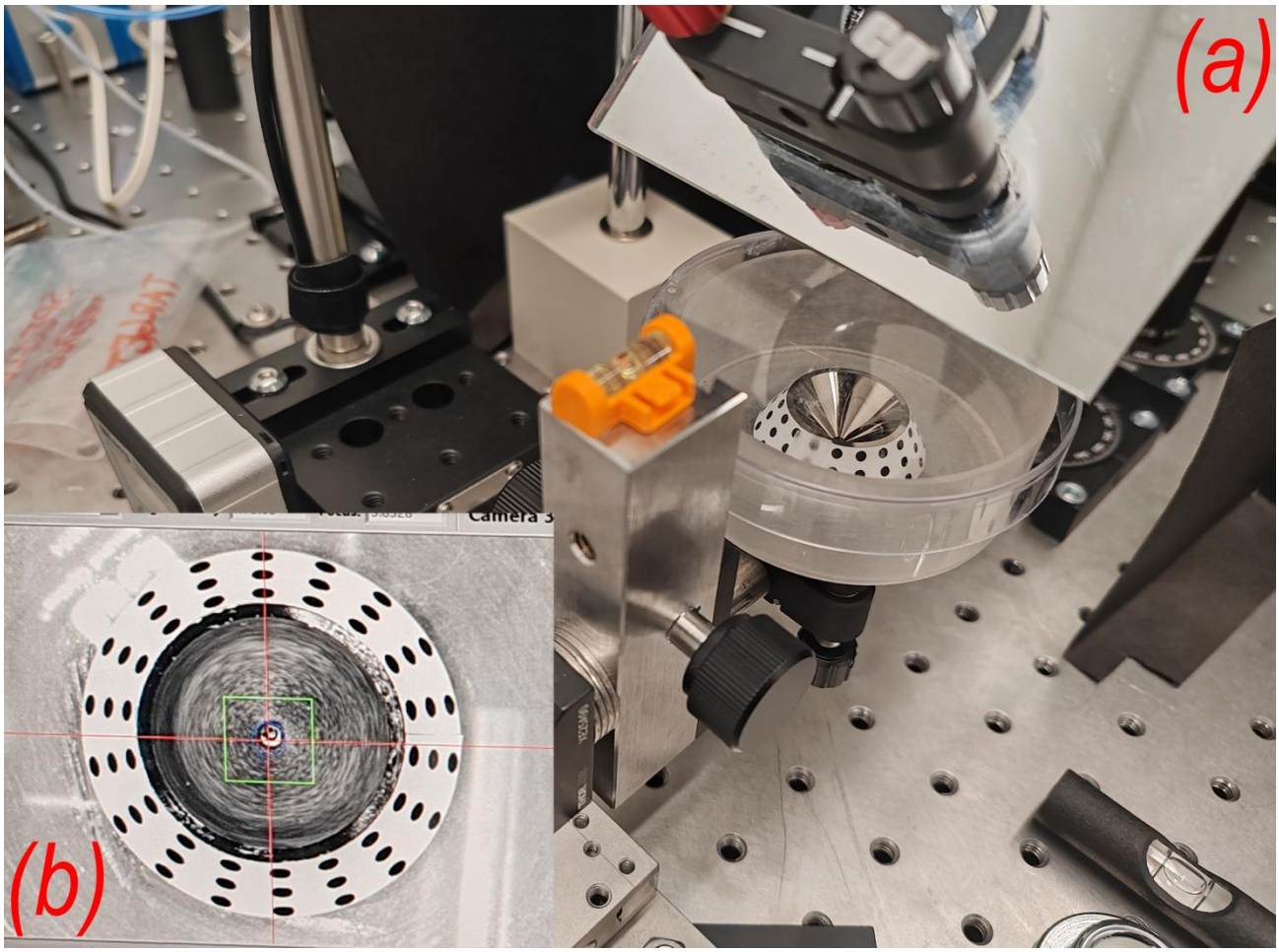

Figure 3. *The concave conical mirror setup. It is ready to place the sample on the needle through the middle hole. (a) The concave conical mirror. (b) The camera view of the concave conical mirror speckle pattern.*

3 Objective

The objective of this research rotation is to further develop the hardware of the panoramic-DIC system in Dr. Bersi's Lab for vascular imaging, arrange the software for image processing, and formulate the accessible steps to use this system.

The ultimate goal is to enhance the utility of pDIC in vascular biomechanics, contributing to a better understanding of vascular diseases and their treatments.

3.1 Hardware: System Calibration

A primary focus of this research project is on calibrating the system to ensure accuracy and reliability in measurements. Calibration is crucial, as highlighted in Genovese *et al.* (2021), where specific calibration routines are employed to account for refraction errors due to sample immersion in physiological solutions. The first step of this project is to make the calibration procedure accessible and user-friendly so that it takes only a little time to complete the hardware calibration with high success rates for vascular imaging.

3.2 Software: Image Processing

In addition to system calibration, software development is another important step when the hardware system is well-set for capturing images. There were already some pre-existing sets of codes in Dr. Bersi's lab; however, there was a need to find the best code for each step of the analysis and formulate a procedure for image processing.

3.3 Other Supplemental Works

Since the ultimate goal of using the pDIC system is to analyze soft tissues, it is important to prepare and process samples properly. Besides, in order to be recognized during the image processing stage, the sample should be dyed as speckle patterns. Furthermore, while the pDIC system contains the pressure control system, it lacks a displacement detector component that is presented in the bi-axial mechanical testing system; Thus, it is important to perform bi-axial mechanical testing for the sample before getting processed by the pDIC system so that researchers can combine these mechanical information together.

4 Methods & Results

4.1 Hardware Advancements

The goal of calibration is to make the hole right at the center and all four cameras show the same or very similar images. However, at the start of the rotation, there are always rotational dislocations happening as shown in Figure 4.

