Subtalar Fusion Fixture Design and Test

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Subtalar Fusion Fixture Design & Test

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ME 4800 Senior Design Project

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4/15/14
ABSTRACT
An experiment was designed to quantify the relative displacement between the calcaneus and talus ankle bones during various types of loading. The ankles were embedded in an epoxy resin and three loads were applied: compressive forces, flexion moments, and inversion moments. A stereo camera system took photographs during the loading process, and the images were correlated via digital image correlation (DIC). The DIC was carried out via a suite of homemade programs written using the open-sourced computational program Octave. Due to errors in transforming coordinates from images in one camera to another, the DIC program is not finished and is being debugged.
DISCLAIMER

This project was accomplished by students in partial fulfillment of an Aeronautical/Aerospace Engineering Degree at Western Michigan University. Neither the University nor the design team make any claims to the accuracy of the information nor accept any responsibility for those choosing to use the information contained within. The components within the prototype were built and assembled by students. Operators of the device do so at their own risk. Western Michigan University and the members of this team are not responsible for any damages or injuries that may occur.
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INTRODUCTION

Subtalar fusion is a medical procedure by which two bones of the ankle joint, the talus and the calcaneus, are surgically connected by the application of screws. It is performed on patients afflicted with conditions such as arthritis, injury, or other ailments of the ankle. Inserting the screws causes the bones to fuse, reducing the ability of the joint to move. This eliminates the phenomena of the two bones rubbing together, removing the pain that patients experienced.

OBJECTIVE

The purpose of this project is to design an experiment to simulate the loading of the ankle during gait and measure the relative displacement experienced by the ankle joint when various configurations of screws are applied. There are currently multiple configurations in which the surgical screws can be inserted. According to various studies\(^1,2\), nonunion rates from these differing procedures can range from 2-30%. Due to the range fusion and nonunion rates experienced by subtalar fusion patients, the relative success rate of each configuration is a parameter of interest.

The data gathered may be used to predict the optimal screw placement to aid recovery time in the days and weeks immediately following the surgery. This may help lower the nonunion rate in patients, as well as speeding up overall recovery time and reducing the need for a second surgery.

DESIGN REQUIREMENTS

The experiment must simulate the loading of the ankle and produce data that can be applied to match our overall objective. The requirements of the experiment include:
• Application of loads that are statically equivalent to walking

• Designing a fixture to hold ankle samples in place during loading

• Develop a method to measure displacement of the talus relative to the calcaneus

• Determine optimal screw configuration to expedite healing process

Multiple possibilities were explored, and the method capable of meeting these requirements most effectively was chosen for use in this experiment.

**BENCHMARKING/PAST DESIGNS**

There have been similar experiments to this conducted in the past. These experiments have measured different variables, such as the screw material, screw length, thread length, etc., than what is being measured in this experiment\[1,2,3,4\]. However, these previous studies do provide insight into certain methods that could be applicable to this experiment, such as fixture options and methods to determine the relative displacement of the talus and calcaneus. These studies concluded that the delta screw configuration demonstrated the greatest stiffness, with no variation resulting from differing screw diameters.

**PLAN OF ACTION**

The primary design decisions that will need to be made for this experiment include deciding on load application methods, fixture construction options, and displacement measurement methods. Multiple options will be considered for each step, and chosen based on a weighted system. Below is the expected design process and timelines for the experiment setup.
DESIGN INTENT/EXPECTATIONS

The experiment includes the compressive forces experienced by the ankle, as well as the moments about the frontal and sagittal plane on the foot. To do this, a fixture was designed that will secure the ankle in place for loading. The compressive force is applied directly to the talus, while the moments are created around the center of rotation of the talus, which are transmitted to the talar dome. The fixture holds the ankle in place, while deforming as little as possible and causing no additional stress concentrations.

The first option for the creation of the fixture is through aluminum casting. A preliminary mold was created from polystyrene, matching the contours of the ankle samples. Evaporative-pattern casting was then applied to replace the polystyrene mold with an aluminum replica, which then serves to hold the ankle in place during the experiment.

Alternatively, an epoxy was also used to form a mold about the sample ankle. This created a similar mold to that made from the casting process. Various types of epoxy were researched and considered as an alternative to the casting option.

In order to allow for the testing of various angles of flexion and eversion, the fixture will be able to rotate at one degree of freedom. This allows for the testing of flexion and eversion moments in two separate trials. This fixture was secured to the loading site in order to eliminate movement of the fixture itself and only measure displacement of the bone.

There are multiple options for measuring the relative displacements of the bone in three dimensions. Some of these would require external hardware to be purchased from the manufacturer. One option is to write a computer program through the open-sourced mathematical software, Octave (Octave 3.6.4, GNU). As Octave is an open-sourced software, there is no need
to purchase additional software and the program can be tailored to fit the hardware currently available for use in this experiment.

**Decision Matrix**

<table>
<thead>
<tr>
<th>Category</th>
<th>Fixture</th>
<th>Displacement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clamp</td>
<td>环氧</td>
<td>腐蚀</td>
</tr>
<tr>
<td>Stress Concentrations</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Repeatability During Test</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Compatibility with Assembly</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Adaptability</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Compatibility with Assembly</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Figure 1: Decision Matrix

In order to make the best decision on what methods to use, the above decision matrix to get a better idea of what would be successful. Multiple options were considered for fixture selection and displacement measurement. The options were weighted based on merits in various categories, with 1 being the worst and 5 being the best.

