

**UNIVERSAL MODEL DEVELOPMENT
OF THE HUMAN ANKLE FOOT REGION
FOR PLY PATTERN GENERATION TO BE USED IN THE
MANUFACTURING OF PASSIVE DYNAMIC ANKLE FOOT ORTHOTICS**

by

Francis J. Fish

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Mechanical Engineering with Distinction

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This work is dedicated to the two women in my life I know I can always count on. Mom, thank you for all the selfless sacrifices you have made over the past twenty-one years so that I have the best possible future. Through all the tribulations you always made sure that Alex and I were taken care of even when it meant making sacrifices on your part. The other is to the Most Holy Blessed Mother who I can always turn to in my hour of need. I ask that you bless this work and those who read it to live peaceful lives. Please also bless and keep close to your heart all who this work is meant to benefit. May they find the strength and courage to face life with the new challenges they now find themselves facing. Hail Mary, full of grace. The Lord is with thee. Blessed art thou amongst women, and blessed is the fruit of thy womb, Jesus. Holy Mary, Mother of God, pray for us sinners, now and at the hour of our death. Amen [14].

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ABSTRACT

The prerogative of the overall program that the research I am conducting fit into is the rapid manufacturing of a low profile, fully customized, passive-dynamic ankle-foot orthosis (PD-AFO) from composites. With a rapid production cycle time of less than 24 hours the mold for a particular patient will produce a uniquely customized PD-AFO, while we are creating a new tool for each patient our ply patterns are designed to be universal across all ankle-foot shapes and stored as a lookup table in a ply book. My focus for this program is to develop the universal ankle foot models which are the foundation for the development of the universal plies to be cataloged as part of a ply book. This all leads to the question can a universal model set be established to meet the needs of the 1st to 99th percentile of the population of the United States Army.

Chapter 1

INTRODUCTION

1.1 Composites

Composite materials are an amalgamation of two or more distinct materials unified at the macroscopic level. This unification yields a product with desired mechanical, electrical, thermal, or optical properties. Composite materials are typically macroscopically inhomogeneous [10]. For several decades polymer composites have been used by many industries. The advantages these materials have over conventional materials are due to their high-performance in their strength to weight ratio. This has attracted aerospace, automobile, infrastructure, marine, and sport industries to adopt composite materials over more traditional alternatives such as steel and aluminum. The design and manufacturing of composite structures was pursued in a myriad of ways ranging from traditional to revolutionary means of manufacturing and processing. They ranged from using hand layup with labor and cost intensive autoclave processing to the use of automated processes such as injection molding and extrusion [9]. Advances in processing have been invented and incrementally improved in just the past few couple decades. Much of this progress has stemmed from trial-and-error for prototype development. Recent pressure has led to the composites industry striving to be cost effective. To assist in this cost avoidance engineers have conspired to use process modeling and simulations to reduce the costs associated with production.

1.1.1 Composition

As previously mentioned composite materials consist of at least two materials that are combined. This is done to suppress undesirable constituent properties to increase the prominence of the more favorable ones. Fiber composites, which this work will focus on, consist of two distinct part fibers and resin. Fibers are referenced as reinforcement while resin is referred to as the matrix. The reinforcement is responsible for the structure of the composite and bears the load of the applied forces. The matrix is responsible to the material resist compressing and shearing, which can be further improved through the addition of nano materials.

1.1.1.1 Fibers

Fiber alignment dictates the strength of the composite. Fibers are generally grouped in tows, which are bundles of filaments on the order of 10^3 . Filaments usually have diameters of the order of $10\mu\text{m}$. Fibers are arranged in various mat forms which range from random mats to highly ordered weaves. Figure 1 depicts some patterns for fiber alignment.




Unidirectional Fiber Orientation	Percentage of fiberglass reinforcement increases strength in direction of fiber orientation		Reinforcement types: Continuous strand roving Processes: Continuous pultrusion, compression molding
Bidirectional Fiber Orientation			Reinforcement types: Continuous strand roving Processes: Filament winding, compression molding Reinforcement types: Woven fabrics, woven roving Processes: Hand lay-up
Multidirectional Fiber Orientation			Reinforcement types: Chopped strands, continuous, chopped strand mat tri axial fabric Processes: Compression and injection molding, spray-up pressure bag, preform

Figure 1: Examples of fiber weaves and orientations. [11]

Figure 1 depicts a few weave patterns and defines their process ability. Fibers come in two variances long continuous and short chopped. Long fibers are highly ordered and provide more strength than the short fibers which are randomly ordered. The composites that this work utilizes are long continuous fiber composites.

1.1.1.2 Resin

Resin is divided into three categories thermoplastics, thermosets, and elastomers. For the purpose of this paper elastomers will not be discussed. Thermoset polymers bond by forming cross-links among atoms. This gives these bonds the strength of covalent bonds. Thermoplastic polymers bond by forming branches that intertwine with each other. Thermoplastics have high viscosities whereas thermosets have low viscosities. While thermosets are typically stronger than thermoplastics, thermoplastics are able to be recycled by reheating the material to cause the polymer to phase transition from a solid back to a liquid. Thermosets cure and are difficult to recycle because they do not melt when heat is reapplied. The addition of heat to a thermoset causes the material to become brittle, but will not melt the polymer regardless of how much heat is added. Figure 2 shows the polymer chains for the different resins.



Figure 2: Image of the polymer chains forming thermoplastics, elastomers, and thermosets. [12]

1.2 Computer Aided Design

Computer aided design often referenced as CAD is the use of computer to accelerate product development. CAD allows the engineer the ability to manipulate, alter, and reuse models that otherwise would be expensive and time intensive to create with physical models or with paper and pencil. CAD models serve as the central point of the development process and the main data source used and shared by most stakeholders [13]. CAD software packages are able to parameterize objects based on their geometries. While there are a plethora of CAD software packages, the system used for the findings in this work was CATIA V5R21.

1.3 Problem Background

Orthotics are externally applied medical devices which are used to reacquire limb functionality. Ankle-foot orthoses (AFOs) are orthotics tailored to the lower extremities specifically the portion below the knee. They restore functionality by limiting the range of motion, prescribed by orthotist, so the patient during the gait cycle will experience less pain. Currently devices are selected from one of two options: custom orthosis tailored to one specific patient or a mass-production off-the-shelf AFO fitted by the patient's shoe size. Recent estimates show that roughly 10% of individuals requiring AFOs can use a standard commercial-off-the-shelf device [1]. The resulting 90% of the population of patients, who have limbs that were salvaged during surgery or have severe deprecation of utility, are unable to utilize these off-the-shelf devices. Advances in medical technology over the past few decades have resulted in the ability to reclaim limbs that at one time the only option was to amputate. All though the patient has been able to retain the limb, the extremity will require assistance provided by an orthotic device to function at an acceptable level of

usage. Based on the severity of the injury and the patient's body geometry, devices are created to meet the function and fit of the individual.

1.3.1 Current Methodologies

There are currently various ways customized PD-AFOs can be manufactured and from a variety of materials. One of the most straight forward manufacturing practices is to heat a sheet of thermoplastic to form it around the patient's lower extremity. Manufacturing braces in this manner is a minimalistic approach to add stability and functionality, and they are inexpensive to produce. Conversely, the use of composite materials to produce PD-AFOs provides high levels of stability due to their high strength-to-weight ratio. Production of composite PD-AFOs begins with the casting of the extremity subsequently followed by tedious sculpting and surface refinement to best match the anatomical geometry. Hand lay-up for vacuum infusion or prepreg placement on to the mold is typically performed by a professional orthotist or technician. The orthotist will rely on their experience and conduct numerous iterations followed by testing in order for the device to meet the conditions of the patient. Due to this iterative manufacturing production, this process results in extensive cycle times (6-8 weeks) with production cost upwards of \$15,000 per orthotic [2, 3].

A unique mold is necessary for each patient by these methods. During the rehabilitation of the patient, new devices are generally required throughout the process due to changes in function or geometry. Manufacturers generally hold molds for about sixty days because of storage space constraints. This requires the process to be repeated from the beginning to the end each time the patient needs refitting. Refitting is generally needed once every two years [3].

Currently researchers have concentrated on additive manufacturing in addition to the aforementioned PD-AFO manufacturing methods [2]. To achieve this, the patient's extremity is quantified by means of scanning molds of the extremity. The scans are then imported into computer aided design (CAD) software where it is processed and delivered to a 3D printer. PD-AFOs manufactured using the aforementioned method have been shown to have production times 24 hours and up. Additionally, the mechanical properties of the material used in 3D printing are significantly lower than continuous fiber composites. Carbon fiber composite PD-AFOs are also thinner; allowing them to more easily fit inside shoes; lighter weight, and can be tuned to varied stiffness and durability levels to meet the lifetime requirements for the AFO (3 million cycles).

1.4 Purpose

This work plans to show how the development of a universal set of CAD models is used to improve the manufacturing process by reducing cost and time. The requirements for a PD-AFO production system are set by DARPA's Open Manufacturing Program [4]. The purpose of this program is to design a production process to rapidly manufacture carbon fiber composite AFOs. This paper provides discourse of the progression of the development of the universal model set for use in the manufacturing of composite PD-AFOs. The evolution of the model set details and includes the implementation of the models for production.

Chapter 2

METHODOLOGY

2.1 Patient Measurements

In order to deploy the proper model set for the patient certain measurements need to be made. The extent of the number of measurements has changed over time from a long array to a concise set of dimensions.

2.1.1 The narrowing of Measurements

When the quest to establish the necessary quantities for accurately modeling the foot began virtually any and every factor that could be affect ones foot shape and size was evaluated. The original belief that a several measurements regarding the patient's foot would be needed as described by the US Army's anthropometric data tables [6]. Here the anthropometric survey details measurements for ball of foot circumference, ball of foot length, bimalleolar breadth, heel breadth, heel ankle circumference, lateral malleolus height, ankle circumference, foot length, foot breadth horizontal, stature, and weight. From this long list, the variance of each dimension was evaluated to determine the prominent contributors. From this stature, weight, foot length, and foot breadth horizontal were found to have the greatest variances as shown in figure 3.

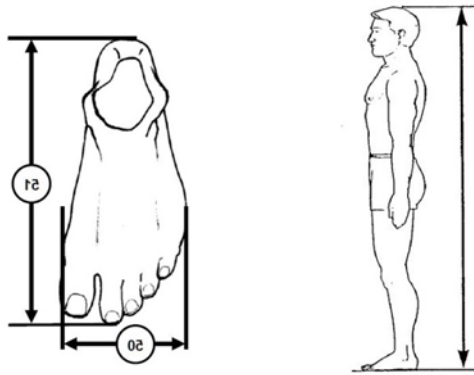


Figure 3: Set up for foot length and width measurements and stature. Images come from the ANSUR data. [6]

It was then that a volunteer had his foot casted and scanned. He also provided the additional height and weight information. With this scan several modeling packages and options were evaluated for gaining the best anatomical fit to the volunteer's proportions. As it will be discussed in greater detail later ethnicity ended up playing a role in the model selection for the proper foot shape, while the patient's weight was found to be irrelevant.

2.2 Modeling

When posed with developing the universal model for the DARPA Create Orthotics Project, two options for modeling were proposed. The first was to build the universal model from a clean slate. While this would allow for tight adherence to the anthropometric data, it would be arduous and had the potential for taking longer than the time left in the project. The other option was to adopt a model that was created by a third party. This option while easier could potentially have legal issues. Ultimately the latter was selected as resources were readably available.

Several modeling programs were evaluated ultimately resulting in selection of the MakeHuman open source software. For the MakeHuman model to fit the ANSUR data better, the model set was divided up into sections which represent a compilation of aggregate heights and mingling ethnicities. From these adjustments the MakeHuman foot model mimicked the projections from the ANSUR data for the shortest, sixty-three inches, to the tallest, seventy-five inches, which is shown in figure 4. Models were then imported to CATIA where they were scaled to account for size deviations. At this point it is more accurate to designate the models based on the US Army Shoe Size [8].

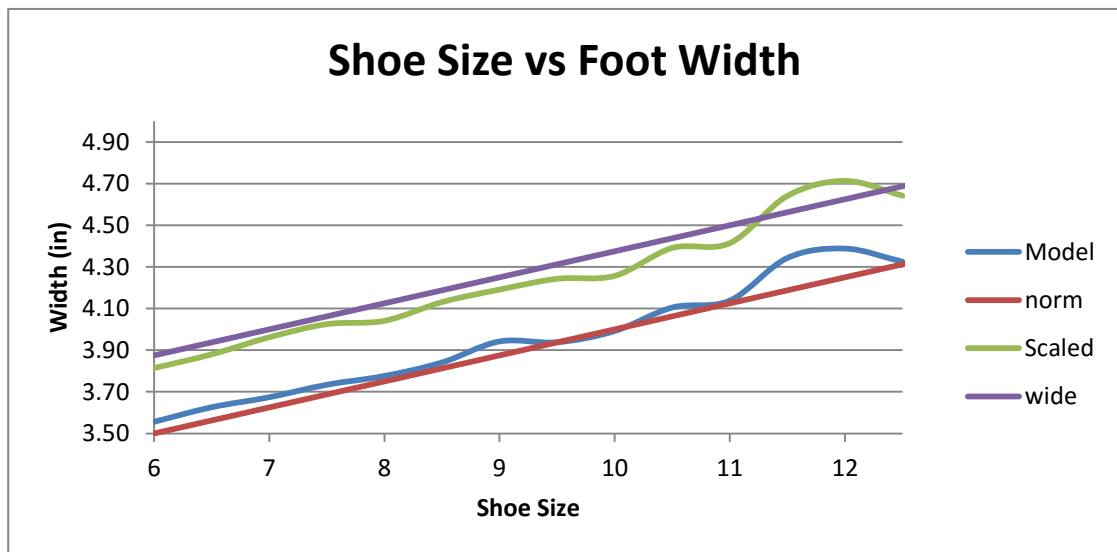


Figure 4: Graph of the US Army shoe size versus the foot widths of the model set.

2.3 Ply Generation

The entire reason for generating the models is to have the ability to precut plies for the manufacturing of the orthotics at a later time. The ply generation from the

models enables cost savings over the previous methods for manufacturing orthotics. An example is displayed in figure 5. These cost savings stem from the reduction in scrap material, unique ply cuts for each iteration, and time savings. Previous methods had orthosis packing on vast amounts of excess material and then cutting off the unwanted parts. This method repeated on the multiple iterations which patients will undergo leads to an expensive overhead cost. The cost saving ability of generating plies for individuals at each size of orthosis will ultimately bring the average cost of custom orthosis down to be competitive with the price point of the shelf orthotics.

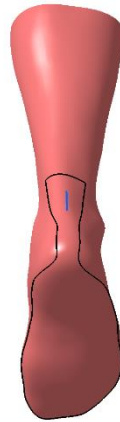


Figure 5: Example of a ply generated on the universal models set by Narinder Singh, Ph.D.

2.4 Binning

Binning which refers to the process of taking all the respective parts to manufacture the entire array of orthotics sizes and degrees of stiffness and having them readily available to the technician manufacturing the orthosis. Binning of the orthosis parts is made possible by the universal ply sets generated from the universal

model set. By binning the plies and rods, the production time of the orthosis can be achieved in the twenty-four hour window which was set as part of the DARPA initiative.

Chapter 3

MODEL SELECTION

For the model to be implemented into the manufacturing process for the PD-AFOs, plans for how to best fit the models into the process were established. The models were to be based on the measured geometries from the Anthropometric Survey (ANSUR) II Pilot Study: Methods and Summary Statistics in addition to the 1988 Anthropometric Survey of U.S. Army Personnel: Summary Statistics Interim Report [5, 6]. The model should be able to either scale from the 1st -99th percentile of patients based on ANSUR II, or a model set should be able to achieve the aforementioned range [5]. The models then can be enlarged to accommodate the draping and the cushioning which allows for comfort to the patient. Several options for proceeding with the model development were perused. The open source software MakeHuman, CATIA's Ergonomics Package, and generating a model from the prescribed data were looked at as options for development.

3.1 Anthropometric Model

From the 1988 Anthropometric Survey and the ANSUR study three measurement criteria were established for parameterizing the human foot: the foot length, the foot breadth horizontal, and the heel breadth, which was later found to be of minimal importance. For the purpose of model generation, stature, distance from head to foot base, was used to compare the models to the Anthropometric data which was characterized by percentile rankings. The stature percentile correlation was

utilized to represent the heights at each percentile for the three criteria linking all the data. Which led to the early development of a model to determine feasibility, figure 6 depicts the early model and compares it to a projection from a patient scan.

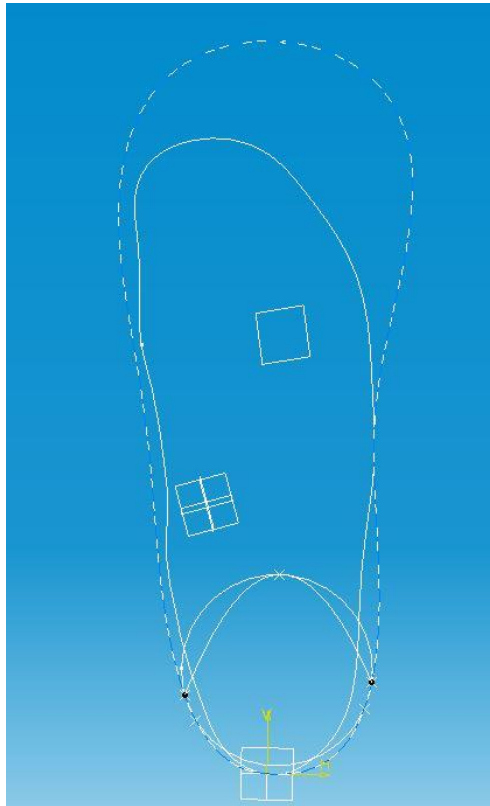


Figure 6: Comparison of the projections of a scanned model and that developed strictly from the anthropometric data.

Building a model from the numerical information provided by the Anthropometric Survey and ANSUR was a sound viability, but these sources provided no information regarding foot surface topography. To provide additional detail Modelling foot height and foot shape-related dimensions, Ergonomics were needed to

determine part of the foot topography [7]. The bottom of the foot still was not topographically defined this lead to the discontinuation of this method as an avenue for developing a universal model.

3.2 CATIA Model

The CATIA Ergonomics Package provided a manikin whose dimensions were controlled by selecting from a prescribed array of gender, population (ethnicity), and size percentile (height). By adjusting the three parameters it was found that the foot dimensions could be altered. The dimensions of the foot were then compared to the ANSUR data. The comparison found that for foot length and foot breadth horizontal the models were larger than the data described for statures under seventy inches; however, for statures above seventy-three inches the projected dimensions were bigger as shown in figure 7.

Foot Breadth Horizontal

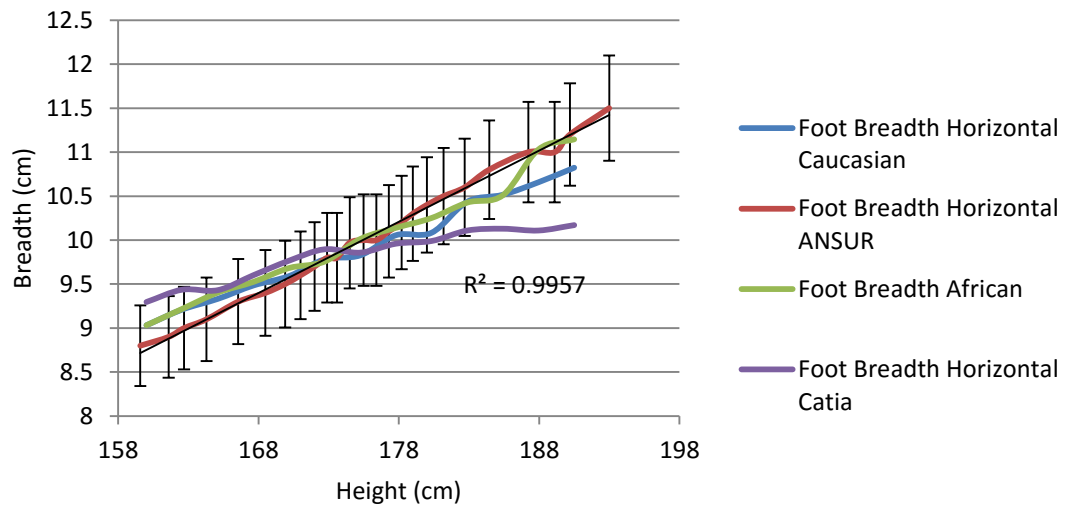


Figure 7: Foot breadth horizontal of the models compared to the stature of the models.

Similar to how the development from the ground up approach lacked topographical information; the CATIA Ergonomics Package provides low resolution contours for body parts, visible in figure 8. The package was also inflexible when it came to adjusting the model. Due to these limitations, the search continued for a parametric model.

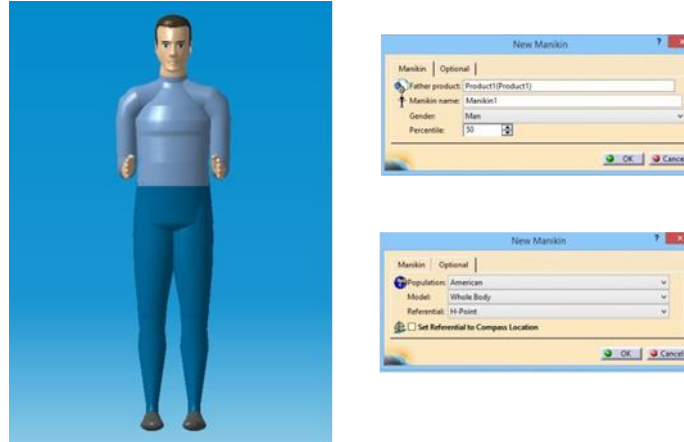


Figure 8: The CATIA Ergonomics Package manikin and to its right is the dropdown parameter menu for adjusting the model.

3.3 MakeHuman Model

The open source software MakeHuman was also evaluated. MakeHuman generates stl surfaces based on nine parametric controls. Alterations to the foot surface were found to be controlled by four of the nine parameters: gender, age, height, ethnicity (African, Asian, and Caucasian). The age was held constant at the average military age of twenty-five. The MakeHuman models were then broken into two categories based on the ethnicity parameter, Caucasian and African. The Asian ethnicity was neglected since they represent a minority of the military population, and they are covered by the Caucasian foot sizes. For the Caucasian foot models, statures below sixty-seven inches closely matched the data as described by ANSUR and the Anthropometric Survey. The African models followed the path of the projected values up to seventy inches in stature. Unlike the other aforementioned methods, MakeHuman provided the topographical detail that was desired, and in some instances the topographies were too well defined as in the toe region. Figure 9 shows the MakeHuman model with its adjustment controls.



Figure 9: The MakeHuman model and to its right is the scale for adjusting the model.

3.4 Selection

The MakeHuman software provided simple parametric control over the foot shape and dimensions; therefore, it was selected for use in the model development. In order for the MakeHuman model to better fit the projected data, the model set was divided into sections, which were developed from a compilation of increasing height and combining the ethnicities (Caucasian and African). From doing this the adjusted MakeHuman foot model matched the projected data from the shortest stature, sixty-three inches, to the tallest stature, seventy-five inches. The models were then imported into CATIA and scaled to account for size standard deviation. It is at this point it was no longer accurate to describe the models based on stature. The models now are based on the US Army Shoe Size [8], see table 1. Figure 10 compares the model with the scaling to the ANSUR data and the model without scaling.

Table 1: Table of Army Shoe sizes both narrow and wide. Units are imperial as this is a table for the US market.

