Quantitative Assessment of Hallux Valgus Metatarsal Pronation with the Use of Inertial Axes

by

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Hallux Valgus affects the feet of people of all ages, predominantly elderly women. While the current standard of care involves x-rays, bunions are a three-dimensional deformity which includes rotation of the longitudinal axis of the first metatarsal. While this rotation has been proven to exist there currently is no standard means to quantify this angle. Recent studies have evaluated this angle using solid models of the foot which analyzed this rotation using points picked on boney landmarks. While this is a valid way of identifying the rotation, complications arise with replicability between raters. The current research seeks to show that the inertial (principal) axes from these anatomical models not only properly measures this angle but also alleviates the issues revolving around reproducibility.

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Preface

I would like to recognize my parents and siblings for always being supportive of me in my endeavors. Very special thanks to my advisors, Dr. Mark Carl Miller and Dr. Stephan Conti, for their support and help through my work.

1.0 Anatomic Background

1.1 Hallux Valgus Deformity

Hallux Valgus, otherwise known as a bunion, is a deformity that plagues many and causes moderate to severe discomfort. While Hallux Valgus is known to deteriorate load-bearing capabilities, physiologically there are many unanswered questions. Bunions are characterized as a progressive foot disorder for which the bones in the first metatarsophalangeal joint become increasingly displaced. (Figure 1) This displacement causes discomfort and decreases utility. [1] Those with Hallux Valgus have described their condition to have the following symptoms: a boney protrusion (usually on the outside of the big toe), inflammation and discoloration (redness) around the metatarsophalangeal joint, Corns/calluses (sign that there is a weight distribution problem), sporadic to persistent pain (described mostly at places where there is weight loading but can be consistent), arthritis formation (usually evident through rigidity and constricted movement), and gait adjustment (shifting weight to more comfortable side/ raising heel to reduce discomfort around the joint/ degenerated balancing capabilities on affected side/ and a pronation deformity). [2][3][4]

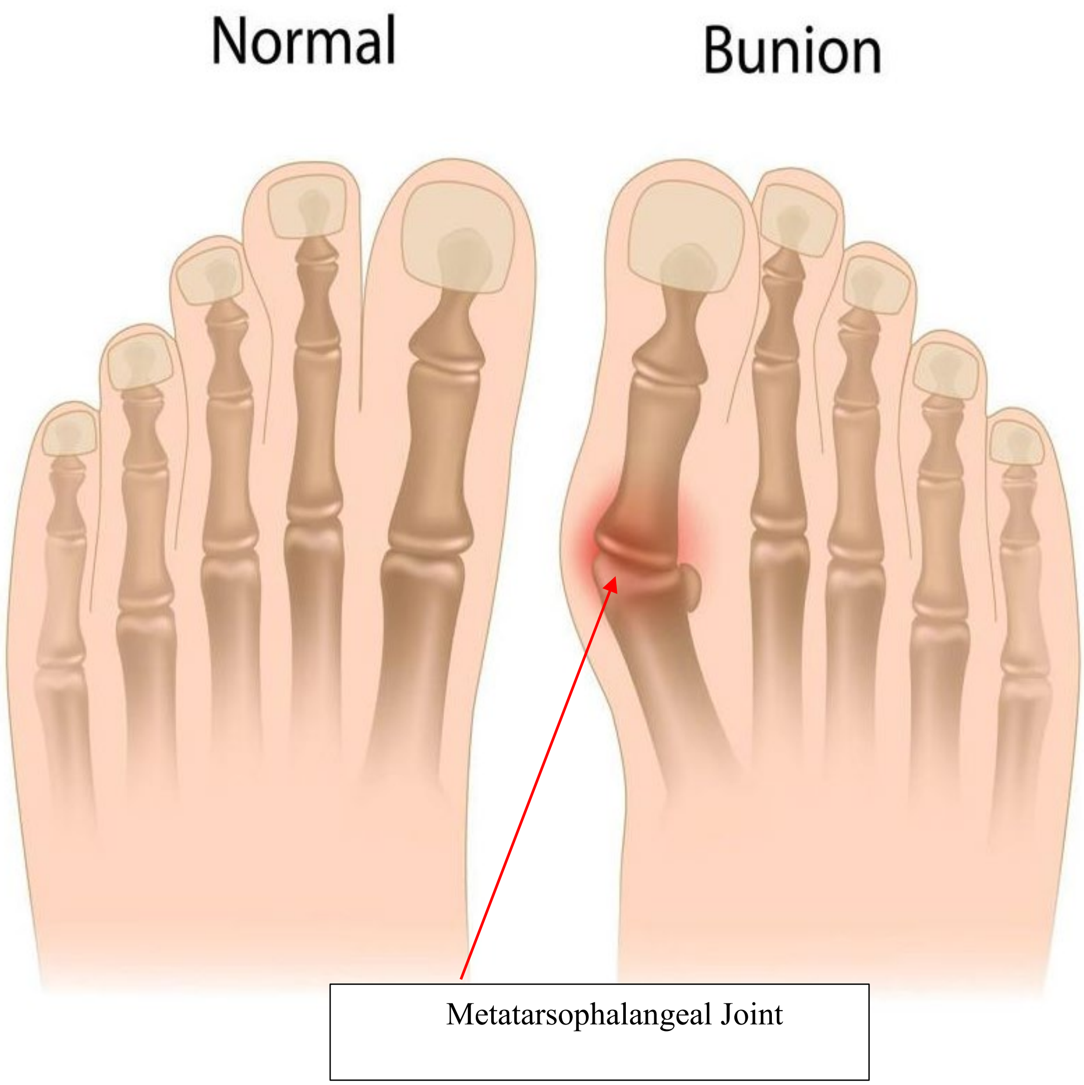

Figure 1: Hallux Valgus Deformity (Highlighting Metatarsophalangeal Joint)

1.2 Demographics

While bunions occur in all age groups, certain demographics are more likely to be affected. Among all demographics, 23 percent of the population between ages 18 to 65 have some degree of deformity and that percentage increases to 35.7 percent for the population over the age of 65. While it has been shown that Hallux Valgus affects much of the population, to varying degrees, its prevalence among other demographics is not so evenly distributed. It generally affects the elderly at a much higher rate and it has been shown that women are much more at risk of this deformity than men. From previous research, it was found that 30 percent of the female population have a bunion of some degree while only 13 percent of the male population show these signs. Thus, one might ask, why are women more prone to this deformity than men? While no conclusive research is known, many believe that ill-fitting footwear (e.g., high heels) and a greater susceptibility to arthritis (which can exacerbate Hallux Valgus) are explanations. [5][6]

1.3 Progression

Evidence supports the possibility that Hallux Valgus can be either an acquired or a genetic disorder. Many of the progression factors can be attributed to normal wear and tear on the foot, but one risk factor includes wearing high heels which through the inclination itself impels the foot into an unnatural position, inducing displaced weight distribution on the toes. Secondly, ill-fitting shoes may force the foot into unnatural positions and force the user to adjust their gait [7]. Ill-fitting shoes can be described as too small, narrow, or tapered; basically, anything that impedes that natural shape of the foot. Prolonged use of these footwear, ill-fitting or high heels, will have a negative effect on foot morphology [8]. While much of the progression can be attributed to physical characteristics, other causative factors also have an effect on one's susceptibility to this deformity: these are best described as hereditary issues. One problem is a rheumatoid arthritis (RA). RA is an autoimmune disorder in which the immune system mistakenly attacks one's own tissue; inducing swelling, erosion of tissue/bone, and deformity [9]. This can affect one's mobility as well as causing mild to severe pain. This form of arthritis can make one susceptible to Hallux Valgus as one shifts weight to the more comfortable foot, morphology issues continue. It has also been found that a number of bunion cases are hereditary [10]. People are more likely to develop a bunion if family members have also been affected. [11][12]

1.4 Bones

While true bunions affect the greater toe and the majority occur around the Metatarsophalangeal Joint, certain forms like Tailor's Bunion, or 'bunionette', affect the joint surrounding the small toe, thus involving the fifth ray. A traditional bunion is characterized by angular displacement of the bones of the forefoot. These displacements shift bones at the metatersophalangeal joint. [13] The displaced bones include the proximal phalanx, first metatarsal, sesamoids, and associated movement of the second ray. Current research is underway to analyze movement in the first and second cuneiform, navicular, talus and calcaneus (Figure 2). [14]

