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Structural Health Monitoring of Bioprinted Materials

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in
Mechanical Engineering.

By
Kathryn McIntosh
Under the mentorship of Dr. Jinki Kim

Abstract

Bioprinting is a new method that utilizes additive manufacturing to construct organs, tissues, and other biostructures. This method presents endless possibilities - less reliance on organ donors (according to the Health Resources and Services Administration, 17 people die each day waiting for an organ transplant in the U.S.), more transplant opportunities, and the ability to save significantly more lives. While bioprinting has opened a new frontier in the biomedical field, there may be some research issues that need to be addressed. For example, numerous researchers have focused on creating novel approaches to print complicated geometries. However, the structural integrity or reliability in these printed structures are not what they could be. There has been research aimed toward assessing the structural integrity of these printed materials, yet it is generally focused on destructive approaches and may require contact-based methods that interfere with the manufacturing process and its quality. Recent research utilizing laser-based approaches provide non-contact measurements with high reliability. However, these may not work for translucent materials that are often found in biomaterials and cannot view the entire specimen. This research proposes a novel approach that can advance the state-of-the-art by non-contact and entire structure analysis. The new idea is to assess the structural integrity of the bioprinted materials during manufacture. Utilizing video-based vibrometry for analyzing vibration characteristics, defects in the printed structure are experimentally monitored, which provides good quantitative agreement with numerical investigation results. With this method, the structural integrity of the bioprinted organs could be verified effectively, showcasing the significant potential of bioprinting to ultimately save more lives.

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1. Introduction

Due to the large discrepancies between the number of people who require an organ transplant versus the number of people who actually receive an organ transplant, there are tremendous wait times when it comes to organ harvesting and waiting on the organ transplant list. The supply of organs that can be utilized in a transplant procedure is far lower than the demand for such organs [1]. Figure 1 shows the differences between the numbers of patients on the organ transplant waiting list versus the number of transplants actually performed for various organ types.

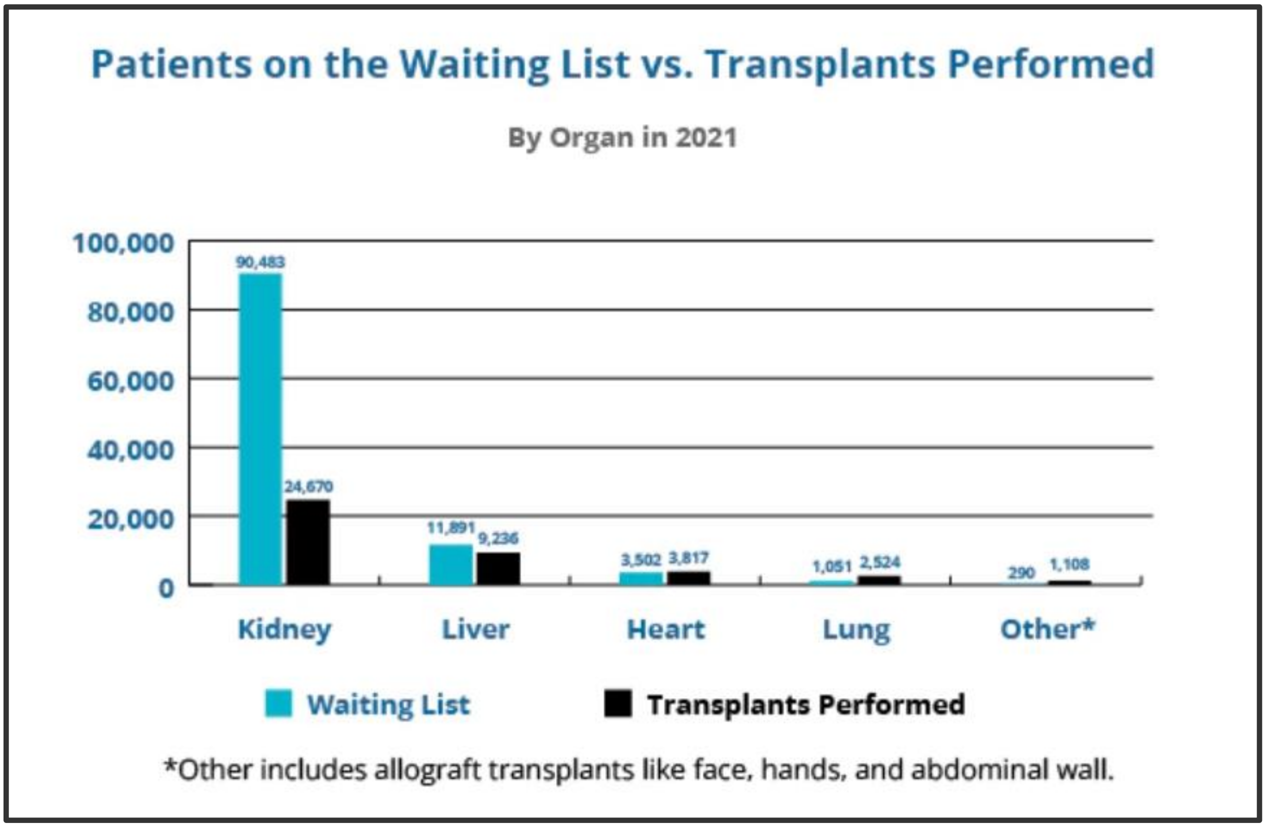

Figure 1: Patients on the Transplant Waiting List vs. Organ Transplants Performed in 2021 (courtesy of organdonor.gov) [2]