Actual Length (in)	Shoe Size (in)	Norm Width (in)	Wide Width (in)
9.3125	6	3.5	3.875
9.5	6.5	3.5625	3.9375
9.6875	7	3.625	4
9.8125	7.5	3.6875	4.0625
10	8	3.75	4.125
10.1875	8.5	3.8125	4.1875
10.3125	9	3.875	4.25
10.5	9.5	3.9375	4.3125
10.6875	10	4	4.375
10.8125	10.5	4.0625	4.4375
11	11	4.125	4.5
11.1875	11.5	4.1875	4.5625
11.3125	12	4.25	4.625
11.5	12.5	4.3125	4.6875
11.6875	13	4.375	4.75
11.8125	13.5	4.4375	4.8125
12	14	4.5	4.875
12.1875	14.5	4.5625	4.9375
12.3125	15	4.625	5

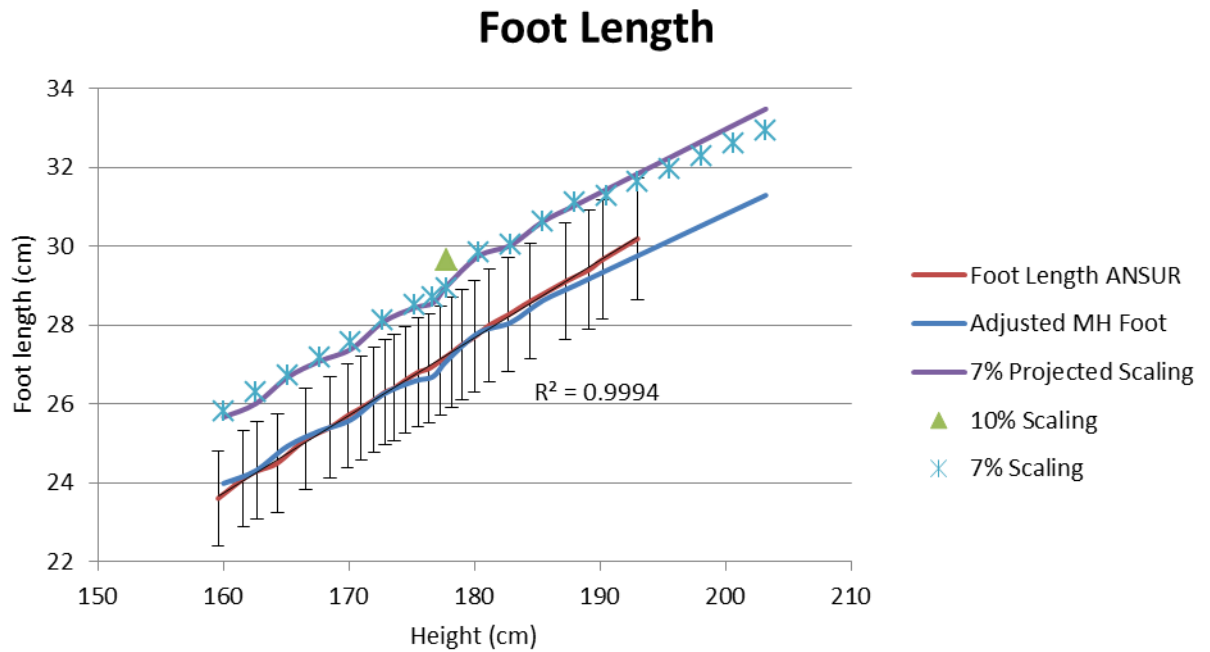


Figure 10: Foot length of the measured adjusted model set compared to the ANSUR data and the projected scaling.

The standard deviations for the dimensions of the foot length and the foot breadth horizontal were found to be .56 cm or 5.58 % and .89 cm or 8.66 % respectively. To accommodate the difference in deviations the length and width were scaled separately. The length was scaled by 7 % which allows for coverage of 88 % of the population. The next size up should be used to cover up to 95 % of the population because there is a 2 % length increase prior to scaling as shown in figure 11. The width which is further defined for shoes into normal and wide required a larger scaling of 18 % which allows for coverage of 98.7 % of the population. The remainder of the population can be covered by moving up to the next size as shown in figure 12.

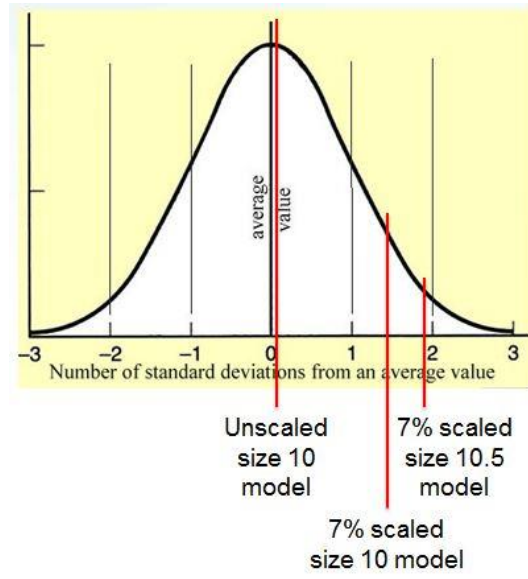


Figure 11: Standard deviation distribution of length coverage for a scaled size 10 model.

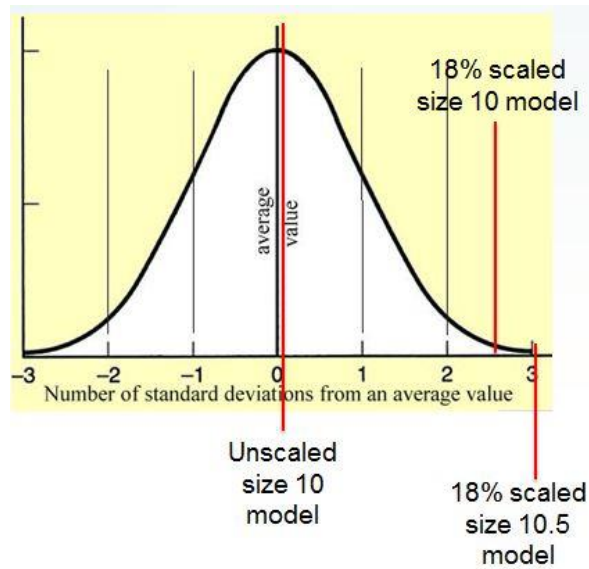


Figure 12: Standard deviation distribution of the width coverage for a scaled size 10 model.

Chapter 4

MAKEHUMAN MODIFICATION

4.1 Baseline

The MakeHuman software was selected to be used as the baseline for building the model set. As mentioned in Chapter 3, the MakeHuman package offers high resolution and acceptable means of controlling the dimensions of the foot. The model was divided into sections based on ethnicity. Where each ethnic section accurately represented a sector of the whole data distribution as laid out in the ANSUR data [5, 6]. Caucasian heights up to 170.2 cm, 67 inches, best imitated a sizes 6 to 8 boots. African heights from the 170.18 cm to 177.8 cm, 70 inches, best matched boot sizes 8.5 to 10. To account for the remaining sizes 10.5 to 15, an adjusted height set of African models was used. The adjustment was made by adding 2.54 cm, 1 inch, to the heights corresponding to the ANSUR data [5, 6]. Table 2 shows the correspondence between shoe sizes and foot dimensions. The table is also color coded where blue is the Caucasian model, red is the African model, and brown is the African model with the added height to stature.

4.2 Custom Set

From this template the model needed to be modified so CATIA could generate ply patterns on the surface of the model. In addition to the spliced ethnic regions of the model set, additional modifications to the models were needed. The unadulterated model possessed fine definition of the metatarsal region of the foot. In order to develop a surface for ply generation the metatarsal region needed to be simplified from showing individual toes to an almost mitten style covering where the toes were

smoothed together. The models were then scaled to incorporate coverage of the population as aforementioned in chapter 3.

Table 2: Shoe size table for foot model dimensions. Dimensions are in inches in this table because they are being designed for use in the United States where imperial units are standard.

Shoe Size	Height	Foot Length (in)	Foot Breadth Horizontal (in)	Heel Breadth (in)
6	63	9.44	3.56	2.55
6.5	64	9.57	3.63	2.61
7	65	9.81	3.67	2.65
7.5	66	9.96	3.73	2.67
8	67	10.08	3.78	2.71
8.5	68	10.33	3.84	2.75
9	69	10.46	3.94	2.78
9.5	69.6	10.51	3.94	2.82
10	70	10.67	3.99	2.84

10.5	71	10.95	4.11	2.91
11	72	11.05	4.14	2.96
11.5	73	11.27	4.34	2.98
12	74	11.42	4.39	3.05
12.5	75	11.57	4.33	3.12
13	76	11.72	4.33	3.19
13.5	77	11.87	4.33	3.27
14	78	12.02	4.32	3.34
14.5	79	12.17	4.31	3.41
15	80	12.32	4.30	3.49

4.3 Scaling

The models were scaled to account for the variation at each shoe size, so the majority of individuals at each distinct size will be covered. Originally, the plan was to scale in the length and width directions equally based on estimation that a seven percent scaling would be adequate to cover the variations at each size. Seven percent was selected because the ANSUR data shows a coefficient of variance less than six

percent see figure 13 for coverage. Upon validation performance, it was clearly visible that the seven percent scaling of the width was too narrow for the scans. There seemed to be a disconnect between what the survey data predicted and what was being found. Upon further investigation it was found that using the military boot size chart [8] the fit of the width appeared much better. It was decided to keep the limiting coverage factor as the foot length, so the foot width was scaled to have a larger coverage than the length as visible in figure 14.

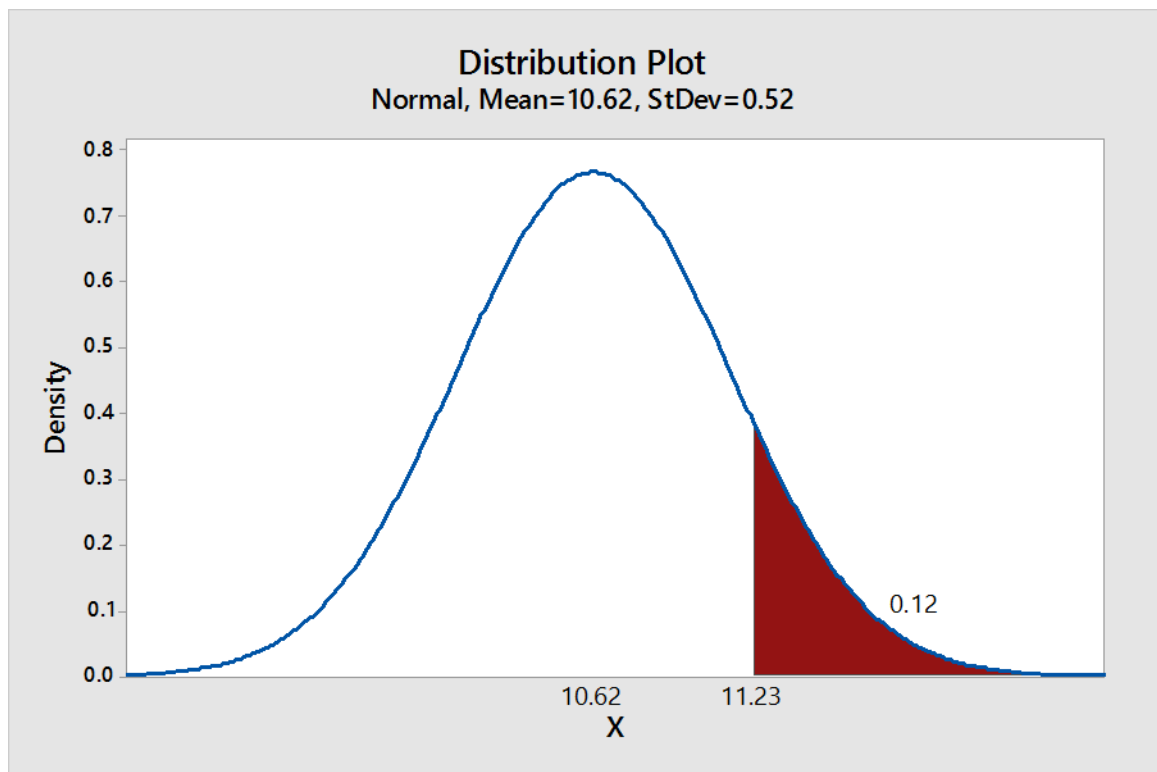


Figure 13: Normal distribution plot. Here it represents the area coverage of a seven percent scaling of the foot length [5].

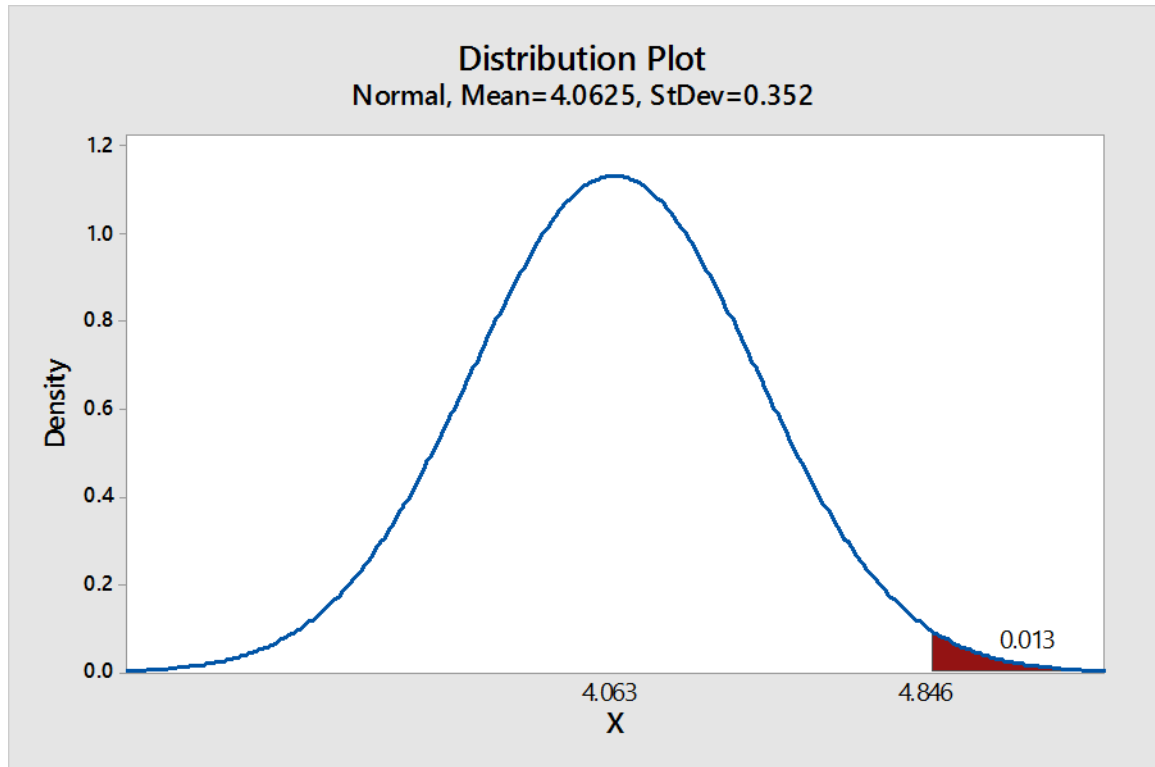


Figure 14: Normal distribution plot. Here it represents the area coverage of an eighteen percent scaling of the foot width from military boot size [8].

Chapter 5

VALIDATION

The model set was then compared to actual human feet. This was done by casting participants of varying shoe sizes using fiberglass casting socks. The socks were applied up to the region just below the knee. The subjects were then cut out using a cast saw in order to minimize any damage to the cast from removal. The casts were then closed and filled with plaster. The plaster molds were cleaned and prepped for scanning. The molds were scanned using the Go!SCAN hand held 3D scanner. The scans were imported into CATIA where they were compared to the models generated by MakeHuman.

5.1 Casting and Scanning

5.1.1 Casting

People were selected for casting based on their boot size. The size of the cast was recorded, but no other information on the participants was recorded. Casting began by setting up a sitting station with a bucket of room temperature water nearby. The floor in front of the seat has fiberglass matting placed down which was then covered with plastic. This was done so the bottom of the cast will have the contours of to the ball of the foot and the insole. The plastic was there so the fiberglass cast does not bond to the mat made of fiberglass on the floor.

The participant sat in the chair and had a plastic bag pulled over his leg to above his knee. The bag was then taped so it is tight around the individual's leg. A

half inch tube was then taped to the top of the person's foot and continues all the way up to above the knee. The tube was placed to provide protection and a guide for cutting the participant out of the cast. It was done on the top of the foot because this part of the cast is unsuitable for future parts of the molding process.

Wearing gloves the fiberglass sock was then removed from its bag and fed over the technician's thumbs till they touch the toe region of the sock. The scrunched up sock was then submerged in the bucket of water for ten seconds. The sock was then immediately pulled over the participant's foot and lower leg. The chair that is being used should either be braced by a second technician or be against a wall. The technician then rubbed the sock with moist gloves to ensure the entire sock was wet.

The participant was then asked to stand on the mat in a walking position with the casted leg as the lead leg, visible in figure 15.



Figure 15: Image of participant being casted. Notice how the casting foot is slightly forward of the other leg.

The volunteer was informed that they will feel the sock heat up a little and to expect something of a bubbling feeling in the sock. After three to five minutes the volunteer was instructed to sit back down with the cast elevated off the ground so as to not be disturbed by any contact. This position should be held for approximately five minutes or until the cast is reasonably dry. Then using a cast saw the participant was cut out along the ridge of the tube. The cast was now gently removed and spirally taped so as to prevent leaks when it is filled. Figure 16 shows the cast once it is hardened.



Figure 16: Image of a casting sock from STS Socks [16].

The cast was then filled with plaster. The plaster on average took two to three hours for full cure. The tape was then cut away to remove the cast from the hardened mold. The mold was then hand sanded to remove any rough edges. Figure 17 shows one of the molds just prior to sanding.



Figure 17: Image of an 11.5 size mold prior to sanding. Note the definition of the bottom and back of the mold.

5.1.2 Scanning

The models were then transported to the Center for Composite Materials Applications & Technology Transfer Laboratory where they were scanned using a GO!SCAN 50 with an accuracy of .1 mm. The scans were saved as .stl files so they could be easily imported into CATIA for surface comparison. Table 3 provides the specifications for the Go!SCAN 50. The scans were done in a well-lit area on a flat surface to minimize any noise in the scanning.

Table 3: The Table list the specifications for the Go!SCAN products [15]. The GO!SCAN 50 was used for scanning of the foot molds.

	Go!SCAN 20	Go!SCAN 50	Notes
Weight	930 g (2.05 lbs.)	950 g (2.1 lbs.)	That's less than a liter of milk.
Dimensions	154 x 178 x 235 mm (6 x 7 x 9.2 in.)	150 x 171 x 251 mm (5.9 x 6.7 x 9.9 in.)	Think about a box of tissues.
Light Source	White light (LED)		Similar to your LED flashlight!
Resolution	0.100 mm (0.004 in.)	0.500 mm (0.020 in.)	Smaller than a grain of sand (but please don't try to scan one...)
Accuracy	Up to 0.100 mm (0.004 in.)		Thinner than a human hair!
Part size range (recommended)	0.05 – 0.5 m (2 – 20 in)	0.3 – 3.0 m (1 – 10 ft)	From the size of a chicken egg to a sub-compact car: the possibilities are very wide!
Texture Resolution	50 to 250 DPI	50 to 150 DPI	Enough to provide a clean and crisp texture.
Texture Colors	24 bits		Millions of colors for the widest palette of possibilities.
Output Formats	.dae, .fbx, .ma, .obj, .ply, .stl, .txt, .wrl, .x3d, .x3dz, .zpr		Don't even try to find a software that won't open these files...

5.2 CATIA Shape

The .stl files of the scans were imported into CATIA V5, and they were cleaned up using the CATIA Shape Digitalized Shape Editor. The Digital Shape Editor first was used to remove the point cloud generated by the table surface as part of the foot scans. Then the point clouds were turned into surfaces first by using the tessellation feature with the distance between points made large enough to fill any holes, on average .89 cm. Then using quick surface reconstruction the tessellations were turned into surfaces. The scan was then compared to the models using CATIA V5 Digital Model Utility Analysis Workbench.

5.3 Digital Model Utility Analysis

The surfaces were initially compared using CATIA's DMU Space Analysis Package where a band analysis was performed on each of the sets. The distance was set to its max setting for product comparison, .201 cm. The band analysis then generated the three color bands on the two surfaces: red was used to represent the model, green for the scanned surface, and yellow for where both were within the range of .201 cm. As it is seen, in figure 18, that the model being bigger than the surface is a good thing and overlap is acceptable the analysis shows percentages of surface fit. To interpret the coloring of the regions images of the models were taken and evaluated using ImageJ. From ImageJ a color analysis was performed which found the average fit between the model surface and the scanned surface was 87.24 %. This is a positive correlation with the standard deviation distribution which expected that for length, the limiting factor, the model should fit up to 88 % of the population.

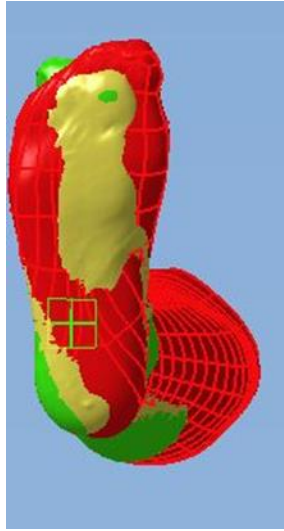


Figure 18: Image is of a CATIA DMU band analysis of a size 10 model, which has a 7 % length scaling and an 18 % width scaling. Red is the model. Green is the scanned surface. Yellow is overlap.

5.4 Cross-Section Analysis

Next, a cross-section analysis of the scanned surface overlapped with the model surface was taken. The cross-sections were broken-up by left, center, and right of the foot in plane with the heel and toes, shown in figure 19. The heel and ball of the foot were also sectioned. Images of the cross-sections were taken and imported into ImageJ to determine nineteen distinct measurements. The pixels were counted and the pixel count was then converted to inches using the grid on the images. This analysis average measurement for each of the regions was: 1.753 cm for the left, .965 cm for the center, 1.448 cm for the right, .940 cm for the heel, and .890 cm for the ball. This method was rather subjective which leads to the measurements to be higher. Essentially the cross-section analysis provides a worst case scenario for the differences.

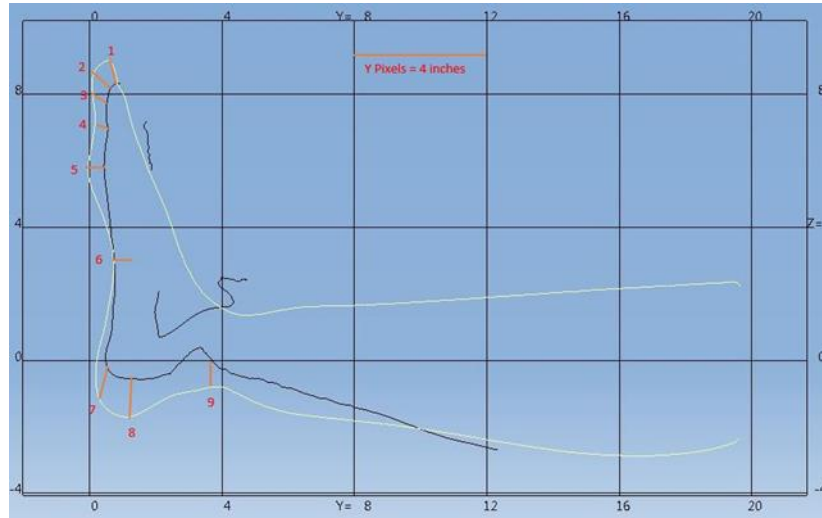


Figure 19: The image is a center cross-section of a model overlapped with the scanned surface. The image displays the nine points where measurements were taken.

5.5 Point Projection Analysis

Finally, a point projection analysis was implemented to provide a more accurate measure of the differences between the scanned surfaces and the model surfaces. This method involved placing points on the scanned surface and then projecting them normal to the scanned surface on to the model surface, visible in figure 20. The distance between the point and its projection was then measured. This is a more accurate method than that of taking the cross-sections and eyeballing point correlation. By doing this the average distance measured between a point and its projection was .49 cm with a range of .21 cm. With an average difference less than .51 cm the model set is acceptable as a universal model set.

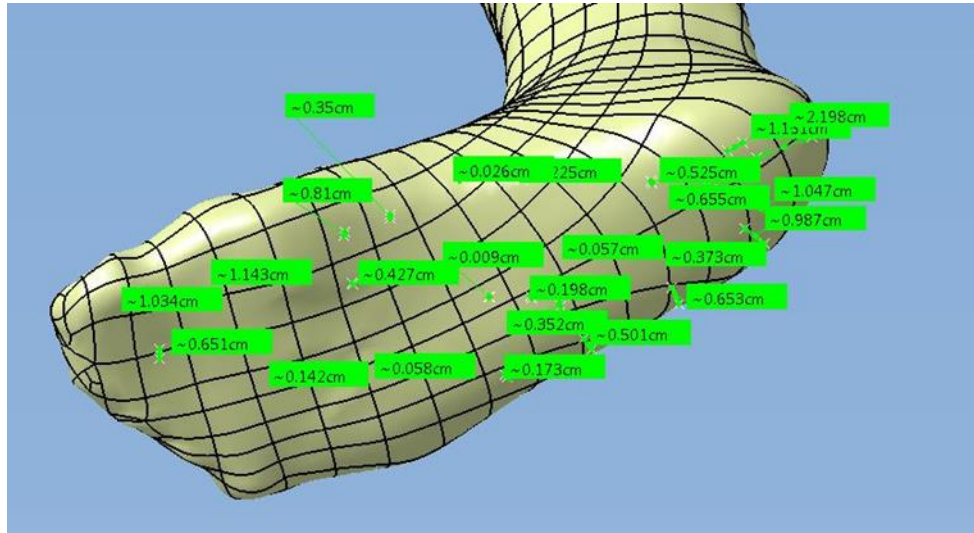


Figure 20: Image is of the point projection measurements. Those points were projected normal to the scanned surface onto the model surface.