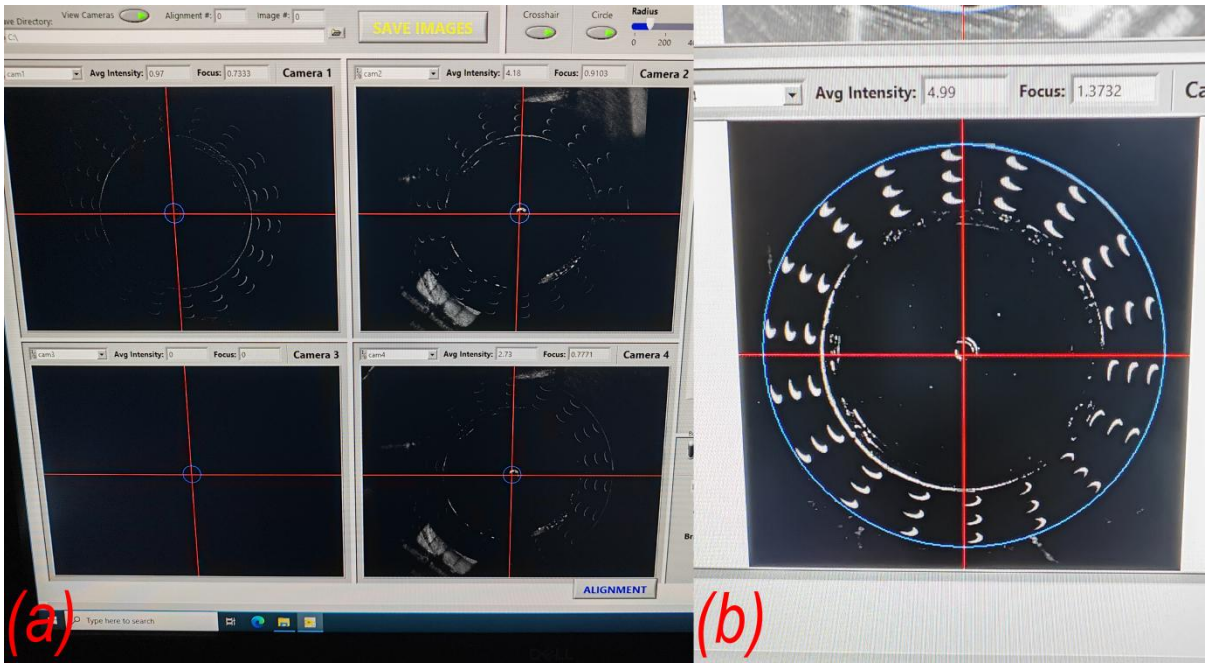

Figure 4. *Calibration of camera views compared to the view of camera 3, where light indicates dislocations and dark indicates a match. (a) A good calibration. (b) A frequently appearing rotational dislocation.*

To make the calibration process more accessible and user-friendly, the cameras and the mirrors should be easy to adjust. However, the previous system setup, as shown in Figure 5, sets the camera locations to be controlled by three screws; this can be hard to calibrate rotational dislocations since each screw would change both horizontal and vertical orientations at the same time. Thus, a rotational stage is

needed to calibrate the frequently appearing rotational dislocation.

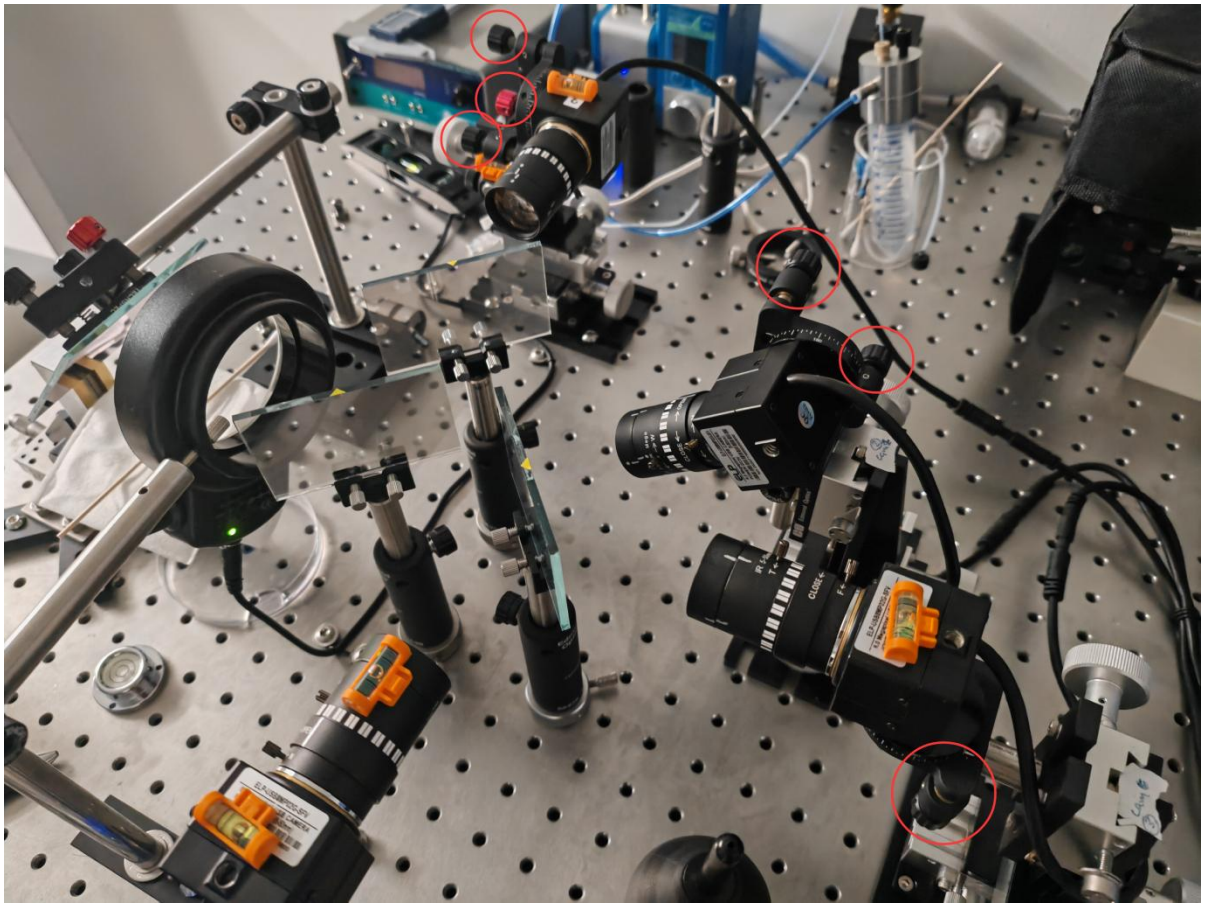

Figure 5. *Screws circled in red are used in the previous pDIC setup to control the camera orientation.*

To set up a rotational stage, the original back plate of the camera is replaced by a connecting piece so that it can be anchored to the rotational stage. This connecting piece is designed to fit the space that the original camera back plate fits, while also having a fitting part to be able to stay stationary inside the rotational stage. This model was designed through AutoDesk Inventor and fabricated by 3D printing as shown in Figure 6. Figure 7 shows the replacement steps for building the rotational stage for each camera.