Also, a Gantt chart mapping out the schedule of the project can be seen in Figure 2.
| Task                                      | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 | Week 9 | Week 10| Week 11| Week 12| Week 13| Week 14| Week 15| Week 16| Week 17| Week 18| Week 19| Week 20| Week 21| Week 22| Week 23| Week 24 |
|-------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Meet with Casting Specialist             |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Create Design Prototypes                 |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Modify Design Options                    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Familiarize with Octave Program          |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Create Loading Model Prototype           |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Research Alternatives to Measure Relative Displacement |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Finalize Final Design(s)                 |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Create Final Polyethylene Models         |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Final Measurement Method Decisions       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Create Mounting Options                  |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Finalize Mounting Design                 |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Mesh Future and Mount Designs            |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Write 3D Displacement Code               |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Finalize and Analyze Final Structure     |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Attack Casings and Simulate Test Scenario|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Cast Final Futures                       |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Experience                               |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| Deliver Final Results                    |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
DESIGN APPROACHES
Per the decision matrix in Figure 1, there are two options that appear to be equally valid options for securing the ankle. The options are epoxy casting and aluminum casting. Further investigations were made in order to decide which method would be a better suit for the experiment. Visual imaging was chosen to measure displacement, primarily due to the cost advantages of not needing to purchase extra software or hardware. The design team was able to write coding for experimental use without using additional commercial products.

FIXTURE METHOD EVALUATIONS

Epoxy Resin Casting
In order to investigate the option of epoxy casting, a prototype was made. An initial mold was made from wood. The mold can be seen below.

Figure 3: Wooden Prototype Mold. Calcaneus Mold (left) and Talus Mold (right)
An epoxy resin was poured into the calcaneus mold first, using a wire to suspend the ankle as shown. Once the calcaneus was embedded in the mold, the entire assembly was inverted and suspended over the talar mold to allow the top casting to cure. The finished casting can be seen below.

![Figure 4: Epoxy Casting Prototype](image)

Due to the adhesive nature of epoxy resins, the wooden mold had to be destroyed in order to remove the sample. While this is acceptable for the initial prototype, this approach is unacceptable to apply to a large sample size due to repeatability issues. A more repeatable
method had to be devised to continue with epoxy casting, which shall be further discussed in subsequent sections.

As can be seen from Figure 4, the liquid epoxy created a clamp that perfectly matched the contours of the embedded ankle. This minimized stresses experienced by the ankle. Also, due to the strong material properties of many epoxies, the casting itself deforms a negligible amount during loading, reducing the error in displacement measurements.

The main disadvantage to using epoxy casting is the issue of repeatability when embedding multiple samples. Another disadvantage is the relatively high cost of purchasing epoxy, which is approximately $300. The advantages and disadvantages were compared with those of the aluminum casting method, as described below.

**Evaporation Pattern Casting**

The other design option for holding the calcaneus and talus for testing was an evaporation pattern casting method using aluminum which would encase the bones. The casting process started by shaping the negative form of the bones into a block of polystyrene. Carving the negatives of the bones was done via a Dremel tool using multiple attachments. An example of the polystyrene negative encasing the bone is shown in Figure 5.
After carving out the negative of the bones in the polystyrene, they were coated in a ceramic compound. The ceramic compound is used to hold the shape of the polystyrene once the aluminum is poured. Once the ceramic coating is dry the polystyrene molds are placed in sand containers. The sand is then compacted down around the ceramic coated polystyrene with a small portion of the mold exposed. The sand adds structural support, insulates the polystyrene from the aluminum and helps maintain the shape of the mold after the aluminum is poured. A funnel shaped asbestos cylinder was placed on top of the exposed polystyrene to direct the aluminum in to the mold.

The aluminum is heated to 1,250ºF and then poured into the polystyrene where the evaporation takes places. Once the polystyrene evaporates, the aluminum takes the exact shape of the mold. After the aluminum cooled, the mold was removed from the sand and excess pieces
were cut off to get the final mold.

The advantages of this method were the increased repeatability and lowered manufacturing cost. The repeatability of this method was also a major advantage since there are 30 trials of bones to test. However, one major disadvantage outweighed the advantages and ultimately led to the dismissal of this option. This disadvantage was the inaccuracy of the bone negative in the polystyrene. The carving of the negative was done by hand as stated above which led to human error. The bone itself has many curves and is not a simple shape that would have made it easy to carve in to the polystyrene. The inaccuracies of the mold then led to stress concentrations that were not desired, as well as motion of the calcaneus within the fixture during loading. Since the primary purpose of the fixture is to secure the ankle, the polystyrene-based method was deemed unacceptable.

Improvements of the mold were attempted by using a scanned 3-dimensional model of the calcaneus and a CNC router. The scans were taken using a NextEngine 3D Scanner HD (3D Scanner HD, Next Engine, Santa Monica, California, USA), using ScanStudioHD (ScanStudioHD, Next Engine, Santa Monica, California, USA) software to render the image.
Figure 6: STL File of Ankle

The 3-dimensional model could be uploaded to a CAD package where a negative of the model would be rendered. The CNC router would then follow the negative image created and cut out the desired mold, eliminating the human error associated with the previous process. This option was not performed due to errors in converting formats of the data files containing the ankle geometry.

**Fixture Method Selection**

Due to the inaccuracies of the casting method and the inability to create a CNC-generated model, epoxy resin was chosen as the method for securing the ankles. The epoxy matches the contours of the ankles, as it is in a liquid form when first applied. This eliminates stress concentrations. Once a repeatable method was devised for multiple ankle samples, epoxy proved to be the superior casting option for this experiment.