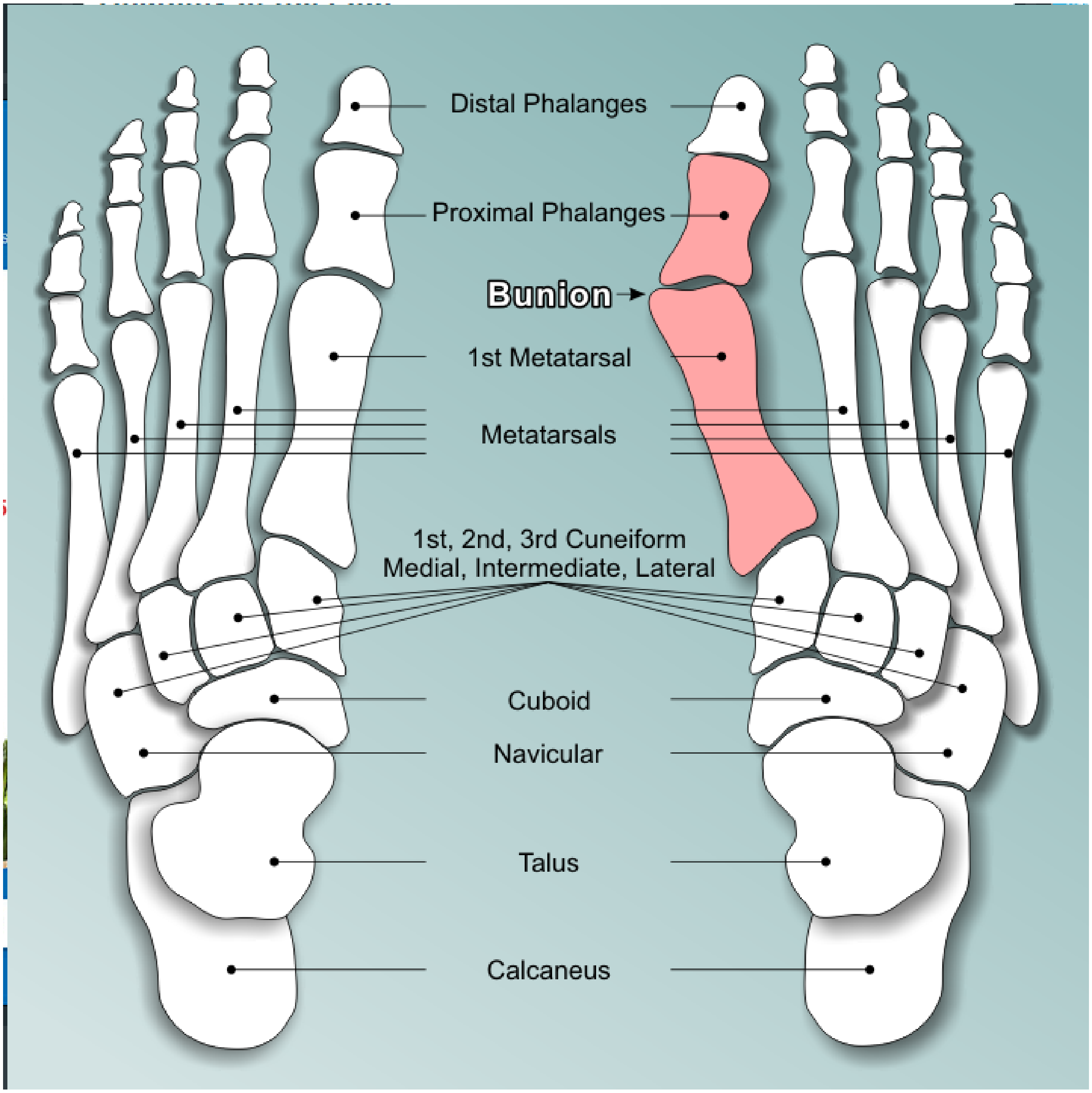

Figure 2: Bones in Question

1.5 Diagnosis

Due to the prevalence of bunions, physicians and surgeons have become adept at diagnosing the early signs of Hallux Valgus. While much of this scrutiny can be done visually, i.e. observing any boney protrusions, current standard of care dictates that the disorder is evaluated radiographically to properly understand its severity. The patient undergoes a series of plain film x-rays, at the very least in the axial (transverse) plane and anteroposterior (AP) plane. This allows the physician to observe the deformity from multiple points of view and get a proper measure of the angulation of the deformity. In the diagnosis of this deformity there are four main angles which are examined: Intermetatarsal Angle, Hallux Valgus Angle, Distal Metatarsal Articular Angle, Hallux Valgus Interphalangeus Angle (Figure 3). Firstly, the intermetatarsal (IM) angle is the long axis angle between the first and second metatarsal. If this angle is greater than 9 degrees it is indicative of a bunion. Secondly the hallux valgus angle (HVA) is angle between the long axes of the first metatarsal and the proximal phalanx. If this angle is greater than 15 degrees it is indicative of a bunion. Thirdly, sometimes included is the distal metatarsal articular angle (DMAA), the angle between the long axis of the first metatarsal and a line through the distal articular cap. Lastly the hallux valgus interphalangeus angle (HVIA) is described as the angle between the distal phalanx and the proximal phalanx. Also, if the DMAA is found to be greater than 10 degrees or the HVIA is found to be greater than 10 degrees it can be described as an abnormality. IM and HV are the two most important. [15] [16]

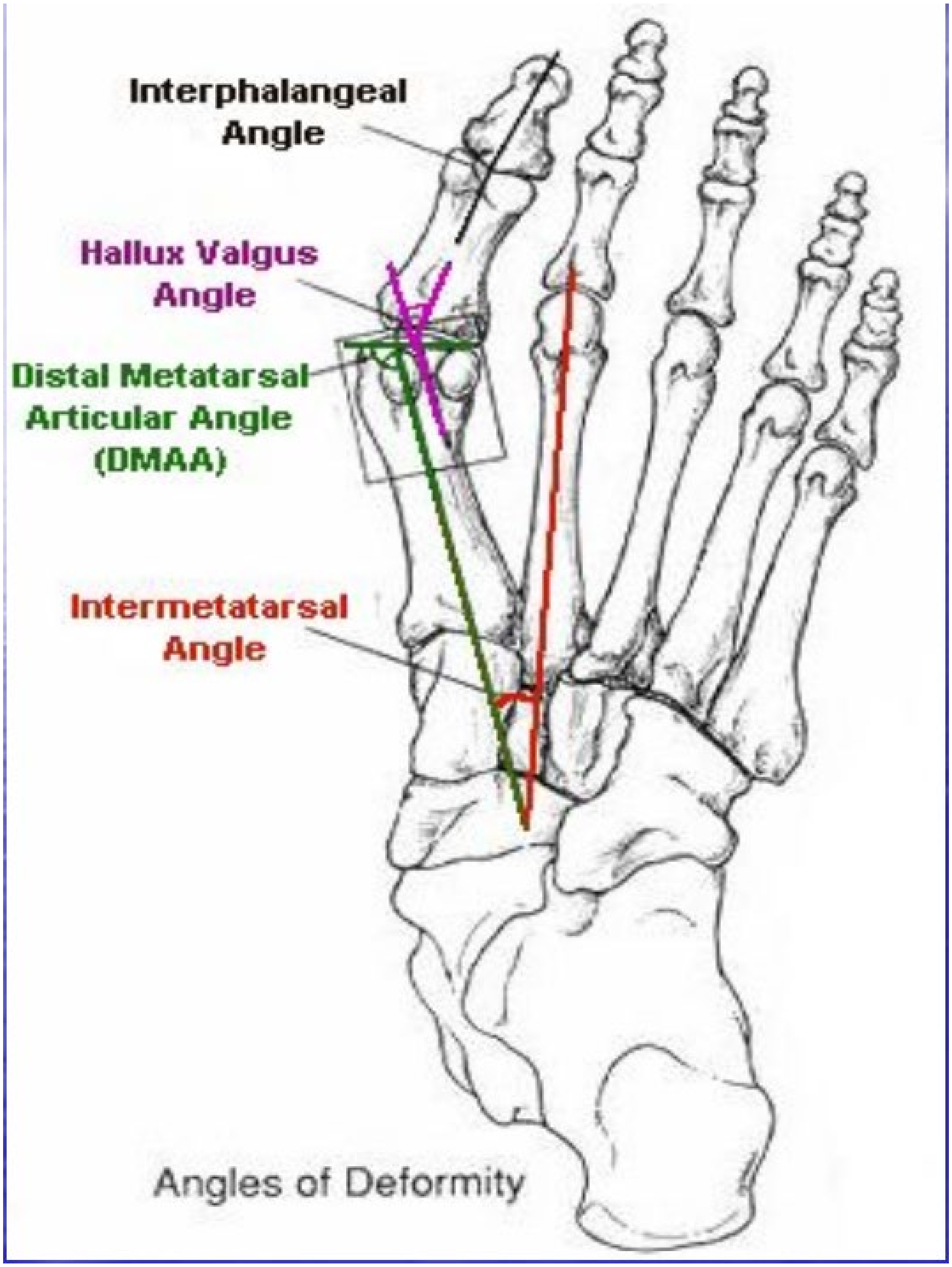

Figure 3: Diagnosis - Important Two Dimentional Angles

1.6 Surgical Procedures

Many treatment options are available to those who require it. Before any surgical adjustment is performed, physicians will look into non-operative solutions (i.e., change in footwear, gait). If the deformity has been found to need surgery, there are recommended procedures (physical therapy), depending on the severity [17]. The first procedure, called the Austin/Chevron Procedure, is used in the case of mild deformities. Here the first metatarsal is cut medially to laterally and the removed section of bone is replaced, using screws, to correct for the slight angular discrepancy. The second procedure is the Reverdin Procedure in which a part of the first metatarsal head is removed and placed dorsally. The articular surface is also rotated as needed. Fixation is achieved using screws or a K-wire. When the deformity is considered to be more severe, the Closing Base Wedge procedure can be used. Here a wedge is removed from the proximal metatarsal, making room for the first metatarsal to be position neatly with the second. Fixation is again done with screws. Another procedure for severe deformities is the Lapidus Arthrodesis [18]. Here a piece of the articular surface is removed and a fusion is performed between the cuneiform and first metatarsal, restricting movement. Fixation is done using screws and plate [19]. One of the last used options to treat this deformity is the First Metatarsal-phalangeal Joint arthrodesis. Here the proximal phalanx is fixed to the first metatarsal, restricting movement of the first ray. This is normally only done if there is a separate pathology alongside the deformity (i.e., degenerative arthrosis). Lastly, an up-and-coming procedure being explored is the Lapiplasty (Treace Medical Concepts inc.) procedure (Figures 4-5). This surgical intervention attempts to take into account the three-dimensional rotation of the first metatarsal, which has been found to exist concurrently with the deformity. Using this procedure allows the surgeon to separate the bones in the first ray and allow the first metatarsal to be manually rotated to correct the deformity. The Biplanar fixation plates are held to the bone using screws which corrects the three-dimensional deformity as well as allowing for rapid recovery and weightbearing. [20][21]

Figure 4: Lapiplasty In-Vivo

Figure 5: Lapiplasty Device

2.0 Engineering Background

2.1 Bones/Pronation

While Hallux Valgus affects many functional and physical aspects of the foot as a whole, currently the morphology of the bones are being quantified, specifically, how the structural changes in the foot can affect gait and foot shape. One of the main indications of a bunion is the evolution of a protrusion between the first metatarsal and the proximal phalanx. This bump indicates an unnatural rotation of the bones themselves. Through this rotation around the longitudinal axis, which will now be described as a pronation, the shape of the foot changes which can initiate many of the aforementioned consequences relating to the deformity (Figure 6). As the first metatarsal pronates, the person suffering from the bunion has been shown to alter their gait for more comfortable movement, exacerbating the problem. Previously, surgery ignored the pronation of the bones and simply shaved down the protrusion. This, while reshaping the bone to look normal, did not address the problems which initiated the pain in the first place. Currently surgeons look more closely at the adjustment of the foot and reshape to alleviate much of the suffering but surgical success rates are. [22][23]

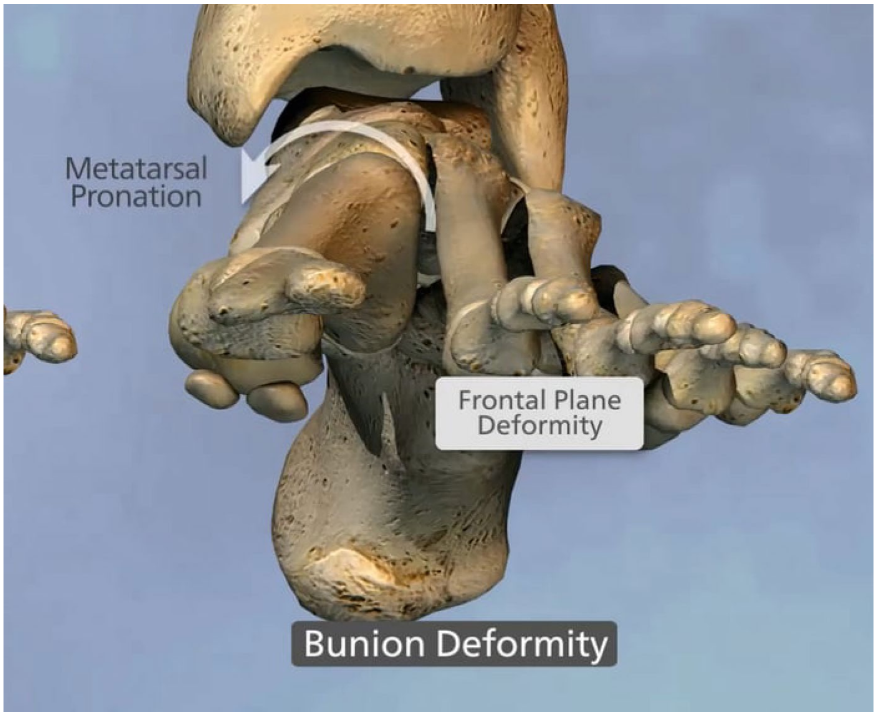

Figure 6: Pronation (Treace Medical Concepts inc.)

2.2 Quantification

While there is no currently accepted way to measure pronation, there are approaches that seek to quantify this rotation. The current method involves making computer models of the bones in question (using programs such as Mimics) by isolating them in CT scans taken of the foot. By singling out the bones one can look at them singularly or in combination while keeping them in the physical space in which they were imaged. Using analytic software one can view these bones as needed and show what only needs to be seen. Using any selected bone, a set of axes are determined using a set of points picked on bony landmarks. From here a series of steps attach orthogonal axes to each bone and evaluate the orientations of the bones in comparison to some baseline. One of the resulting three rotational angles is the pronation of the bone. [24]

2.3 Previous Research

Previous research has been done around the calculation of pronation. One study was done by Dr. Bradley Campbell who looked at the comparison between individuals who had Hallux Valgus and those that did not. He looked at how pronation accompanied the progression of the deformity, confirming its prevalence. Associated with this study was a look into how the affects weight bearing CT scans affected model quality and angle acquisition. This showed that pronation values increased as the individual placed their full weight on the deformity [24]. In a separate study, done by Dr. Tadashi Kimura et al., mobility of the first metatarsophalangeal joint was also studied using three-dimensional analysis. They found that metatarsal mobility is increased in those with Hallux Valgus and showed that loading of the foot caused a displacement of bones throughout the first ray. [25]

2.4 Clinical Importance

Surgeons are always looking for the best way to treat patients. CT scans are not part of the standard of care for bunions. Demonstration that the deformity is three dimensional has focused the attention of many physicians on the idea that there needs re-examination of the deformity. While the three-dimensional method of angle acquisition might be tedious and time consuming it does highlight that there is an unaddressed underlying problem.