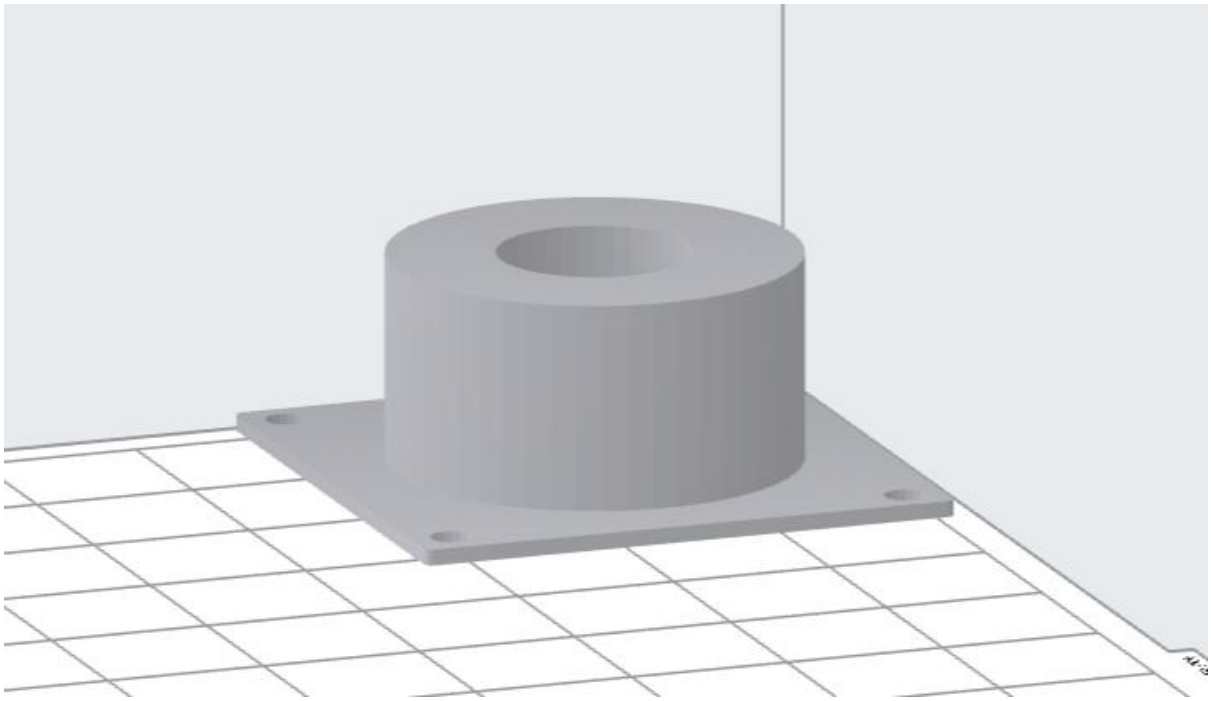

Figure 6. *The design of the connecting piece.*

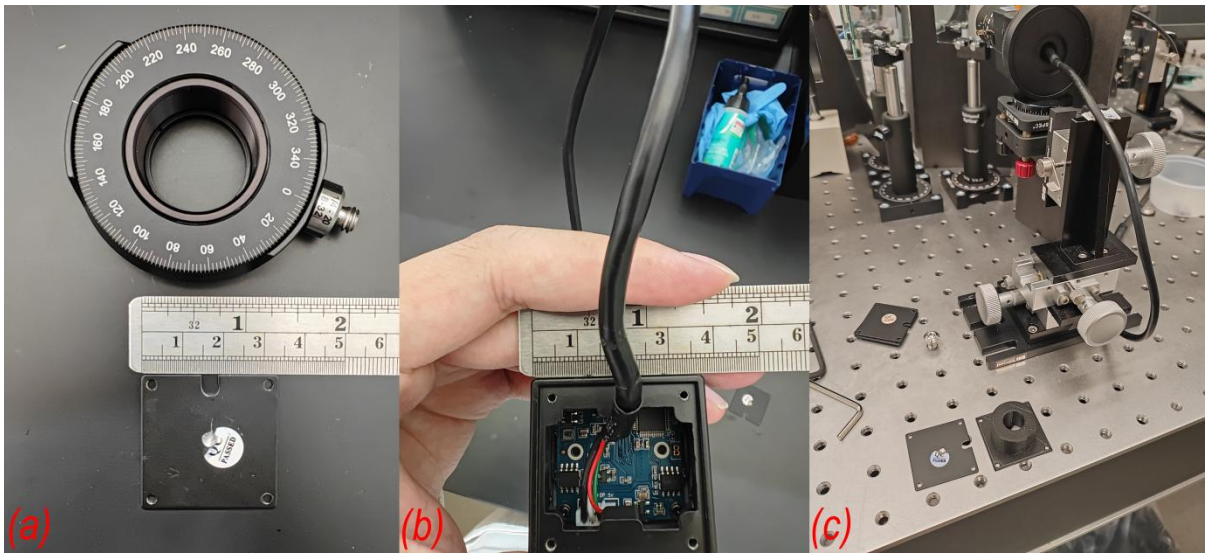

Figure 7. *The camera back plate is replaced with the 3D-printed connecting piece to anchor the camera on the rotational stage. (a) The back plate and the rotational stage. (b) The back plate is removed. (c) The comparison of the back plate and the 3D-printed connecting piece.*

With the stage replacement, the camera can be easily adjusted to any orientation. Figure 8 shows a complete setup of the camera. Notice the one-way mirrors are fixed in the position as shown in Figure 5; the rotational stages used for cameras are also set for the one-way mirrors as shown in Figure 7*(c)* and Figure 8. This can help to adjust the angle of the mirror to keep it always at 45 degrees.