**EPOXY RESIN CASTING DEVELOPMENT**

Once epoxy resin had been elected as the primary fixture method, some of the issues concerning its use needed to be addressed. First, an epoxy had to be selected for use in the
experiment. The epoxy needed to have strong physical properties, so as to resist deformation during loading. Also, the epoxy needed to have a pot life and cure that allowed the epoxy to settle and degas after pouring. Some epoxies that were considered are shown in Figure 7.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxacast 650</td>
<td>1.5</td>
<td>4</td>
<td>10.36</td>
<td>4.89</td>
<td>.983</td>
</tr>
<tr>
<td>Epoxacast 655</td>
<td>.5</td>
<td>3</td>
<td>14.06</td>
<td>9.67</td>
<td>.865</td>
</tr>
<tr>
<td>Epoxacast 670 HT</td>
<td>3</td>
<td>24@22.5°C, plus 2@80°C, plus 3@ 150°C</td>
<td>2.28</td>
<td>1.75</td>
<td>.699</td>
</tr>
</tbody>
</table>

Figure 7: Epoxy Selection

Based on the information above, Epoxacast 650 and 655 (Epoxacast 650 & Epoxacast 655, Smooth-On, Easton, Pennsylvania, USA) both exhibit similar physical properties.

Epoxacast 655 has a higher Young’s and Flexural modulus than Epoxacast 650, but has a lower Compressive Modulus. The goal is to have an epoxy that will deform as little as possible during loading. Epoxacast 655 was selected, primarily because of its high rigidity and ease of pouring and curing.

A reusable mold was next designed to improve the repeatability of epoxy castings. The new mold was created from a 1/10” thick steel plate, cut and welded into the desired shape. This is shown in Figure 8 below.
The most prominent issue with reusing the mold is the tendency of the epoxy to mechanically bond with its mold. To counteract this issue, two approaches were taken. The first was to counteract the mechanical bonding as much as possible. The surface of the mold was polished, and a commercial release agent was purchased. The release agent, Ease Release 200 (Ease Release 200, Smooth-On, Easton, Pennsylvania, USA), was recommended as the most effective option by the epoxy manufacturer. This release agent can be applied to surfaces and will reduce the adhesive effect between the epoxy and the sides of the mold. Also, a taper of $5^\circ$ was applied to the sides of the mold. The taper acts to redirect the forces applied to remove the epoxy from the mold, requiring less force to extract the casting. The other approach was to line
the mold with wax paper. The wax resisted the bonding of the epoxy, and allowed for easy removal of the casting once the epoxy had cured.

Even with the taper and the release agent applied to the mold, the epoxy had issue of bonding to the mold. The casting could be removed through the use of an arbor press, but this risked damaging the casting and the mold. Alternatively, the wax paper allows easy removal of the casting with no damage caused. The tradeoff is that the corners of the casting are rounded and less precise than those of the mold. The rounded corners do not interfere with any dimensions that mate the casting to the fixture, nor do they add any additional stress concentrations. As such, the wax paper method was selected for use, due to its easy use and repeatability. A wax paper-lined mold can be seen in Figure 9.

![Wax Paper Lined Mold](image)

**Figure 9: Wax Paper Lined Mold**

Once the reusable molds were created, a system needed to be devised that would embed the ankles in the same location, with as little variation as possible. In order to meet this requirement, a suspension system was created that would secure the calcaneus by resting on a
steel bar and support the talus via a fixed length of twine secured at both ends. The talus would then be suspended in the epoxy filled mold while the upper section of the casting cured. The setup can be seen in Figure 10.

Figure 10: Talus Casting Process

In order to ensure that the ankle had the same orientation with each suspension, a few steps needed to be followed. First, the same length of twine is to be used for each sample. This will help ensure the ankle is suspended at the same height for each specimen. Also, care must be taken when suspending the ankle, as there are two “catch” points on the ankle where it will rest at its lowest energy state. The operator must take care to ensure the ankle rests in the proper orientation. The two catch points can be seen below.
Additionally, rests are attached to the bar on which the calcaneus leans. This serves as a physical marker to ensure the calcaneus rests on the same bar location for each pouring. These rests can be seen in Figure 10.

Once the upper casting had finished and been extracted from the mold, the flat surface of the now hardened epoxy can be used to brace the talus while suspending the calcaneus over the second part of the mold. The flat surface of the upper casting can rest on a set or parallel steel bars, creating a consistent method to embed the lower casting.
DISPLACEMENT MEASUREMENT

The basis of displacement measurement for this Subtalar fusion loading experiment is digital image correlation (DIC). This method is based on using a camera, or multiple cameras, to take pictures of a specimen under loading. The images are then correlated using a computer script to track corresponding points in sequential images. The available open source program, aside from being modified to operate in Octave, also had to be modified to operate in three dimensions. The algorithms used in this software follow the procedures outlined by Sutton et al.\(^6\)

In order for this script to operate correctly and accurately in three dimensions, multiple cameras must be used. In this experiment, two cameras were utilized, resulting in chronologically matched pairs of images. The two cameras used for this experiment were a Canon Rebel XT 60D and Canon Rebel XT (for more on camera setup see section on Camera Configuration). The cameras being used were first calibrated in order to obtain accurate results. A modified calibration script, first written using MATLAB (Simulink, MATLAB, Natick, Massachusetts, USA) by professors at Western Michigan University\(^7,8\), was used to calibrate the two cameras. The calibration process included taking a picture of a calibration plate with known
coordinate points painted on its surface. To match the image coordinates with the desired points, the user must click the image where desired. This is shown graphically in Figure 13. The calibration program reads the input of the mouse click and determines the maximum grayscale intensity value in the immediate region. As long as the point remains inside the targets in the image, the calibration will output appropriate results.

Figure 13: Target Clicking for Camera Calibration (note crosses on second image).