In addition, there are many people on the organ transplant list who never even receive the life-saving organs. According to the Health Resources and Services Administration, roughly 17 people die per day waiting on an organ transplant in the United States alone [2]. An alternative to the current organ harvesting technique could allow for more lives to be saved and shorter wait times for organs.

One proposed solution is a new field of medical science called organ bioprinting [3]. With bioprinting, the complex organ geometries are printed on demand using bio-inks that are compatible with the human body. Being able to print these organs instead of waiting on organ harvesting could drastically reduce the wait times for organs, ultimately saving more lives. There have been various research efforts to fabricate complicated organ geometries. On the other hand, research going into investigating the structural integrity of these organ bioprints is yet to be explored. Therefore, this research investigates preliminary studies on identifying structural defects of bioprinted structures. The proposed method for this research is to use a novel method called video-based vibrometry. With this method, a high-speed video camera captures movements that may go unnoticed by the naked eye. The raw video is run through a phased-based motion estimation technique to identify the natural frequencies of the bioconstruct. Each natural frequency corresponds to an individual mode shape. Since the characteristics such as natural frequency and mode shape are tied to the structural integrity of the bioprint, we believe that the proposed method could be used to tell whether or not a print will be structurally sound during the printing process. If the structure is deemed to be structurally compromised before the print is completed, the print can be stopped. This would save both time and money from wasted printing time and bio-ink.

For this preliminary research, the INKREDIBLE Bioprinter from Cellink was utilized to print 12mm cubes with an eight-degree draft angle using a water-soluble bio-ink called CELLINK START [4]. Each of these cubes were tested using the vision-based vibrometry technique to get natural frequency for both healthy and damaged samples. In addition, these samples were tested using laser vibrometry so that a comparison could be made. All experimental methods and results are highlighted in the following segments of this paper.

2. Literature Review

Bioprinting, a form of additive manufacturing (AM) [5], utilizes the concept of 3D printing to combine organic and inorganic materials to produce new hard and soft tissues. In fact, some researchers are using 3D bioprinting technology to print cranio-maxillofacial bones that can be used for implants [6]. There are a variety of different methods that allow for the 3D printing of these biomaterials and a variety of different printing materials (bio-inks) that have been created [3]. For example, one method being used to create 3D printed biostructures is extrusion-based bioprinting. This method has a variety of applications and can be utilized with many different kinds of biological materials. However, there are a lot of factors that can lead to an imperfect print, such as clogged nozzles leading to uneven bio-ink flow [7] [8]. There are various methods and materials to create these bio-inks and biostructures, but next to nothing on the structural testing of these materials. More research in this area is a necessity, since some bioprinting methods can even cause damage to the structure while undergoing printing. For example, the printing process could cause shear stress-induced damage, temperature-induced damage, or even photo-induced damage [9].

Since vibration characteristics are sensitive to the underlying material properties that may be affected by dimensional or embedded defects, vibration-based methods have been employed for structural health monitoring [10][11][12][13]. In light of the success of identifying defects in aerospace, civil and mechanical structures, research has been conducted in identifying the various types of anomalies that can occur using a 3D bioprinter [14]. This research, however, has difficulties maintaining accuracy when working with transparent materials, such as bio-inks [14]. The overall quality of the bioprints is something that is still under research and investigation [15] [16]. This being the case, it is increasingly necessary that an accurate and effective way to monitor the structural health of bioprinted structures be utilized.

One method that can measure natural frequency of a given structure is a strain gauge. The strain gauge is a low-cost, contact mechanism that accurately measures strain in the form of an electrical signal [17]. This method can potentially measure the natural frequency of bioprinted material, but it is a contact method which could cause damage to the biomaterial or interfere with the structure’s natural motion. In addition, the strain gauge may not work well with structures that are ‘jigglier’ in nature. Accelerometers have also been utilized in the field of structural health monitoring, especially in civil infrastructure applications. They are a contact-based method with relatively accurate results [18]. A potential issue that could arise when using accelerometers to measure the characteristics of biomaterial is biostructure damage. This is due to the fact that accelerometers are a contact method. Since it is a contact method, it could possibly damage the structure or inhibit its natural motion.