2.5 Inertial Axes

This research explores the use of inertial axes in the determination of these 3 rotational angles (yaw-pitch-roll), pronation, as an alternative approach to angular acquisition (Figure 7). Inertial axes, also commonly known as principal axes, are a way of describing the orientation of a body in three-dimensional space. These are the eigenvectors of the inertial tensor. These axes all pass through the center of mass of the object describing the body by its physical layout rather than by boney landmarks. A major concern underlying this study is that the previous use of axes determined from picked points does not produce completely consistent results. While Dr. Campbell found a 0.87 user reliability rating in his study, different users may find different results [24]. Most of these issues revolve around the reproducibility of these results between separate people analyzing the same sample. The issue of model differences (i.e., discrepancies between two models of the same scan) is one potential problem. If the points are user defined and described over areas of a small space, there are opportunities for user error. Solving this issue computationally (i.e., without the input of a user) all but eliminates the problem of duplicability. By using inertial axes instead of picked points by using identical models, the same results can be reproduced by any person. The use of inertial axes is expected to be an improvement on the current approach of determine these angles.

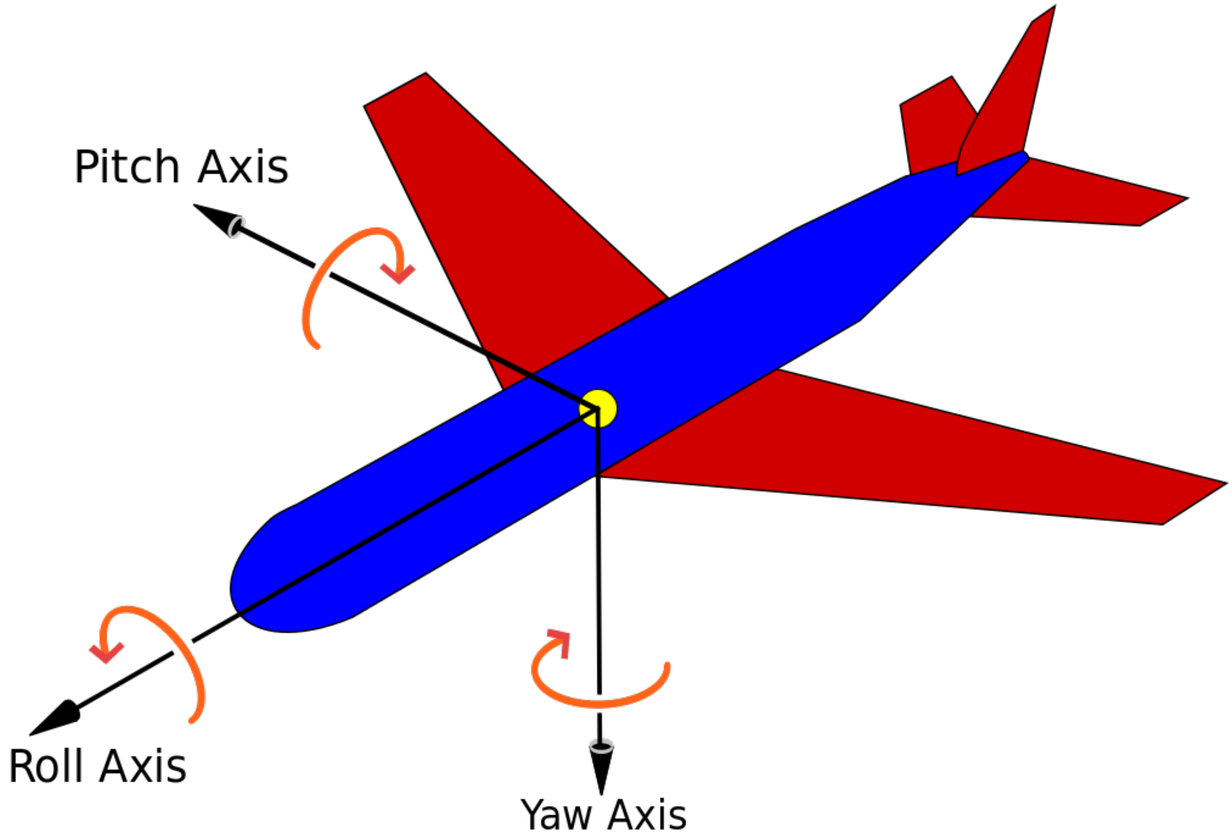

Figure 7: Inertial Axes (Plane Examle as taken from CoM)

3.0 Methods

3.1 Imaging

Due to the prevalence of Hallux Valgus among females, this research focused on the study of women with the deformity. With Institutional Review Board (IRB) approval, women underwent multiple forms of imaging in order to get an improved understanding of the affliction (Figure 8).

3.1.1 University of Pittsburgh Medical Center (UPMC) Passavant

Previously, in an earlier study, 20 women, 10 of whom had the deformity and 10 of whom did not (normals), underwent CT scanning and plain film imaging. The CT scanning was performed twice, in order to determine how weightbearing affected the deformity. All of the CT scanning was completed in a horizontal non-weightbearing CT scanner at UPMC Passavant Hospital. The first analysis sought to determine whether weightbearing affected the rotation of the bones of the foot. This required the subjects to undergo a second set of CT scanning (done at the same time) in order properly compare the two results. Due to the lack of an imaging system that included standing, a simulated weight bearing device was used to replicate standing conditions. This simulated weightbearing apparatus was placed in the bore of the CT scanner and allowed the subjects to push down on a spring-loaded platform to simulate the conditions of body weight. Along with the two forms of CT scanning, these patients also underwent a set of X-ray imaging in order to compare the results to what is the common practice in diagnosing this disorder. [24]

3.1.2 Hospital for Special Surgery (HSS)

With the use of Hospital for Special Surgery (HSS) in New York, subjects were able to be imaged using a standard standing weightbearing CT scanner. This allows the measurement of true weight bearing as the subjects are standing naturally within the vertical bore of the scanner. Using this method, an additional 32 subjects underwent weightbearing CT scans and X-ray imaging. For the most part, this was done in two stages, one being a pre-operative look into the deformity and the second done post-operatively (in order to see what the corrections are doing to bones after all is said and done). This allowed a second comparison, looking at subjects pre- and post- operatively to obtain a better understanding of the deformity.

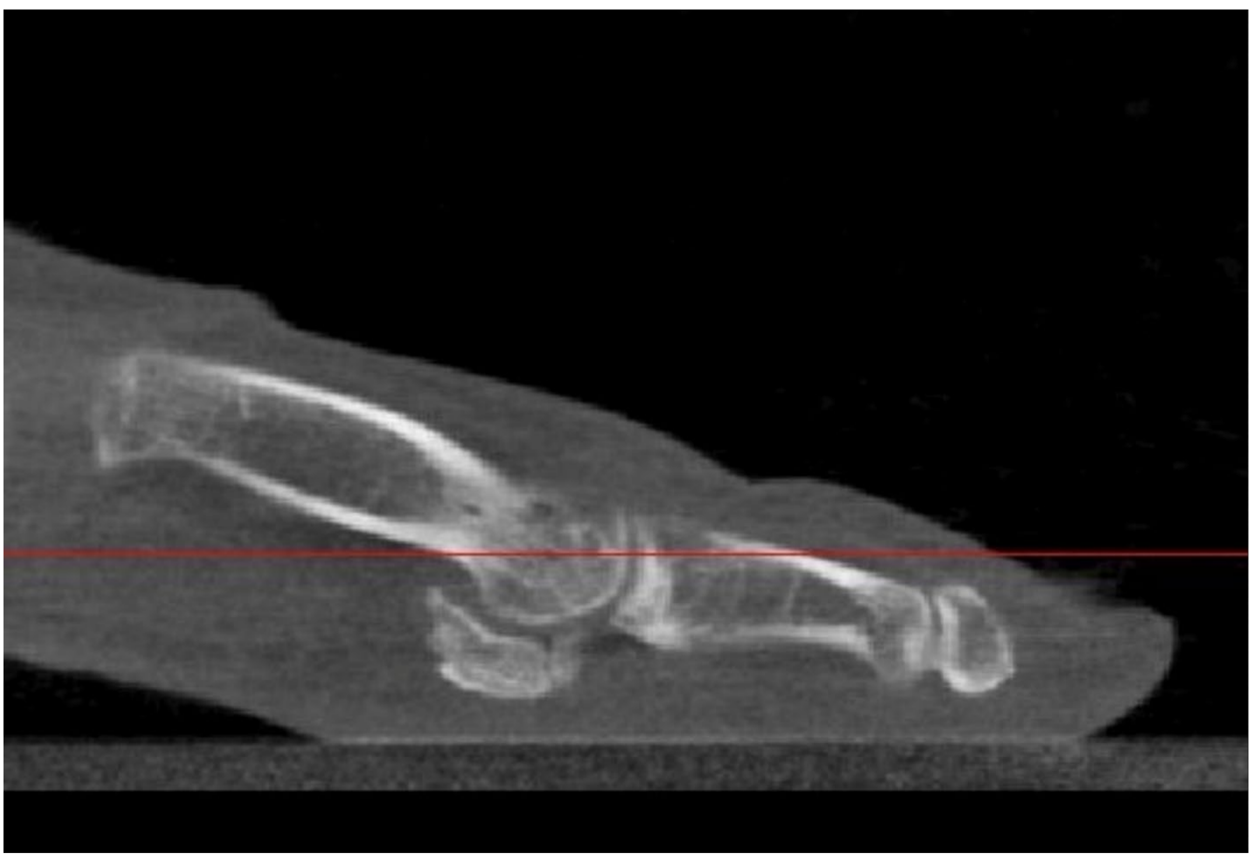

Figure 8: CT Scans taken of the Hallux Valgus deformity

3.2 Segmentation

After subjects were scanned and X-rayed, three-dimensional solid models were created from the CT scans. These scans were in the form of DICOM images. These DICOMs were uploaded into the software Mimics (Materialize; Leuven, Belgium) in which the images could be edited. An adjustable threshold, i.e., a density driven contrast, selected regions that are of a similar density and created a framework of a preliminary model of the foot. In order to identify multiple bones and single out each bone, the thresholded image was edited to remove anomalies and interconnections. With an editing tool, the non-important areas were removed and holes filled. The bones were separated from each other. These steps were repeated until all of the bones were separated and could be viewed individually. The models were further smoothed automatically to remove unwanted peaks and holes. The models were then exported from Mimics as STL for use in in subsequent steps (3 planes shown in Figures 9 – 11).