Figure 14: Calibrated Image Coordinates
The script then provided the values of a transformation matrix for each camera that related the local coordinates of the camera to the global coordinate system of the calibration plate.

\[
\begin{bmatrix}
X_i \\
Y_i \\
Z_i
\end{bmatrix} = \begin{bmatrix}
R & X_G \\
Y_G & Z_G
\end{bmatrix} + [T]
\]

Eq. (1)

Where \([R]\), the rotation matrix and \([T]\), the translation vector, are the components of the transformation that are found from the calibration process. The vectors \([X_i Y_i Z_i]\) and \([X_G Y_G Z_G]\) correspond to the coordinates of camera \(i\) and the global coordinate system, respectively.

These parameters were attained through the use of the method of Direct Linear Transformation (DLT) and also using the linear least squares method. The basis of the DLT method is the iterative process comparing a set of points in an image to the previously measured object space coordinates. This iterative process solves multiple simultaneous equations in order to determine the parameters. The number of equations is determined by the number of control points on the calibration plate, while the number of variables is determined by the number of parameters the user requires. The minimum number of control points necessary to solve these equations is eight; however, this experiment uses twelve to create an over-determined set of equations.

The parameters necessary for camera calibration are in the form shown in Eq. (2), where \(L\) is a \(n \times 1\) vector, with \(n\) equal to the number of parameters being solved for.
\[ X \ast L = Y \]  
Eq. (2)

Where \( X \) is a \( m \times n \) matrix, with \( m \) being equal to the number of control points used. To solve this, since \( X \) is not a square matrix, the least squares method is used and has been shown to be the following:

\[
X^T X \ast L = X^T \ast Y
\]

\[
(X^T X)^{-1} X^T \ast L = (X^T X)^{-1} X^T \ast Y
\]

\[
L = (X^T X)^{-1} X^T \ast Y
\]

Eq. (3)

The camera coordinates obtained were then translated directly into image coordinates using the intrinsic parameters unique to each camera, which were also found with the calibration program. The complete transformation is shown in Eq. (5).

\[
M = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} + \begin{bmatrix} t \end{bmatrix} 
\]

Eq. (4)

Where the vector \( M \) contains the camera coordinates, \( \{X_w, Y_w, Z_w\} \) are the object coordinates, and \([R]\) and \(t\) are the rotation matrix and translation vector, respectively, obtained from the camera calibration.

\[
\tilde{m} = \alpha \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} = [K] M
\]

Eq. (5)
Where $\vec{m}$ is a set of sensor coordinates, $\alpha$ is a scaling factor and $[K]$ is equal to Eq. (6).

$$[K] = [A][P] = \begin{bmatrix} f S_x & -f S_x \cot \theta & -S_x \hat{c}_x - \hat{c}_y \cot \theta & 0 \\ 0 & f S_y / \sin \theta & -S_y \hat{c}_y / \sin \theta & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$  Eq. (6)

Eq. (6) can be simplified, by assuming that $\theta = 0$, to the following:

$$[K] = \begin{bmatrix} f_x & f_x & c_x 0 \\ 0 & f_y & c_y 0 \\ 0 & 0 & 1 0 \end{bmatrix}$$  Eq. (7)

All of the elements of matrix $[K]$ based on focal length, sensor size, and pixel spacing specific to each camera.

Once the calibration is completed, the experimental data is to be collected. The experiment to be performed is described in more detail in the Experimental Procedures section. The pictures can then be compiled into file lists (generated by “filelist_generator.m”, part of the two-dimensional DIC program) that are then stored for use by other scripts in the two-dimensional DIC program. Next, a grid of points to be tracked is placed on the first image in the loading sequence from camera one. This is done using the script file “grid_generator.m.” An example grid is shown in Figure 15.
After the first grid has been acceptably placed, it is hypothetically translated onto the chronologically corresponding image from the second camera. This would be accomplished by translating the set of grid image points back into the object space and subsequently into the coordinate system of camera number two. This series of translations is shown in Figure 16.

The transformations required to translate points from the image plane to the object plane and into another image plane are mathematically complex. First, the points are translated into the sensor plane and converted from [pixel] units to [mm]. Next, the points were translated into the camera coordinate system. Finally, they were translated and rotated back to the object coordinate system.
This transformation is shown mathematically by Eqs. (8-10).

\[ M = \alpha (A^T \Lambda)^{-1} \Lambda \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} \]  \hspace{1cm} \text{Eq. (8)}

Where

\[ \Lambda = [K | T] \]  \hspace{1cm} \text{Eq. (9)}

\[ [T] = \begin{bmatrix} R_{3 \times 3} & t_{3 \times 1} \\ 0_{1 \times 3} \end{bmatrix} \]  \hspace{1cm} \text{Eq. (10)}

The matrices \( K, R, \) and the vectors \( t \) and \( M \) are equivalent to those in Eq. (4) and Eq. (7). To transform these points from object coordinates into the image plane of camera two, the reverse transformation was applied, using values for the rotation and translation matrices from object to camera two coordinate systems.
Once both image sets have corresponding grid points, the points can be tracked using the “automate_image.m” function, which measures the correlation between image $i$ and image $i+1$ for each camera and computes the difference in positions from one image to the next. The data sets from camera one and two were then mathematically combined, using the Longuet-Higgins method\[^9\] to calculate a z-position for each x-y pair.

As mentioned above, the Z component of the specimen being tested was lost during translation into image plane coordinates. To recover these coordinates, the Longuet-Higgins method was used to reconstruct the third dimension from the series of tracked points in the two image sets. The main equation for this method is shown in Eq. (11).

$$z = \frac{\left( r_1 - y'_1 \right) \cdot t}{\left( r_1 - y'_1 \right) \cdot y} \quad \text{Eq. (11)}$$

In this equation $z$ corresponds to the object z-coordinate, $r_1$ and $r_3$ are equal to the first and third row of the rotation matrix shown above, $t$ is the translation vector, $y'$ is the translation vector, $y$ is the set of image coordinates for camera one, and $y'_1$ is the x-component of image coordinates from camera number two. These recovered points were then paired with their corresponding x- and y-coordinates in the object plane and the displacements were calculated using the DIC program.