Chapter 6

FUTURE PLANS

6.1 Single Leg Scaling

With the success of the model set, the program has now moved toward the use of a single model that has scaling to allow it to be used for the full array of sizes. Currently, the effort is to take the smallest size, size 6, and scale it incrementally up to size 15. Figure 21 demonstrates how this would be done.

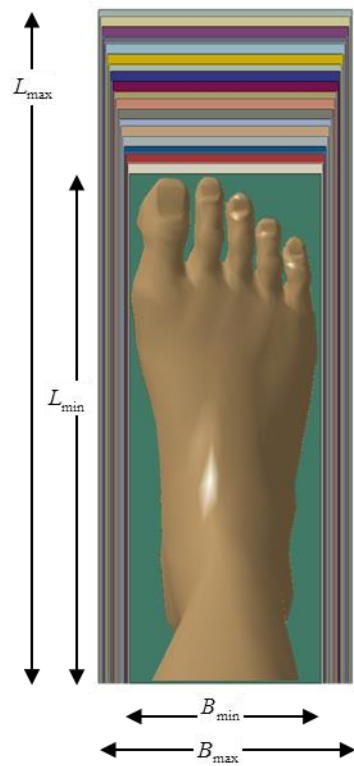


Figure 21: Rendering of a foot with the color schema representing how the one model would be grown to accommodate the other foot sizes. Image created by Narinder Khattri Ph.D.

The advantage to this one model approach over the current model set is that the set requires new patterns to be generated on each of the models. The single model approach relieves this burden by simply updating the ply generation once the scaling is altered.

6.2 Ply Generation

So far most of the plies used in prototype production have been generated using a scanned model. A few of the plies have started to be generated using the model set. The plies used in the production of the cuff region of the AFO were generated using a universal model. From visual inspection, those patterns appear to conform well to the casted mold of the participant. As mentioned in section 6.1 generating plies on the full universal model set would be very taxing, which is why the scaling of the single model is currently being pursued. Figure 22 is an example of one of the plies generated.

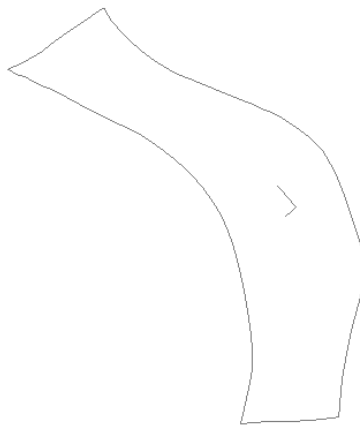


Figure 22: A LB1-0 ply generated from the universal model set.

6.3 Center for the Intrepid Implantation

When the technology is fully delivered to the Center for the Intrepid, they will be able to mass produce the custom orthotics for wounded veterans. The system they will follow to create the orthotics is input the patient data and AFO requirements into the proprietary software. Then the technician adds in device specifications based on the activity level of the patient. Behind the scenes the software compiles the ply patterns and orders them based on the needs of the patient. The software then generates production information. That information is then used to construct the orthotic device by using the selected binned plies that were selected by the software. Figure 23 shows the software portion of the process for manufacturing the AFOs. For more information see the sample traveler document in appendix A.

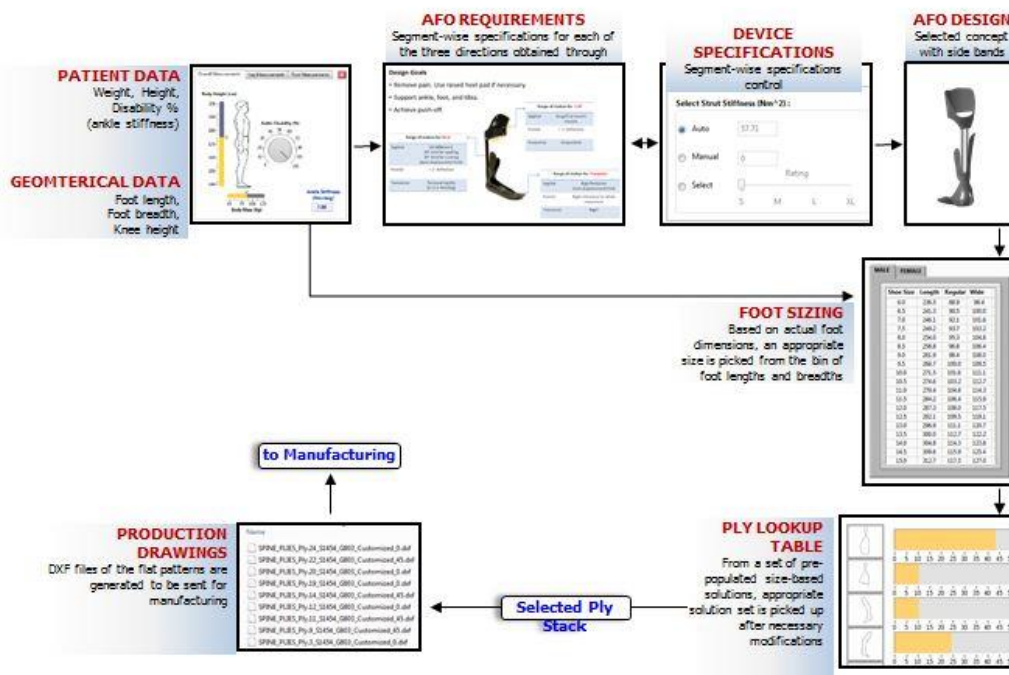


Figure 23: Software interface design scheme for the manufacturing of the AFOs.

Chapter 7

CLOSING REMARKS

7.1 Center for Composite Materials

Special thanks to the Center for Composite Materials at the University of Delaware for the opportunity to work on this project for the past four years and for providing materials and personal to make this program successful. This program was also assisted by the professionals of the Applications & Technology Transfer Laboratory for their contribution of resources throughout the program.

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Appendix A

SAMPLE AFO MANUFACTURING TRAVELER

The tables and figures below represent the AFO Manufacturing Traveler document sent to the Center for the intrepid.

AFO Manufacturing Traveler

Table A1: General Information for Traveler Document.

General Information	
Date:	
Author:	
Part Name:	
Traveler ID:	

Note: No data to be entered that is patient specific

Overview

The scope of this traveler is the fabrication of a composite AFO based on the Orthotist prescription.

Table A2; Approvals for Traveler Document.

Approvals	
Orthotist	

Manufacturing	
---------------	--

Resource List

Table A3: Material Information Part for Traveler Document.

Material Information - Part			
Item	Description	Manufacturer	Quantity
1	Carbon Prepreg/G83 C	Toray	
2	Strut Rods	?	2
3	Strut Insert – Aluminum 6061	-	1

Table A4: Material Information Process Aids for Traveler Document.

Material Information – Process Aids			
Item	Description	Manufacturer	Quantity
1	Nylon Bagging Film	Airtech	4 ft ²
2	Release Film		3 ft ²
3	Silicone Film		
4	Acetone		
5	Breather Material		
6	Super 77 Spray Adhesive		
7	Tacky Tape		
8	Silicone (Reusable Silicone Bag)		

Table A5: Equipment List for Traveler Document.

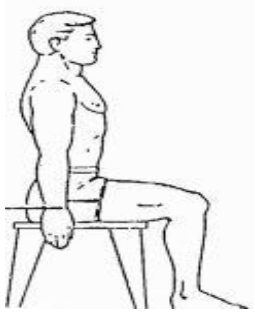
Equipment List			
Item	Description	Manufacturer	Quantity
1	Convection Oven	Toray	1
2	STx-48" Plotter/Cutter	Carlson Design	1
3	Vacuum Pump	-	1
4	High Temp Vacuum Tube		5 ft
5	Metal L – Bracket (For Silicone Molds)		1
6	Thermocouple		1
7	Cutting Scissors		1
8	Dremel		1


Table A6: Safety Precautions for Traveler Document.

Safety Precautions			
Item	Description	Reference	Quantity
1	Wear safety glasses	Toray	
2	Wear latex gloves while handing all the materials	?	2
3	Wear a lab coat at all times	-	1

10 Tool Preparation

Table A7: Foot Casting Process for Traveler Document.

Foot Casting Process		
Task No.	Description	Reference
1	Patient removes shoe and sits in a chair with the back braced.	
2	Flexible tubing is cut and the tip is sliced off at roughly a 30 degree angle.	
3	A bag is placed over the patient's leg and taped so not to be loose.	
4	The flexible tubing is then applied to the top of the patient's foot and held in position with tape.	
5	The casting sock is opened and scrunched until thumbs touch toe region of the sock.	
6	The sock is then plunged in water for ten seconds.	
7	The sock is then put on the patient and hand coated with water.	
8	The patient then stands on a cushioned surface.	
9	The cast should be mostly dry before the patient is allowed to sit with the cast elevated.	
10	The cast is then cut along the tubing with a cast saw.	
11	The cast is then wrapped with tape to prevent the plaster from leaking.	
12	Plaster is then poured into the cast and allowed to harden.	

13	The plaster form is then removed from the cast.	
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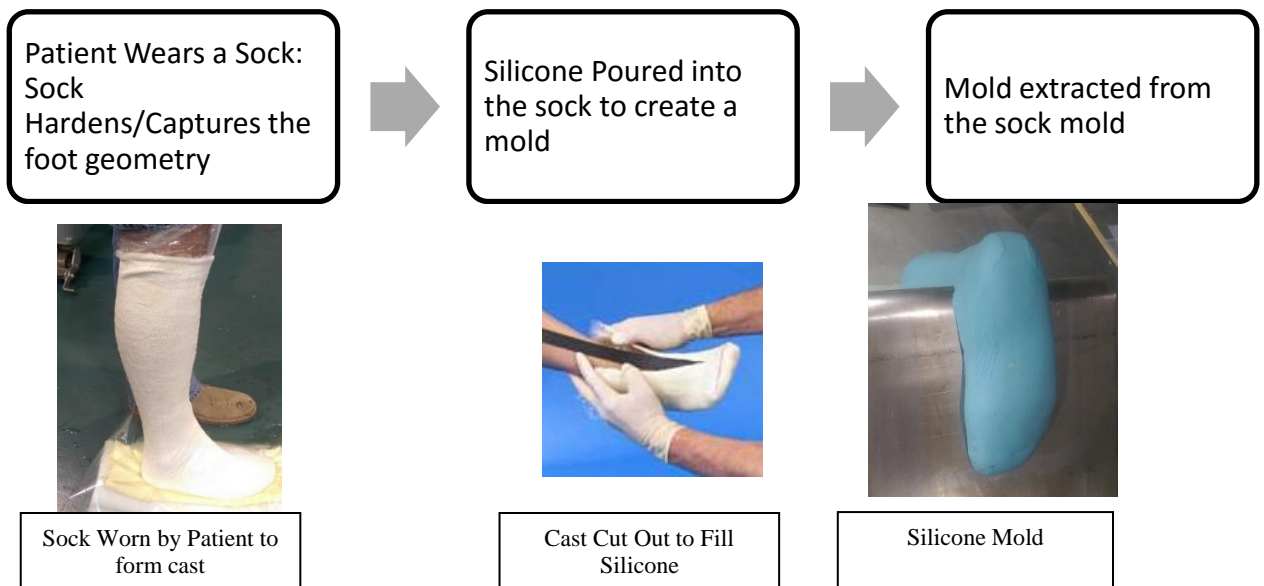
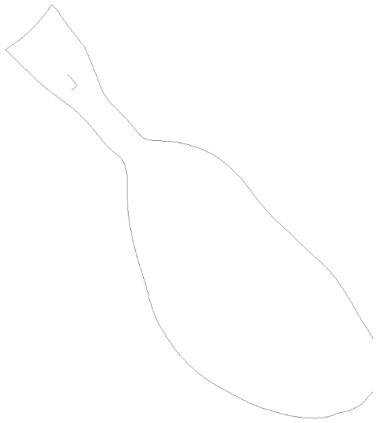
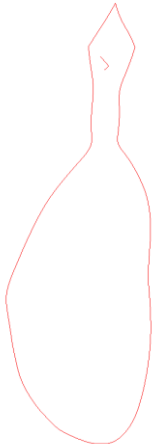
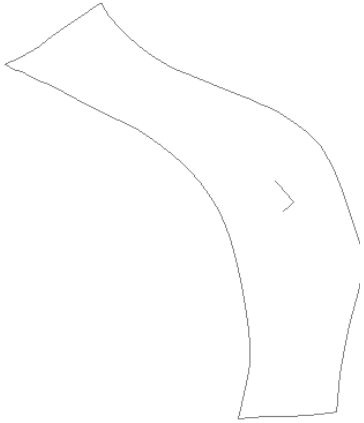
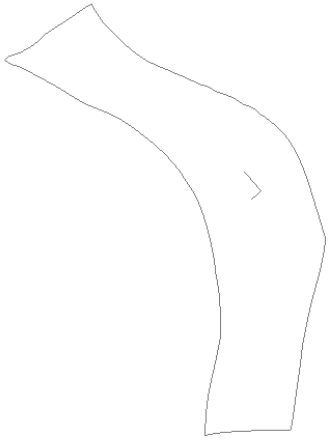
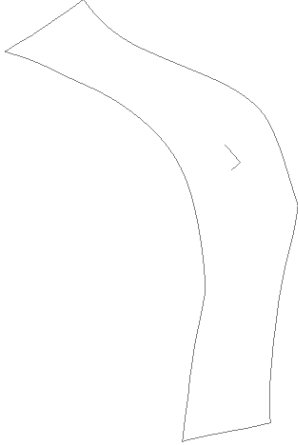
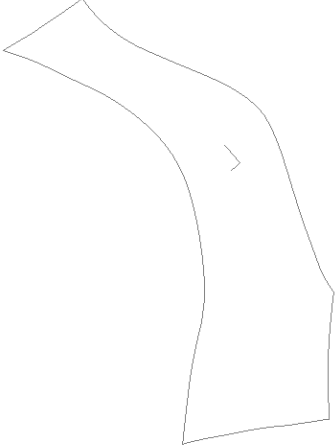


Figure A1: Sock cast manufacturing for Traveler Document.

20 Ply Cutting and Kitting

Ply patterns and layup sequence are automatically generated by the Orthotist prescription software interface. There are 12 unique patterns that are repeated as needed to build the complete AFO.

Table A8: Unique Ply Patterns for Traveler Document.

Unique Ply Patterns		
 B-0	 BaseF-45	 LB1-0
 LB2-0	 LB3-0	 LB4-0

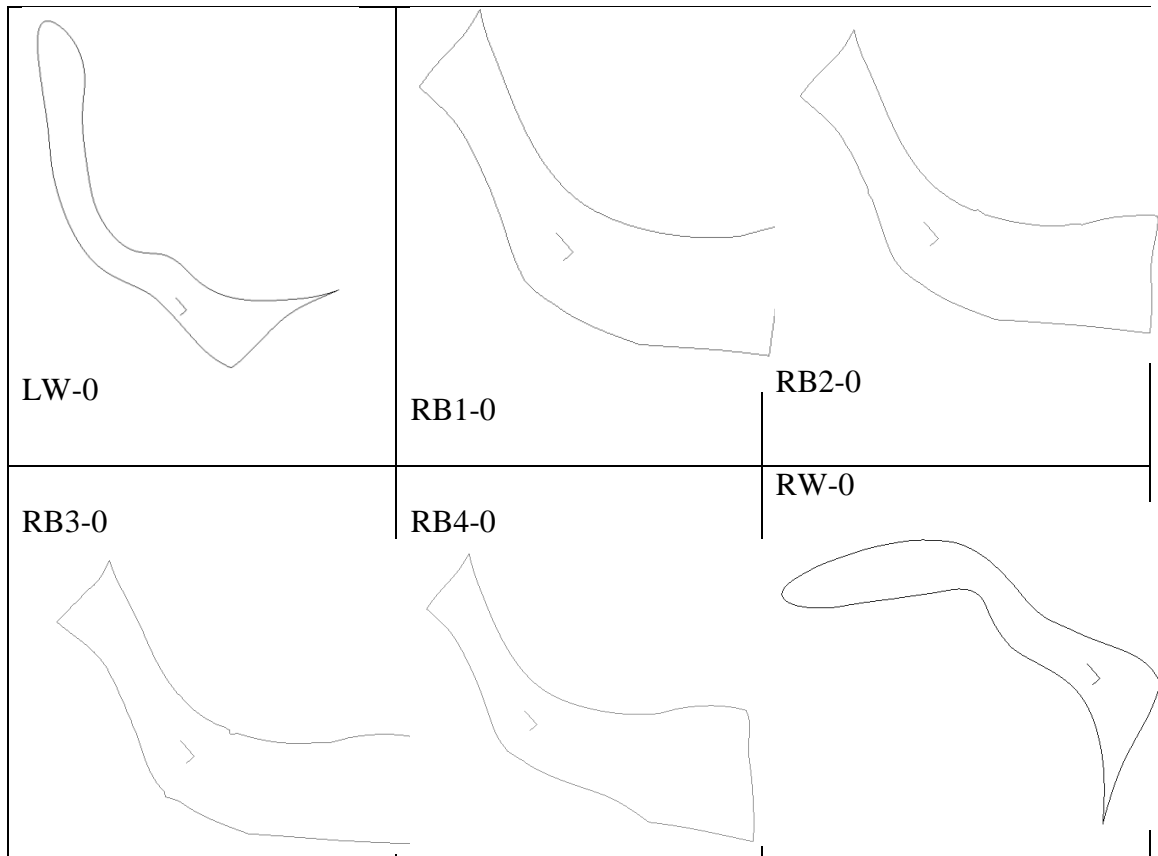


Table 1 – AFO Ply Sequence

Table A9: AFO Ply Sequence for Traveler Document.

		Base	Region Wise Ply Counts			
			L-Band	R-Band	L-Wing	R-Wing
		17	32	32	16	16
1	BF-45	1				
2	BF-n45	1				
3	LBW-0		1		1	
4	RBW-0			1		1
5	LBF1-0		1			
6	RBF1-0			1		
7	B-0	1				
8	LBW-0		1		1	

9	RBW-0			1		1
10	LBF2-0		1			
11	RBF2-0			1		
12	B-0	1				
13	LBW-0		1		1	
14	RBW-0			1		1
15	LBF3-0		1			
16	RBF3-0			1		
17	B-0	1				
18	LBW-0		1		1	
19	RBW-0			1		1
20	LBF4-0		1			
21	RBF4-0			1		
22	LBW-0		1		1	
23	RBW-0			1		1
24	LBF1-0		1			
25	RBF1-0			1		
26	B-0	1				
27	LBW-0		1		1	
28	RBW-0			1		1
29	LBF2-0		1			
30	RBF2-0			1		
31	B-0	1				
32	LBW-0		1		1	
33	RBW-0			1		1
34	LBF3-0		1			
35	RBF3-0			1		
36	B-0	1				
37	LBW-0		1		1	
38	RBW-0			1		1
39	LBF4-0		1			
40	RBF4-0			1		
41	B-0	1				
42	RBF4-0			1		
43	LBF4-0		1			
44	RBW-0			1		1
45	LBW-0		1		1	
46	B-0	1				

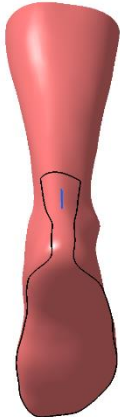
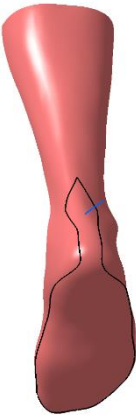
47	RBF3-0			1		
48	LBF3-0		1			
49	RBW-0			1		1
50	LBW-0		1		1	
51	B-0	1				
52	RBF2-0			1		
53	LBF2-0		1			
54	RBW-0			1		1
55	LBW-0		1		1	
56	B-0	1				
57	RBF1-0			1		
58	LBF1-0		1			
59	RBW-0			1		1
60	LBW-0		1		1	
61	RBF4-0			1		
62	LBF4-0		1			
63	RBW-0			1		1
64	LBW-0		1		1	
65	B-0	1				
66	RBF3-0			1		
67	LBF3-0		1			
68	RBW-0			1		1
69	LBW-0		1		1	
70	B-0	1				
71	RBF2-0			1		
72	LBF2-0		1			
73	RBW-0			1		1
74	LBW-0		1		1	
75	B-0	1				
76	RBF1-0			1		
77	LBF1-0		1			
78	RBW-0			1		1
79	LBW-0		1		1	
80	BF-n45	1				
81	BF-45	1				

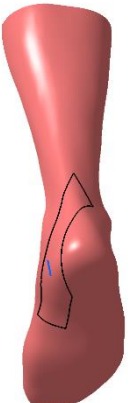
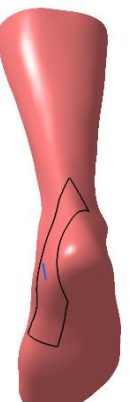
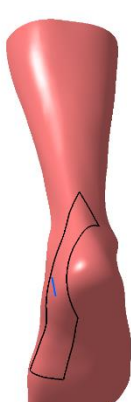
Table A10: Additional Materials Cutting for Traveler Document.

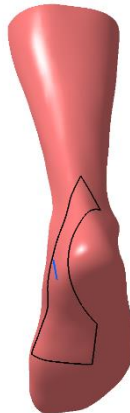
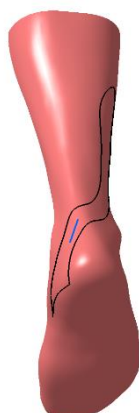
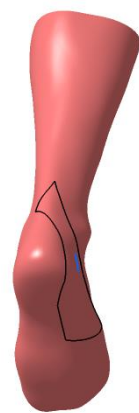
Additional Materials Cutting			
Task	Operation Description	Visual Reference	Reference
1	Cut the silicone film to the shape of mold	Image	
2	Cut the breather materials to cover the entire mold	Image	
3	Cut the release film to cover the surface of the mold after material is laid up	Image	

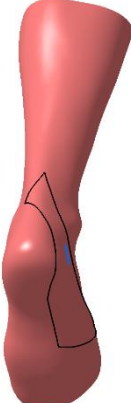
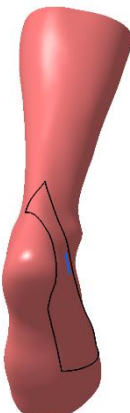
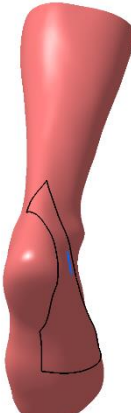
30 Ply Layup

Table A11: Ply Lay-up for Traveler Document.

Ply Lay-up			
Task	Operation Description	Visual Reference	Reference
4	Clean the tool surface with sand paper to remove any wrinkles	Image	
5	Once the surface is clean, apply some spray adhesive to the surface of the mold	Image	
6	Based on Table 1, select the first ply and place it on the mold starting at the seed point location as marked in the Figure.		To add Animated GIF showing ply placement procedure
7	Select the second ply from Table 1, and place the next play		

Ply Lay-up			
Task	Operation Description	Visual Reference	Reference
8	Select the next ply, and place is as shown in the image, making sure the ply is properly aligned		
9	Place the next ply		
10	Place the next ply as shown		

Ply Lay-up			
Task	Operation Description	Visual Reference	Reference
11	Place the next ply as shown		
12	Place the next ply as shown		
13	Place the next ply as shown		

Ply Lay-up			
Task	Operation Description	Visual Reference	Reference
14	Place the next ply as shown		
15	Place the next ply as shown		
16	Place the next ply as shown		

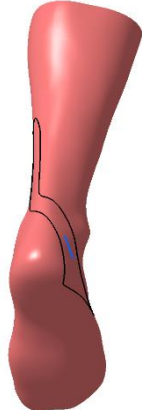
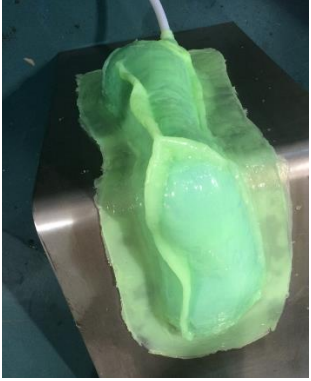

Ply Lay-up			
Task	Operation Description	Visual Reference	Reference
17	Place the next ply as shown		
18	Follow the de-bulk steps as shown in Table 3 below		
19	Continue ply lay-up and debulking steps per Ply Table (Table 2). Debulk every 12 plies until lay-up is complete		

Table 2 - De-Bulk Steps

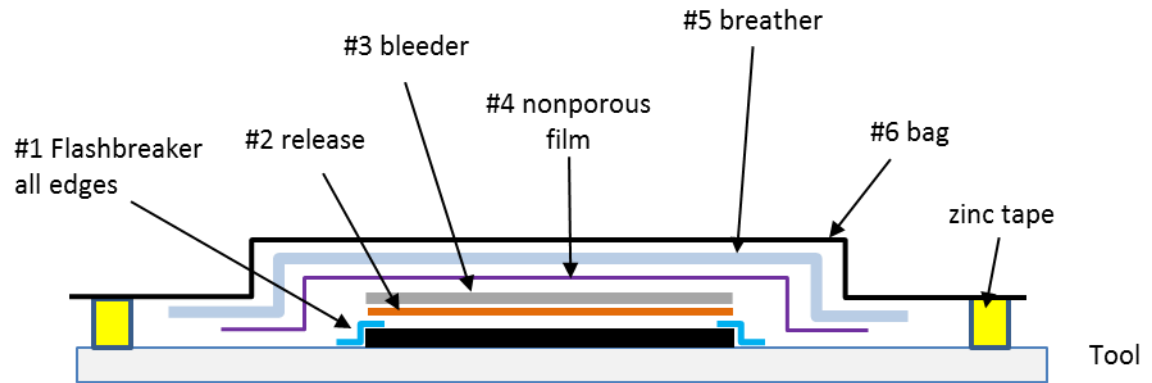
Table A12: De-bulking for Traveler Document.