One method that could potentially offer a non-contact solution to measuring the structure of the bioprinted material is laser vibrometry. Laser vibrometry has been utilized to measure the natural oscillation of structures remotely (from a distance). Research results have shown that the laser vibrometry method is able to accurately measure the motion of structures [19]. On the other hand, an issue that could arise when using the laser vibrometry method is that the laser focuses on only one point [19]. This means that mode shapes for the entire structure would be challenging to obtain.

Vision-based structural health monitoring provides numerous advantages such as being non-contact, allowing for long-distance testing, providing high-precision results, eliminating electromagnetic interference, and allowing for large-range and multiple-target monitoring [20]. Experiments utilizing computer vision-based structural health monitoring have produced promising results. In the civil engineering field, computer vision-based methods, like the video-based vibrometry method proposed, have been able to accurately obtain data regarding the structural integrity of civil infrastructure. This method records data regarding the displacement of structures in a non-contact method [21]. Among various vision-based techniques, phase-based motion estimation has proven to be an effective and accurate method to obtain characteristics such as natural frequencies, damping ratios, and mode shapes for cantilever beams [22]. This method would be beneficial because it allows for non-contact, whole-structure analysis. This method can generate natural frequency, mode shapes, and damping ratios for the whole structure [22], not just a single point. Research has also shown that phase-based motion estimation can be utilized to obtain characteristics such as natural frequency and mode shape at high frequencies [23]. This would be beneficial as it can capture motion that is unseen by the naked eye and magnify it [24] [25].

3. Methods and Materials

For this research experiment, the vision-based vibrometry method was used on five separate bioprinted cubes. Each cube was a 12mm cube with an eight-degree draft angle. All of the cube samples were printed using the INKREDIBLE Bioprinter from Cellink using CELLINK START. Figure 2 shows the INKREDIBLE bioprinter utilized for the experiment.

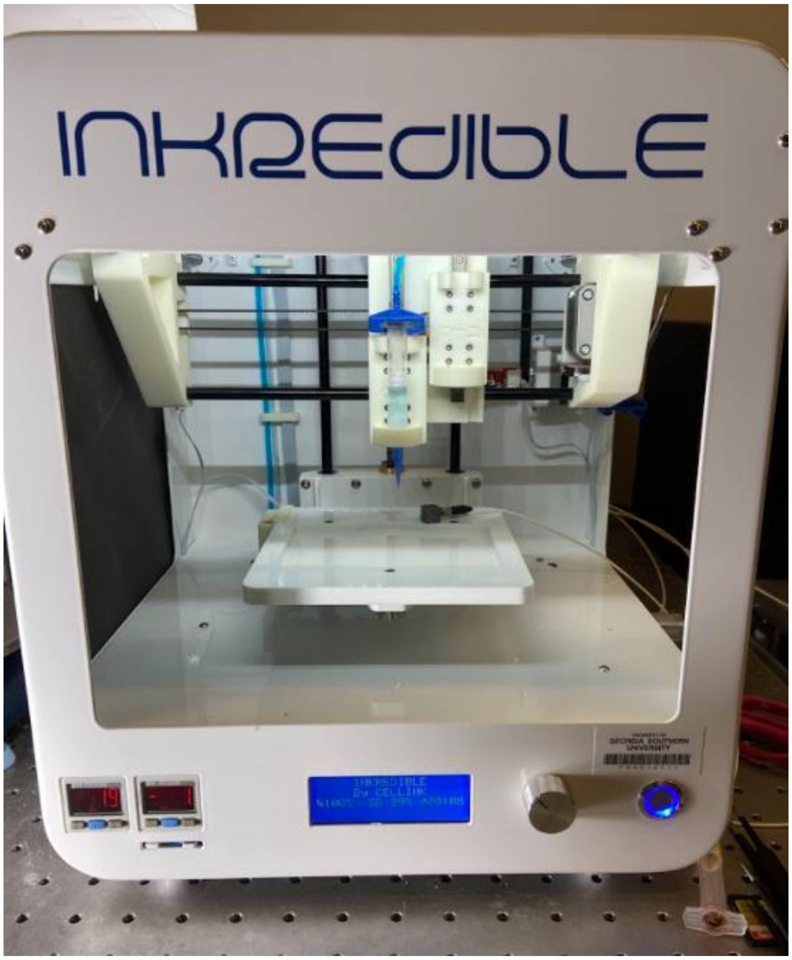

Figure 2: Cellink's INKREDIBLE Bioprinter utilized for experimental methods

Each of the cubes was tested to find their ‘healthy’ baseline responses. For each of the healthy samples, the laser vibrometry (optoNCDT 1420, Micro-Epsilon) method was utilized at the same time with the proposed video-based approach to compare the results. During the testing process, the base of the cube was tapped to induce an impulse response. The free response after the initial tap was recorded using the high-speed camera (Chronos 1.4, Krontech) and run through the phase-based motion magnification using Matlab. Figure 3 shows the experimental setup for gathering the videos of the cubes and gathering the laser data at the same time.