The function file “displacement.m” can be used to both calculate and display the measured data from “automate_image.m.” The existing displacement function was appended to include a section for measuring three-dimensional displacement. This amended section also plotted the acquired data in graphical form for ease of interpretation. Also, to the
“computestrains.m” function file a section was added to calculate the strain in three-dimensions across the entire surface of the specimen.

**CAMERA CONFIGURATION**

As stated in the previous section, 3D DIC requires a two-camera setup in order to capture the correct displacement field. In order to have accurate and repeatable results, a dual-camera configuration had to be designed. The requirements for the configuration included the abilities to move the cameras closer or farther apart for different viewing angles, change the height of the cameras, and change the angle of the stand the cameras would be on. An initial stand was designed to meet these requirements. The initial design consisted of two tripods and a hand-made camera slider.

The tripods would allow for the stand to be adjusted to the necessary height which is limited by the adjustable height feature of the tripods. The stand itself can be tilted at any necessary angle which is also limited by the tripods but for this design can range from -60° to 60°. The slider design was built using steel conduit piping and electrical boxes from a local hardware store. The slider stand allows for the cameras to have a full 360° rotation about the center of fixation, depending on the specimen being measured. On top of the two sliding electrical boxes are steel plates with 1/4” screws to allow for the attachment of any digital single-lens reflex (DSLR) camera. The dual camera slider can be seen in Figure 17.
For this experiment two DSLR cameras were used, a Canon EOS 350D (Rebel XT) and a Canon EOS 60D. Both cameras have separate format parameters, such as the amount of pixels that the sensor can read and the spacing of the pixels on the sensors. These format parameters are specified by the manufacturer and an example of these parameters can be seen in the user manual for the 3D DIC.

Once the cameras are set in place and calibrated, the experiment can be started. In order to sync the two cameras and have them each take a photo at the same time, a shutter release with a self-timer was used. The shutter release was then connected to a 2.5mm splitter that would send the electronic signal to each camera at the same time. With the two cameras connected to the shutter release, the interval timer can be set to any time amount of intervals up to 100 hours. Once the picture taking process begins, the images are automatically downloaded and saved to the designated folder using capture tethered mode in Gphoto2 (Gphoto2, GNU). As of right now the program does not operate in real time but can be modified to include this in future testings. The final designed camera configuration can be seen in Figure 18.
For 3D DIC, matching the matching of images is used to compute 3D displacement. Since the cameras are capturing the same specimen on two separate images, the object has to have a pattern to allow for image correlation. A couple problems can arise when choosing the proper pattern. The first is that if the aperture is too small, points of a pattern will not be seen in the small window which leads to the inability to track the displacement properly. For example if a camera is set to a low aperture and taking a picture of a line, the end points can be seen. When this same camera's aperture is changed to make the opening smaller, the ends of the line disappear and the line can no longer be tracked properly. This problem can be solved by using a dotted pattern instead of a grid or line pattern. The second problem can come from using an ordered dot pattern instead of random dots. When the dots are organized in the same pattern and displaced, the program has difficulty tracking individual points. If displacements are large
enough to move points from one neighborhood to another, the computer will confuse the points and tracking will become impossible.

In order to solve this problem, the pattern has to have random dots of varying size\[6\]. This leads to one plausible solution, a random speckle pattern consisting of a 1:1 ratio of black and white area. The random pattern of varying sized dots allows for the computer to pick up certain points and track them as they move. With a unique pattern, both images can pick up the similar patterns and allow for a more accurate 3D displacement. An example of the speckle pattern can be seen in Figure 19.

Figure 19: Speckle Pattern on Talus

**EXPERIMENTAL PROCEDURE**

The loads experienced during gait can be broken down into component moments and a compressive force\[1,2,3\]. According to von Oldenburg et al., the moments for an 80 kg person are 140 Nm of extension, 30 to 50 Nm of pronation, and 5 Nm of torsional moments. Figure 20
shows the component moments. Since the torsional moment is small relative to extension and pronation moments, it is neglected for this experiment.

![Figure 20: Loads Experienced During Gait][4]

Stauffer et al. also measured the compressive loads experienced during gait[^10]. According to the study, compressive forces in the ankle can reach a maximum of five times an individual’s body weight. For an 80 kg person, this yields a compressive force of 3924 N.

Once the ankles have been embedded in epoxy, they need to be mated with a fixture that will secure them during loading. The fixture needs to be compatible with the load frame available, a Bionix Servohydraulic Test System Model 370 Load Frame (Bionix, Toledo, Ohio, USA). The foundation of the fixture is bolted to the load unit base plate as shown in Figure 21a below. Then, a ninety degree rotating clamp is secured to the mounting plate via a set of bolts and washers.
The epoxy casting is tapered to the shape of the mold, making it difficult to clamp the casting by the sides. Clamping the sides of the epoxy also runs the possibility of applying extra pressure to the calcaneus and causing deformation, which could induce error into the calculations. To resolve this issue, the calcaneal fixture is to be secured along the loading axis to a T-plate, which is gripped by the clamp in turn. The casting and T-plate are mated via four bolts, nuts, and washers. The bolt holes in the epoxy can be machined using the mold as a template, which has four holes in the base. These four holes match the location of the holes in the T-plate, allowing for each casting to mate with the same T-plate. The configuration can be seen below.
Now that the ankle is secured to the load frame, a method to load the calcaneus needs to be added. This is also accomplished by using the mold that was used to mold the epoxy. The mold is bolted to the talus in the same fashion as the calcaneus to the T-plate. Fins are also attached to the sides of the talar mold, which provides a grip for the hydraulic press to apply moments. The fins are located such that the gripping point of the hydraulic press is located at the center of rotation of the talus with respect to the calcaneus\textsuperscript{5}. Compressive forces can also be applied to the flat surface of the talar mold, via a ball bearing assembly.
Figure 23: Compression Loading Setup
In order to apply the moments, the clamp needs to be shifted on the base plate such that the grips are able to clamp on the fins. This requires that the T-plate orientation change to test pronation and supination accordingly.