Figure 9: Segmentation using Mimics (Axial view)

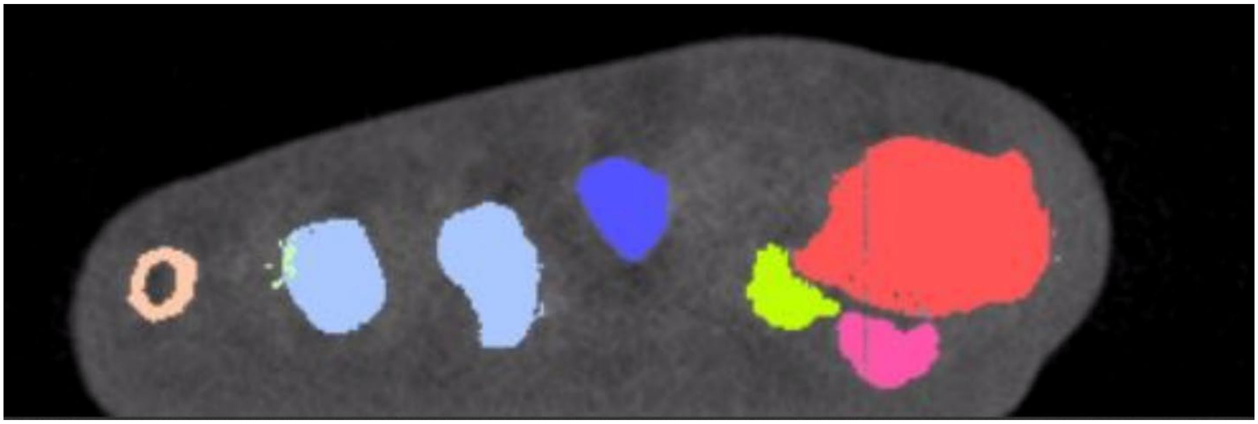

Figure 10: Segmentation using Mimics (Coronal view)

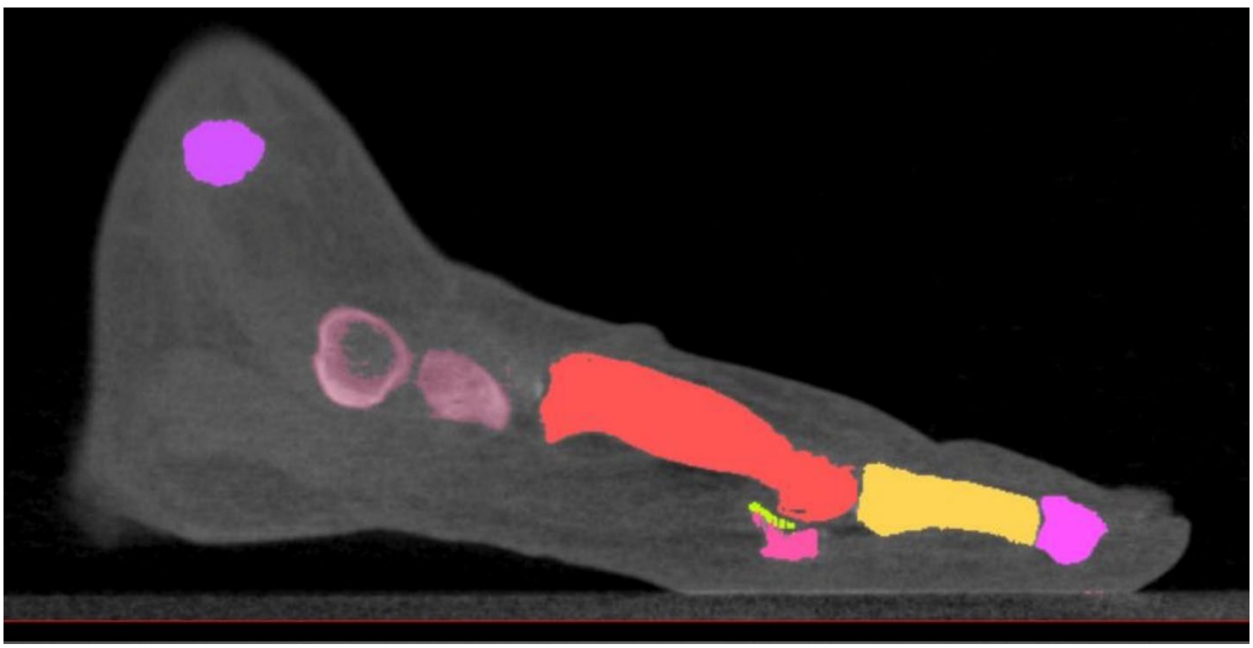

Figure 11: Segmentation using Mimics (Sagittal view)

3.3 Three-Dimensional Analysis

The goal of this study is to compare the use of axes acquired inertially versus axes acquired by using points picked on bony landmarks. This was done by comparing the first metatarsal to the second metatarsal, and the first metatarsal compared to the first phalanx. The output was a set of three-dimensional angles, one of which was pronation. The mathematical details are in Section 3.7.

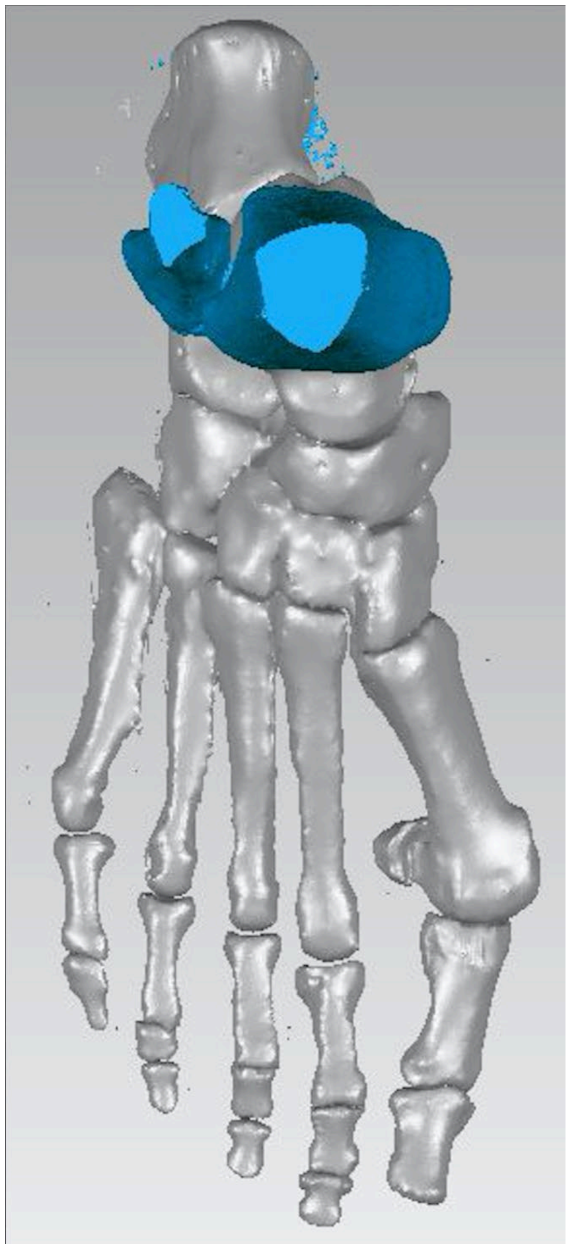

Figure 12: Complete Foot Model (exported as STL)

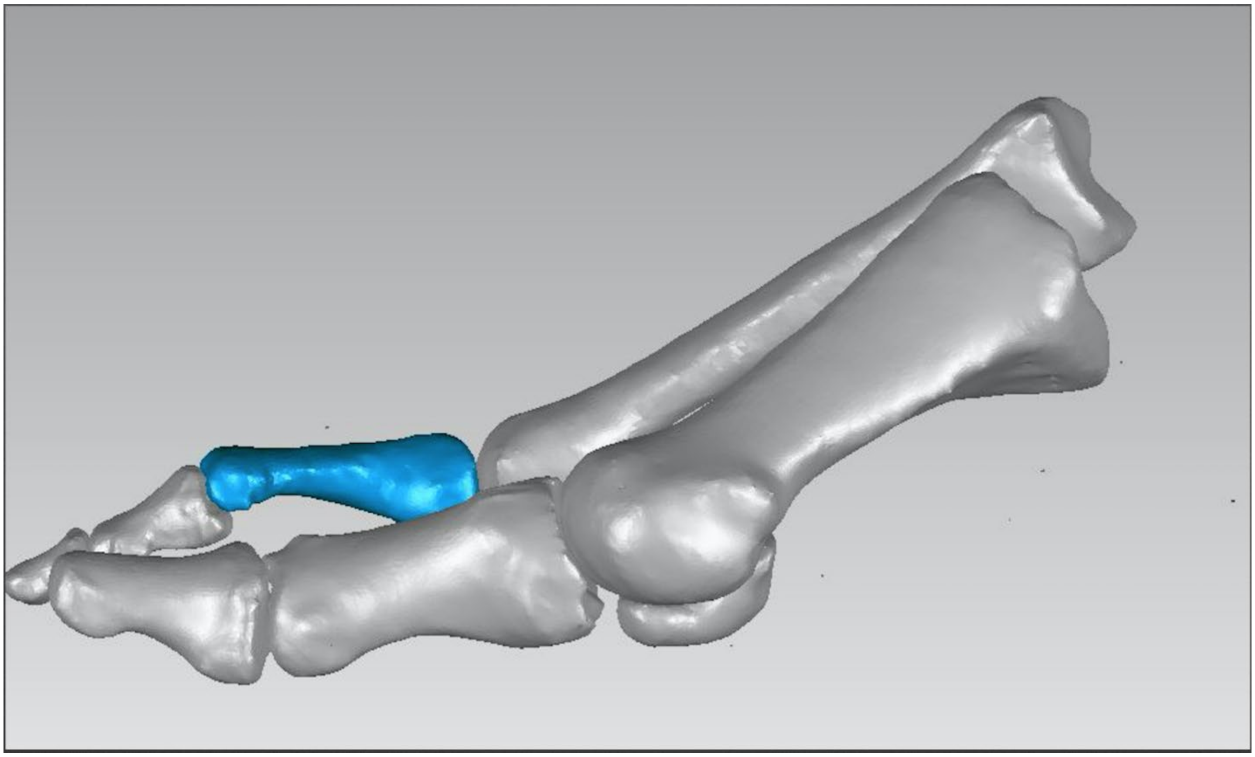

Figure 13: Example of Ability to Isolate Specific Bones

3.4 Geomagic

The STL files were uploaded into Geomagic (3-D Systems; Rock Hill, South Carolina). In this program the individual models of each bone could be recombined to maintain the orientation of the original CT scan (Figures 12 – 13). A set of four points was placed on bony landmarks on the outside of the metatarsal models, two on the head and two on the tail (Figures 14 – 15). These points were created a series of orthogonal axes representing the true relative orientation of each bone. These steps were duplicated for the first metatarsal, second metatarsal and first phalanx. These points were then downloaded as text files and recorded for analysis using Matlab.