De-bulking		
Task	Description	Reference
1	Put a layer of peel ply on the surface	Image
2	Put a layer of breather on top of the peel ply layer	Image
3	Cover the entire mold with the reusable silicone vacuum bag to facilitate vacuum	

		
4	Apply vacuum to the part for one minute	
5	Turn off Vacuum and apply again for one minute	
6	Remove the silicone bag, breather and peel ply from the part	

40 Vacuum Bagging

To ADD: Schematic of Vacuum Bagging (similar to below)



- #1 Flashbreaker tape all edges to tool; 1/8" overlap on top of preform.
- #2 release ply = Release Ease 234 TFP-HP, 4"x7"
- #3 bleeder = 1 layer of N10, 3"x6"
- #4 nonporous film (green vacuum bag), 7"x10"
- #5 breather = 1 layer of N10
- #6 vacuum bag (pink)

Figure A2: Vacuum bagging diagram.

50 Oven Cure

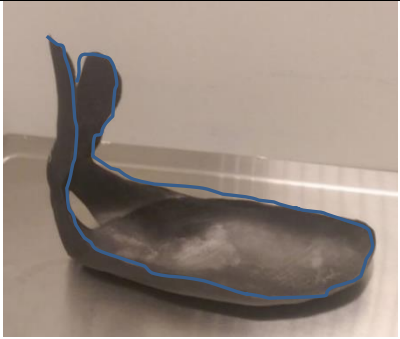
Table A13: Curing Process for Traveler Document.

Curing Process		
Task	Description	Reference
1	Set the oven to ramp to 240 F in 45 minutes	
2	Set the swell time at 240 F to 30 minutes	
3	Set the oven to ramp down to room temperature in 45 minutes	
4	Place the part under vacuum inside the oven for curing, making sure the vacuum level is above 25" Hg	

Time (min)	Temperature (°F)
0	75
45	240
75	240
120	75



60 Demolding and Trimming

Table A14: Post Processing for Traveler Document.

Post Processing		
Task	Description	Reference
1	Turn the oven off and shut off the vacuum	n/a
2	Remove the vacuum bag from the part	
3	Carefully remove the part from the mold	
4	Trim the part in the areas outlined as necessary, making sure the trimming is not done in any other areas or beyond the marked lines	
5	Write traveler number on AFO with permanent marker	
6	Clean the part with a fine sandpaper to remove any splinters and	

70 AFO Inspection and Patient Fit Testing

Table A15: Quality Assessment for Traveler Document.

Quality Assessment		
Task	Description	Comments
1	Measure the Part Weight:	
2	Conduct a Visual Inspection of the part and look for the following: Wrinkles Yes / No Dry Spots Yes / No Delaminations Yes / No Scuffs Yes / No Scratch Marks Yes / No Other Surface Defect Yes / No	
3	Take thickness measurements in the marked zones	
3.1	Thickness Zone 1:	
3.2	Thickness Zone 2:	



3.3	Thickness Zone 3:	
3.4	Thickness Zone 4:	
4	Quality Check: Pass / Fail	
5	Add insole/padding as needed	
6	Fit patient and get feedback on comfort and fit Pressure points Yes / No Pinching Yes / No Size fit Yes / No Wear shoe over it Yes / No	

Table A16: AFO Acceptance for Traveler Document.

AFO Acceptance	
Accept	Date:
Reject	Date:
Comments:	

Appendix B

MANUFACTURING REPORT SAMPLE

Manufacturing report used to evaluate the production process of the test parts made. This report was used to then reevaluate the ply patterns which intern influenced the way the model was generated, processed, and scaled.



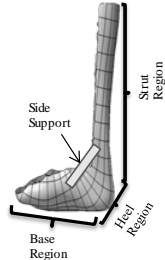
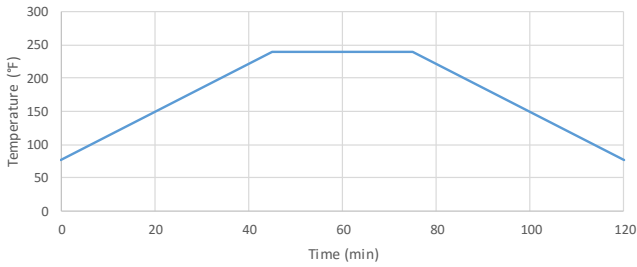
Manufacturing Report													
Date:		August 08 15		Part #: AFO-08-08 15 -D		Manufacture by: Francis Fish							
Layers Overview				Units: Inches		Originator: Francis Fish							
Base Plies Right Wing plies Left Wing plies Right Plies Left Plies Total Plies				Pictures		Regions							
				 									
#1 min. #38 min. #2 min. #39 min. #3 min. #40 min. #4 min. #41 min. #5 min. #42 min. #6 min. #43 min. #7 min. #44 min. #8 min. #45 min. #9 min. #46 min. #10 min. DEBULK min. #11 min. #47 min. #12 min. #48 min. DEBULK min. #49 min. #13 min. #50 min. #14 min. #51 min. #15 min. #52 min. #16 min. #53 min. #17 min. #54 min. #18 min. #55 min. #19 min. #56 min. #20 min. DEBULK min. #21 min. #57 min. #22 min. #58 min. #23 min. #59 min. #24 min. #60 min. #25 min. #61 min. #26 min. #62 min. DEBULK min. #63 min. #27 min. #64 min. #28 min. #65 min. #29 min. #66 min. #30 min. #67 min. #31 min. #68 min. #32 min. #69 min. #33 min. #70 min. #34 min. #71 min. #35 min. #72 min. #36 min. #73 min. DEBULK min. #74 min. #37 min. #75 min.		Region Thickness <table border="1"> <tr> <td>Base Thickness</td> <td></td> <td>Heel Thickness</td> <td></td> </tr> <tr> <td>Strut Thickness</td> <td></td> <td>Side Support Thickness</td> <td></td> </tr> </table>				Base Thickness		Heel Thickness		Strut Thickness		Side Support Thickness	
Base Thickness		Heel Thickness											
Strut Thickness		Side Support Thickness											
				Oven Vacuum: -27 inHg Heating time: 45 min. Cooling time: 45 min.		Temperature: 240 °F Treatment time: 30 min. TOTAL TIME: 120 min.							
				Heating profile 									
				Comment:									

Figure B1: Manufacturing report sample document.

Appendix C

3D CAD MODELS

Set of 3D CAD models that can be manipulated within this document.



Figure C1: 3D CAD Model of a size 6 foot.



Figure C2: 3D CAD Model of a size 10 foot.



Figure C3: 3D CAD model of a size 12.5 foot.

Appendix D

HOW THE PLIES LAY ON THE MODEL

Ply patterns overlaid on the model to show how the plies drape on the part.

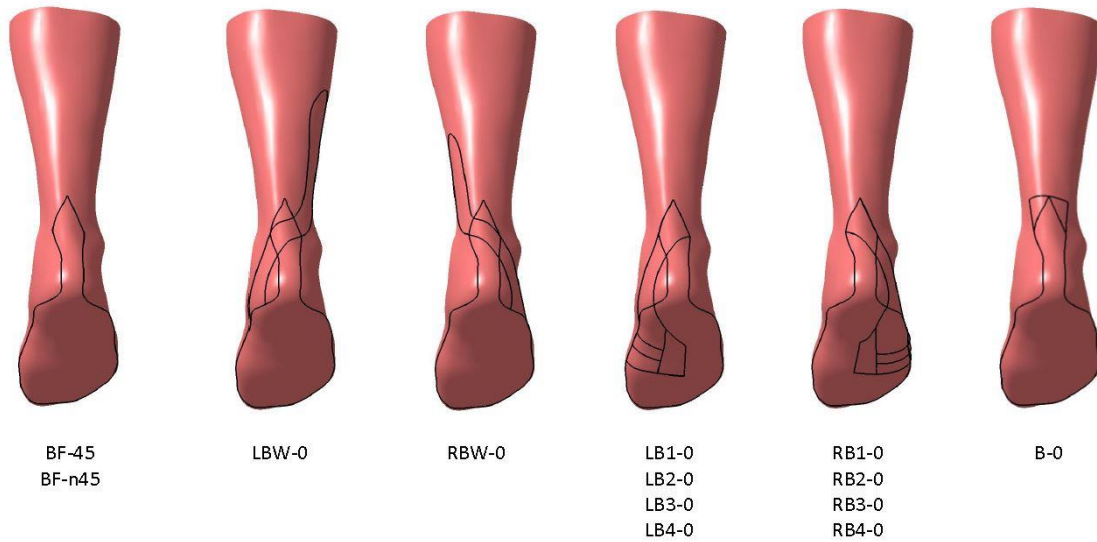


Figure D1: Image of the plies draped over the model.

Appendix E

OVERALL METHODOLOGY

The methodology for the development of this model set can be summarized in five steps. The subject's foot length and width are measured as well as the subject's height. That data is loaded into MakeHuman software to generate a stl. The stl is then imported into CATIA and cleaned. The stl surface is then measured and compared to the ANSUR data. The surface is then used to generate ply patterns for the subject.

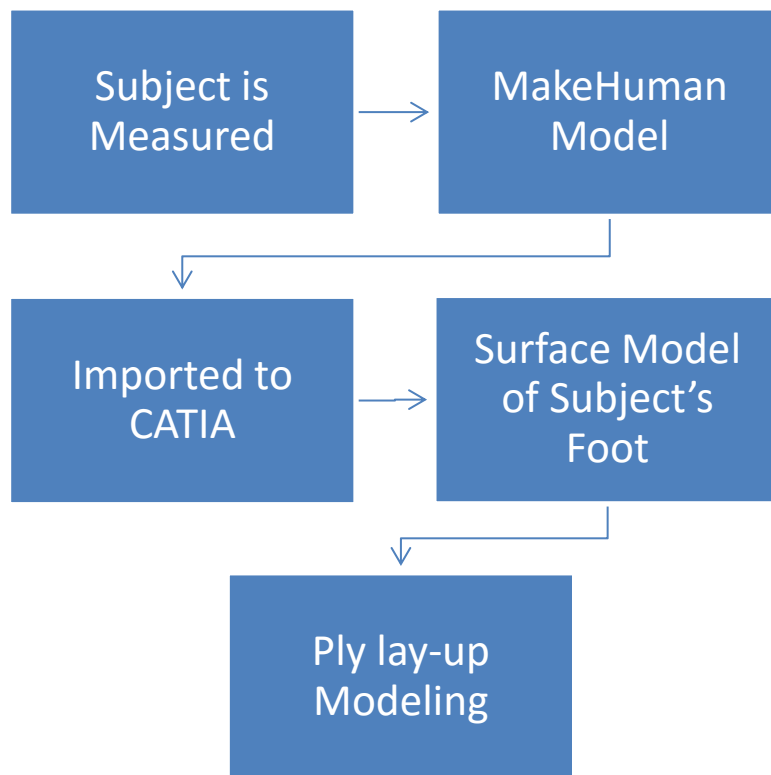


Figure E1: Five steps to model generation.

Appendix F

DIGITAL MODEL UTILITY ANALYSIS

The digital model utility analysis was produced by generating color bands of red, the model, green, the scan, and yellow, the overlap with in .079 in. The percentage of each color in the image was evaluated using a color percentage analysis in ImageJ.

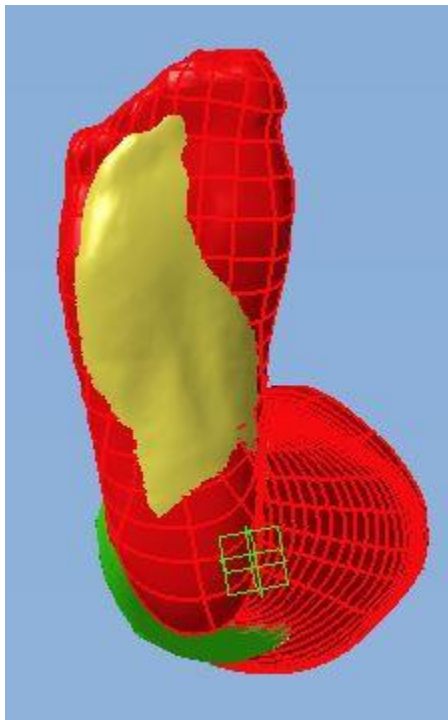


Figure F1: Digital Model Utility analysis of size 9 base view.

Table F1: Band analysis for size 9 base.

9 B		red	green	blue	Freq	RBYG%	RYG %
red	1	194	13	15	23328	28.833	63.57%
blue	2	141	175	216	44210	54.642	
yellow	3	181	168	64	11427	14.123	31.14%

green	4	60	116	18	1943	2.401	5.29%
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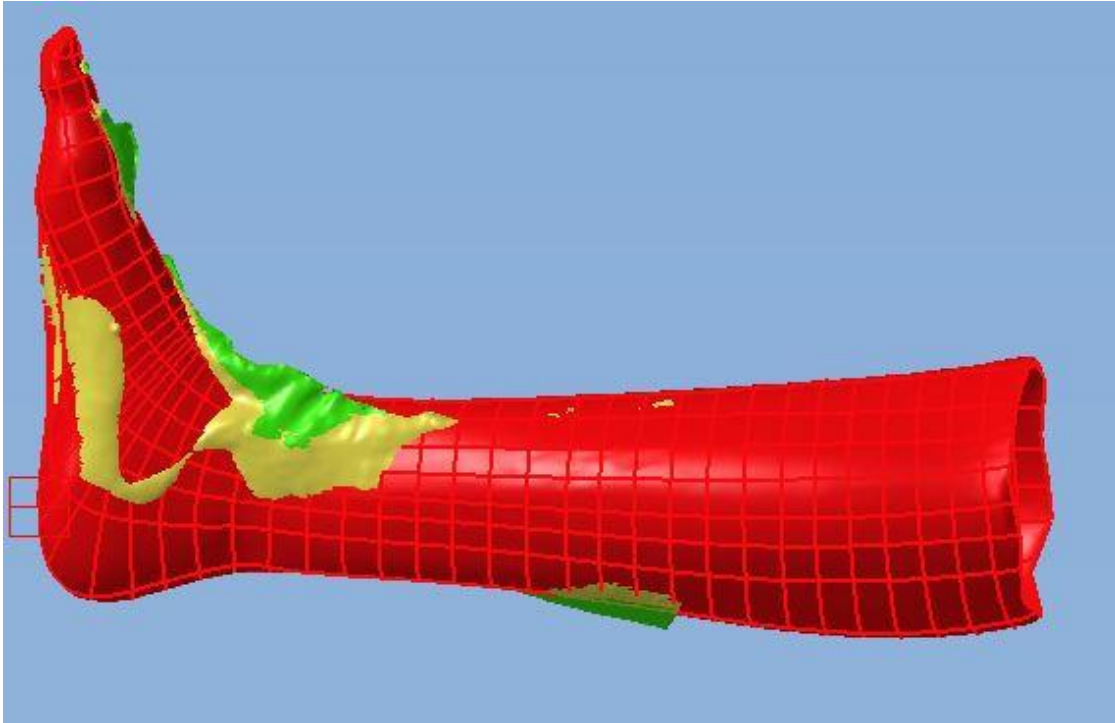


Figure F2: Digital Model Utility analysis of size 9 left view.

Table F2: Band analysis for size 9 left.

9 L		red	green	blue	Freq	RBYG%	RYG %
red	1	189	13	16	56727	27.139	83.30%
blue	2	140	175	216	141014	67.463	
yellow	5	207	172	81	8276	3.959	12.15%
green	1	66	169	29	3093	1.48	4.54%

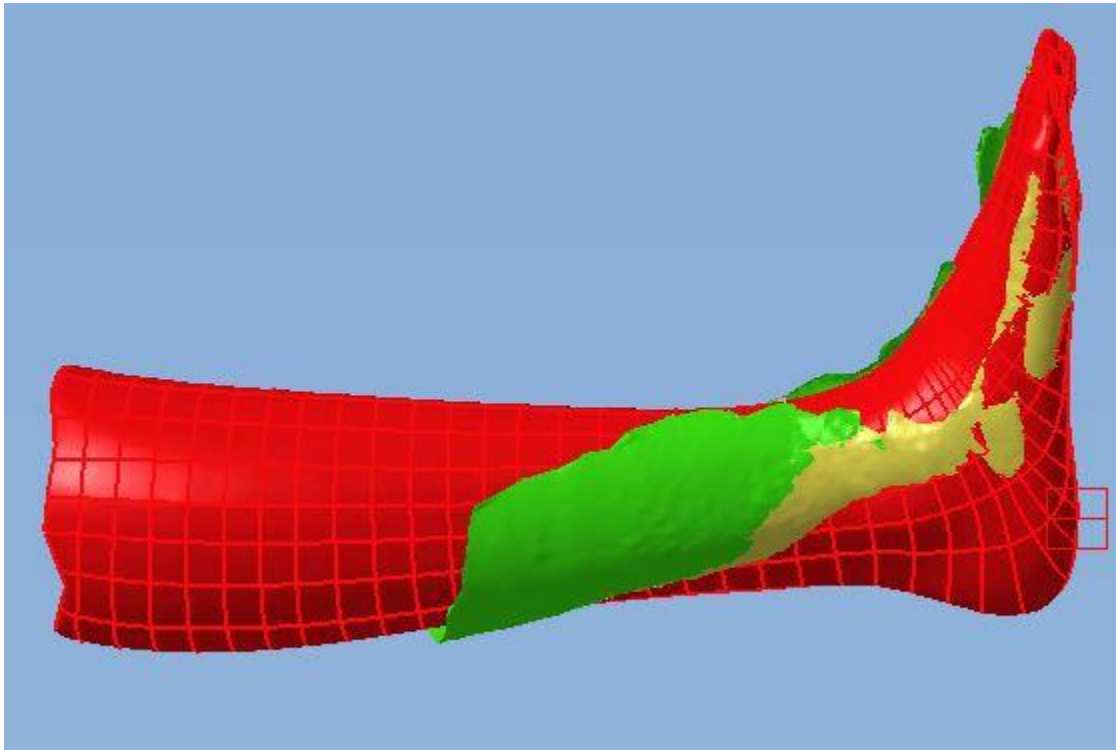


Figure F3: Digital Model Utility analysis of size 9 right view.

Table F3: Band analysis for size 9 right.

9 R		red	green	blue	Freq	RBYG%	RYG %
red	1	196	13	16	47668	22.882	70.05%
blue	2	140	175	216	140266	67.333	
yellow	3	186	156	70	6938	3.33	10.20%
green	4	46	162	15	13446	6.455	19.76%

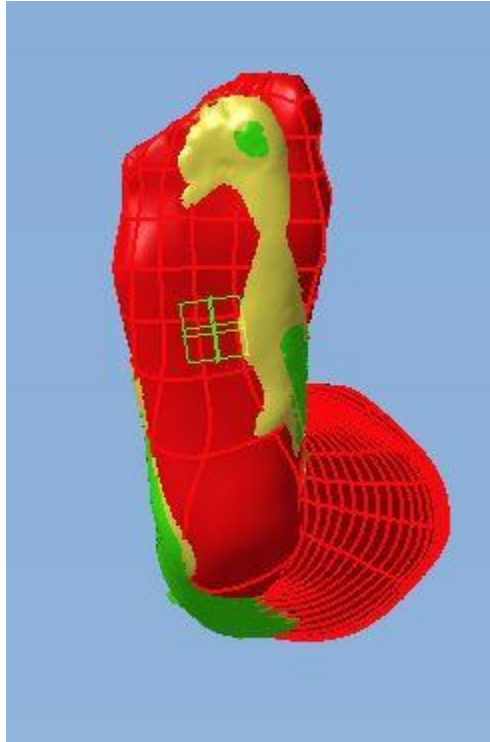


Figure F4: Digital Model Utility analysis of size 10 base view.

Table F4: Band analysis for size 10 base.

10 B		red	green	blue	Freq	RBYG%	RYG %
red	1	191	13	15	22973	25.24	75.58%
blue	2	141	176	216	60623	66.604	
yellow	3	185	168	68	4990	5.482	16.42%
green	4	52	131	18	2434	2.674	8.01%

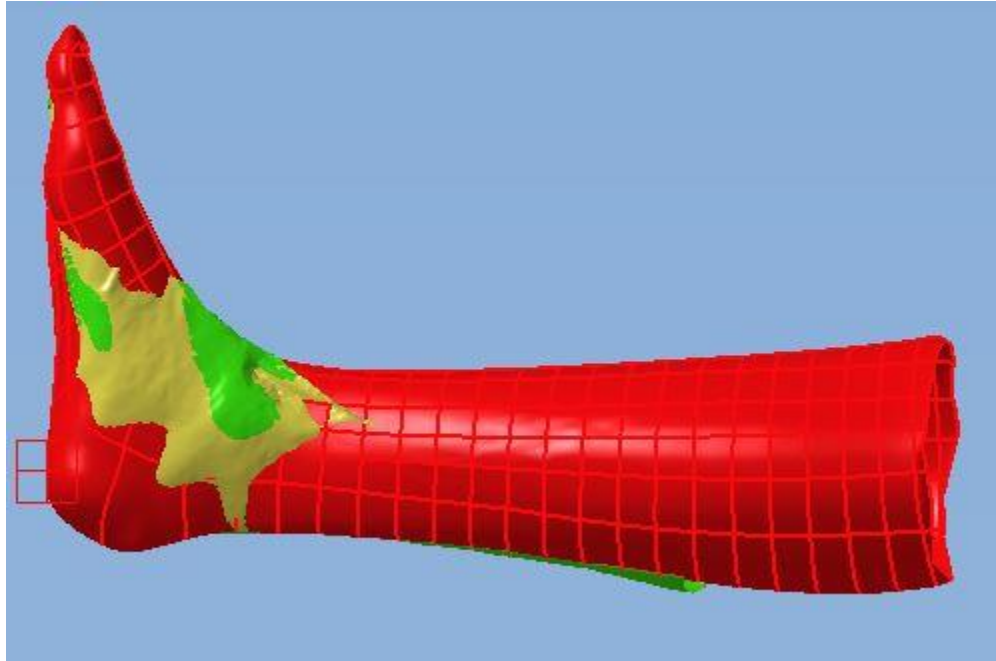


Figure F5: Digital Model Utility analysis of size 10 left view.

Table F5: Band analysis for size 10 left.

10 L		red	green	blue	Freq	RBYG%	RYG %
red	1	222	17	22	26963	16.374	70.79%
blue	2	141	175	216	110683	67.215	
yellow	3	189	155	71	8161	4.956	21.43%
green	4	57	174	21	2967	1.802	7.79%

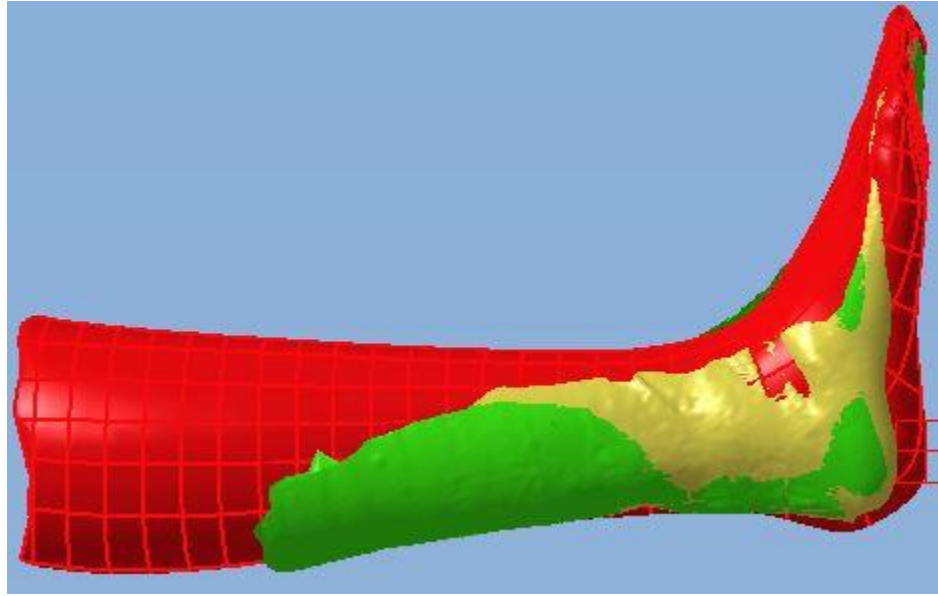


Figure F6: Digital Model Utility analysis of size 10 right view.