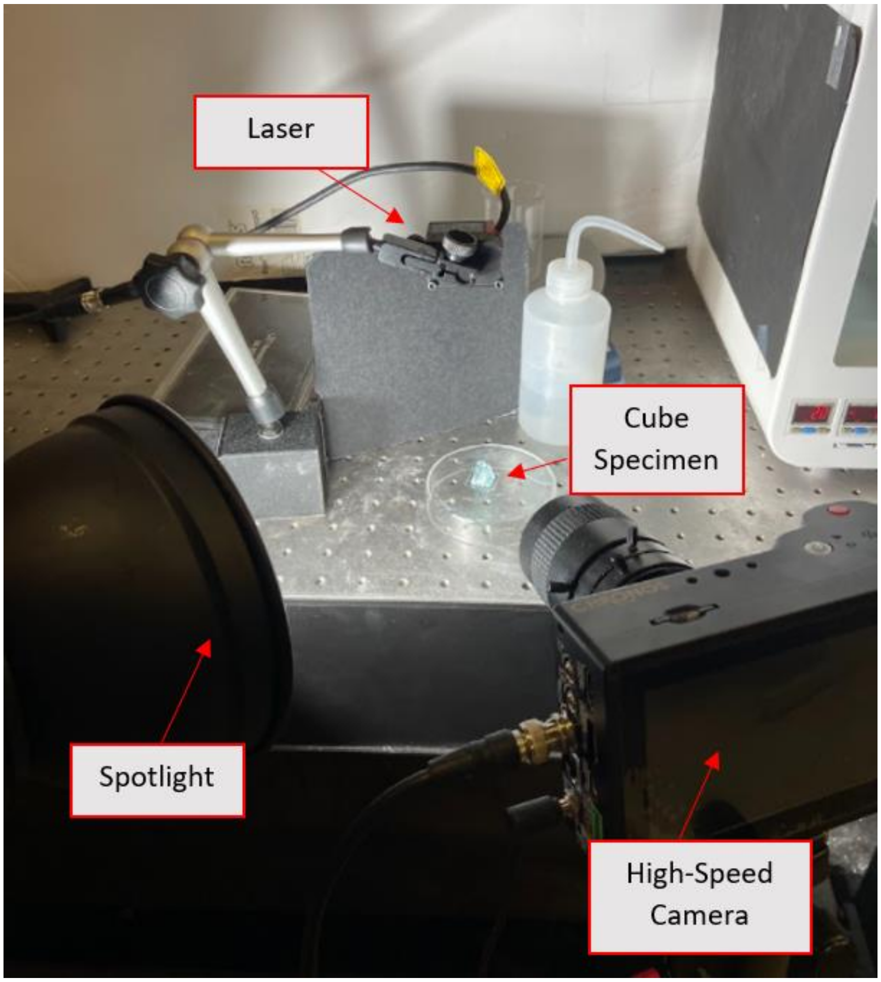

Figure 3: Experimental Setup

Next, one of the cubes was gradually introduced to damage to find out how the frequency response would change. The damage was introduced in the front corner of the cube. Figure 4 shows the difference between a healthy cube and a damaged cube, as well as the location of the damage. Figure 5 shows a model of the healthy cube and damaged cube. For each damage, a slight amount of bio-ink was pulled from the corner of the cube.