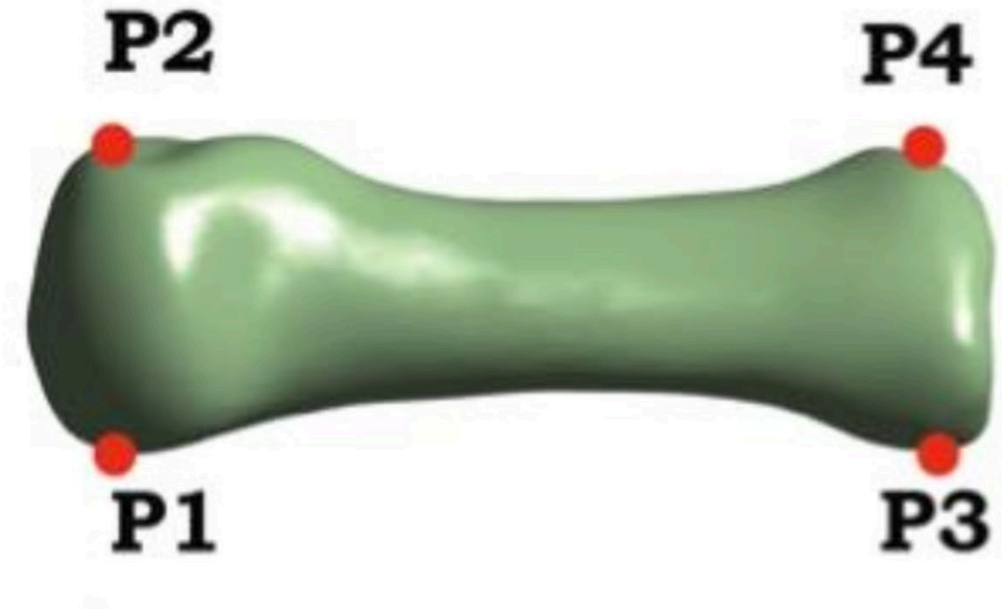

Figure 14: Four Bony Landmarks used to obtain Orthogonal Axes

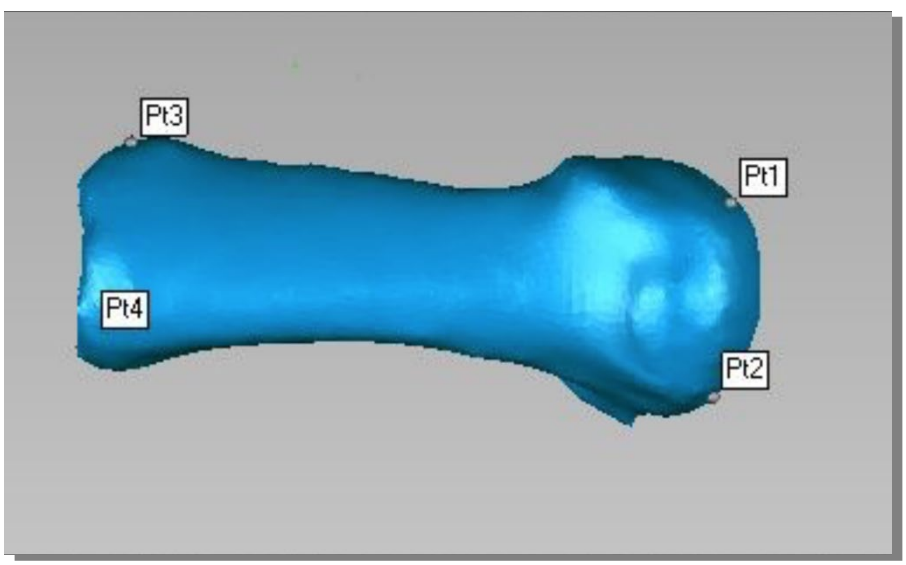

Figure 15: Four Landmarks as shown in GeoMagic

3.5 3-Matic

The second program used for three-dimensional analysis was 3-Matic (Materialize; Leuven, Belgium). This program maintained the STL models in the original coordinate system. Each bone could be viewed separately or as a whole. Unlike Geomagic, 3-Matic computed the principal (inertial) axes of each bone (Figure 16). Normalized principal axes were then transcribed and entered into MATLAB.

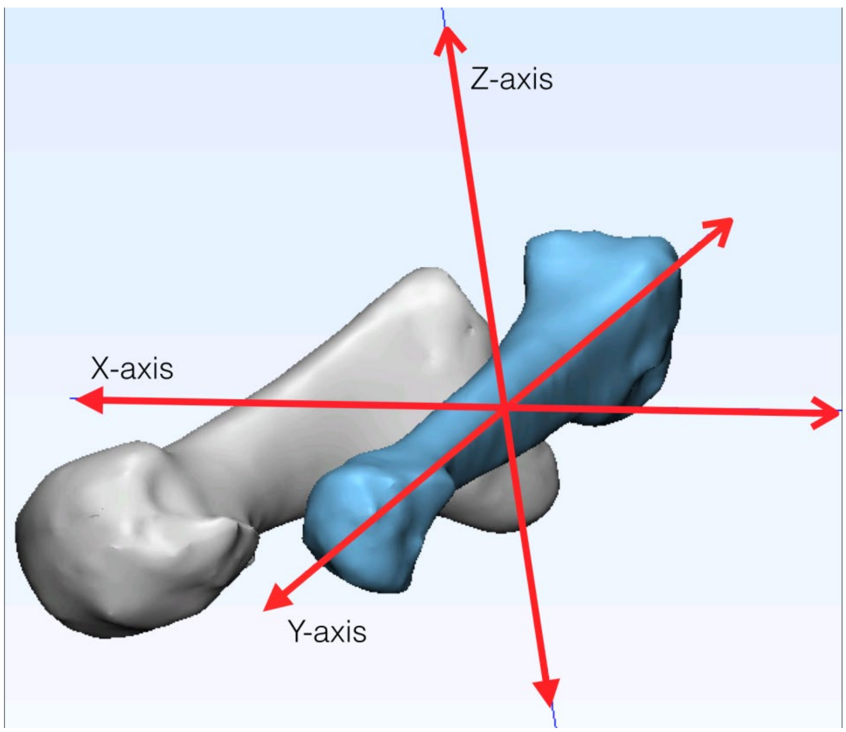

Figure 16: Inertial Axes fitted to each bone in question using 3-Matic

3.6 MATLAB

Once the points were acquired from Geomagic and the inertial axes were obtained from 3-Matic, they could be used numerically in MATLAB. Using the points from boney landmarks, the first step was to create a series of orthogonal axes, using vector methods. Once this set of orthogonal axes was created, they could be analyzed using Matrix methods to find the pronation of one bone compared to the other. The inertial axes were already in the form of orthogonal axes and were analyzed using the same matrix methods in order to determine the pronation and the other rotational angles.

3.7 Mathematical Methods

3.7.1 Vector Methods (Point Picking)

Chosen points were used to define an orthogonal coordinate system. The first step was to find the midpoints of the points on the head and tail of the metatarsal (Figure 15).

$$PA = \frac{1}{2}\,(P1 + P2)$$
$$PB = \frac{1}{2}\,(P3 + P4) \tag{3-1}$$

The next step was to create a vector representing the long axis of the bone by connecting the midpoints of the two ends

$$V1 = PB - PA \tag{3-2}$$

This long axis vector was then normalized (method for normalizing vectors).

$$n(y) = \frac{V1}{|V1|} \tag{3-3}$$

A second axis was determined by connecting the midpoint of proximal end to the point lying on the lateral side.

$$\begin{gathered} V2 = PB - P3 \\ n(x1) = \frac{V2}{|V2|} \end{gathered} \tag{3-4}$$

An axis orthogonal to these two was then computed, representing vertical axis.

$$n(z) = \frac{[n(x1)\ \ X\ \ n(y)]}{|\,[n(x1)\ \ X\ \ n(y)]\,|} \tag{3-5}$$

Lastly, the horizontal axis was then re-determined so it could be orthogonal to the long and vertical axis. All three n(x), n(y), and n(z) normalized.

$$n(x) = \frac{[n(y)\ X\ n(z)]}{|\,[n(y)\ X\ n(z)]\,|} \tag{3-6}$$

3.7.1.1 HVA/IMA Calculation

A second set of vector analysis was done to find the HVA and IMA in three dimensions. This was done first using the same method to find the long axis of the bones. This long axis of the two bones in question were then underwent a dot product to find the angular difference between the two. HVA uses the long axes from proximal phalanx and first metatarsal and IMA uses long axes from first and second metatarsal.

$$\begin{gathered} D\ = dot\ (n1(y), n2(y)) \\ HVA|IMA =\ cos^{-1}(D) \end{gathered} \tag{3-7}$$

The resulting angles would be the HVA and IMA depending on which bones were being analyzed at the time.

3.7.2 Matrix Methods (Point Picking/Inertial Axes)

In order to find the three rotational angles between the bones, a series of matrix methods needed to be used. Since each of these bones now has a set of orthogonal axes attached, determined by either points or principal axes, they needed to be compared three-dimensionally as well. The first step is to combine each of the three axes into separate matrices.

$$M1 = \begin{bmatrix} n1(x)i & n1(x)j & n1(x)k \\ n1(y)i & n1(y)j & n1(y)k \\ n1(z)i & n1(z)j & n1(z)k \end{bmatrix}$$

$$M2 = \begin{bmatrix} n2(x)i & n2(x)j & n2(x)k \\ n2(y)i & n2(y)j & n2(y)k \\ n2(z)i & n2(z)j & n2(z)k \end{bmatrix} \tag{3-8}$$

After this new rotation matrix was created, one for each bone, the two resulting rotation matrices were then dot product-ed together.

$$R_\theta = M1 * \ M2^T$$

$$R_\theta = \begin{bmatrix} dot\big(\ n1(x), n2(x)\big) & dot\big(\ n1(x), n2(y)\big) & dot\big(\ n1(x), n2(z)\big) \\ dot\big(\ n1(y), n2(x)\big) & dot\big(\ n1(y), n2(y)\big) & dot\big(\ n1(y), n2(z)\big) \\ dot\big(\ n1(z), n2(x)\big) & dot\big(\ n1(z), n2(y)\big) & dot\big(\ n1(z), n2(z)\big) \end{bmatrix} \tag{3-9}$$

The result is one matrix which represents the three-dimensional rotation angles between the two bones. With rotation angles, order of determination matters when one is looking to highlight a specific angle (in this case pronation). The proper order for this specific case is using a Z-X-Y rotation matrix (Figure 17).

$$
\begin{aligned}
&R_Z R_X R_Y \\
&= \begin{pmatrix} \cos C & -\sin C & 0 \\ \sin C & \cos C & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos A & -\sin A \\ 0 & \sin A & \cos A \end{pmatrix} \begin{pmatrix} \cos B & 0 & \sin B \\ 0 & 1 & 0 \\ -\sin B & 0 & \cos B \end{pmatrix} \\
&= \begin{pmatrix} \cos C & -\sin C \cos A & \sin C \sin A \\ \sin C & \cos C \cos A & -\cos C \sin A \\ 0 & \sin A & \cos A \end{pmatrix} \begin{pmatrix} \cos B & 0 & \sin B \\ 0 & 1 & 0 \\ -\sin B & 0 & \cos B \end{pmatrix} \\
&= \begin{pmatrix} \cos C \cos B - \sin C \sin A \sin B & -\sin C \cos A & \cos C \sin B + \sin C \sin A \cos B \\ \sin C \cos B + \cos C \sin A \sin B & \cos C \cos A & \sin C \sin B - \cos C \sin A \cos B \\ -\cos A \sin B & \sin A & \cos A \cos B \end{pmatrix}
\end{aligned}
$$

Figure 17: ZXY Rotation Matrix

The rotation angles were then isolated using this series of equations.

$$
\begin{aligned}
angle(x) &= sin^{-1}(R_{32}) \\
angle(z) &= -sin^{-1}(R_{12} \, / \cos[angle(x)]) \\
angle(y) &= -sin^{-1}(R_{31} \, / \cos[angle(x)])
\end{aligned}
\tag{3-10}
$$

4.0 Results

Throughout this study, multiple data sets were reviewed involving comparisons between each of the groups. Data was collected from multiple sources, a series of subjects with and without Hallux Valgus were imaged and processed from UPMC Passavant (weightbearing and non-weightbearing) and an additional source, Hospital for Special Surgery in New York, conveyed CT scans from patients with the deformity, both Pre-operation and Post-operation. The operation done on HSS patients was the Lapiplasty procedure discussed previously. A variety of subjects allowed for many different procedural comparisons to be made. The main comparison that this research is concerned with is how pronation differentiates between two different approaches measuring the same thing. In this particular case, it is the pronation between the first metatarsal in relation to the second metatarsal.