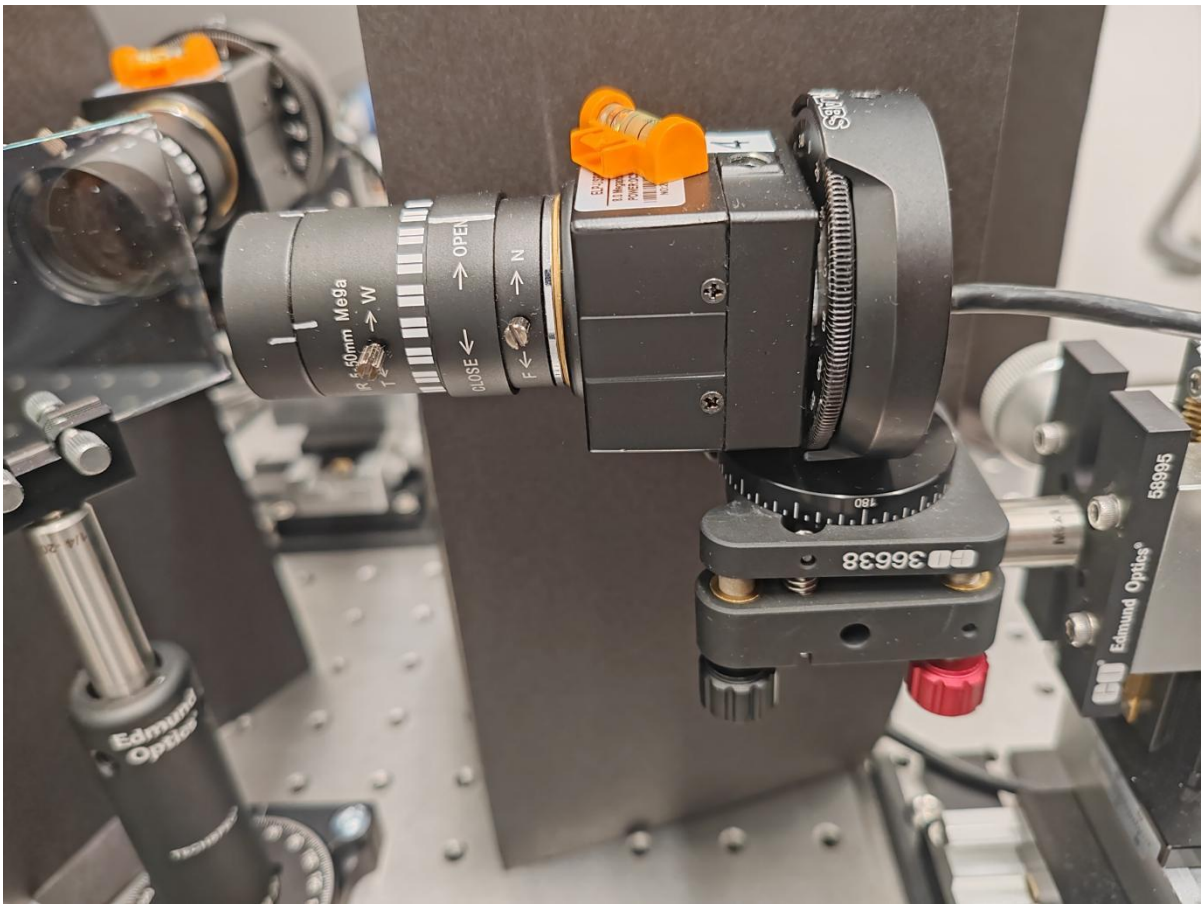

Figure 8. *The complete setup for camera 4. The top vertical rotational stage can easily adjust the rotational dislocation and the bottom horizontal rotational stage can easily adjust the horizontal orientation of the camera. Since the left screw of the traditional screw stage can narrowly adjust the vertical orientation of the camera, there is no need to replace it with another rotation stage.*

4.2 System Calibration

After making the hardware advancements, this pDIC system should be very easy to calibrate. As stated in the last section, the goal of calibration is to make the sample hole right at the center and all four cameras show the same or very similar images. The procedures are:

[1] Calibrate the camera in the order of 3-4-1-2. Because camera 3 is directly capturing the sample image and as the reference, it should be the first one to calibrate. Camera 4 is the only camera capturing the image through the reflection of mirror 7, so camera 4 goes next. Both cameras 1 and 2 capture the image through the reflection of mirror 6, while the image also goes through the reflection of mirror 8, the order is set as camera 1 and followed by camera 2.

[2] When calibrating the single camera, open the aperture to see the bright light. A bright ring can be seen as shown in Figure 9. Then, adjust the large displacement screws to make the ring uniform.

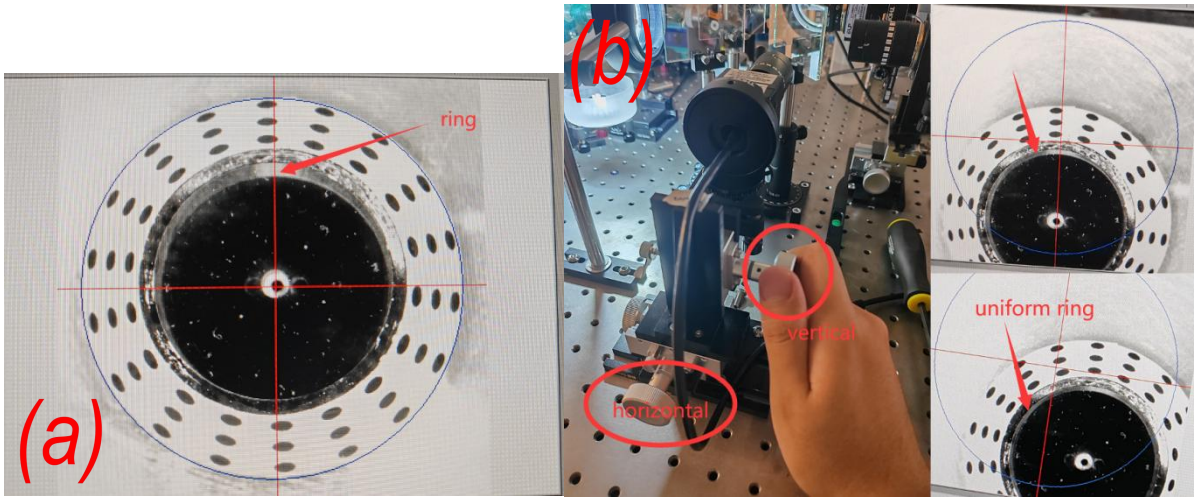

Figure 9. *Calibrate camera 4 to fit the ring. (a) A bright ring. (b) Adjust the camera position through the large displacement screws to make the ring uniform.*

[3] Adjust the camera to make the circle centered without using large displacement screws. Figure 10 shows how to adjust the camera.