Once the fixture has been set up, loads can be applied and images taken to measure displacement using the DIC program written for use in this experiment.

**POTENTIAL IMPROVEMENTS**

**EPOXY CASTING**

The accuracy of the repeated epoxy pourings depends on the suspension on the ankle while casting the talus. Some variables in this process include the rotation of the washers which support the twine, and the grip points on the ankle. In the future, it may be possible to eliminate the rotation aspect that the washers add during suspension. Also, a more concrete method of suspension may be employed that eliminates the catch points between the talus and calcaneus, eliminating the possibility of error during pouring.

**CAMERA CONFIGURATION**

The current camera configuration was designed for simplicity and affordability. However
the current configuration can be further optimized for increased functionality. First improvement for the camera configuration would be designing a new camera stand with the same functionality as the current setup but in one piece of equipment. The new design could be made using aluminum pieces, such as those commercially available from vendors such as 80/20.

The second proposed improvement would be buying another Canon EOS 60D kit and macro lens. This would allow for higher resolution pictures and the ability to take pictures of smaller specimens. The final improvement would be designing a software that would allow the user to capture images from the camera using their computer. Gphoto2 has the functional capability for one camera and is ran in two separate terminals in order to download photos from each camera simultaneously. However to improve the configuration, a code could be written for a two camera system where only one terminal would be required. This would eliminate the need for the shutter release and any timing errors that may come from it. Pricing estimates for the optimized camera configuration are listed in Figure 25.

<table>
<thead>
<tr>
<th>QTY.</th>
<th>PRODUCTS</th>
<th>PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stand (80/20)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.5 feet 1575 profile</td>
<td>$16.80</td>
</tr>
<tr>
<td>2</td>
<td>5 feet 1501-LS profile</td>
<td>$54.00</td>
</tr>
<tr>
<td>2</td>
<td>2 feet 1503-LS profile</td>
<td>$21.60</td>
</tr>
<tr>
<td>2</td>
<td>¼ inch drop in t-studs</td>
<td>$0.38</td>
</tr>
<tr>
<td>6</td>
<td>90 deg inside corner connectors</td>
<td>$54.00</td>
</tr>
<tr>
<td>2</td>
<td>4358 pivot arm</td>
<td>$30.00</td>
</tr>
<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td><strong>$176.78</strong></td>
</tr>
<tr>
<td></td>
<td>Camera</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Canon EOS 60D EF-S 18-135mm IS Lens Kit</td>
<td>$899.99</td>
</tr>
<tr>
<td>1</td>
<td>EF 100mm f/2.8L Macro IS USM</td>
<td>$1,049.00</td>
</tr>
</tbody>
</table>

Figure 25: Pricing Options
**CONCLUSION**

In conclusion, the experiment is to be run using an epoxy casting mated with associated hardware to secure the ankle to the load frame. Moments simulating flexion and eversion are to be applied, as well as a compressive point force on the talar dome. Images can be taken at regular intervals during loading, using the DIC displacement program to track a speckle pattern during loading. The images will be taken by a dual camera configuration, which has been calibrated to match the test setup. The results can be used to compare the stiffness of various subtalar fusion screw configurations, and hopefully aid the recovery of patients following surgery.
This manual will take a user step by step through the 3D DIC process but there are a few requirements before beginning. First the user must have installed the following packages in your octave system:

Second the user must have the correct camera format parameters set up for both the calibration process and the 3D DIC. An example of the camera formats for the Canon 60D can be seen below. The first two lines of the camera format file are the amount of pixels in the horizontal and vertical direction. These values are specified by the camera manufacturer and can be found on the manufacturers website or user manual for the camera. The third and forth lines are the pixel spacing on the camera sensor. This is simply the size of the camera sensor, in millimeters, divide by the first two numbers. For the Canon 60D the sensor size was 22.2 mm by 14.9 mm in the horizontal and vertical direction respectively.

Once the packages are properly installed and loaded in to your octave and the camera formats are saved properly, one may employ the following steps for 3D DIC:
CAMERA CALIBRATION

1. Run `clicking_targetExample`
   a) Load the proper image you wish to calibrate your camera with
   b) Type in the number of object plate coordinates you have
   c) Click the center of each of your targets (may take some time after each click)
   d) Once you have clicked each target, close the image

2. Run `camcalexample_V1`
   a) Load the camera format of your camera (a “.dat” extension)
   b) Load the coordinates of your object calibration plate (a “.dat” extension)
   c) Load the saved coordinates “xyImagCoord.dat”
   d) The program will now run to calculate the orientation parameters
   e) Once the program has finished you may save the orientation data for camera 1 or 2

3. Repeat steps 1 and 2 for your second camera

4. Both cameras are now individually calibrated and ready for the experiment

3D DIC

1. After concluding the experiment, collect the images from the two cameras in the appropriate folders

2. Run `filelist_generator`
   a) This program will generate the list of all images needed for the DIC
   b) After running this program save the file list name in the appropriate location