4.1 Dr. Bradley Campbell's Approach (Point Picking)

Dr. Bradley Campbell's approach to obtain pronation involved selecting a set of points on the models. The points were allocated based on boney landmarks present on the head and tail of each bone. Data was collected from the first and second metatarsal in order to create a series of three orthogonal axes that could be analyzed and compared in order to find the rotational angles between the two. During Dr. Campbell's pronation study, he imaged and analyzed subjects both with and without the deformity from UPMC Passavant. This method was also continued for use with the HSS subjects. [24]

4.2 Computational Approach (Inertial Axes)

The second method of comparison was using Inertial axes that were assessed to the same bones (the same models). These axes are calculated from the mass distribution of the bones themselves and create a set of three orthogonal axes, much like the previous method. This approach was used on both Dr. Campbell's subjects as well as HSS. This means that comparisons could be drawn between patients with Hallux Valgus and those without, pre-operative patients and post-operative patients, weight-bearing versus non weight-bearing and between those each individually as a look into axes determined from points picked contrasted to those determined from inertial axes.

4.3 First/Second Metatarsal Pronation Comparisons

4.3.1 Hallux Valgus Vs. Normal

Using Dr. Campbells subject set, a comparison was done between the two methods (picked points and inertial axes) of metatarsal pronation.

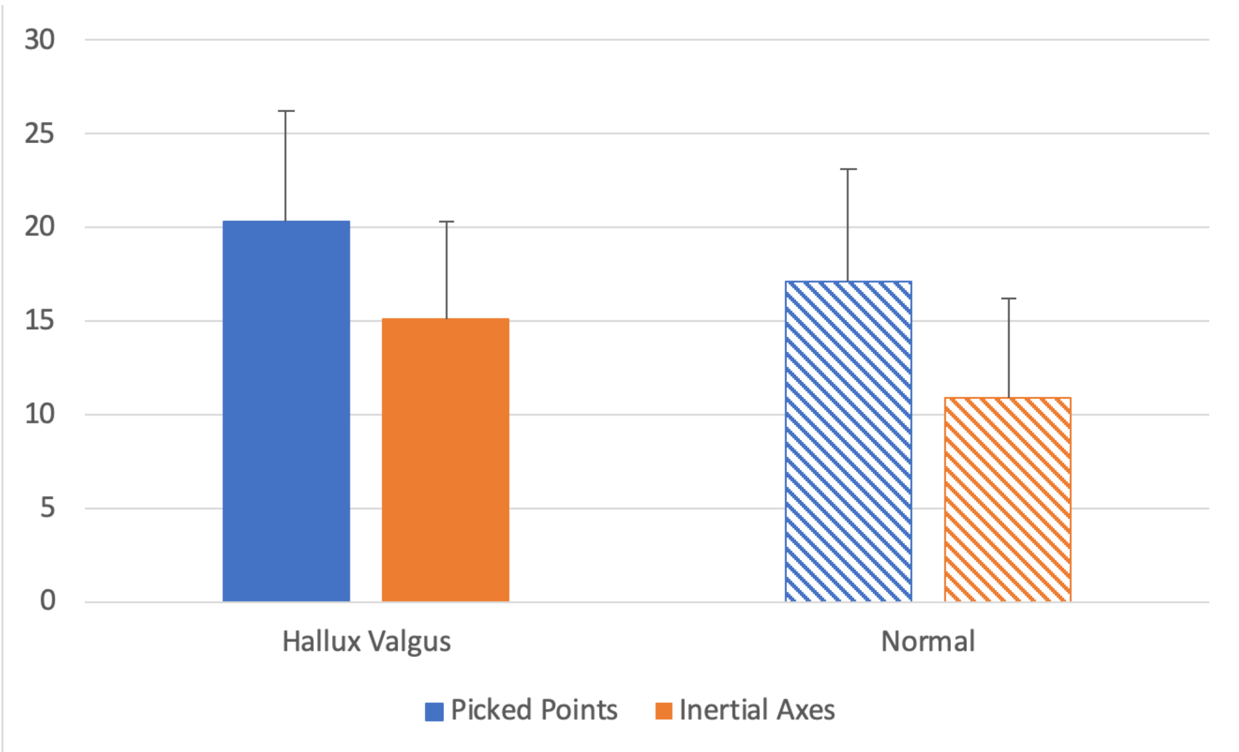

Figure 18: Pronation Angle (Hallux Valgus Vs. Normal)

4.3.2 Pre-Operative Vs. Post-Operative

Using the HSS subject set, a comparison was done between the two methods using data pre-operatively and post-operatively.

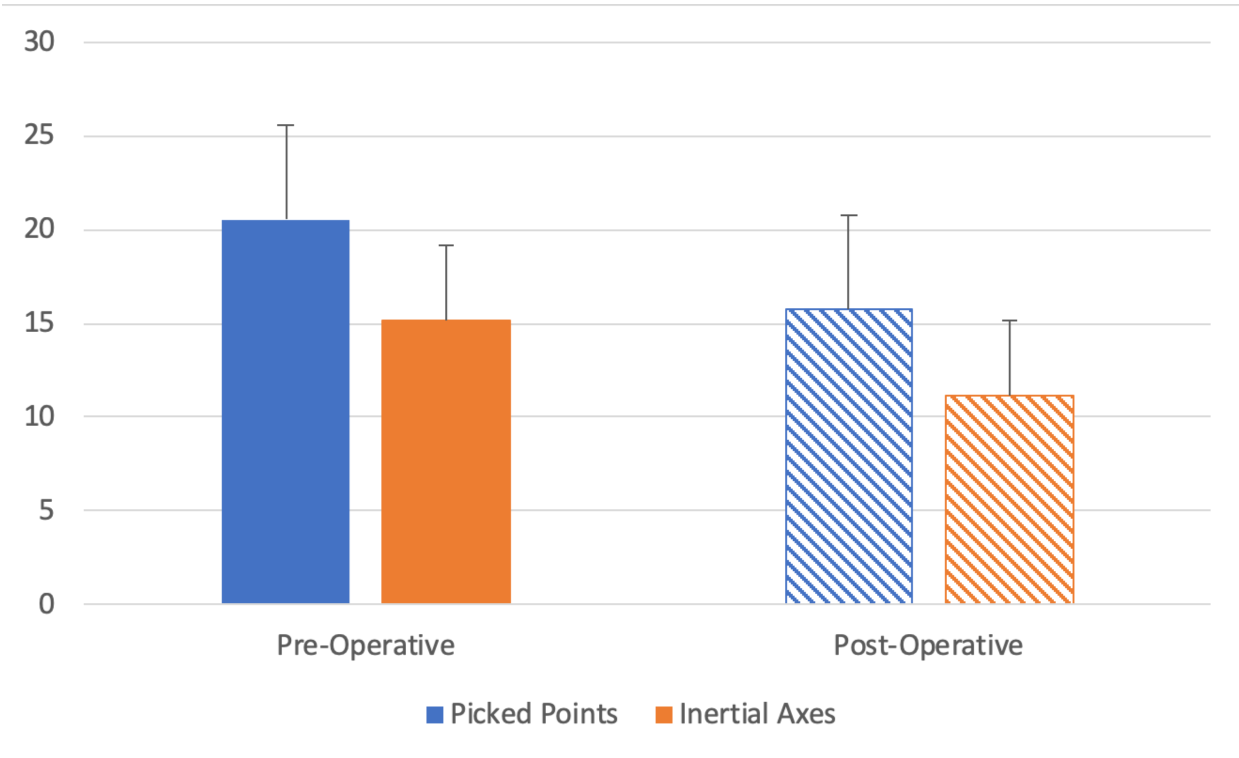

Figure 19: Pronation of Hallux Valgus subjects Pre-Operatively Vs. Post-Operatively

4.3.3 Weightbearing Vs. Non-Weightbearing

Using a data set collected from subjects who provided weightbearing and non-weightbearing data, a comparison was done between the two methods.

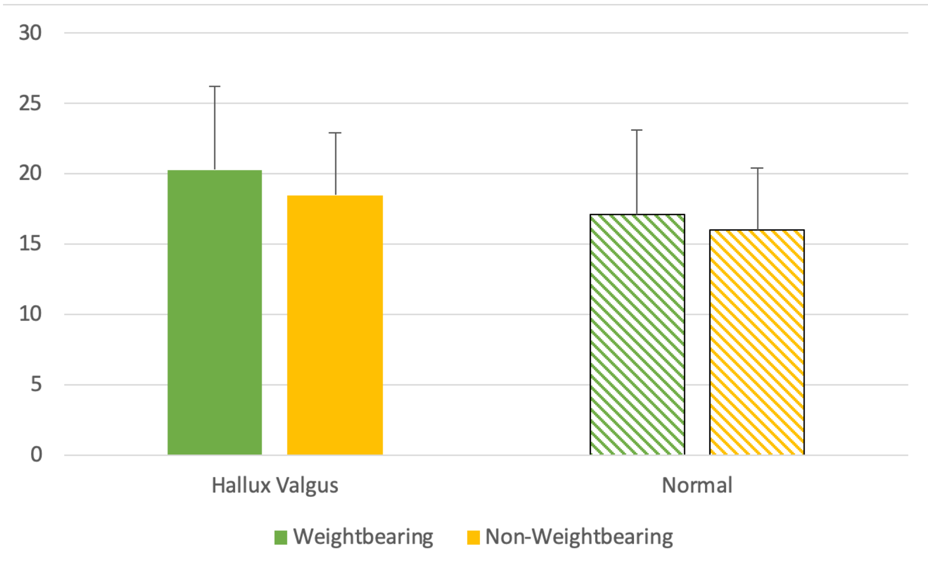

Figure 20: Hallus Valgus Weight-bearing Vs. Non Weight-bearing (Points Picked)

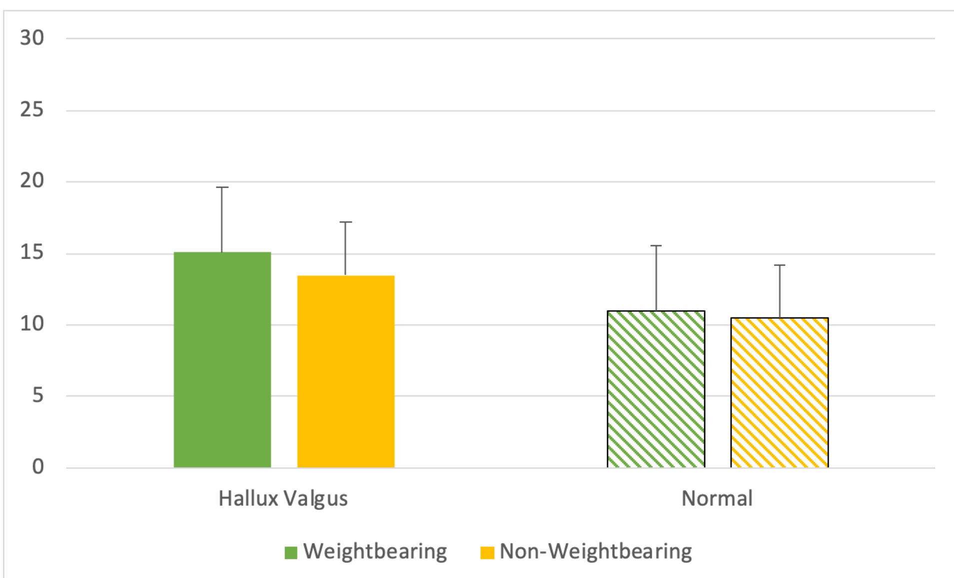

Figure 21: Hallux Valgus Weight-bearing Vs. Non Weight-bearing (Inertial Axes)

4.4 Hallux Valgus Angle and Intermetatarsal Angle

As well as comparing the pronation between these different sets of data, both using points picked and axes determined inertially, other important angles could be evaluated three dimensionally using these methods. As stated earlier, the current method of diagnosing Hallux Valgus is looking at the degree of adjustment happening between the first metatarsal, second metatarsal and the proximal phalanx. These angles are better known as the hallux valgus angle and the intermetatarsal angle. These can be gathered from the plain film x-rays themselves, which are cheaper and easier to obtain for surgeons. While these values can simply be gathered from X-Rays, it is important to review these three dimensionally as well since Hallux Valgus is to be considered as a three-dimensional deformity. One of the axes that is determined from the use of points picked and from those obtained inertially are a long axis that dictates the direction from the head of the bone to the tail. By using the axis, and a series of vector methods, these two important angles can be evaluated three dimensionally and compared to those acquired by use of plain film X-rays.