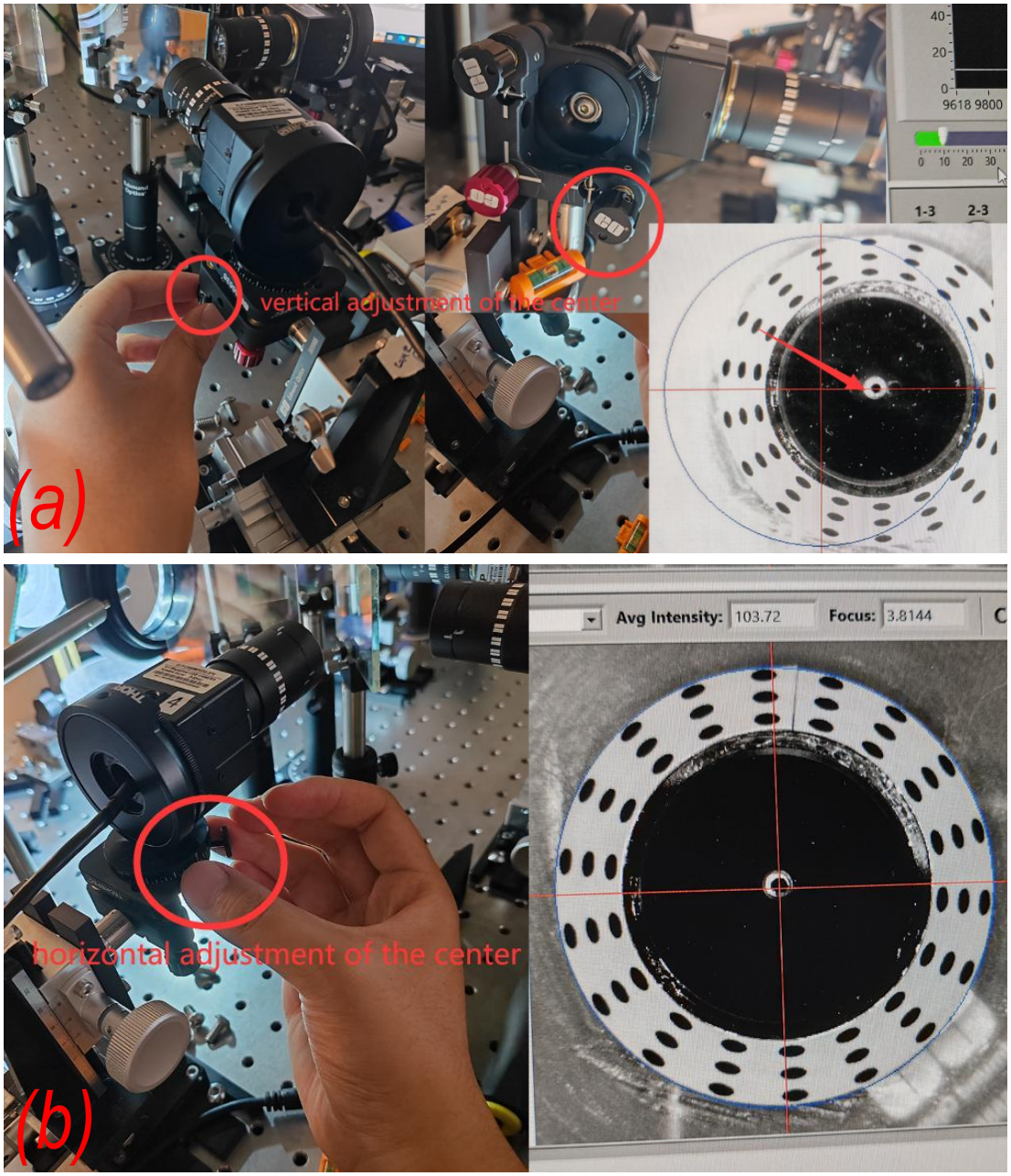

Figure 10. *Calibrate camera 4 to fit the center. (a) Vertical adjustment of the center. Note that this stage is for cameras 3 and 4. In the case of cameras 1 and 2, the stage used here is the horizontal adjustment. (b) Horizontal adjustment of the center. In the case of cameras 1 and 2, the stage used here is the vertical adjustment.*

[4] After adjusting the ring and the center, adjust the zooming and the focus. Note that the zooming can also be adjusted by the third large displacement screw as shown in Figure 11*(a)*.

[5] Make the final calibration for the camera. Rotate the camera if needed. Figure 11*(b)* shows the use of the top rotational stage.

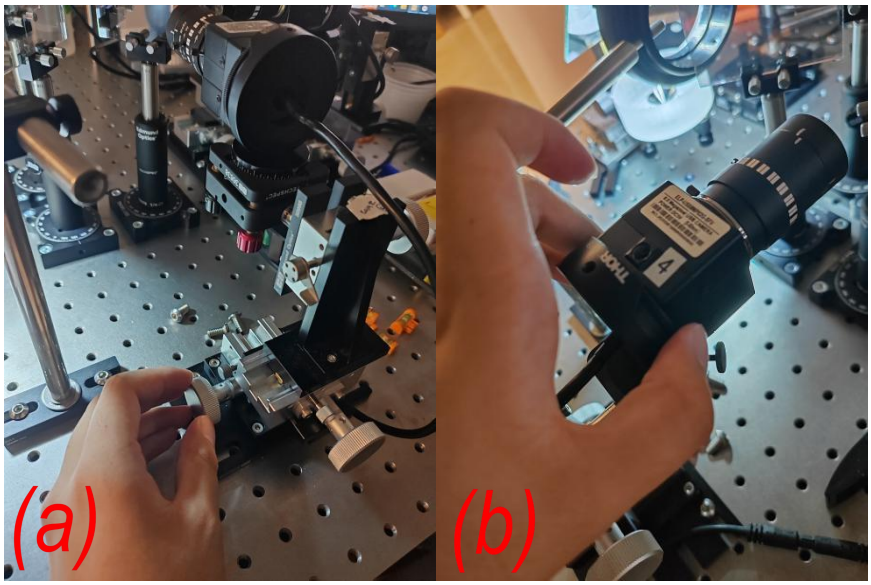

Figure 11. *Final calibrations for the single camera. (a) Adjust the zooming through the use of the third large displacement screw. (b) Rotate the top rotational stage to adjust the rotational dislocation.*

Table 1. Disparities Applied on Each Camera after Calibration

Camera Number	Translational Displacement	Rotational Displacement
1	+z Direction (going up)	-z Direction (going down)
4	+x Direction (going right)	-x Direction (going left)
3	+y Direction (going forward)	-y Direction (going toward)
2	-z Direction (going down)	+z Direction (going up)

[6] Repeat steps [1] to [5] and calibrate all 4 cameras to show the same or similar images as indicated by dark calibration areas on the screen.

[7] After calibrating all four cameras, a displacement is now applied to each camera as shown in Table 1. Note that it is assumed that the table is in the xy-plane, camera 3 is directing to the -x direction, camera 4 is directing the +y direction, and the concave conical mirror is facing the +z direction.

First, the translational displacement is applied to each camera with a distance of about 200 to 300 microns. For example, for camera 1, a translational displacement is applied to move it vertically up for 250 microns. The precise displacement measure can be accessed by the image with a reference square as shown in Figure 12.

After applying translational displacements, rotational displacements are applied to each camera. The rotational displacement is to adjust the orientation of the camera so that the image of the concave conical mirror hole goes back to the center.