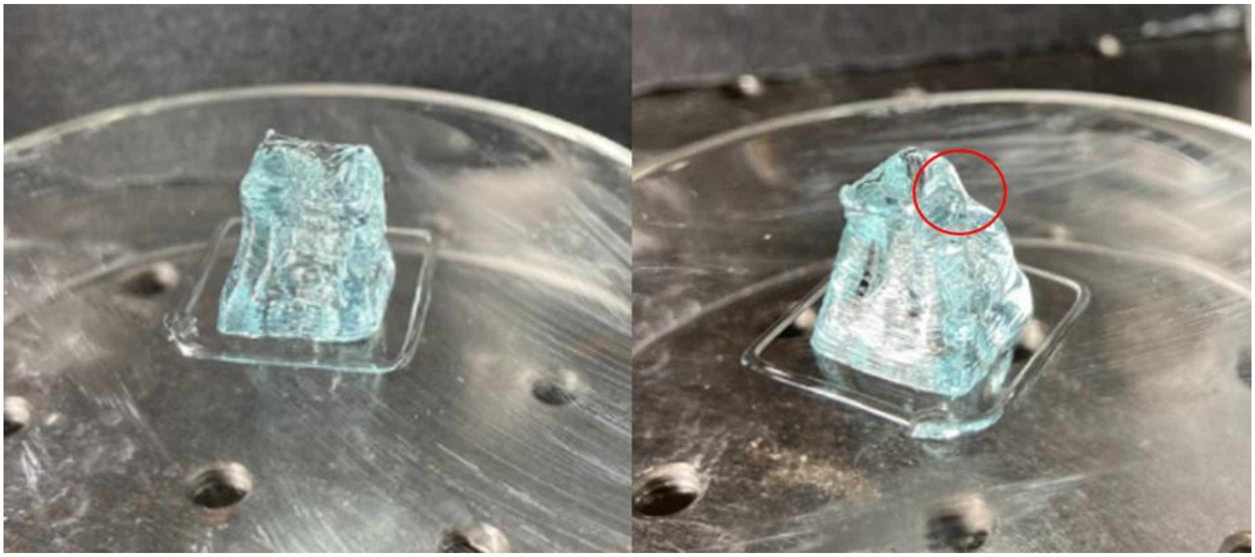

Figure 4: Healthy Print (left) versus Damaged Print (right)

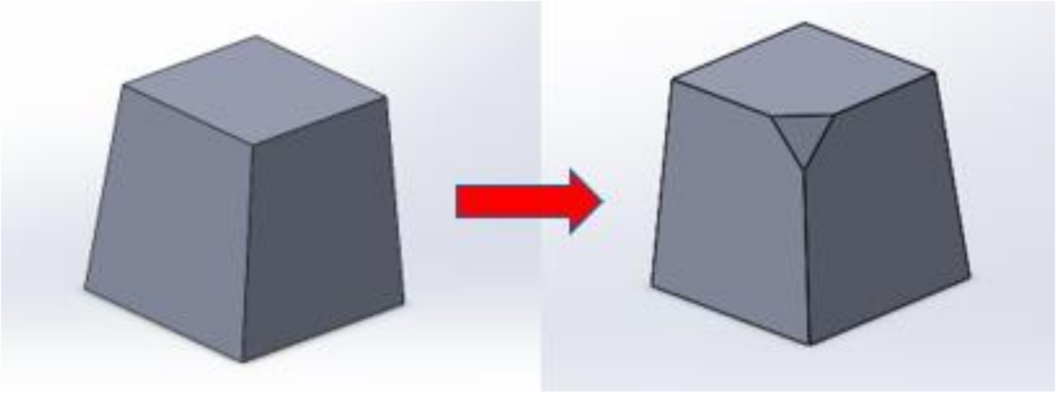

Figure 5: Healthy vs. Damaged Model

Just like the healthy cubes, these damaged cubes were tapped on their base and their free response was recorded using the high-speed camera and the laser displacement sensor. ANSYS Workbench simulations were utilized to reinforce the healthy cube frequency responses and mode shapes. In addition, ANSYS Workbench simulations were utilized to confirm the frequency changes as damage is gradually introduced to the cube.

4. Results and Discussion

4.1 Measurement Validation

The first portion of this research focused on getting reliable and repeatable natural frequencies for the healthy cube samples. Table 1 shows the first natural frequency for each of the healthy cubes.

Table 1: Natural Frequency Data for Healthy Cube Samples

Healthy Cube #	First Natural Frequency (Hz)
1	22.03
2	23.26
3	24.51
4	22.1
5	24.88

For each of these natural frequencies, the corresponding mode shape was magnified. All of these natural frequencies had the fundamental flexural mode shape (back-and-forth sway), validating that our results are accurate. The healthy cube prior to motion magnification is seen in Figure 6 and a graphical representation of its mode shape can be seen in Figure 7.

Figure 6: Healthy Cube before Magnification

Figure 7: Magnified Mode Shape for Healthy Cube

For this data set, the average first natural frequency was 23.356 Hz and the standard deviation was 1.183 Hz, which is approximately 5% of the average value. Being that this is preliminary data with a new method, these are very promising results.

The next part of the measurement validation was comparing the video-based vibrometry method to the existing laser-based vibrometry method. Figures 8, 9, and 10 all show the Fast Fourier Transforms (FFTs) for the three laser trials and Table 2 shows the natural frequency data.