Table F6: Band analysis for size 10 right.

10 R		red	green	blue	Freq	RBYG%	RYG %
red	1	204	14	17	30408	21.904	56.45%
blue	2	140	175	216	84958	61.198	
yellow	3	192	176	72	9326	6.718	17.31%
green	4	45	150	14	14132	10.18	26.24%

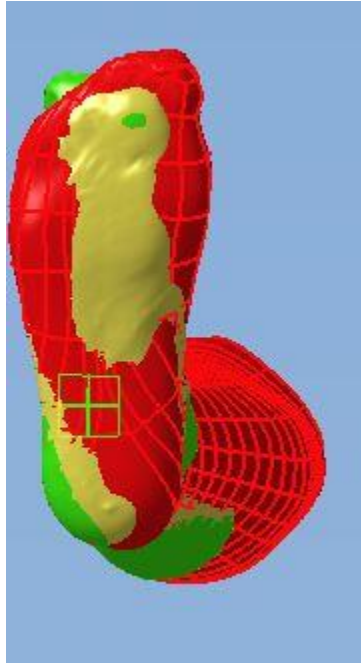


Figure F7: Digital Model Utility analysis of size 11 base view.

Table F7: Band analysis for size 11 base.

11 B		red	green	blue	Freq	RBYG%	RYG %
red	1	189	14	15	16623	27.746	61.88%
blue	2	141	176	216	33048	55.162	
yellow	3	186	172	67	7117	11.879	26.49%
green	4	65	132	22	3123	5.213	11.63%

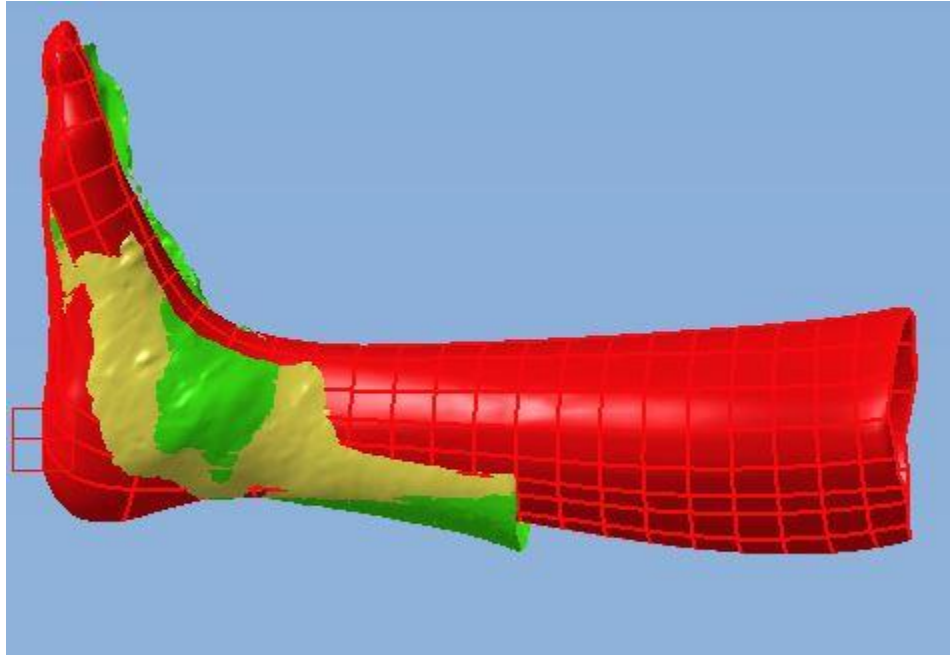


Figure F8: Digital Model Utility analysis of size 11 left view.

Table F8: Band analysis of size 11 left.

11 L		red	green	blue	Freq	RBYG%	RYG %
red	1	199	14	17	34817	22.368	68.83%
blue	2	141	176	216	105067	67.501	
yellow	3	193	160	72	9414	6.048	18.61%
green	4	59	158	21	6354	4.082	12.56%

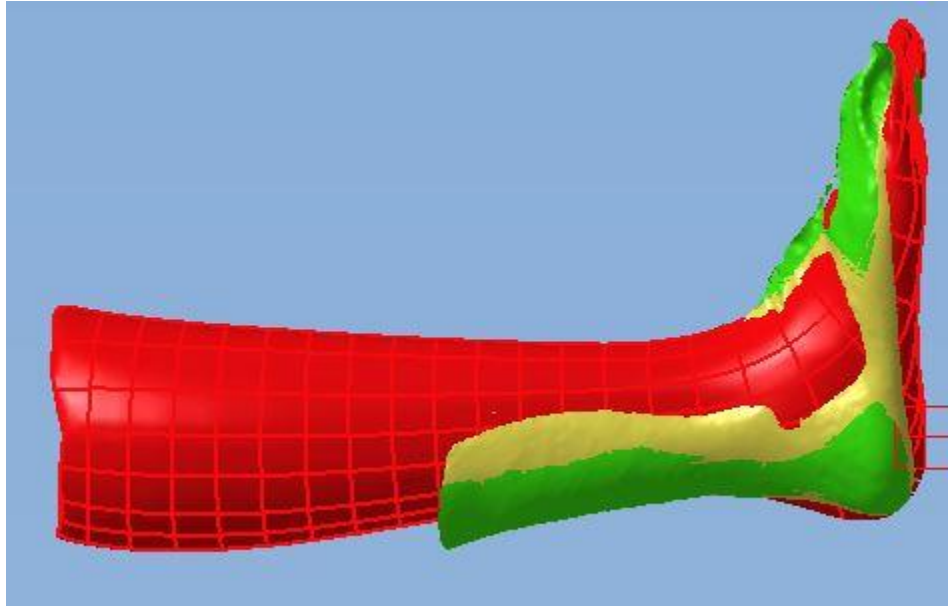


Figure F9: Digital Model Utility analysis of size 11 right view.

Table F9: Band analysis of size 11 right.

11 R		red	green	blue	Freq	RBYG%	RYG %
red	1	204	14	18	33488	23.345	66.28%
blue	2	140	175	216	92923	64.777	
yellow	3	190	172	72	7742	5.397	15.32%
green	4	47	152	16	9297	6.481	18.40%

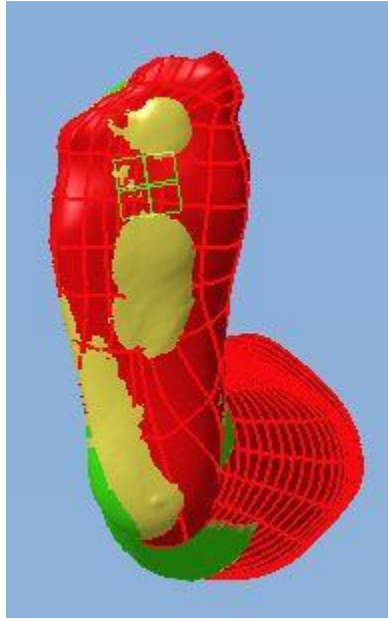


Figure F10: Digital Model Utility analysis of size 11.5 base view.

Table F10: Band analysis of size 11.5 base.

11.5 B		red	green	blue	Freq	RBYG%	RYG %
red	1	192	14	16	18215	30.328	69.53%
blue	2	141	175	216	33864	56.384	
yellow	3	187	168	67	6123	10.195	23.37%
green	4	52	125	17	1858	3.094	7.09%

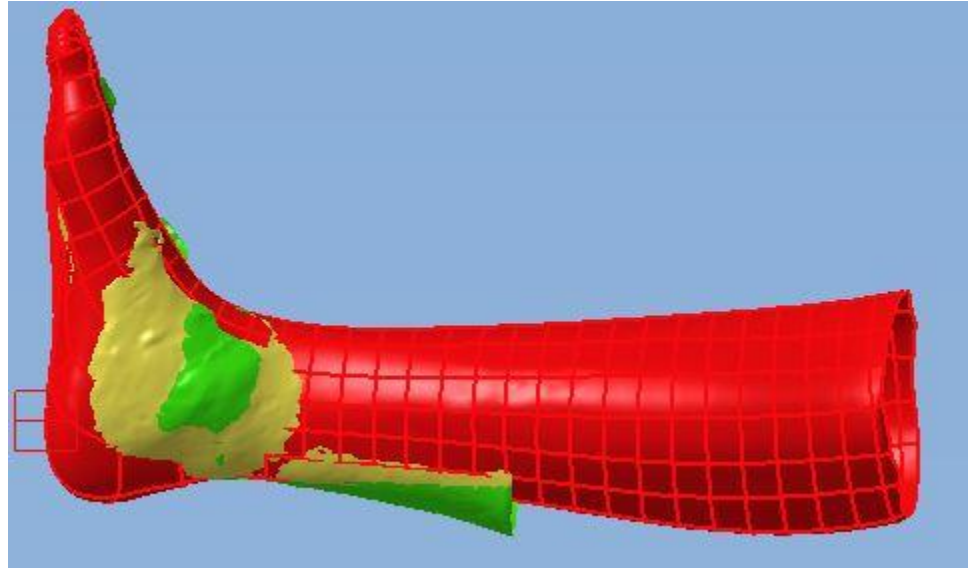


Figure F11: Digital Model Utility analysis of size 11.5 left view.

Table F11: Band analysis for size 11.5 left.

11.5 L		red	green	blue	Freq	RBYG%	RYG %
red	1	189	13	16	37250	27.195	75.29%
blue	2	141	175	216	87495	63.878	
yellow	3	190	153	71	8329	6.081	16.83%
green	4	55	154	20	3898	2.846	7.88%

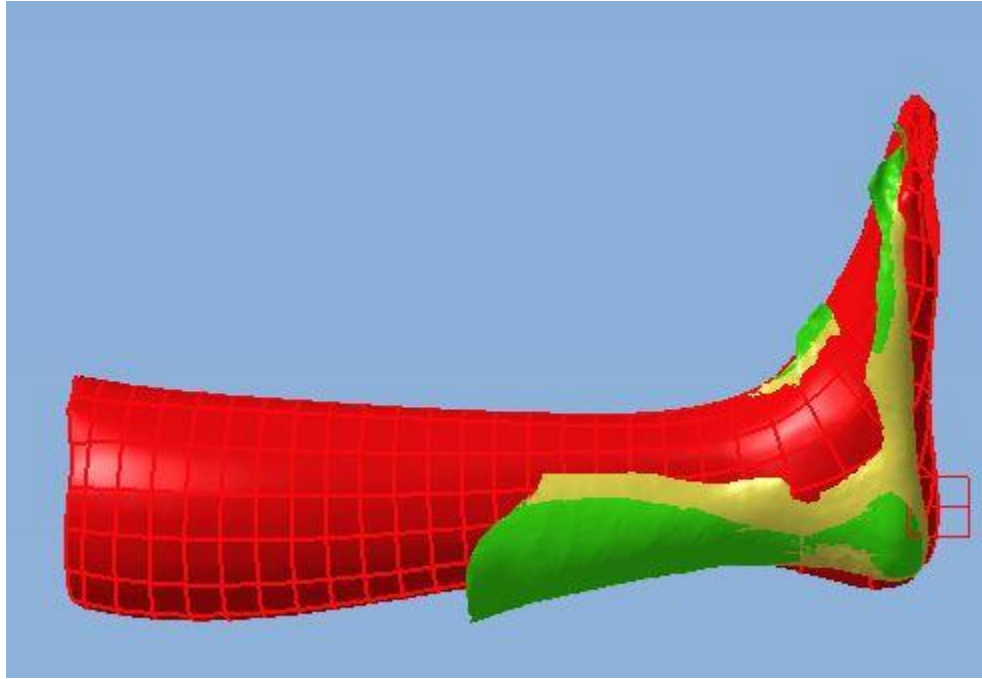


Figure F12: Digital Model Utility analysis of size 11.5 right view.

Table F12: Band analysis of size 11.5 right.

11.5 R		red	green	blue	Freq	RBYG%	RYG %
red	1	203	14	17	34239	20.631	69.30%
blue	2	140	175	216	116553	70.23	
yellow	3	188	164	71	6590	3.971	13.34%
green	4	46	147	15	8576	5.168	17.36%

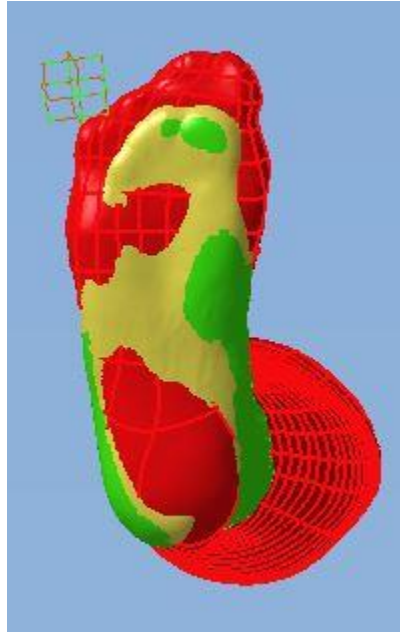


Figure F13: Digital Model Utility analysis of size 12 base view.

Table F13: Band analysis of size 12 base.

12 B		red	green	blue	Freq	RBYG%	RYG %
red	1	199	14	16	15870	25.065	59.16%
blue	2	141	176	215	36491	57.634	
yellow	3	184	172	67	6987	11.035	26.05%
green	4	49	146	16	3967	6.265	14.79%

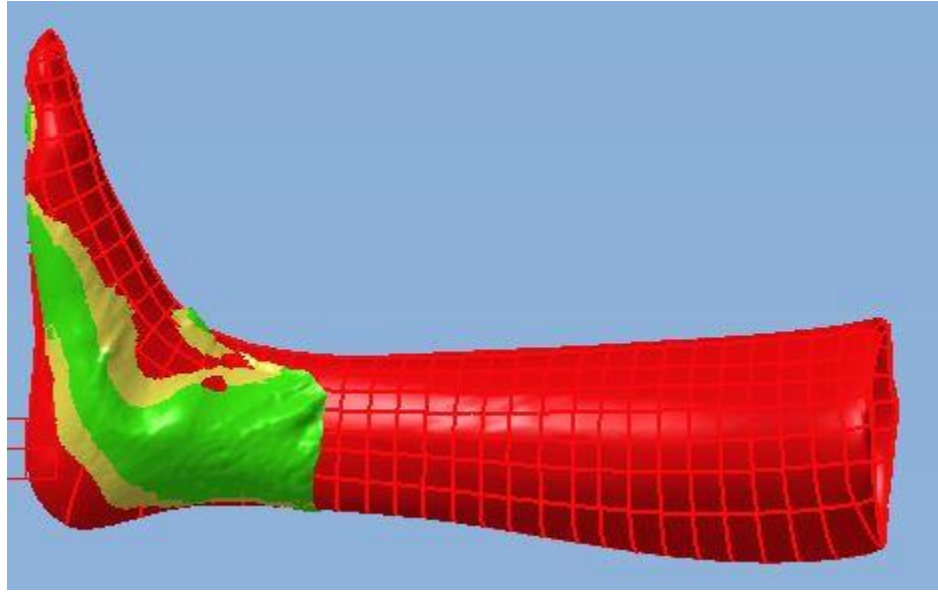


Figure F14: Digital Model Utility analysis of size 12 left view.

Table F14: Band analysis of size 12 left.

12 L		red	green	blue	Freq	RBYG%	RYG %
red	1	185	12.5	15.5	35530	25.768	73.74%
blue	2	141	175	216	89701	65.054	
yellow	3	195	160	78	4719	3.422	9.79%
green	4	53	177	18	7936	5.755	16.47%

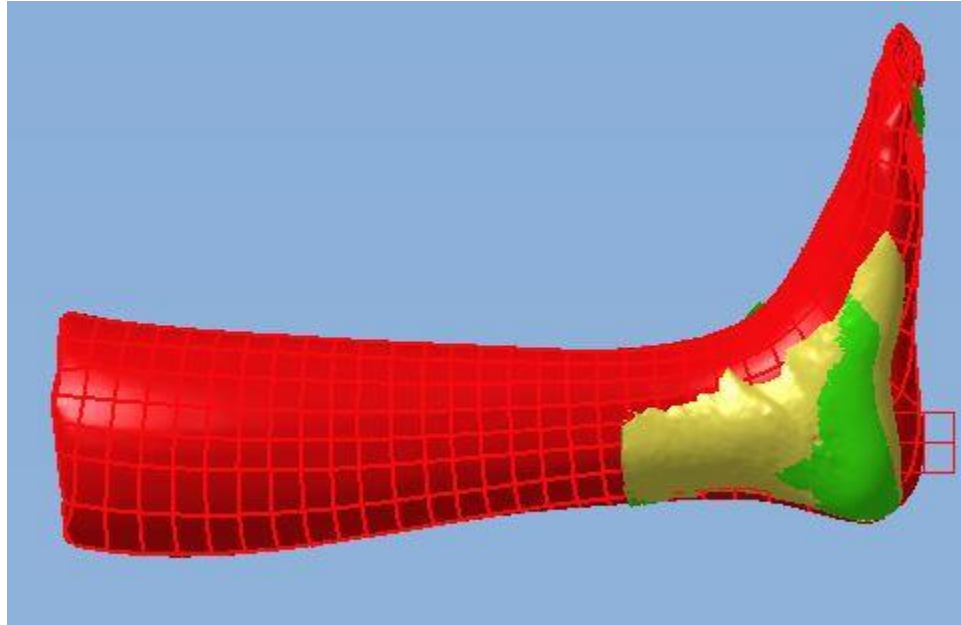


Figure F15: Digital Model Utility analysis of size 12 right view.

Table F16: Band analysis of size 12 right.

12 R		red	green	blue	Freq	RBYG%	RYG %
red	1	186	12	15	37289	24.899	77.51%
blue	2	141	176	216	101651	67.876	
yellow	3	200	177	79	5287	3.53	10.99%
green	4	74	142	24	5533	3.695	11.50%

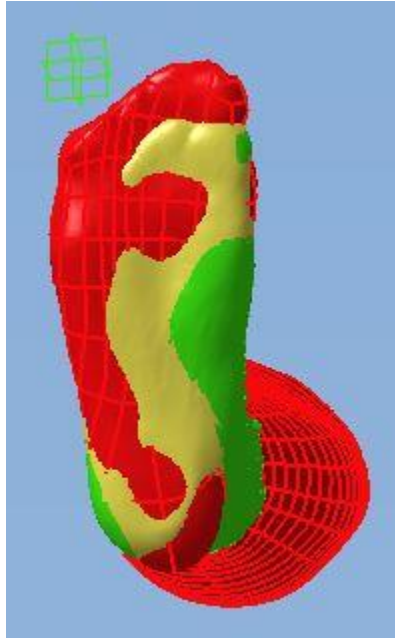


Figure F16: Digital Model Utility analysis of size 12.5 base view.

Table F16: Band analysis of size 12.5 base.

12.5 B		red	green	blue	Freq	RBYG%	RYG %
red	1	200	14	16	16060	25.507	58.04%
blue	2	141	176	215	35295	56.056	
yellow	3	187	174	68	7147	11.351	25.83%
green	4	45	141	14	4462	7.087	16.13%

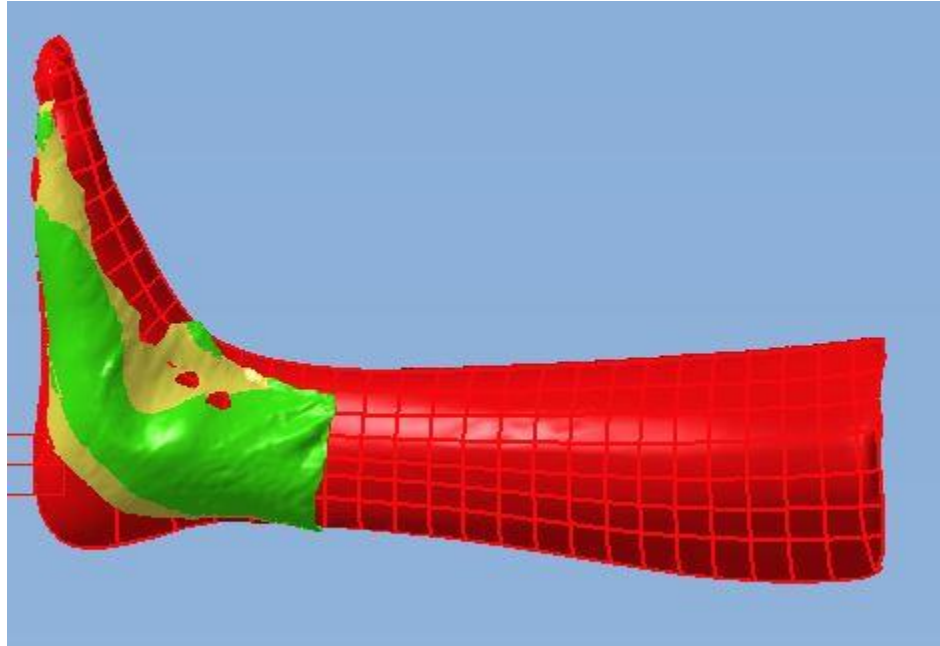


Figure F17: Digital Model Utility analysis of size 12.5 left view.

Table F17: Band analysis of size 12.5 left.

12.5 L		red	green	blue	Freq	RBYG%	RYG %
red	3	195	14	17	33504	22.023	69.09%
blue	2	141	175	216	103640	68.125	
yellow	4	190	158	75	5357	3.521	11.05%
green	1	52	179	18	9632	6.331	19.86%

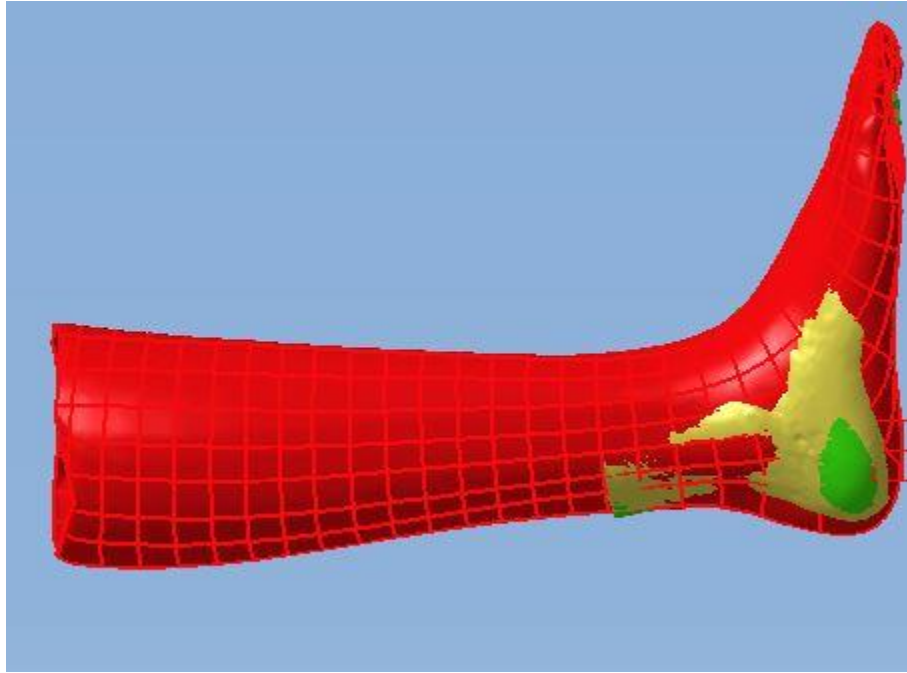


Figure F18: Digital Model Utility analysis of size 12.5 right view.

Table F18: Band analysis of size 12.5 right.

12.5 R		red	green	blue	Freq	RBYG%	RYG %
red	1	200	60	60	43713	28.678	88.33%
blue	2	141	176	217	102937	67.533	
yellow	3	184	168	64	3580	2.349	7.23%
green	4	87	131	29	2195	1.44	4.44%

Appendix G

CROSS-SECTION ANALYSIS

The cross-section analysis involved aligning the model and the scan over top of each other. Then the cross-sections were taken. Distances were measured and averaged at each of nineteen points on each size.