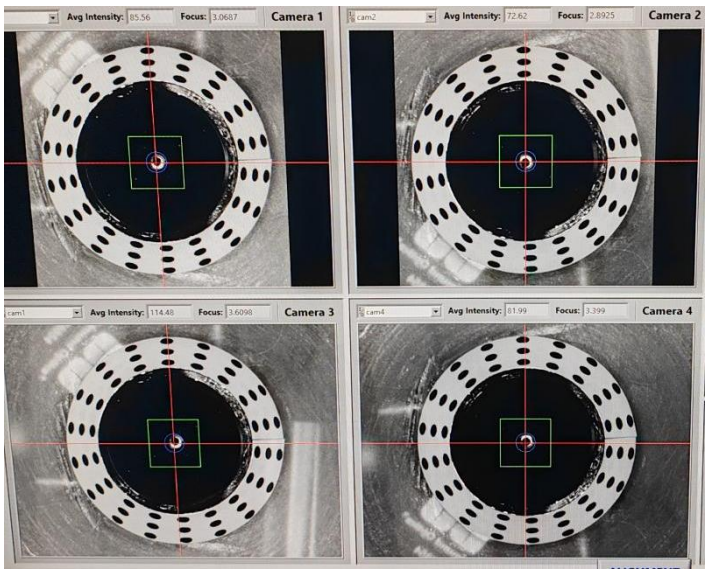

Figure 12. *The reference square with a side length of 250 microns. During the translational displacement, make sure the hole does not move out of the square.*

After calibrating all four cameras and applying displacements to them, the pDIC system is ready to capture sample images.

4.3 Sample Preparation

After preparing the pDIC system hardware, it is time to prepare some samples for imaging. During the rotation, there have been several chances for me to practice dissecting mice. Figure 13 shows some of the dissections of the mice aorta.

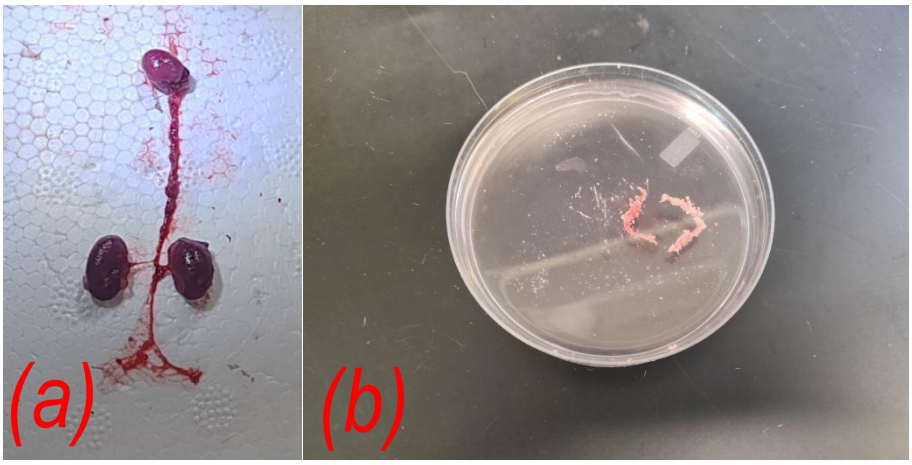

Figure 13. *Dissection samples of mice aorta. (a) Dissected mice aorta, including heart and kidneys. (b) Descending aorta samples are kept in Phosphate-buffered saline (PBS) in the petri dish.*

In practice, samples are not directly placed in the concave conical mirror. Samples are placed onto the needle and dyed with speckle patterns before imaging. During the rotation, there has been a chance for me to practice dyeing the needle alone with the speckle patterns. The setup for the dyeing is shown in Figure 14.

After dissection and dyeing, the sample on the needle is ready to be placed through the concave conical mirror hole facing towards the +z direction. With the

sample well-suited there, it is time to start capturing images through the pDIC system.

Figure 14. *The setup of dyeing to make the speckle pattern on the sample.*

4.4 General Procedures of Image Processing

Through reading and analyzing different sets of the pre-existing codes for the pDIC system in Dr. Bersi's lab, the following procedure is formulated:

[1] Setup the pDIC system and collect the sample

[2] Collect images by running the pDIC system to get images from four cameras.

[3] Calibrate the cameras based on each image through the following steps: first, extract the centroids for each image; then, order the centroids based on all the speckle points of each image; after that, select the centers for each image; finally, perform the direct linear transformation (DLT) or TSAI to calibrate cameras, enabling

the transformation of 3D coordinates into 2D coordinates. In practice, DLT works better than TSAI calibration.

[4] Unwrap the image. The previous step to select the center is required to unwrap the image. To do the unwrapping, the code converts the Cartesian coordinates of the image to polar coordinates and sorts the data; then, it duplicates and sorts this data to cover a 360-degree range. This process is repeated for images from different cameras.

[5] Mask the image from camera 3 to select a reference area.

[6] Perform scale-invariant feature transform (SIFT) between the masked image from camera 3 and the image from camera 1. To do so, the code reads these two images, converts them to a format suitable for processing, and then applies the SIFT algorithm to each to detect key features. Then, the code tries to match these features between the two images by identifying corresponding points. An example illustration is shown in Figure 15.

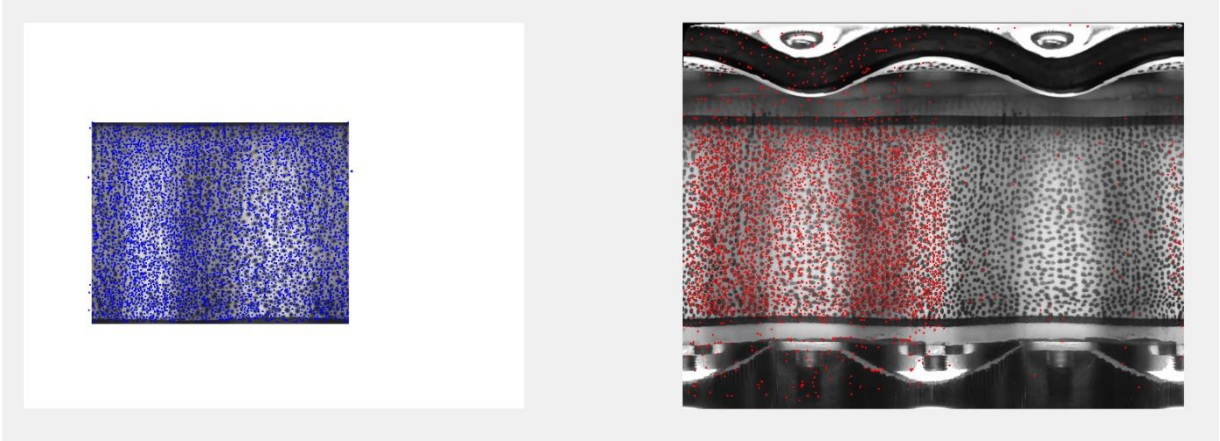

Figure 15. *Illustrations of the SIFT. The left image is the masked image and the colored points represent the corresponding features.*

[7] With the SIFT results, the next step is to smooth the data points to get rid of useless information. This step can be completed by editing the actual points or using the code to predict patterns.

[8] After smoothing, morph the image from camera 1 to be the reference image from camera 3 by matching the identified corresponding points.[12,13] Then perform the DIC to measure the displacement by comparing different points to track the movement of patterns in the images. Save the information regarding displacements and disparities. This step is repeated for several iterations to reduce the disparities.