4.4.1 Hallux Valgus Angle (HVA) and Intermetatarsal Angle (IMA): Pre-Operative

The bar chart below contains the results of a pre-operative comparison done between the three methods using the HVA and IMA.

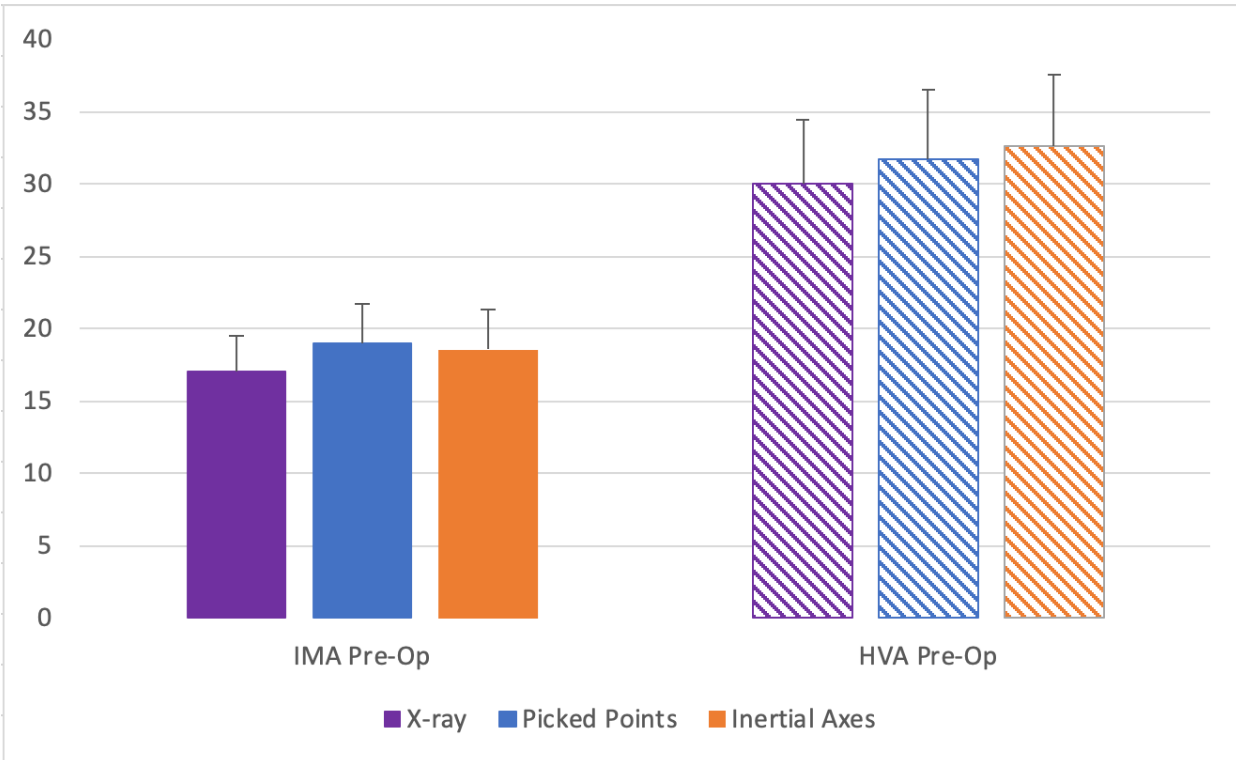

Figure 22: IMA and HVA Pre-Operative

4.4.2 Hallux Valgus Angle (HVA) and Intermetatarsal Angle (IMA): Post-Operative

The bar chart below contains the results of a post-operative comparison done between the three methods using the HVA and IMA.

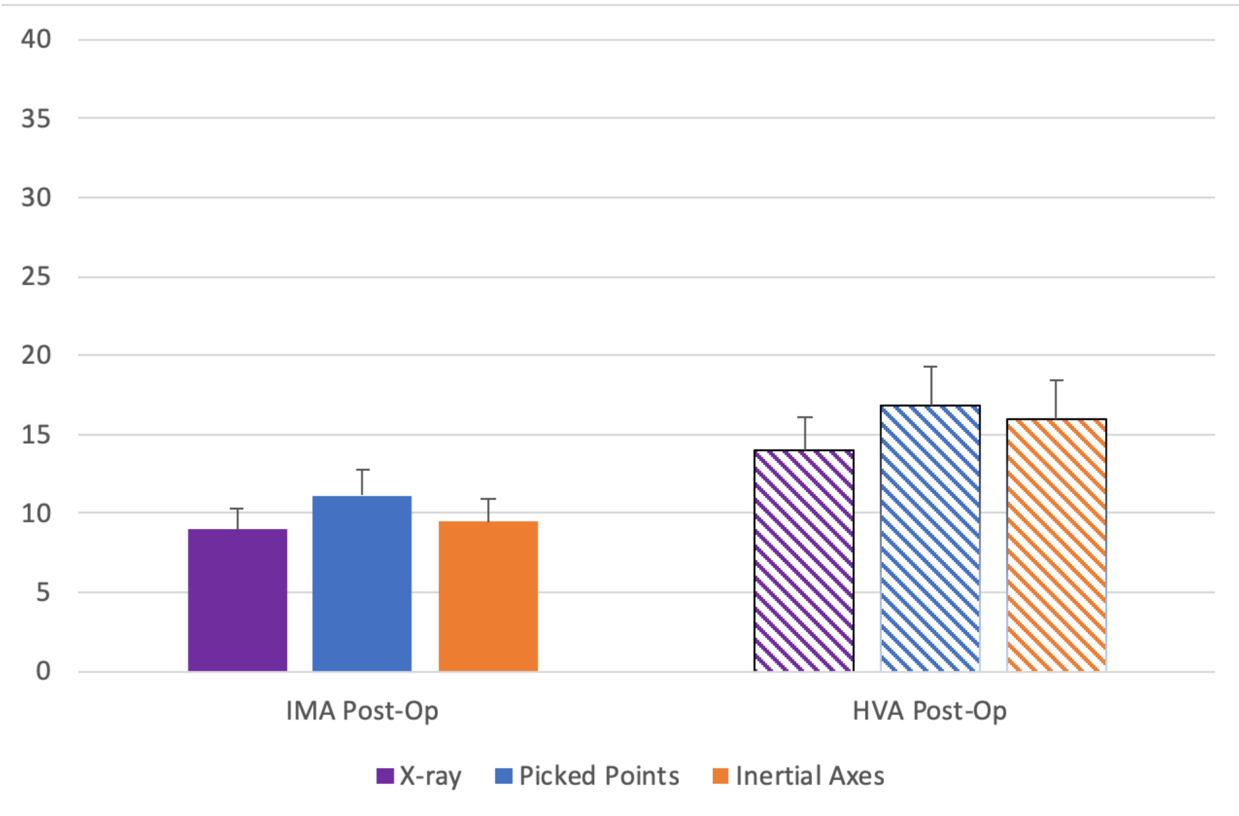

Figure 23: IMA and HVA Post-Operative

4.4.3 Hallux Valgus Angle (HVA) and Intermetatarsal Angle (IMA): Normal

The bar chart below contains the results of a Hallux Valgus negative comparison done between the three methods using the HVA and IMA.

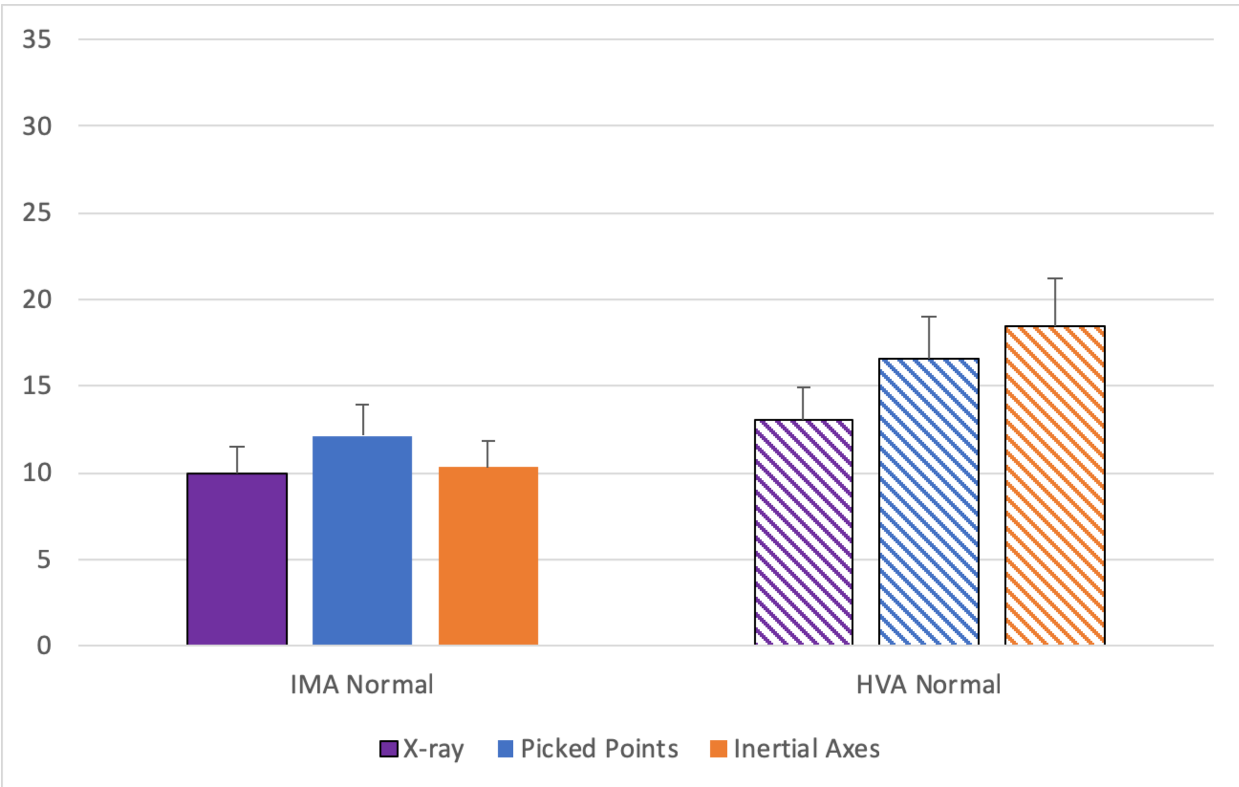

Figure 24: IMA and HVA Normal

Table 1: Hallux Valgus Angle (HVA) and Intermetatarsal Angle (IMA) using three methods

	X-ray	Picked Points	Inertial Axes
IMA Pre-Op	17	18.93	18.54
IMA Post-Op	9	11.13	9.46
IMA Normal	10	12.13	10.30
HVA Pre-Op	30	31.70	32.65
HVA Post-Op	14	16.79	15.97
HVA Normal	13	16.56	18.48

5.0 Discussion

5.1 Initial Hypothesis

The main goal of this research was to compare two different methods of acquiring pronation data between the first and second metatarsal, with the goal of attaining a reproducible way of determining these angles. The objective was to provide consistency in results, which is especially important for clinical diagnoses. The less difference two physicians have between their evaluations, the higher the standard of care. In this research, the goal was to show that using Inertial Axes not only provides this consistency but also produces a replicable approach for finding these three-dimensional angles. Also, this research sought to confirm that the Hallux Valgus deformity in general should be looked at three-dimensionally.