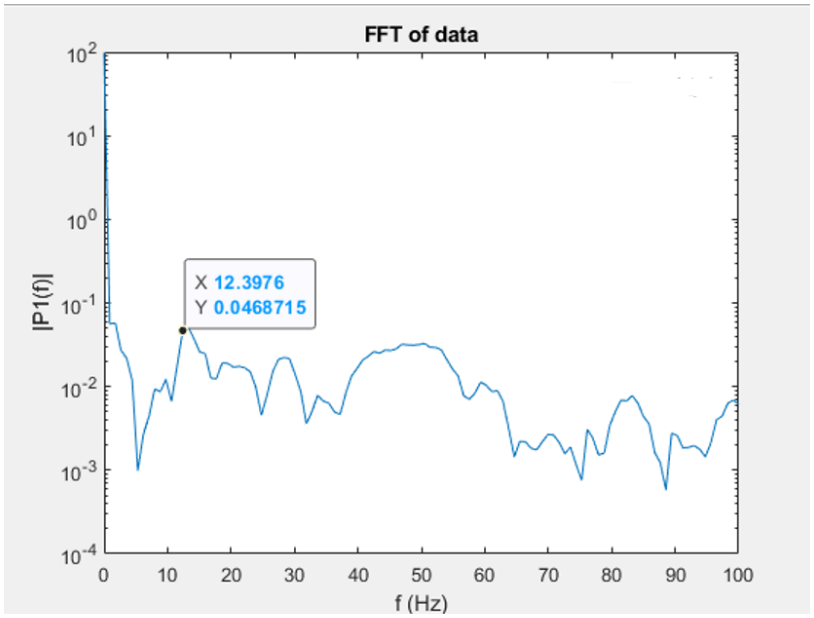

Figure 8: FFT for Healthy Cube 1 (Laser Method)

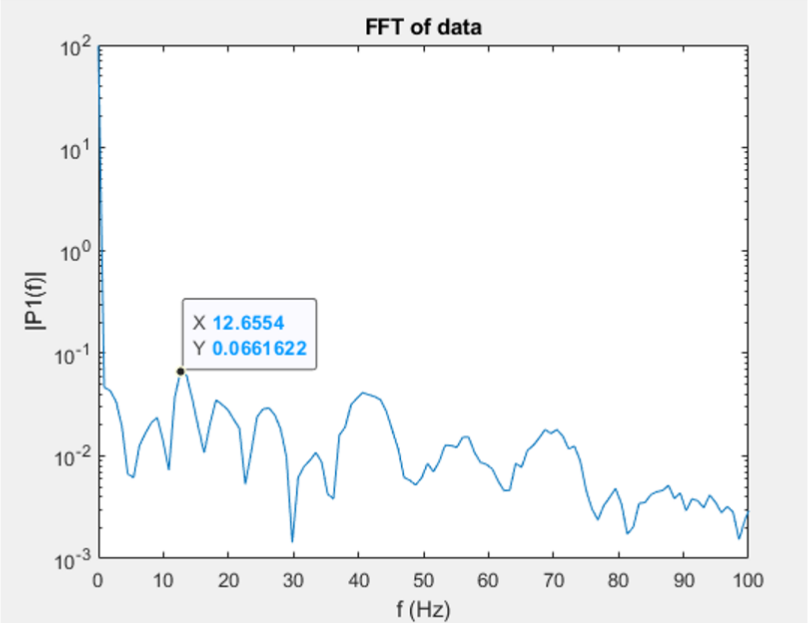

Figure 9: FFT for Healthy Cube 2 (Laser Method)

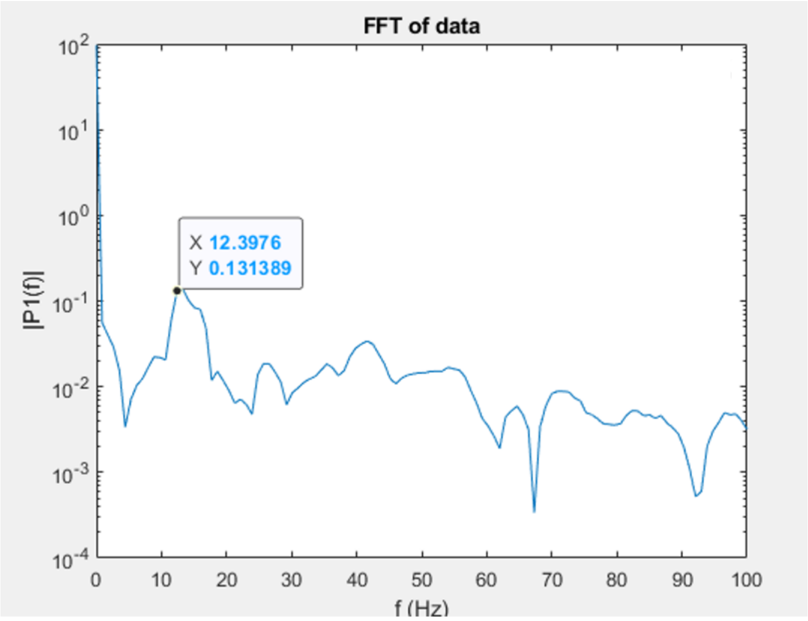

Figure 10: FFT for Healthy Cube 3 (Laser Method)

Table 2: Natural Frequency Data for Healthy Cube (Laser Method)

Healthy Cube #	**First Natural Frequency (Hz)**
1	12.3976
2	12.6554
3	12.3976

The average natural frequency from the laser data is 12.483 Hz and the standard deviation is only .1488 Hz. While this is a smaller standard deviation than the video-based vibrometry, there are still issues regarding the laser data. For one, the laser-based vibrometry method has difficulty working with translucent samples, such as the cubes made from bio-ink. Next, the laser data was very precise, but not very accurate. When compared to ANSYS Workbench simulations, the natural frequencies for the bio-ink cubes matched much more accurately with the video-based vibrometry method, not the laser vibrometry method. There will be more discussion on this in the numerical analysis section of the results and discussion. Overall, based on the results from our experiments with the healthy cubes, we can see that our video-based vibrometry method is a more accurate method to find the natural frequencies and extract mode shapes.