[9] Repeat steps [6] to [8] for other images with respect to the reference image from camera 3. After that, it is time to convert these processed images from the polar coordinates to Cartesian coordinates.

[10] After transformation, the building code can perform the 3D reconstruction of points with the help of loading calibration parameters.

4.5 Remodel of Cylindrical Needles

Though the final code is not completed, there has been a chance to use a previous code to remodel cylindrical needles. Figures 16 and 17 show some results.

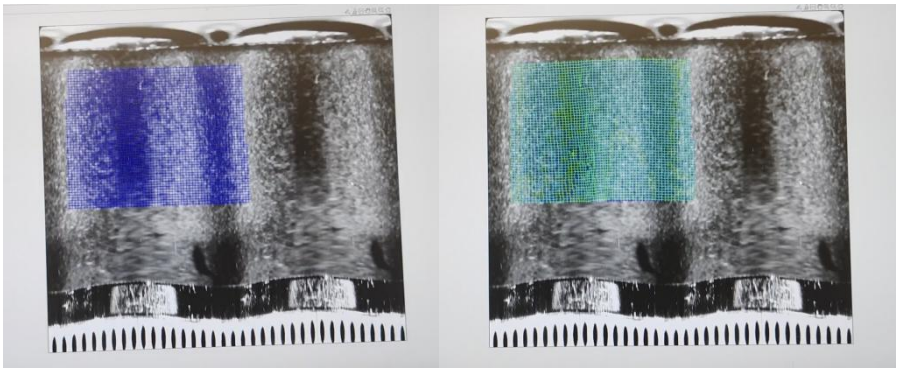

Figure 16. *The SIFT and DIC process.*

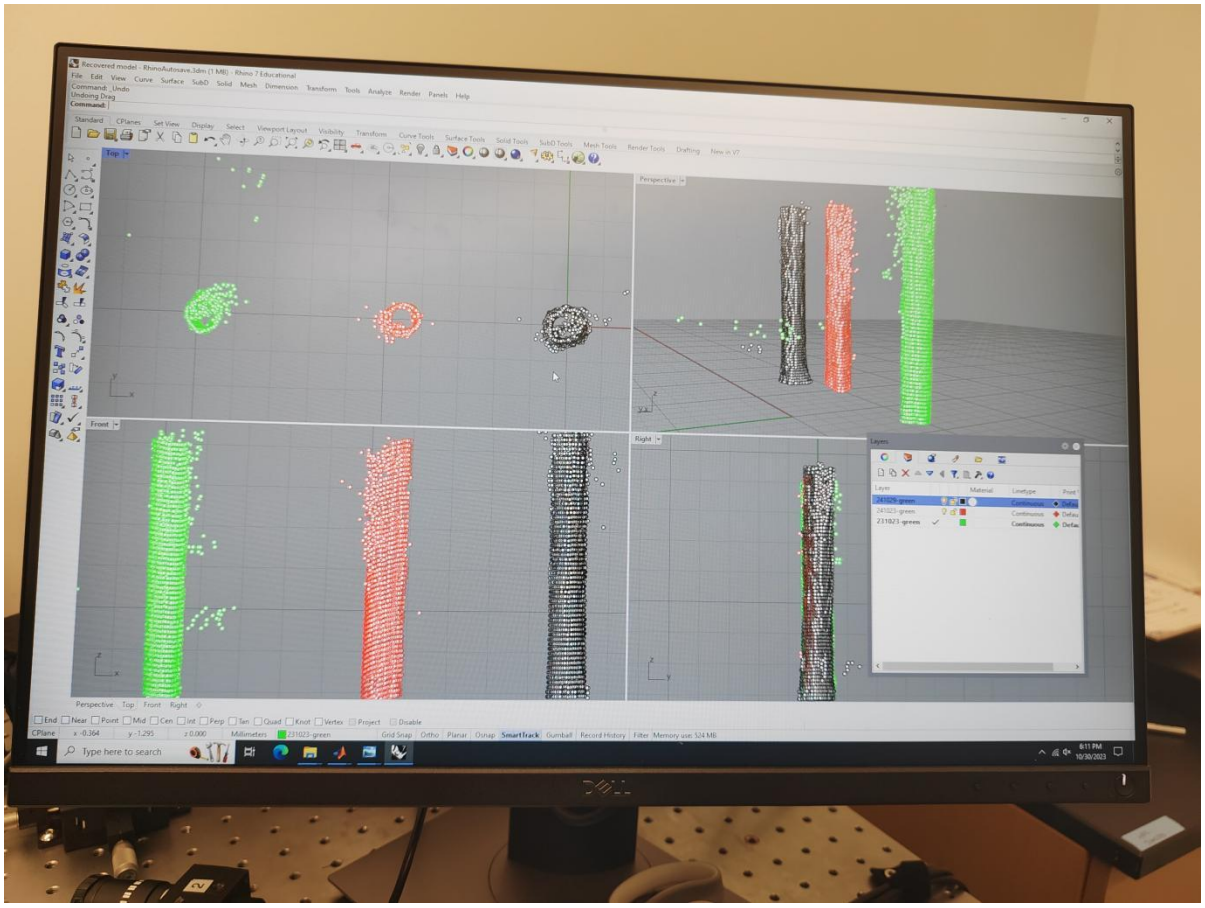

Figure 17. *The reconstructed cylindrical needles with diameters of 20, 19 and 20 millimeters respectively.*

4.6 Bi-axial Mechanical Testing

While the pDIC system does not have a displacement detector component, the use of the bi-axial mechanical testing system is helpful for getting more information on the tissue. The simple procedure is as follows:

[1] Estimate the unloaded parameters for the first time. The unloaded stretch can be estimated by compressing and/or extending the vessel by small displacement intervals.

[2] After estimating the unloaded parameters, zero the force and reinitialize

motors to prepare the first estimation of *in vivo* stretch.

[3] Preconditioning the vessel by setting up pressures between 10mmHg and 140mmHg four times. During the preconditioning, adjust the stretch to find the constant force.

[4] Then, re-estimate the unloaded parameters, zero the force, and reinitialize the motors again.

[5] Next, sketch the axial-stretch plot by setting the pressure between 60mmHg and 140mmHg while recording data for every 10mmHg. If the curve goes up, it means the stretch is higher than the *in vivo* stretch; if the curve goes down, it means the stretch is lower than the *in vivo* stretch. Try to find a flat curve by narrowing the stretch selection, then estimate the *in vivo* stretch from the plot.

[6] Now, record all the data, set parameters, and run the mechanical testing.

There have been chances for me to perform the bi-axial mechanical testing for two descending thoracic aorta samples as shown in Figures 18 and 19.