5.2 Numerical Comparisons

As shown in the graphs in the previous section the results that came out of the inertial axes approach appeared to have smaller pronation values but on average the difference between data sets remained consistent.

5.2.1 Hallux Valgus Vs. Normal

The first data set that was compared was between patients with hallux valgus and those one would consider normal. This is an important comparison as it creates a baseline average for what to expect for pronation values for what might be considered abnormal. Both of these two groupings were compared using a simulated weight bearing device in order to remain consistent and were analyzed using both aforementioned approaches. Using the point picking approach, the average pronation for those that have been determined to have Hallux Valgus was 20.34 degrees and those without the deformity were 17.15 degrees (Figure 18). This produced a difference of approximately 3.5 degrees between the two data sets. Alternatively, the same data set was also analyzed using the inertial axes approach (Figure 19). The average pronation from those that have Hallux Valgus came out to around 15.06 degrees and those without the deformity were shown to have around 10.93 degrees. This produced an average difference of around 4 degrees rotation. Even though the two approaches were not expected to produce the same pronation values, as they are measuring pronation separately, the average difference between the two came out very consistently 3 to 4 degrees.

5.2.2 Pre-Operative Vs. Post-Operative

The second set of data involved Hallux Valgus patients pre-operatively and post-operatively. This is important to review because it is expected that the correction of this deformity would result in an average similar to the normals. All of the pre-operative and post-operative patients were measured using a true weight bearing CT scanner at the Hospital for Special Surgery in New York. Using the point picking approach of finding pronation, the average resulting value the pre-operative angle was approximately 20.54 degrees. Alternatively, the average resulting angular value of pronation of the post-operative patients was determined to be 15.79 (Figure 20). The average difference between the two values, as obtained using the points picked on boney landmarks approach was assessed to be approximately a 5-degree difference. On the other hand, using inertial axes the average resulting value of the pronation between the first and second metatarsal, under pre-operative conditions, was determined to be around 15.17 degrees. Alternatively, using the same approach, the value of the rotational angle was assessed to be around 11.15 degrees (Figure 21). The resulting average angular difference between pre-operative and post-operative condition (using the inertial axes approach) was approximately 4 degrees. Again, the two approaches resulted in different angular values, as expected, but the difference between the two approaches remained consistent at around 4 to 5 degrees.

5.2.3 Weightbearing Vs. Non-Weightbearing

The third set of data that was analyzed was a comparison between weight-bearing and non-weightbearing conditions (as determined from subjects imaged at UPMC). This is an important case as the current standard of care does not involve the use of a CT scanner to diagnose Hallux Valgus. The images that were taken in Pittsburgh were acquired using a simulated weight-bearing apparatus. As discussed previously using the point picking approach, the value of pronation between the first and second metatarsal under weightbearing conditions for patients with Hallux Valgus was assessed to be approximately 20.30 degrees and the value of the same angle using inertial axes was determined to be 15.06 degrees. Alternatively, the pronation angles under non weight-bearing conditions was calculated to be 18.50 degrees using the point picking approach and 13.48 degrees using inertial axes (Figure 22 – 23). The same angle was calculated for patients who were determined to not have the deformity. Under weight-bearing conditions the pronation value was calculated to be 17.15 degrees and the angle was calculated to be 10.94 degrees using inertial axes. Alternatively, under non weight-bearing conditions the pronation angle was calculated to be 15.99 degrees using the point picking method and 10.48 degrees using inertial axes (Figure 22 – 23). The averages came out to be around a 2-degree difference between patients with Hallux Valgus (comparing between weight-bearing and non-weightbearing conditions) using the point picking approach and a difference of around 1.5 degrees using the inertial axes approach. Alternatively, using the patients assessed to be normal, the difference was around 1 degree (between weight-bearing and non-weight-bearing) using the point picking approach and around 0.5 degrees different using inertial axes.

5.3 Inertial Axis Comparison

Comparing the point picking and inertial axes approach of determining rotational angles shows that the average difference between the conditions remained the same. T-tests were conducted to compare the two approaches (point picking and inertial axes) and the resulting p values ($p < 0.5$) showed statistically differences between data sets. These results are to be expected as there are fundamental distinctions in how the axes are found. The two approaches, point picking using boney landmarks and assessing inertial axes to the solids, evaluate the axes differently. Although the approach of converting the axes to rotational angles remains the same and consistent, the methods to determine these axes are entirely different. Using the inertial axes approach, these axes are calculated using the true shape of the bones themselves. The real determining factor is that the angular differences between the two approaches shows relevance and significance.

5.4 Hallux Valgus Angle and Intermetatarsal Angle Comparisons

The current stand of care (in the diagnosis of Hallux Valgus) involves reviewing the Hallux Valgus Angle (HVA) and the Intermetatarsal Angle (IMA) using two-dimensional plain-film. The HVA, taken between the first metatarsal and the proximal phalanx, is considered abnormal if the angle exceeds 15 degrees and the IMA, taken between the first and second metatarsal, exceeds 9 degrees. These angles from the subjects modelled (pre-operative, post-operative, and normal) were analyzed using the three different methods (plain-film, point picking, and inertial axes).

5.4.1 HVA/IMA Plain-film

From plain film the average HVA from the groups are 30 degrees from the pre-operative subjects, 14 degrees from post-operative, and 13 degrees from the normal. This shows that after the patients went through the surgery the deformity, between the first metatarsal and proximal phalanx, reached normal levels. The average IMA for the same groups was 17 degree for the pre-operative group, 9 degrees from the post- operative group and 10 degrees from the normal. Once again, when looking at this angle two-dimensionally, the post- operative patients reached standard levels.

5.4.2 HVA/IMA Point Picking

When the subjects were looked at using the point picking method, the pre-operative HVA for HV patients was 31.70 degrees (compared to the 30 degrees using plain film), 16.79 degrees for the post-operative group (compared to the 14 degrees from plain film), and 16.56 degrees for the normal (compared to the 13 degrees from the same set using plain film). The average IMA using the same method was 18.93 degrees for the pre-operative group (compared to the 17 degrees from plain film), 11.13 degrees from the post- operative group (9 degrees plain film), and 12.132 degrees from normal (10 degrees plain film).

5.4.3 HVA/IMA Inertial Axes

The subjects were also looked at using the inertial axis approach and the average HVA came out to 32.65 degrees for pre-operative, 15.97 degrees post-operative, and 18.48 degrees normal (30 degrees, 14 degrees, and 13 degrees respectfully in plain film). The average IMA for the inertial axes approach came out to 18.54 degrees for pre-operative, 9.46 for post-operative and 10.30 for the normal group (17 degrees, 9 degrees, and 10 degrees respectfully using plain film).

5.5 Consistency

The key reason that inertial axes are a stronger approach in analyzing these angles is reproducibility. One of the drawbacks of using the point picking approach is that there are subjective differences between two different ratings. Although in Dr. Bradley Campbells study he showed a 0.87 integrated reliability rating, it also does show that there are differences between two people picking points on the same model. Using the inertial axes approach, this limitation is all but removed. Since the axes are assessed computationally using the true shape of the models, if two people analyzed the same model using the inertial axis approach they would convene at the same result. This has great clinical relevance as physicians are always looking to provide consistency in alleviation to their patients. [24]

5.6 Limitations

One limitation to both of these processes is the fact that the creation of these solid models is very time consuming and requires extensive user input. The solid models are created scan by scan and need to be adjusted and trimmed by hand at the user's discretion. Since the models need to be created using user input, imperfections in the models themselves result in shapes that may deviate from the exact anatomic shape. This affects one's ability to locate the boney landmarks and consequently puts more user input into placing these points on the solid surface. Also, the adjustment of these models by hand affects the mass distribution. Although the inertial axes are determined computationally, problems can arise when the same foot is modeled by different analysts because the mass distribution would not be the same between models. Currently there does not exist a way to model bones without these imperfections so at the moment they must be completed by hand.

Appendix A MATLAB Code

A.1 Orthogonal Axes

```
for i = 1:size(filenames,1)

    data = textscan(fopen(filenames(i,:)),'%s %n %n %n');

    X = data{2};
    Y = data{3};
    Z = data{4};

    points = [X Y Z];

    P1 = points(1,:);
    P2 = points(2,:);
    P3 = points(3,:);
    P4 = points(4,:);

    PA = 0.5*(P1 + P2);
    PB = 0.5*(P3 + P4);

    PC = (PB - PA);
    abs1 = norm((PB - PA));
    ny = PC/abs1;

    PD = (PB - P3);
    abs2 = norm((PB - P3));
    v = PD/abs2;

    c1 = cross(v,ny);
    abs3 = norm(c1);
    nz = c1/abs3;

    c2 = cross(ny,nz);
    abs4 = norm(c2);
    nx = c2/abs4;

    save(['vecs' num2str(i) '.mat'],'nx','ny','nz')
      end
```

A.2 Angular Calculation

```
X1 = vecs.nx;
X2 = vecs.ny;
X3 = vecs.nz;

X1Prime = vecsPrime.nx;
X2Prime = vecsPrime.ny;
X3Prime = vecsPrime.nz;

I1 = [1 0 0];
I2 = [0 1 0];
I3 = [0 0 1];

X = [X1; X2; X3];
XPrime = [X1Prime; X2Prime; X3Prime];

R11 = dot(I1, X1);
R12 = dot(I1, X2);
R13 = dot(I1, X3);
R21 = dot(I2, X1);
R22 = dot(I2, X2);
R23 = dot(I2, X3);
R31 = dot(I3, X1);
R32 = dot(I3, X2);
R33 = dot(I3, X3);

Q11 = dot(I1, X1Prime);
Q12 = dot(I1, X2Prime);
Q13 = dot(I1, X3Prime);
Q21 = dot(I2, X1Prime);
Q22 = dot(I2, X2Prime);
Q23 = dot(I2, X3Prime);
Q31 = dot(I3, X1Prime);
Q32 = dot(I3, X2Prime);
Q33 = dot(I3, X3Prime);

R2 = dot(X,XPrime);

R = [R11 R12 R13; R21 R22 R23; R31 R32 R33];
Q = [Q11 Q12 Q13; Q21 Q22 Q23; Q31 Q32 Q33];

I = R*R';

M = Q*R';
```

```
ax = -asin(M(3,2)) ;
az = asin(M(1,2)/(cos(ax)));
ay = asin(M(3,1)/(cos(ax)));

ax2 = ax * (180/pi);
ay2 = ay * (180/pi);
az2 = az * (180/pi);

disp([ax2 ay2 az2]);

aa = [ax2 ay2 az2];
```

A.3 IMA/HVA

```
for i = 1:size(filenames,1)

  data = textscan(fopen(filenames(i,:)),'%s %n %n %n');

    X = data{2};
    Y = data{3};
    Z = data{4};

    points = [X Y Z];

    P1 = points(1,:);
    P2 = points(2,:);
    P3 = points(3,:);
    P4 = points(4,:);

    PA = 0.5*(P1 + P2);
    PB = 0.5*(P3 + P4);

    v = PB - PA;

    save(['vecs' num2str(i) '.mat'],'v')

  end
```

```
vec1 = load('vecs1.mat');

vec2 = load('vecs2.mat');

V1 = vec1.v;

V2 = vec2.v;

D1 = dot(V1,V2);

abs1 = norm(V1);

abs2 = norm(V2);

rad = acos(D1/(abs1 * abs2));

ang = rad * (180/pi);
```

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