3. Run step 2 for the second camera's group of images

4. Run `grid_generator`
   a) Load the file name list for grid selection
   b) If an old grid from a previous experiment is saved that may be used, if not create a new grid
   c) Select the new grid for the range of options
   d) Follow on screen prompts to create the proper grid
e) After the grid is generated, select to keep it or make a new one
f) Once final grid is created the program may be ended

5. Run *stereomatch*
   a) The program will automatically load the grid coordinates, file list for both sets of images, camera formats of both cameras and the orientation parameters of each camera
   b) This program will call both *automateimage* and *findz* to correlate the images in the file list and find the z component for each grid point
   c) A set of secondary grids will be mapped on the second file list of images

6. Run *displacement*
   a) Select the 3D DIC displacement option

7. Run *computestrains*
   a) This program is extra and can be used to find the strain of your specimen
APPENDIX B

Form 1
Student Completes

Assessment of Student Outcome #5
ME4800

The MAE faculty members have identified “An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability” as one of the student outcomes for both mechanical and aeronautical engineering programs. As part of your design project, we ask you to answer the following questions. You are required to submit the completed form with your final report in ME 4800. In your final report, please include page references in response to each question below.

Evaluation of student outcome “An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability”

1. This project involved the design of a: system / component (process)
   Description:
   1. Evaluated 5 test were configurations of screw insertion on Saleh's motor.

2. The need:
   Optimize a surgical procedure and expedite recovery.

3. The constraints: (Explain and justify any constraint that was relevant to the project. At least 3 constraints must be addressed.)
   Economic:
   Open surgical suite was used to avoid producing commercial equipment.

   Environmental:

   Social:

   Political:

   Ethical:

   Health & Safety:
   Entry required in the form hand and body position were bilateral and
   medium there.
4. Is there a potential for a new patent in your design? Explain and compare with related patents.

N_0,
Form 2
Student Completes

Assessment of Student Outcome #9
ME 4800

The MAE faculty members have identified "A knowledge of contemporary issues" as one of the student outcomes for both mechanical and aeronautical engineering programs. Contemporary issues are any issues that you hear on the news related to new and old products and their safety, new innovations, technologies, standards and regulations in general. As you develop your proposal for your senior design project, we ask you to start answering the following questions. These questions will guide you in the development of ideas you need to include in your proposal and final project reports. You are required to submit the completed form with your final proposal in ME 4790 and again with your final report in ME 4800. In your proposal and report, please include page references in response to each question below.

Evaluation of student outcome "A knowledge of contemporary issues"

1. Why is this project needed now?

   Various issues related to different fuel configurations have recently come to light. This project helps provide validation.

2. Describe any new technologies and recent innovations utilized to complete this project.

   3D DPL software and testing setup.

3. If this project is done for a company—how will it expand their potential markets?

   N/A

   ---how will it improve satisfaction of the company's existing customers?

   N/A

   ---identify the competitors for this kind of a product, compare the proposed design with the company's competitors' products.

   N/A

4. How did you address any safety and/or legal issues pertaining to this project (e.g., OSHA, EPA, Human Factors, etc.).

   N/A

5. Are there any new standards or regulations on the horizon that could impact the development of this project?

No.
Form 3
Student Completes

Assessment of Student Outcome #12
ME 4800

The MAE faculty members have identified “An understanding of the impact of the engineering solutions in a global, environmental and societal context” as one of the student outcomes for both mechanical and aeronautical engineering programs. As you develop your proposal for your senior design project, we ask you to start answering the following questions. These questions would guide you in the development of ideas you need to include in your proposal and final project reports. You are required to submit the completed form with your final proposal in ME 4790 and again with your final report in ME 4800. In your proposal and report, please include page references in response to each question below.

Evaluation of student outcome “An understanding of the impact of the engineering solutions in a global, environmental and societal context”

1. Is this project useful outside of the United States? Describe why it is or is not provide details.
   Yes, this project is useful globally.

2. Does your project comply with US and/or international standards or regulations? Which standards are applicable?
   N/A

3. Is this project restricted in its application to specific markets or communities? To which markets or communities?
   No, it is used by the global medical community.

4. If the answer to any of the following is positive, explain how and, where relevant, what were your actions to address the issues?

Design is focused on serving human needs. Design also can either negatively or positively influence quality of life. Address the impact of your project on the following areas.

Air quality?

Water quality?

Food?

Noise level?
<table>
<thead>
<tr>
<th>Does this project impact:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Human health?</strong></td>
</tr>
<tr>
<td>Yes -  improves after surgery</td>
</tr>
<tr>
<td>Wilderness?</td>
</tr>
<tr>
<td>Vegetation?</td>
</tr>
<tr>
<td>Does this project improve:</td>
</tr>
<tr>
<td><strong>Human interaction?</strong></td>
</tr>
<tr>
<td>Well being?</td>
</tr>
<tr>
<td>Helps treat patients with arthritis of the ankle</td>
</tr>
<tr>
<td>Safety?</td>
</tr>
<tr>
<td>Others?</td>
</tr>
</tbody>
</table>
APPENDIX C

Andrew J. Campbell
30950 Sudbury St.
Farmington Hills, MI 48331
Cell: 248-302-1480 Email: andrew.j28.campbell@wmich.edu

Objective:
To obtain a position where I can hone my technical talents while improving the efficiency and profitability of the company.