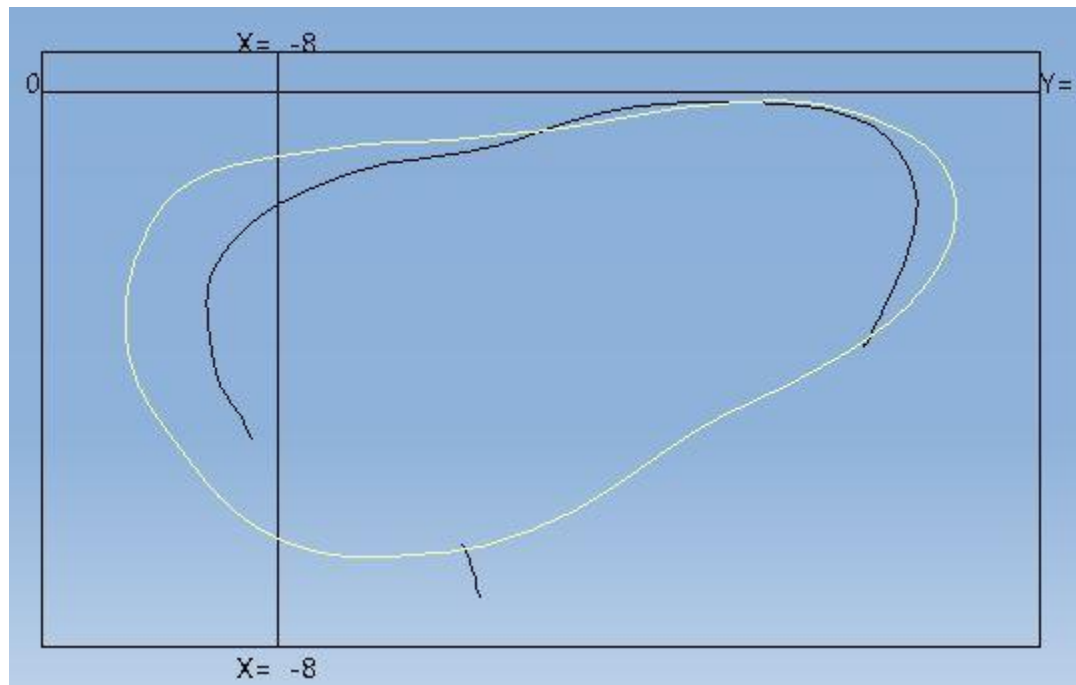


Figure G1: Cross-section analysis of the ball region for size 9.

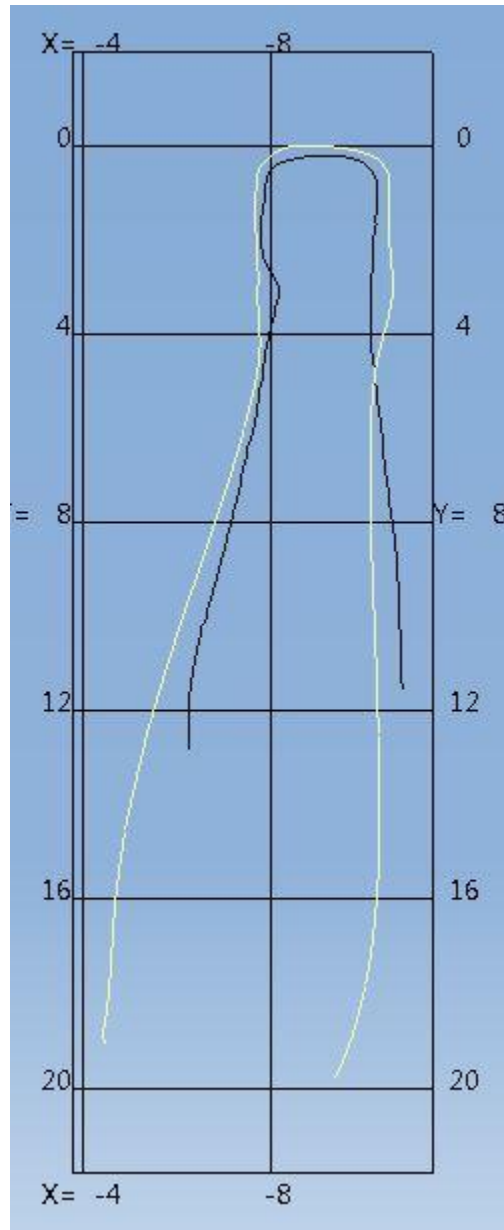


Figure G2: Cross-section analysis of the heel region for size 9.

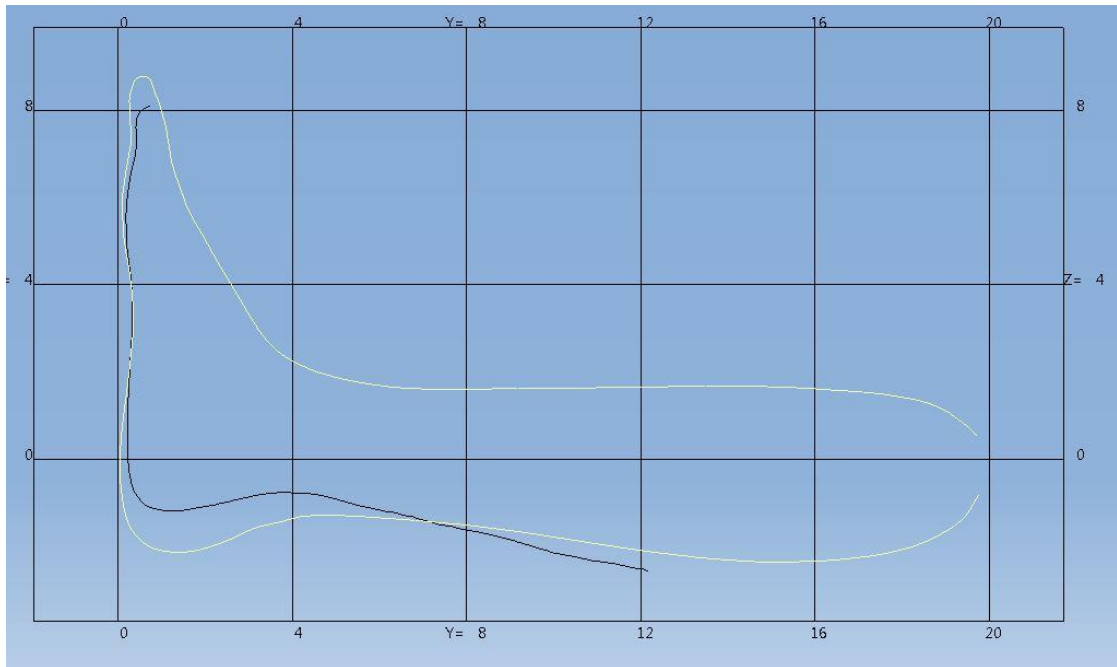


Figure G3: Cross-section analysis of the center ZY region for size 9.

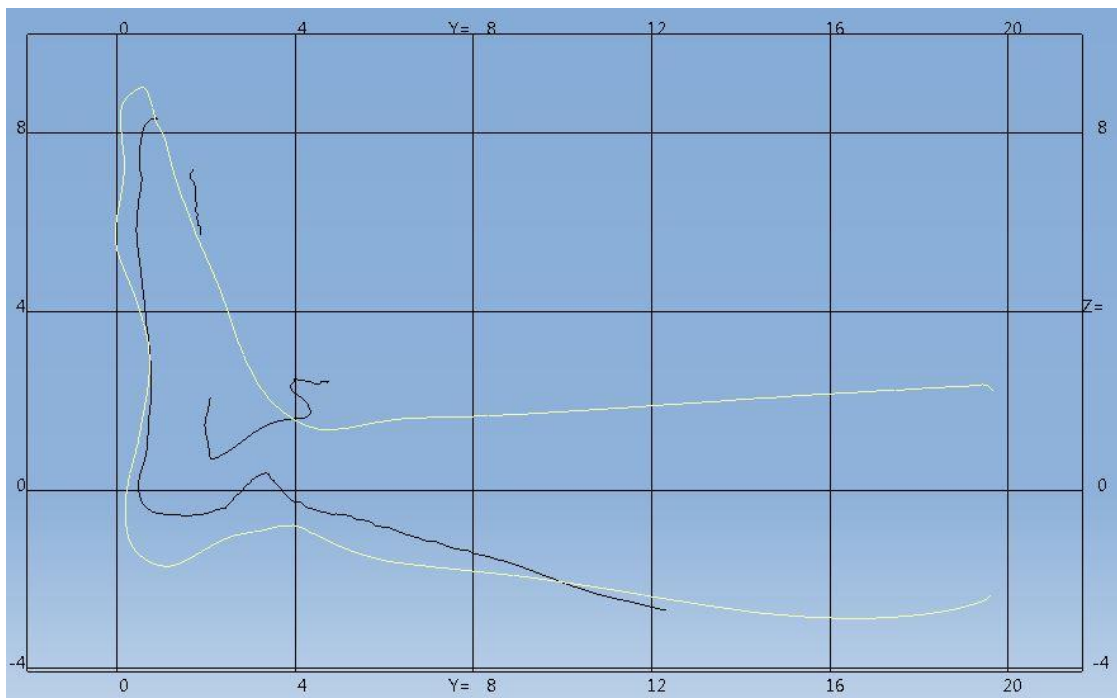


Figure G4: Cross-section analysis of the left ZY region for size 9.

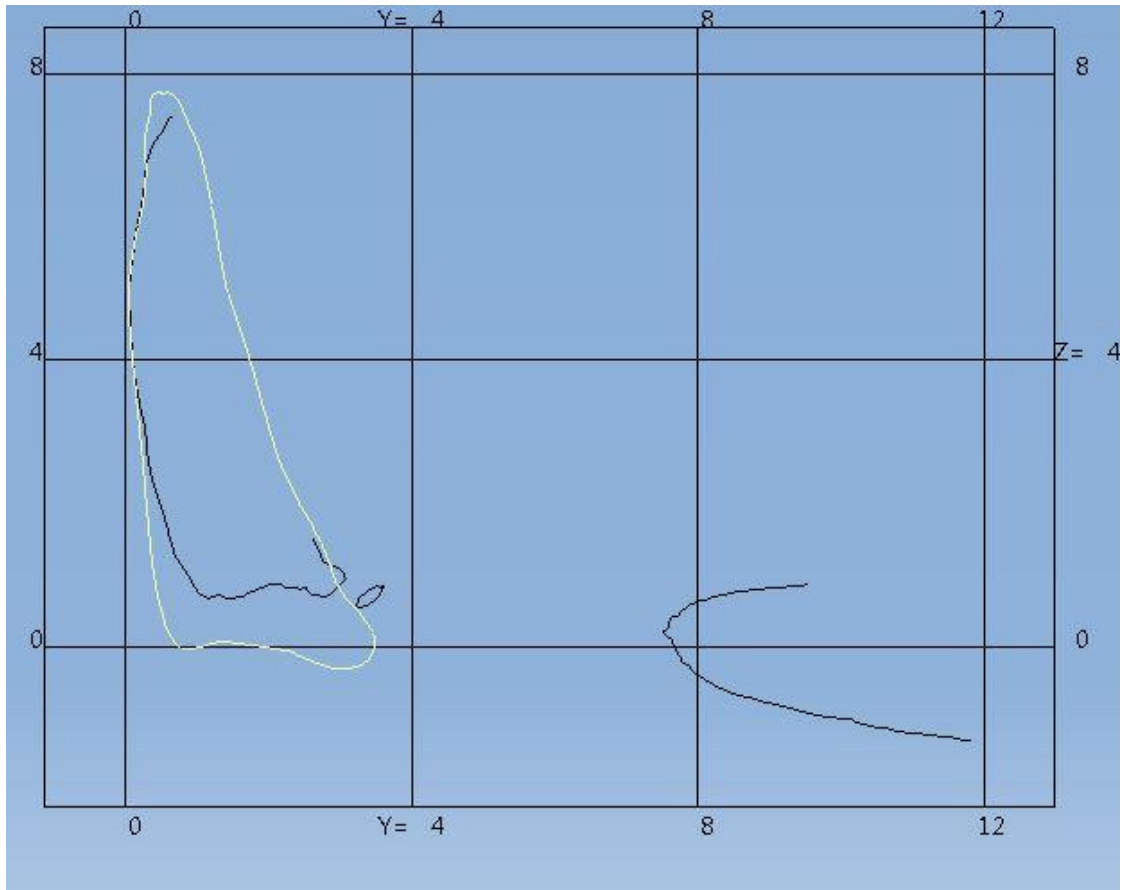


Figure G5: Cross-section analysis of the right ZY region for size 9.

Table G1: Size 9 distance measurements and averages at each of the nineteen points.

Size 9									
ZY_L		ZY_C		ZY_R		XY_Heel		XY_Ball	
1	0.81	1	0.69	1	0.28	1	0.47	1	0.49
2	0.77	2	0.68	2	0.30	2	0.31	2	0.40
3	0.41	3	0.23	3	0.18	3	0.17	3	0.00
4	0.44	4	0.15	4	0.03	4	0.33	4	0.08
5	0.54	5	0.14	5	0.00	5	0.43	5	0.18
6	0.00	6	0.06	6	0.06		0.34		0.23
7	0.78	7	0.58	7	0.74				
8	1.17	8	0.94	8	0.60				
9	0.66	9	0.53	9	0.85				

0.62	0.44	0.34
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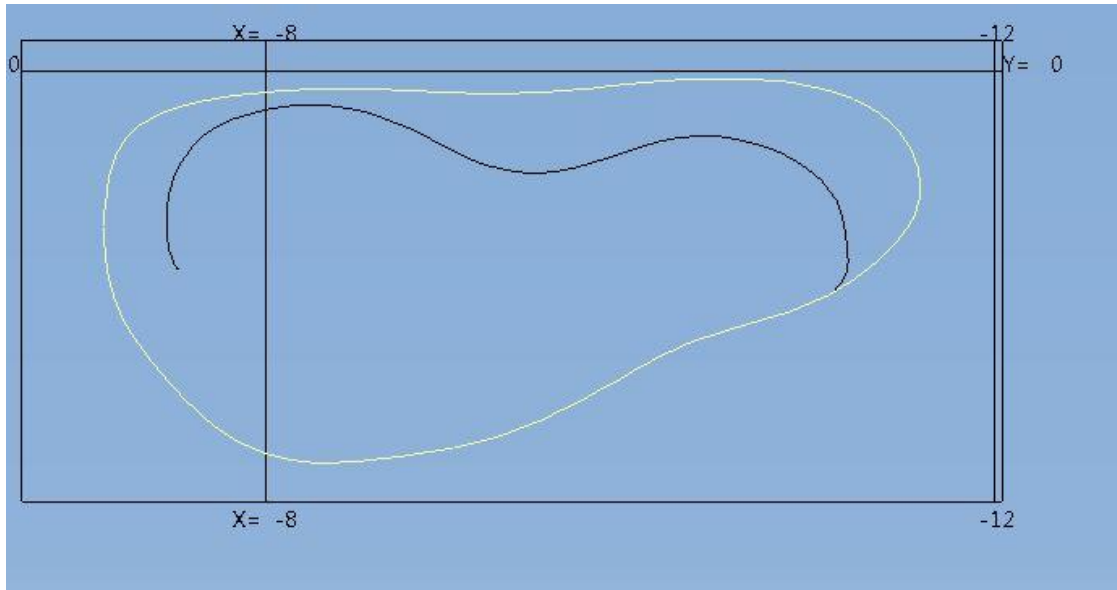


Figure G6: Cross-section analysis of the ball region for size 10.

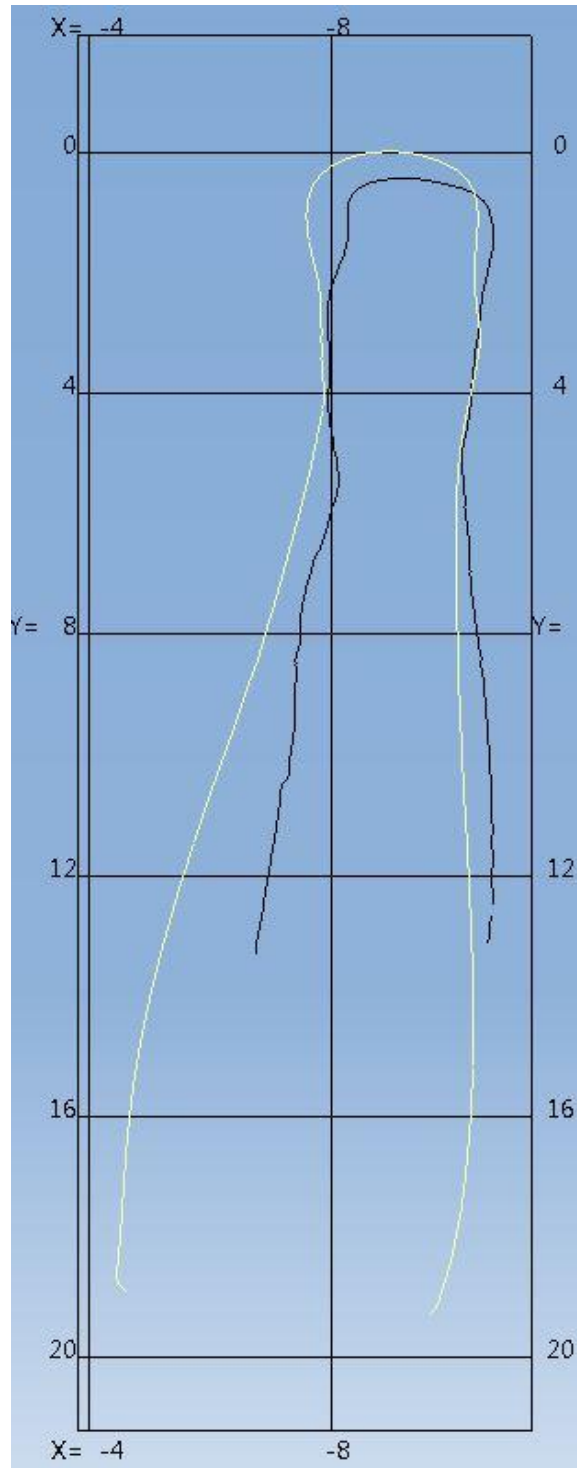


Figure G7: Cross-section analysis of the ball region for size 10.

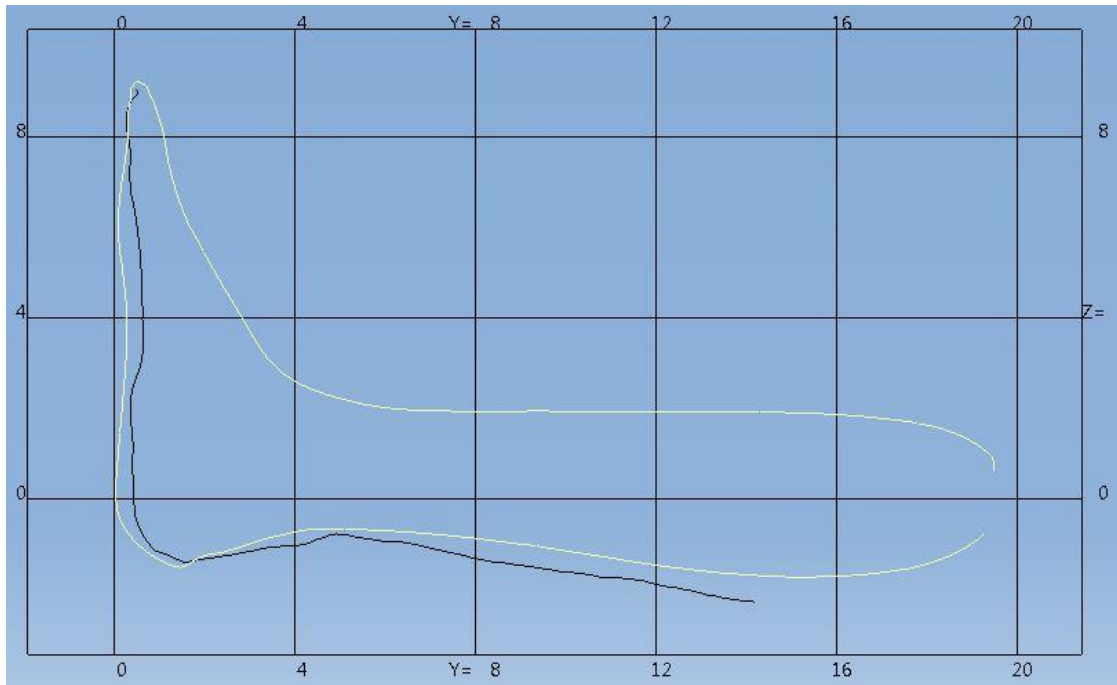


Figure G8: Cross-section analysis of the center ZY region for size 10.

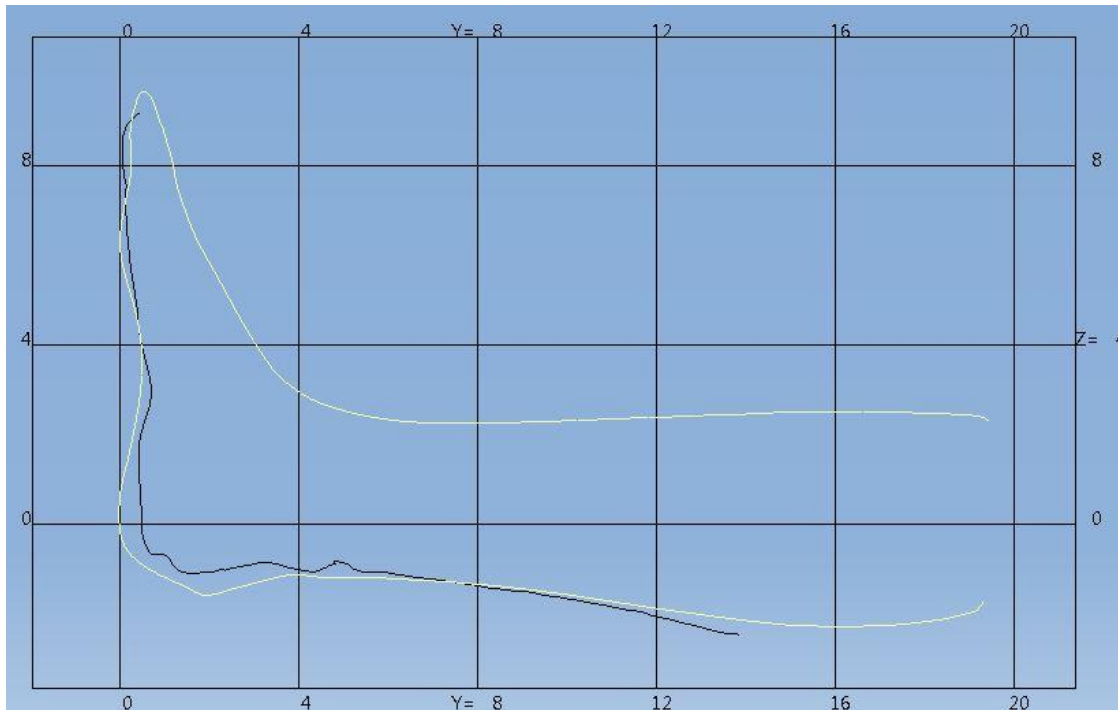


Figure G9: Cross-section analysis of the left ZY region for size 10.

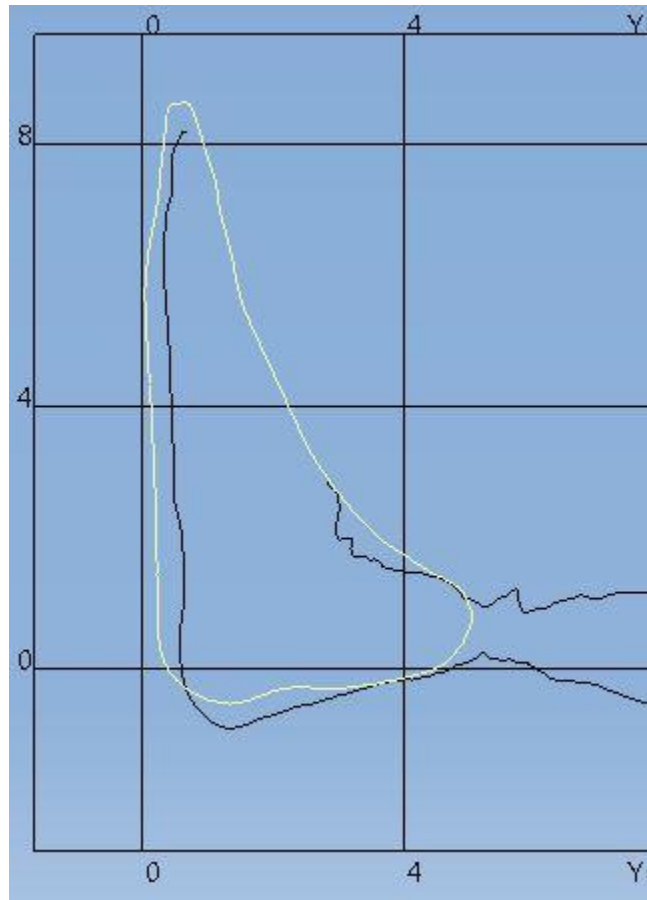


Figure G10: Cross-section analysis of the right ZY region for size 10.

Table G2: Size 10 distance measurements and averages at each of the nineteen points.