4.2 Healthy vs. Damaged Behavior

The second part of the experiment focused on the frequency response trend when a gradual damage is introduced to the healthy cube. For this section, one healthy cube was printed and its natural frequency was gathered from tapping. This natural frequency was magnified to ensure that the mode shape was accurate. Next, a slight damage was introduced to the corner of the cube. The cube base was tapped and the natural frequency and mode shape was recorded. Finally, a larger damage was introduced to the same corner of the cube and the experiment was repeated. Table 3 shows the frequency responses for the healthy and damaged cubes obtained from the video-based method.

Table 3: Natural Frequency for Increased Damages using Video Method

Natural Frequency (Healthy) (Hz)	**Natural Frequency (Small Damage) (Hz)**	**Natural Frequency (Large Damage) (Hz)**
22.03	24.27	25.97

As can be seen in the results, the natural frequency increases with an increase in damage. This is to be expected because the formula for natural frequency is $\sqrt{\frac{k}{m}}$, where k is stiffness and m is mass. The stiffness will not change much from sample to sample because they are all made of the same bio-ink material. However, the removal of material each time will cause a decrease in the mass of the specimen. Thus, the natural frequency would be expected to increase as the damage increases.

The natural frequency behavior for the damaged specimen shows promising results. While there is still more research to be done to perfect the measurement of the natural frequency, the fact that a slight damage can correspond to a noticeable difference in natural frequency shows that the video-based vibrometry method could be used to indicate a damaged specimen.

4.3 Numerical Analysis

The final portion of the experimental process was to validate the healthy cube natural frequency and modal response to ANSYS Workbench simulations. In order to do this, the model of the cube was added to ANSYS Workbench. Table 4 shows the bio-ink properties that were added to ANSYS in order to properly simulate the results.

Table 4: Bio-ink Properties

Density ($\mathbf{kg/m^3}$)	975
Young's Modulus	6415.6
Poisson Ratio	.44414

A modal analysis was completed on the healthy cube sample and the first natural frequency that was observed was 23.667 Hz. The average experimental natural frequency was 23.356 Hz, which is only a 1.3% between the two natural frequencies. In addition, the same mode shape was observed at this natural frequency as was observed from the first experimental natural frequencies. Figure 11 shows the mode shape for the healthy cube. As seen, the mode shape was a flexural vibration mode (back-and-forth swaying of the cube). The numerical and experimental results provide excellent quantitative and qualitative agreement.

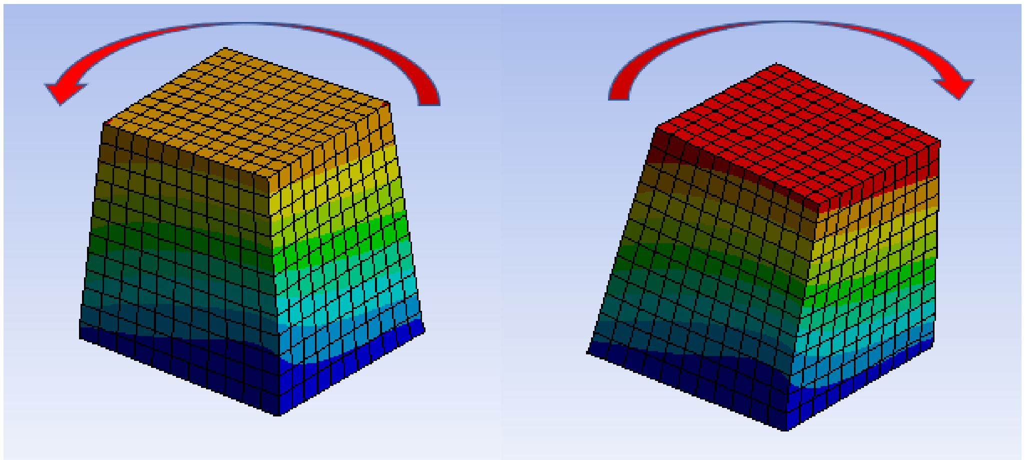

Figure 11: Mode Shape Results from ANSYS Simulation for Healthy Cube

Next, ANSYS Workbench was utilized to validate that the natural frequency will increase as the damage is increased. Figure 12 shows the cubes with increasing damage that were utilized in the ANSYS simulations. This portion of the experiment was very preliminary, but we did see an increase in the natural frequencies for the damaged cubes using ANSYS simulation. Figure 13 shows the mode shape for the damaged samples (as seen, it is the same mode shape from the healthy samples). Table 5 shows the natural frequencies for each of the damaged specimens. The trend from the simulation matches with the trend from the experimental data, validating our process and results. Future works will be focused on enhancing the accuracy of the numerical investigation results.