Education:
Western Michigan University  Aug. 2010 – Present
Kalamazoo, Michigan
Major: Aerospace Engineering GPA: 3.48 Expected Graduation Date: May 2014

Work Experience:
General Electric Aviation
West Chester, Ohio
- Organized the Design Record Book (DRB) system into an easy-to-use layout for the Commercial Low Pressure Turbine (LPT) team by devising a simple format and rearranging the existing structure to match the desired layout (approx. 5,000 documents).
- Worked as a member of the GE90 LPT team to devise a repair process for a faulty scavenge tube and managed the instrumentation and preparation of said tube for testing.

Evendale, Ohio
- Worked as part of a team to exceed requirements necessary for the Evendale site to pass the upcoming OSHA audit (Voluntary Protection Program, Star Status).
- Documented and mapped 100% of operations in Evendale Manufacturing Operations, identifying all steps and safety hazards involved in each operation and formatting them into easy-to-use documents for the purpose of training all employees.
- Developed and conducted training sessions for the creation, maintenance, and use of these documents for all hourly employees on all shifts in Evendale Manufacturing Operations (approximately 400 employees).

General Motors Corp. May 2011- Aug. 2011
Engineering Intern: Crankshafts Dept.
Flint, Michigan
- Worked alongside professional engineers to successfully reduce the scrap produced on the machining floor. Reduced scrap produced from a specific operation in Crankshafts by 25%, saving the company approximately $24,000/year.
- Functioned as a production supervisor in Crankshafts for two weeks, honing my leadership and management skills while successfully supplying the assembly line with parts operating in a high volume, lean environment.

Honors / Activities:
2011-13 Member of American Indian Science and Engineering Society
2010-13 Western Michigan University Medallion Scholarship Recipient
2010-13 Western Michigan University Lee Honors College Member

Computer Skills
AutoCAD 2011 and 3-D Modeling MATLAB
LabVIEW 2011 Microsoft Office
Maple
Christopher Lucas
5200 Croyden Ave.
Apt. 9203
Kalamazoo, MI 49009

(810)-397-0052
christopher.t.lucas@wmich.edu

OBJECTIVE

Highly motivated and enthusiastic individual with a strong work ethic seeking an aerospace engineering position that will utilize my proven organizational leadership and creative skill in a team-oriented environment.

EDUCATION

Western Michigan University  Kalamazoo, MI
Major: Aeronautical Engineering  Minor: Mathematics  GPA: 2.93
Expected Graduation: May 2014
Bachelor of Science in Engineering

Washtenaw Community College  Ann Arbor, MI
Physics/Pre-Engineering  GPA: 3.30
Graduation: August 2011
Associates of Science

RELEVANT COURSEWORK OR ACADEMIC PROJECTS

- **Machine Design**: Developed leadership and teamwork skills while designing an optimal 4-speed transmission in ROMAX and running various test including stress, strain and overall displacement.
- **Aerodynamics**: Collaborated with fellow students in multiple intensive labs to determine the aerodynamic properties such as dynamic pressure, stagnation pressure and lift coefficient on various objects.
- **Instrumentation**: Gained a vast overall knowledge of measurement devices and gauges while using LabVIEW to examine results and evaluate various stresses and strains on metals and composites.

EXPERIENCE

Lowes Companies, Inc.  Portage, MI  May 2012 - August 2012
http://www.lowes.com/

Receiver/Stocker
- Developed leadership skills to adapt and train in to other departments throughout the company
- Daily goals of stocking 6 aisles were given by management and were met in a fast-paced, team oriented work environment
- Developed a high knowledge of various organizational and multi-tasking skills while satisfying various customer request and needs in different departments

Jeff’s Bronco Graveyard Inc.  Brighton, MI  March 2010 - August 2011
http://broncograveyard.com/

Packaging/Stocking
- Provided outstanding customer service through quality packaging and shipping to ensure safety and overall satisfaction
- Developed teamwork skills and overall knowledge of the company to improve overall speed of work environment
- Organized multiple areas of product to ensure ease of product retrieval and a maximum efficiency for fellow employees

July 2009 - March 2010

Crew Member

- Provided a high level of customer service by thoroughly assisting customers, ensuring food quality and promoting a friendly atmosphere
- Maintained a neatness of the facility by preserving sanitary conditions of the food preparation areas and created an environment free of all miscellaneous debris
- Developed and promoted strong interpersonal skills through interactions with the customers, fellow employees and management

SOFTWARE SKILLS

MATLAB; C++; LabVIEW; AutoCAD 2012; ROMAX; Microsoft Office Suite; Windows XP/Vista/7/8; Mac OS;
Nathan R. Ortiz
3015 Random Road
Kalamazoo, MI 49004
(269) 779-0605
nathan.r.ortiz@wmich.edu

Job Objective
Aeronautical Engineer

Work Experience

Bargain Books, Kalamazoo, MI

Assistant Manager
August 2010 – February 2014
Coordinated day to day operations that included cash register operation, opening and closing of the store. Acted as manager when necessary, making executive decisions and handling daily accounting. Other general activities include updating stock, organizing and alphabetizing books, and managing payroll.

Education

Western Michigan University
B.S. in Aeronautical Engineering
2010 – 2014

Kalamazoo Central High School
National Honor’s Society
2006 – 2010
Marching Band Section Leader
2007 - 2010

Activities and Awards

American Institute of Aeronautics and Astronautics
2013 – Present
Dean’s Scholarship Recipient
2010 – 2011
Lee Honor’s College Member
2010 – Present
Society of Hispanic Professional Engineers-Founding Board Member
2013 – Present
Bronco Marching Band
2010

Computer Skills

Abaqus
AutoCAD
LabVIEW
Linux/Ubuntu
Matlab
Microsoft Office
Octave
REFERENCES


8. Montefort, Javier, Nicholas Pohl, Tianshu Liu, James Gregory, and Jim Crafton. "Thin-Wing