Size 10									
ZY_L		ZY_C		ZY_R		XY_Heel		XY_Ball	
1	0.50	1	0.27	1	0.46	1	0.12	1	0.36
2	0.37	2	0.31	2	0.57	2	0.59	2	0.26
3	0.40	3	0.07	3	0.26	3	0.57	3	0.43
4	0.27	4	0.22	4	0.16	4	0.56	4	0.51
5	0.25	5	0.37	5	0.34	5	0.15	5	0.25
6	0.61	6	0.40	6	0.31		0.40		0.36
7	0.35	7	0.37	7	0.46				
8	0.52	8	0.36	8	0.38				
9	0.18	9	0.60	9	0.06				

0.38	0.33	0.33
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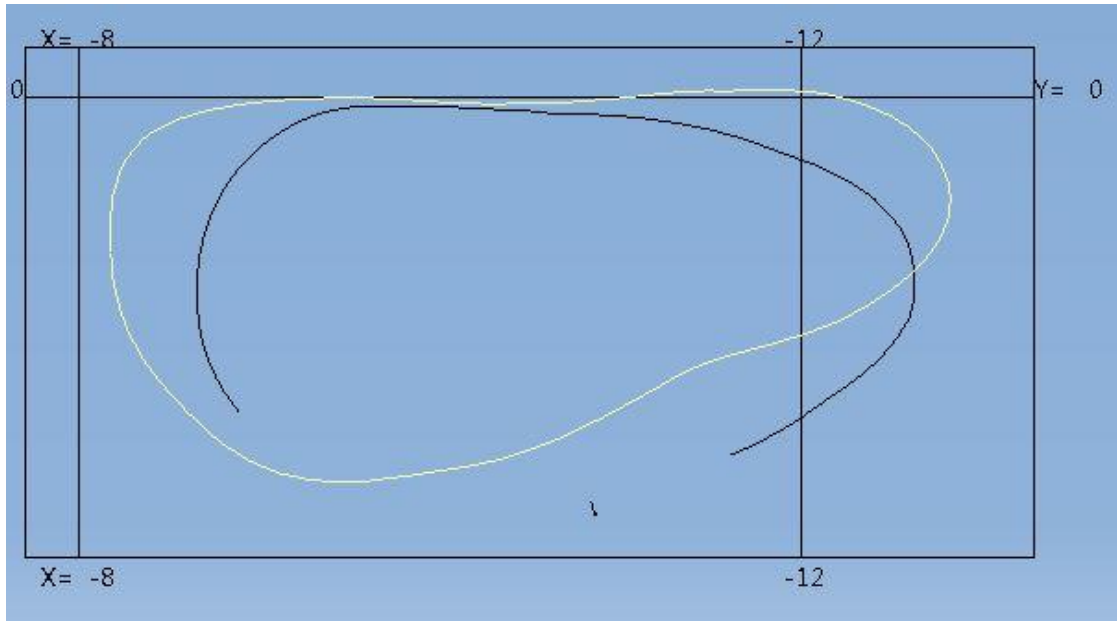


Figure G11: Cross-section analysis of the ball region for size 11.

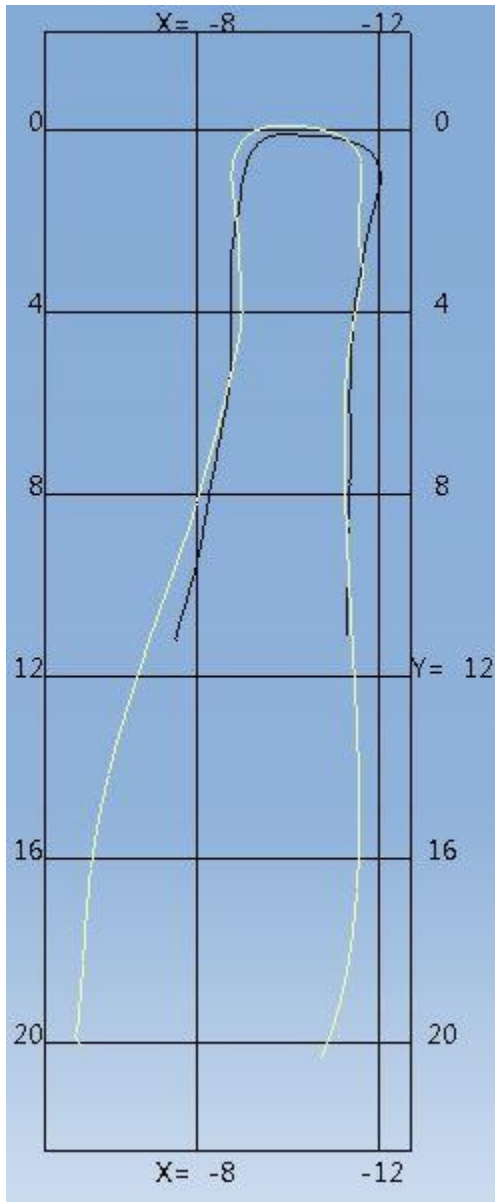


Figure G12: Cross-section analysis of the heel region for size 11.

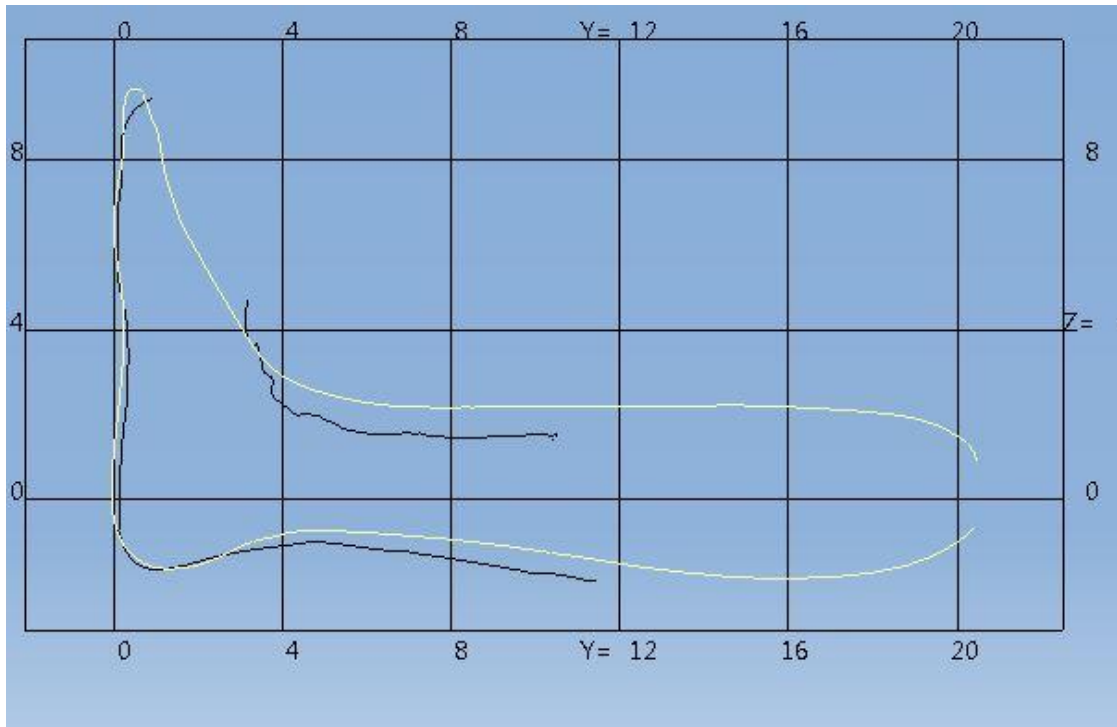


Figure G13: Cross-section analysis of the center ZY region for size 11.

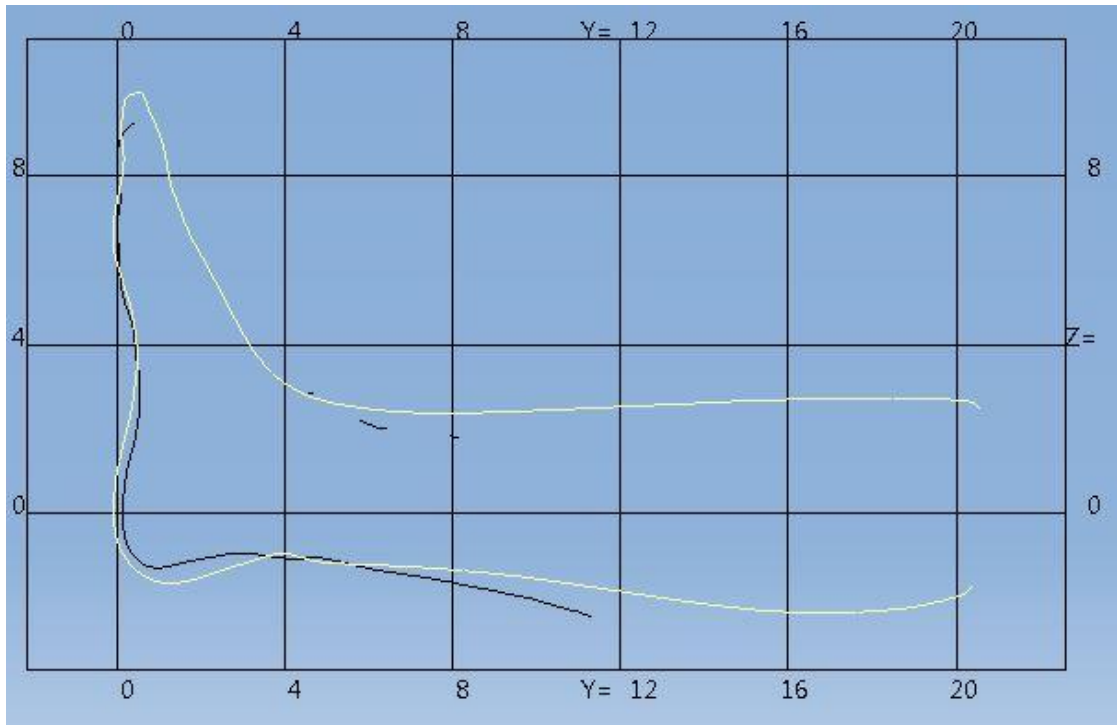


Figure G14: Cross-section analysis of the left ZY region for size 11.

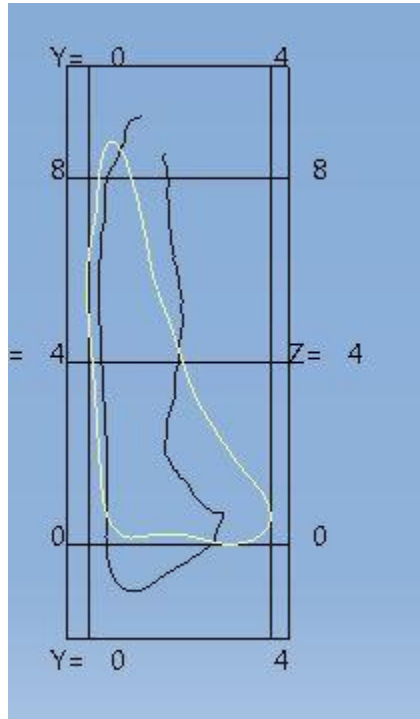


Figure G15: Cross-section analysis of the right ZY region for size 11.

Table G3: Size 11 distance measurements and averages at each of the nineteen points.

Size 11									
ZY_L		ZY_C		ZY_R		XY_Heel		XY_Ball	
1	0.88	1	0.36	1	0.98	1	0.40	1	0.47
2	0.89	2	0.50	2	0.41	2	0.37	2	0.48
3	1.00	3	0.42	3	0.14	3	0.22	3	0.04
4	0.65	4	0.06	4	0.23	4	0.64	4	0.55
5	0.31	5	0.04	5	0.27	5	0.35	5	0.67
6	1.05	6	0.13	6	0.27		0.40		0.44
7	0.26	7	0.00	7	0.98				
8	0.36	8	0.13	8	1.11				
9	0.80	9	0.35	9	0.09				
	0.69		0.22		0.50				

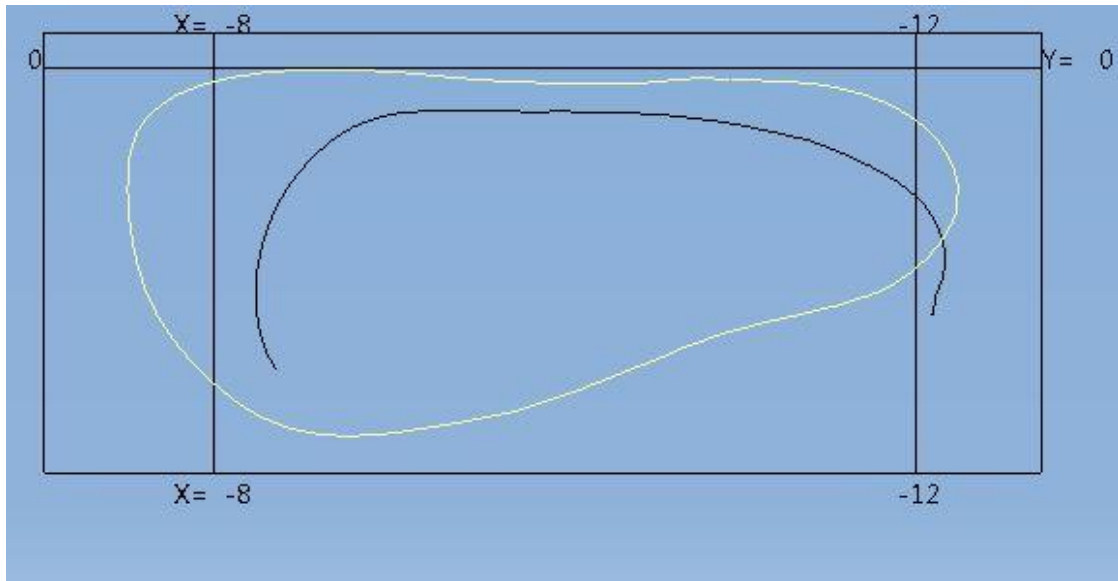


Figure G16: Cross-section analysis of the ball region for size 11.5.

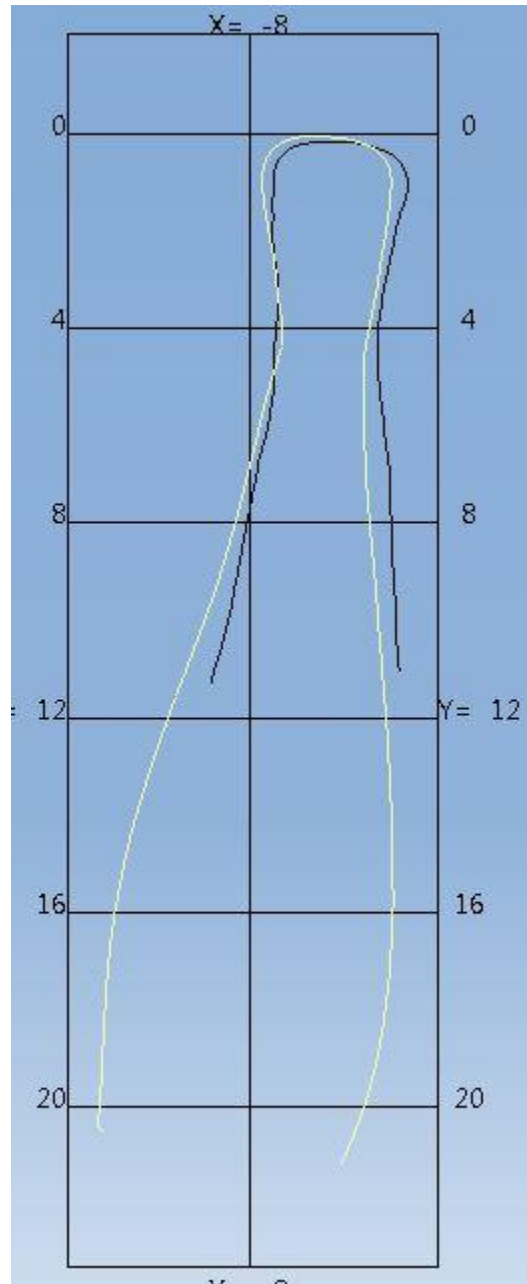


Figure G17: Cross-section analysis of the heel region for size 11.5.

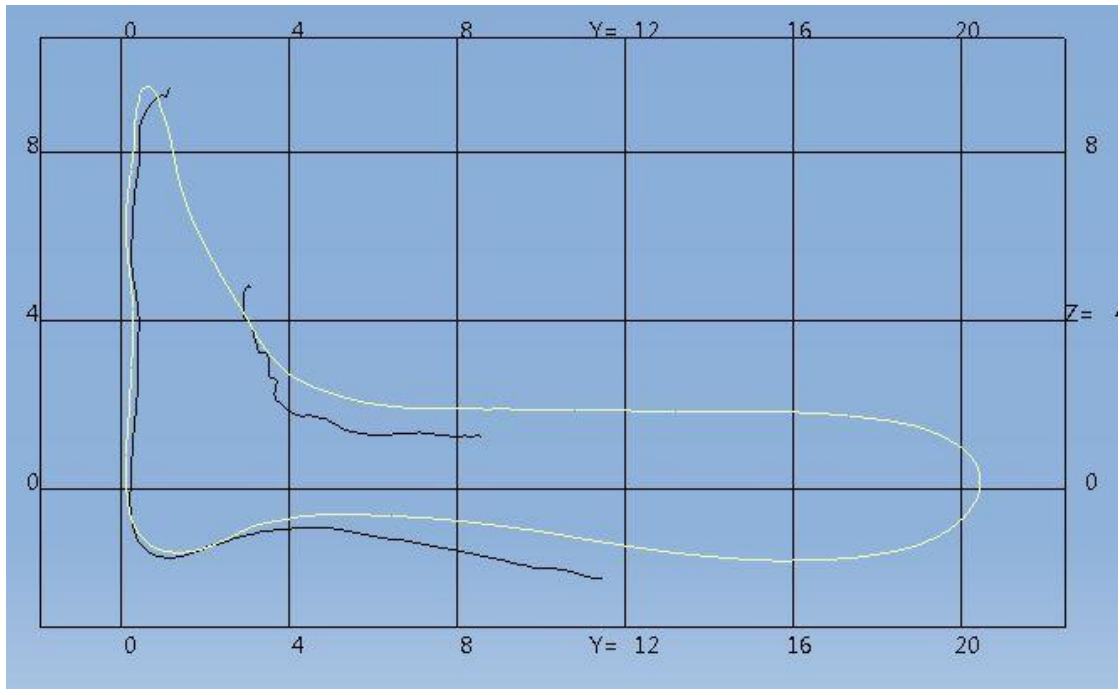


Figure G18: Cross-section analysis of the center ZY region for size 11.5.

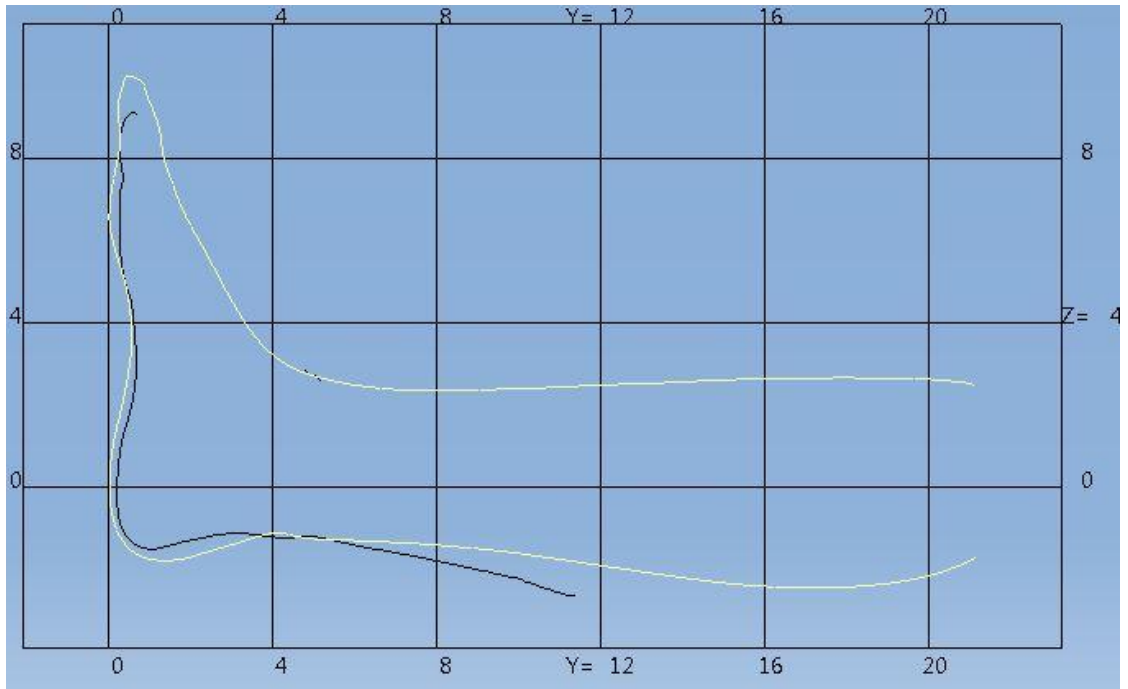


Figure G19: Cross-section analysis of the left ZY region for size 11.5.

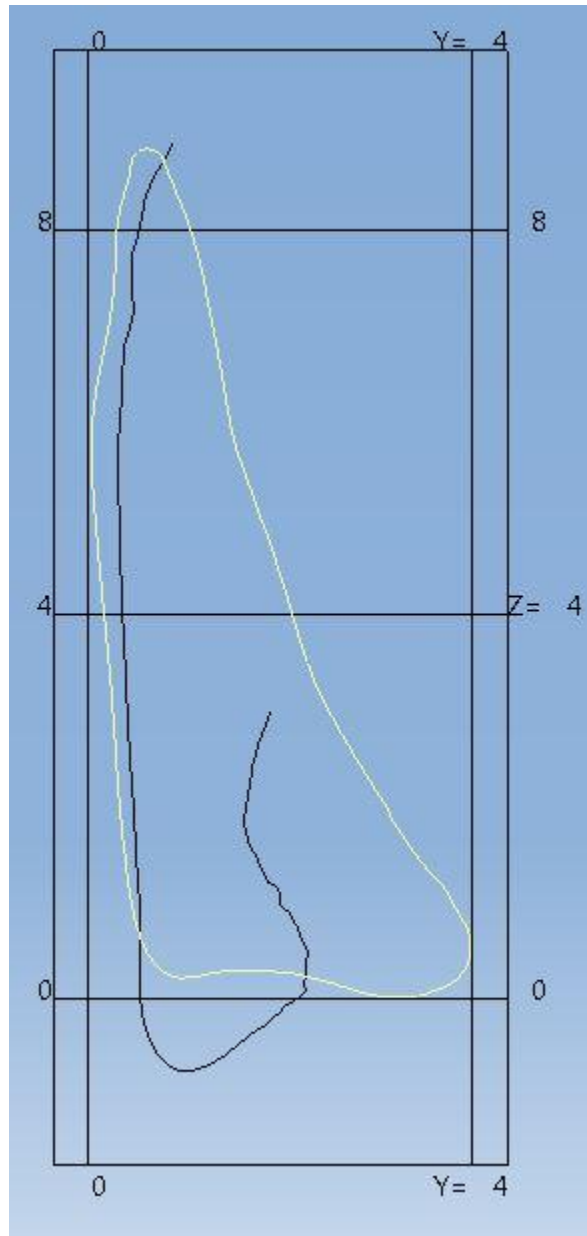


Figure G20: Cross-section analysis of the right ZY region for size 11.5.

Table G4: Size 11.5 distance measurements and averages at each of the nineteen points.