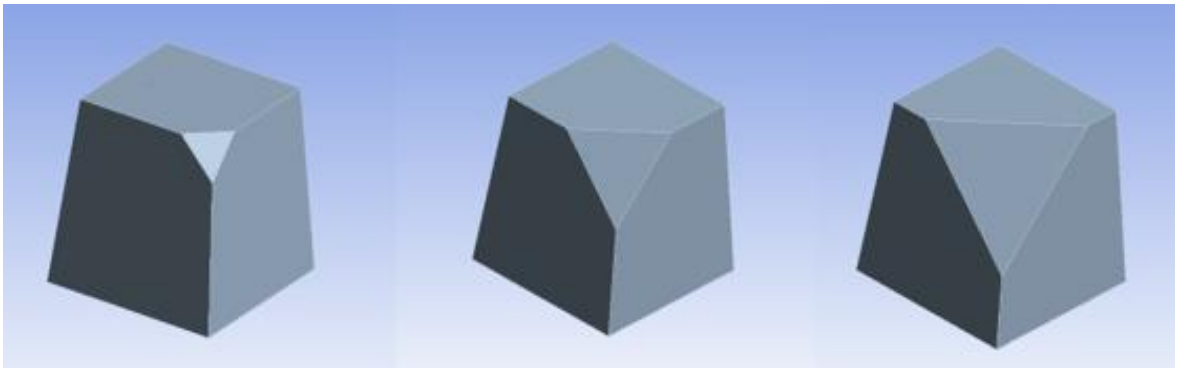

Figure 12: Cubes with Increasing Damage Utilized in ANSYS Simulations

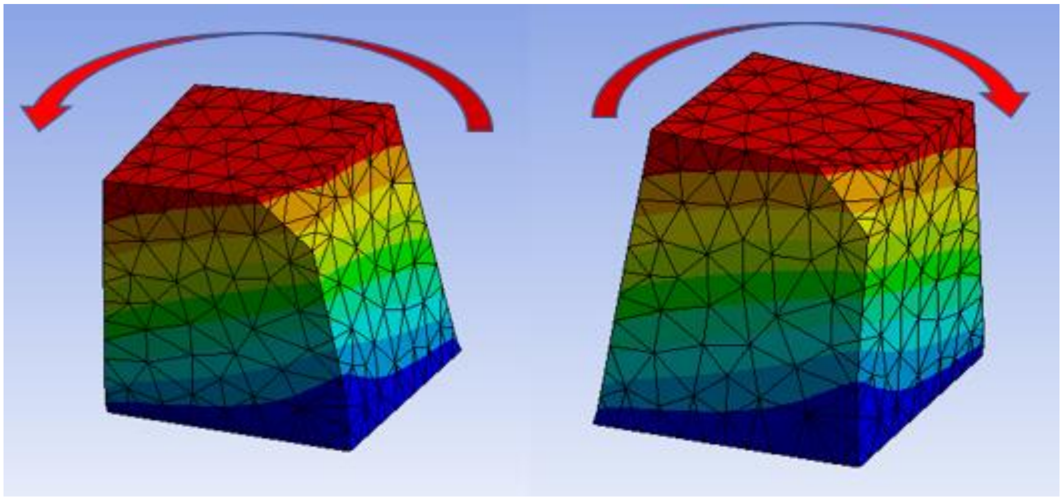

Figure 13: Modal Response for Damaged Cube

Table 5: Natural Frequencies for Increased Damages using ANSYS Simulation

Natural Frequency (Healthy) (Hz)	**Natural Frequency (Small Damage) (Hz)**	**Natural Frequency (Big Damage) (Hz)**
23.818	24.156	24.891

5. Conclusion

Based on the results from the experiment, video-based vibrometry shows promising potential in the field of structural health monitoring for bioprinted structures. For one, the video-based vibrometry method was able to gather the first natural frequency of the bioprinted cubes with minimal experimental error when compared to the ANSYS Simulations. Also, when comparing the video-based vibrometry method to the existing laser vibrometry method, the video-based vibrometry method was significantly more accurate. Next, the experiment was able to show that damage can be diagnosed using the video-based vibrometry method. The natural frequency response from the video-based method matched the predicted trend and it matched the ANSYS Workbench simulation trend. This is very promising for future endeavors. Overall, this research lays the foundation that shows the promise of utilizing video-based vibratory for quality assurance of bioprinted organs. Video-based vibrometry may allow for the structural integrity of prints to be validated with more accuracy, thus providing high-quality organs to be utilized in transplants. This will ultimately save money, time, and the lives of many across the globe.

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