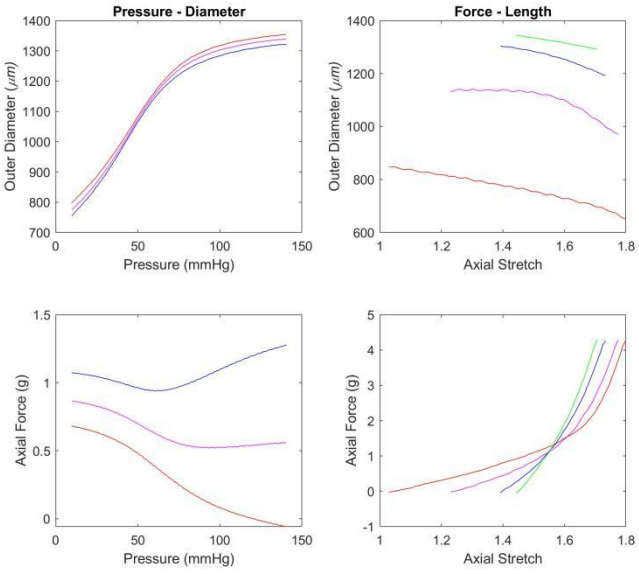

Figure 18. *Unloaded raw data for the descending aorta from the mice with ablation.*

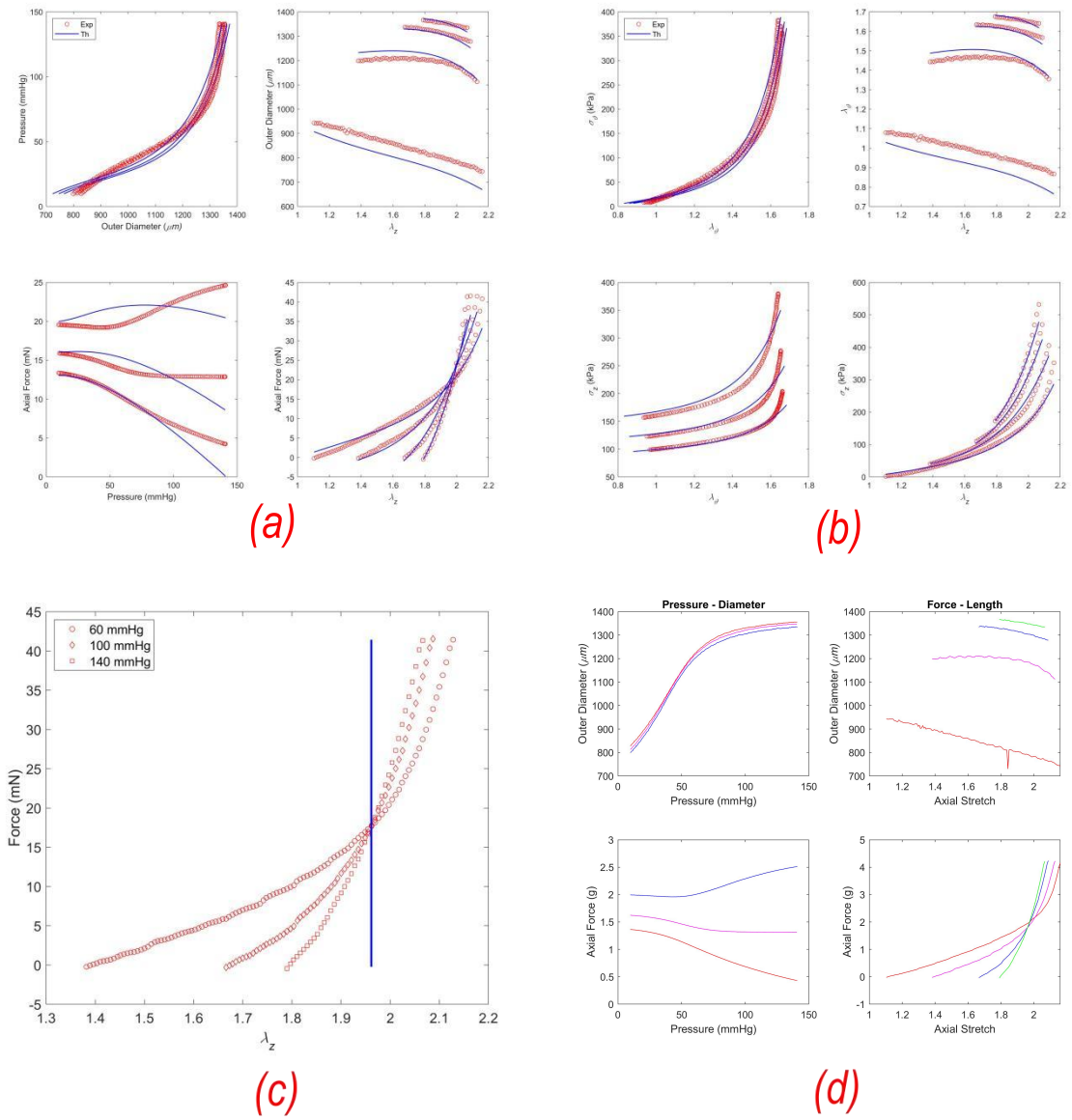

Figure 19. *Mechanical testing data for the descending aorta from the wild-type mice. (a) Post-fitting passive unloading data for loads. (b) Post-fitting passive unloading data for stresses. (c) Post-fitting passive unloading data for stretch. (d) Unloaded passive raw data.*

5 Conclusions

In conclusion, this research rotation in Dr. Bersi's lab has made several improvements in advancing the panoramic-DIC system for vascular imaging. Some main achievements include hardware enhancements for easier calibration, development, and formulation of the procedure of image processing codes. There have also been chances to learn to dissect mice, perform bi-axial mechanical testing, and prepare samples.

However, this work is far from sufficient for the project goal. Future direction may focus mainly on the development and optimization of the codes to process images. Some other developments may include building a displacement measure into the pDIC system or better incorporating bi-axial mechanical testing to complement pDIC data, providing a more comprehensive understanding of soft tissue mechanics.

Overall, it has been a great experience to work with the pDIC system during this rotation, and it is proud that such efforts would enhance the utility of the pDIC system in soft tissue biomechanics.

6 Acknowledgement

I am deeply grateful to Dr. Matthew Bersi for his warm welcome into his laboratory, imparting critical knowledge in biomechanical studies, and providing invaluable guidance. His mentorship has been crucial to my growth and understanding in the field of biomechanical imaging.

I would like to express my gratitude to my senior colleague Yujun Xu for her expert guidance in mice dissection and bi-axial mechanical testing, helping me to enhance my practical skills significantly.

I also want to give special thanks to both Yujun Xu and Niyousha Karbasion for kindly providing practice mice for dissection, as an important component of my learning process.

Finally, I want to express my appreciation to all members of Dr. Bersi's lab for fostering a supportive environment. Their collective support has been fundamental to my successful research rotation.

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