Size 11.5				
ZY_L	ZY_C	ZY_R	XY_Heel	XY_Ball

1	0.79	1	0.51	1	0.20	1	0.25	1	0.66
2	0.90	2	0.44	2	0.37	2	0.36	2	0.95
3	0.41	3	0.12	3	0.23	3	0.08	3	0.17
4	0.77	4	0.23	4	0.27	4	0.21	4	0.43
5	0.40	5	0.28	5	0.22	5	0.25	5	0.12
6	0.61	6	0.16	6	0.17		0.23		0.47
7	0.18	7	0.00	7	1.07				
8	0.29	8	0.16	8	0.90				
9	0.73	9	0.22	9	0.19				
	0.57		0.24		0.40				

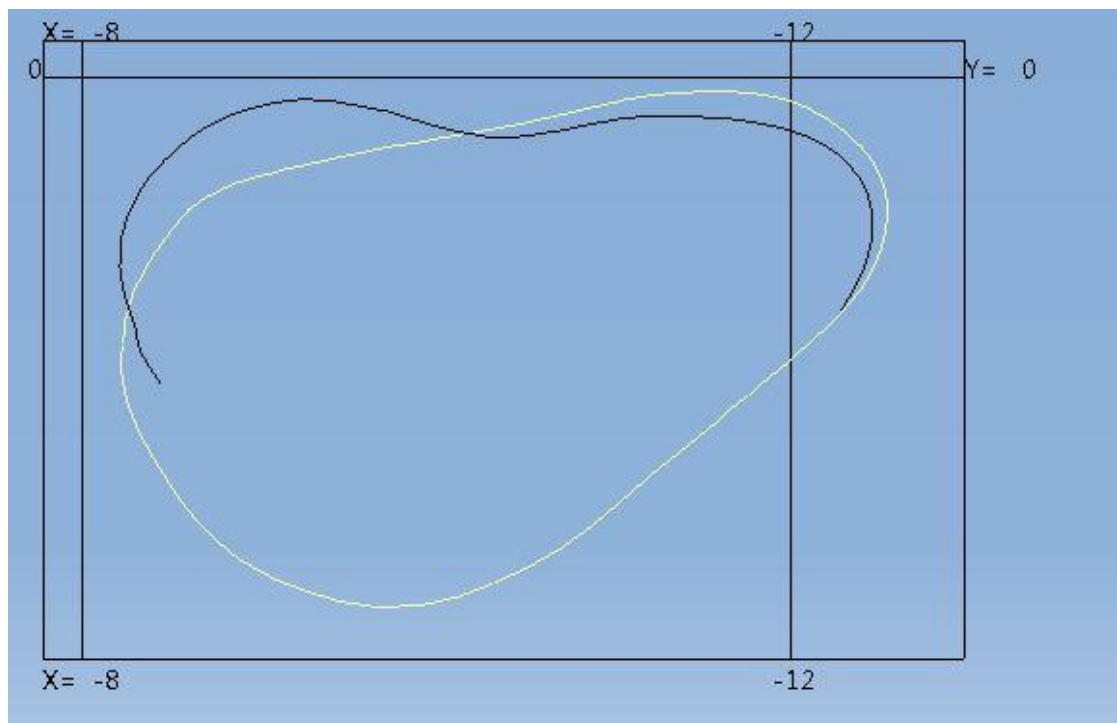


Figure G21: Cross-section analysis of the ball region for size 12.

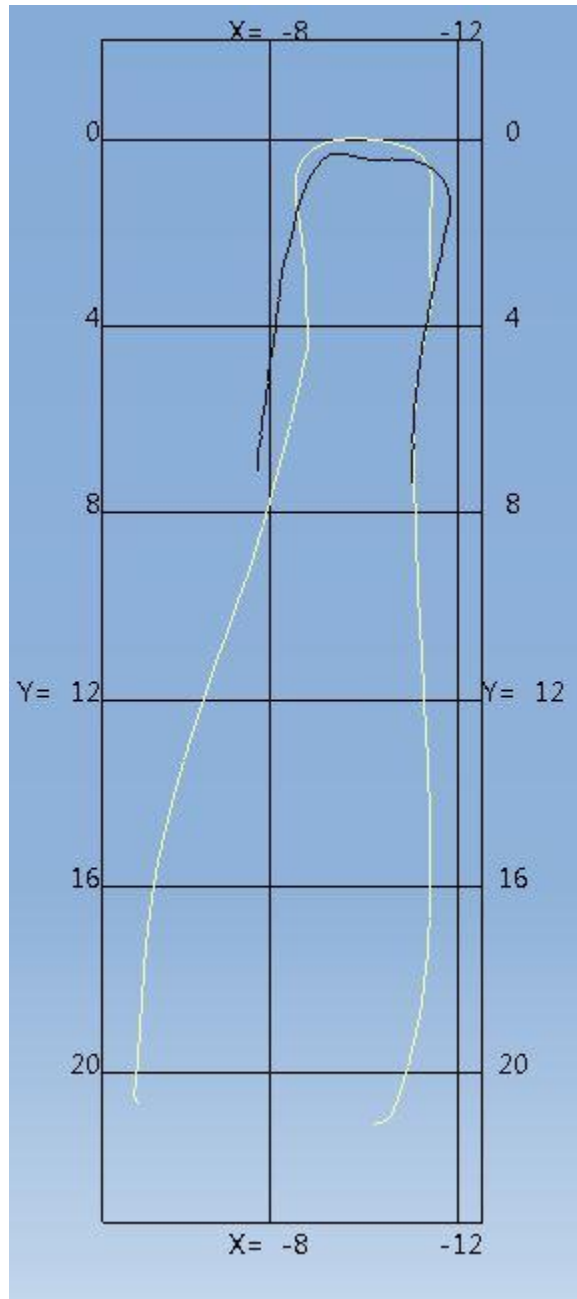


Figure G22: Cross-section analysis of the heel region for size 12.

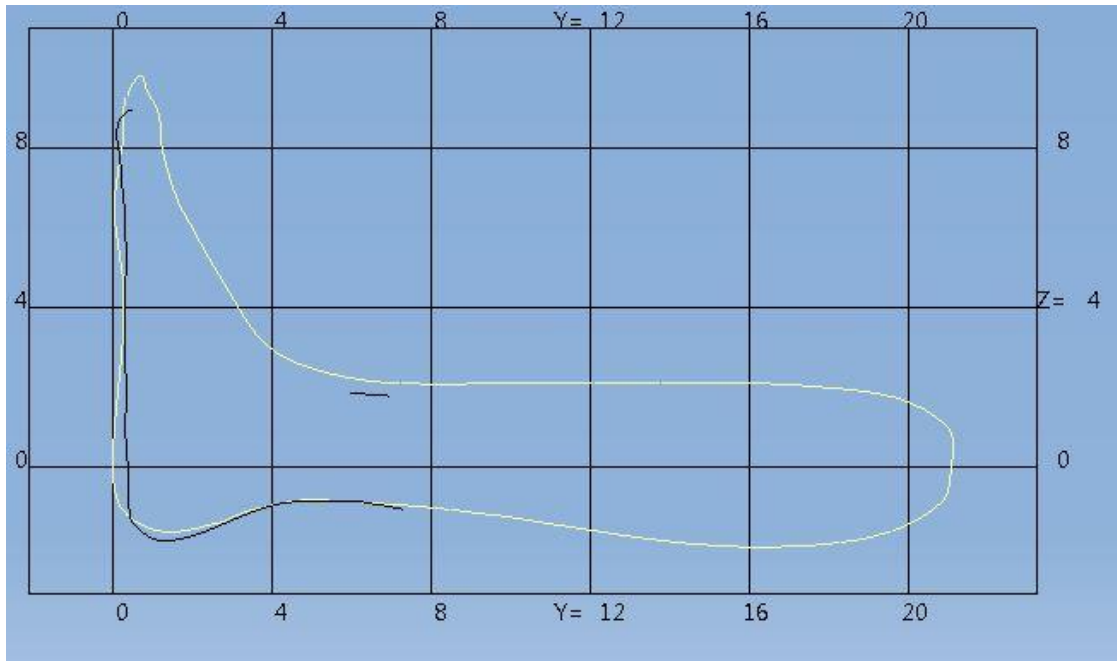


Figure G23: Cross-section analysis of the center ZY region for size 12.

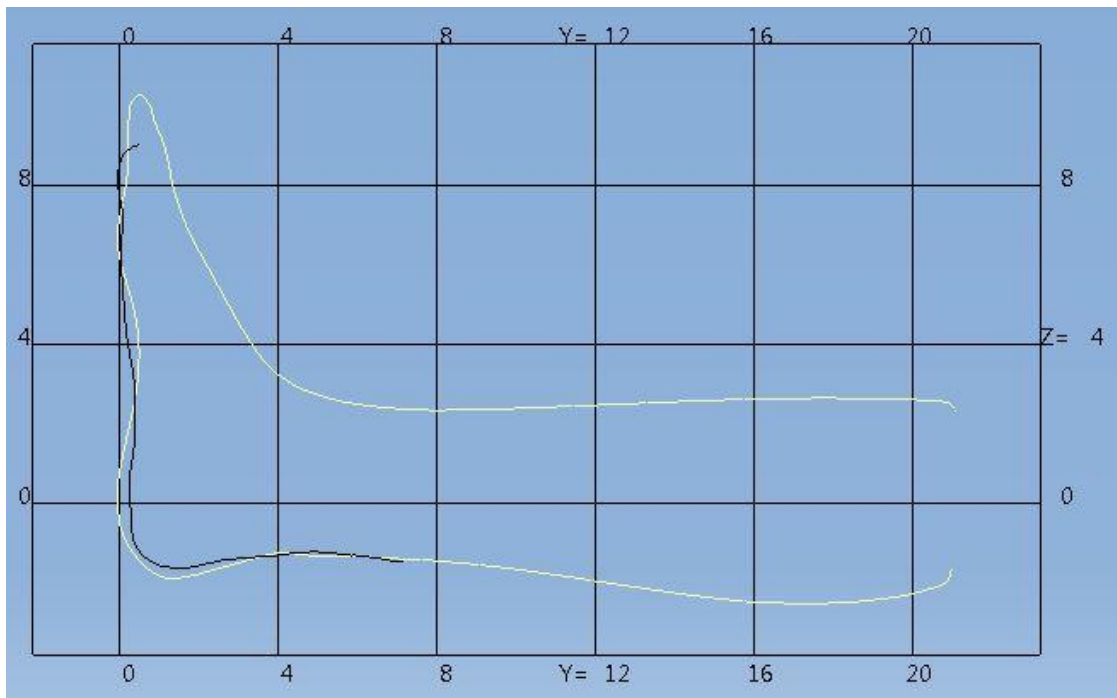


Figure G24: Cross-section analysis of the left ZY region for size 12.

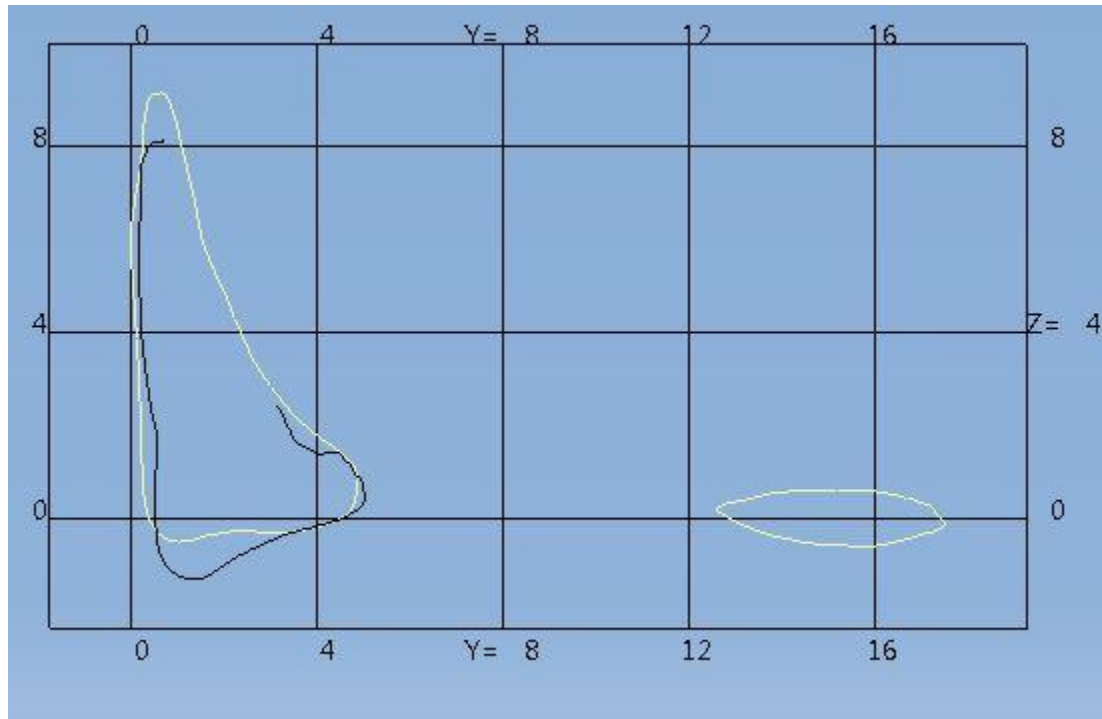


Figure G25: Cross-section analysis of the right ZY region for size 12.

Table G5: Size 12 distance measurements and averages at each of the nineteen points.

ZY_L		ZY_C		Size 12 ZY_R		XY_Heel		XY_Ball	
1	1.33	1	1.00	1	1.08	1	0.59	1	0.19
2	1.08	2	0.74	2	1.00	2	0.30	2	0.39
3	0.89	3	0.40	3	0.77	3	0.46	3	0.07
4	0.96	4	0.82	4	0.96	4	0.66	4	0.19
5	1.56	5	0.35	5	0.25	5	0.42	5	0.06
6	1.12	6	0.00	6	0.73		0.49		0.18
7	0.35	7	0.76	7	1.06				
8	0.34	8	0.34	8	0.90				
9	0.48	9	0.00	9	0.09				
	0.90		0.49		0.76				

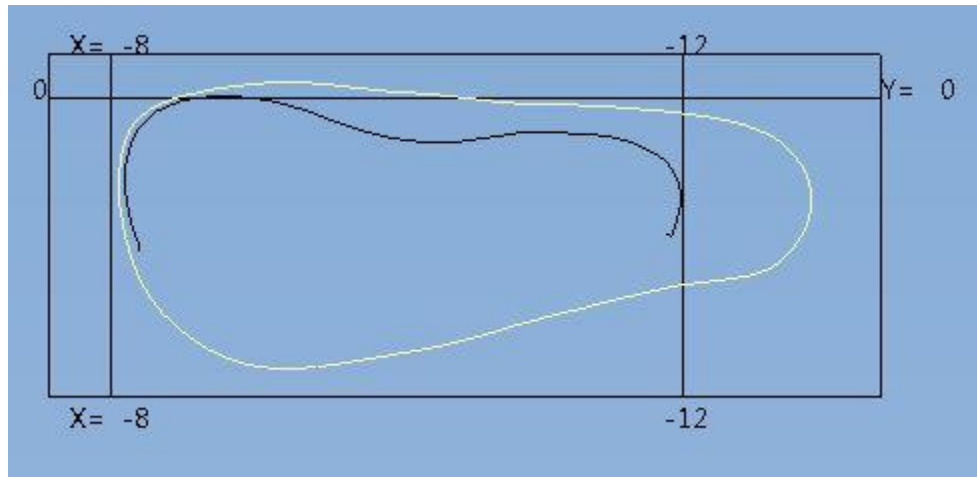


Figure G26: Cross-section analysis of the ball region for size 12.5.

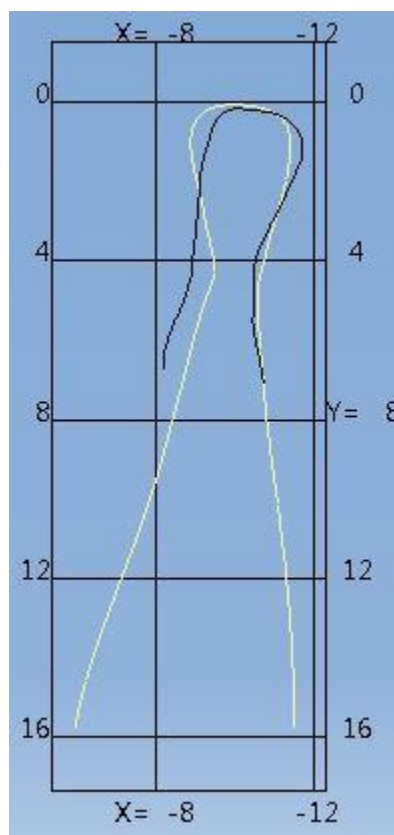


Figure G27: Cross-section analysis of the heel region for size 12.5.

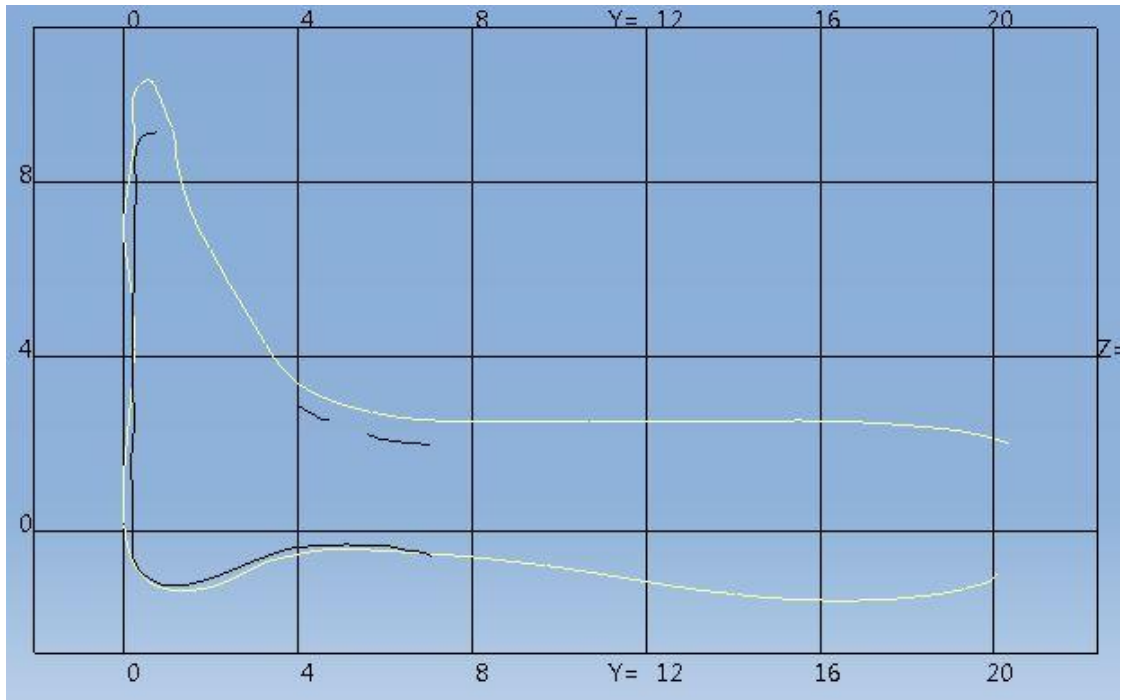


Figure G28: Cross-section analysis of the center ZY region for size 12.5.

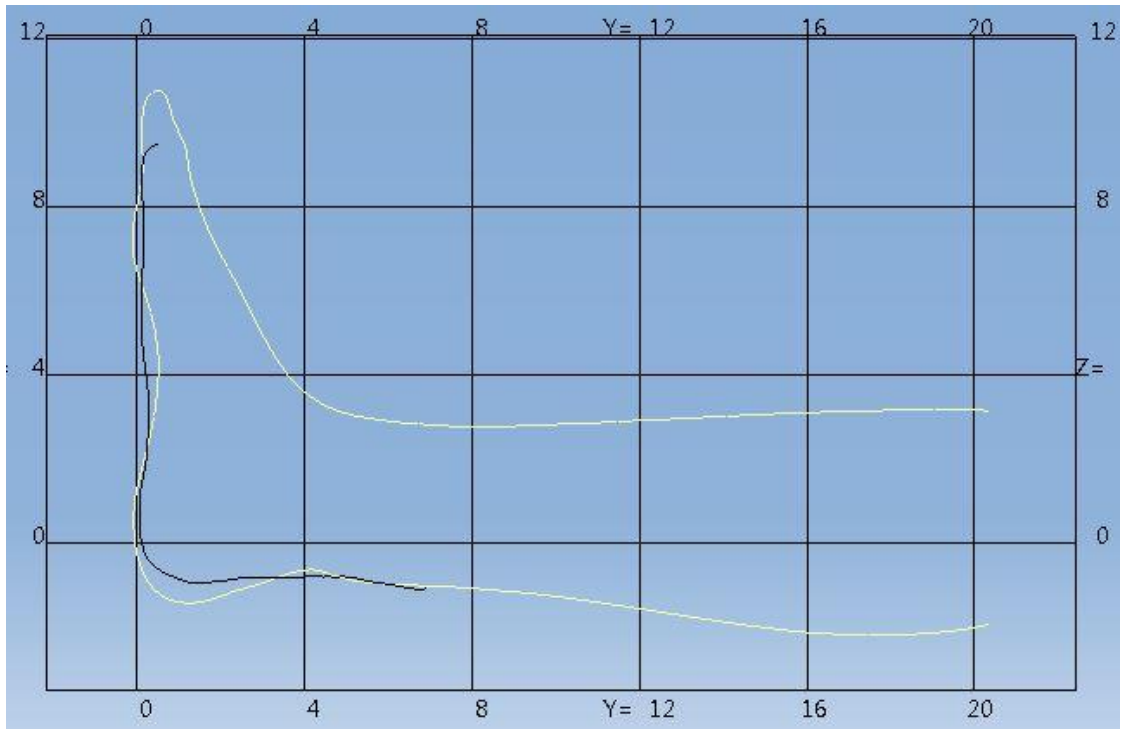


Figure G29: Cross-section analysis of the left ZY region for size 12.5.

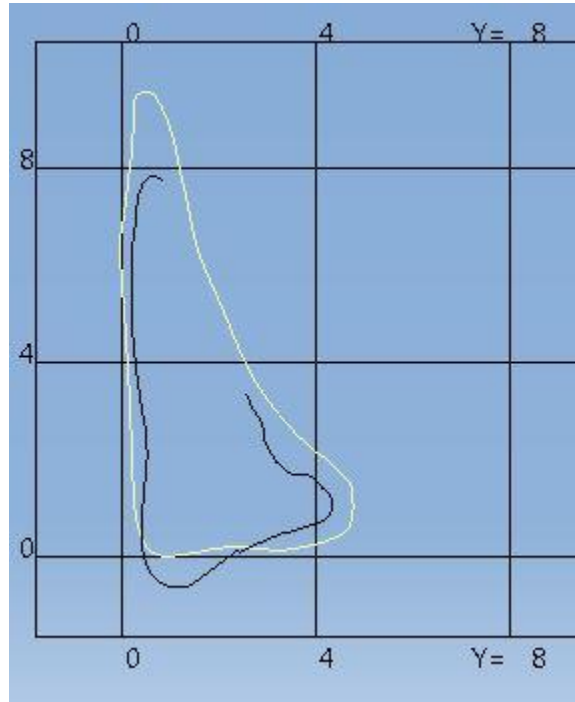


Figure G30: Cross-section analysis of the right ZY region for size 12.5.

Table G6: Size 12.5 distance measurements and averages at each of the nineteen points.

Size 12.5									
ZY_L		ZY_C		ZY_R		XY_Heel		XY_Ball	
1	1.33	1	1.21	1	1.77	1	0.45	1	0.07
2	1.25	2	0.98	2	1.74	2	0.51	2	0.06
3	0.92	3	0.96	3	1.60	3	0.18	3	0.38
4	1.05	4	1.00	4	1.47	4	0.21	4	0.62
5	2.01	5	0.53	5	0.29	5	0.45	5	0.91
6	1.44	6	0.00	6	1.12		0.36		0.41
7	0.13	7	0.00	7	0.67				
8	0.67	8	0.22	8	0.78				
9	0.13	9	0.17	9	0.46				
	0.99		0.56		1.10				

Appendix H

POINT CLOUD PROJECTION ANALYSIS

The point cloud projection analysis was performed by aligning the model over top of the scan. Then points were placed on the model and projected onto the scan. The distance between the points was then measured. The overall average was .201 cm or .193 in.

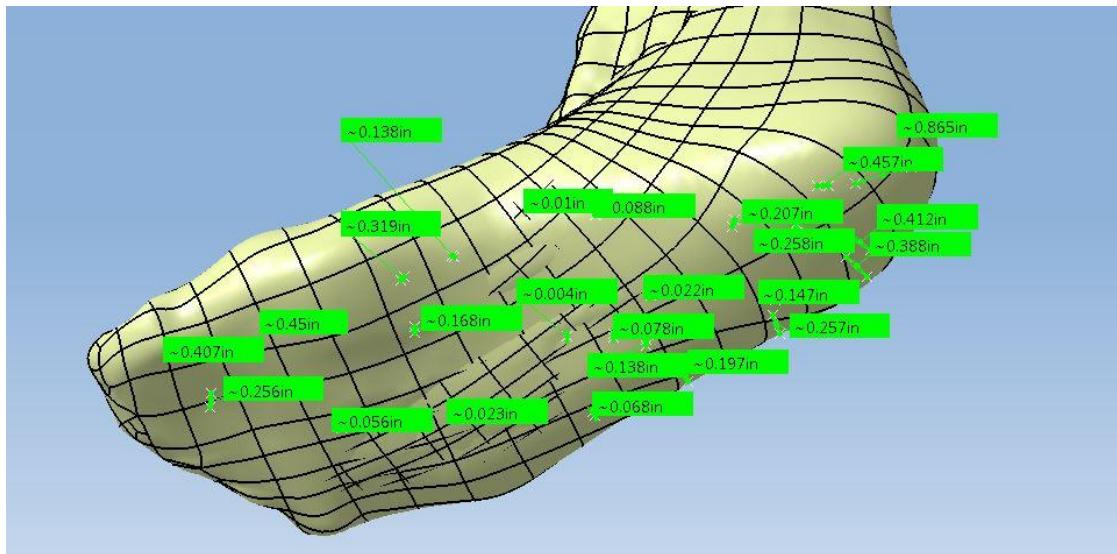


Figure H1: Point cloud projection analysis for a size 9. The average difference was .23 inches.

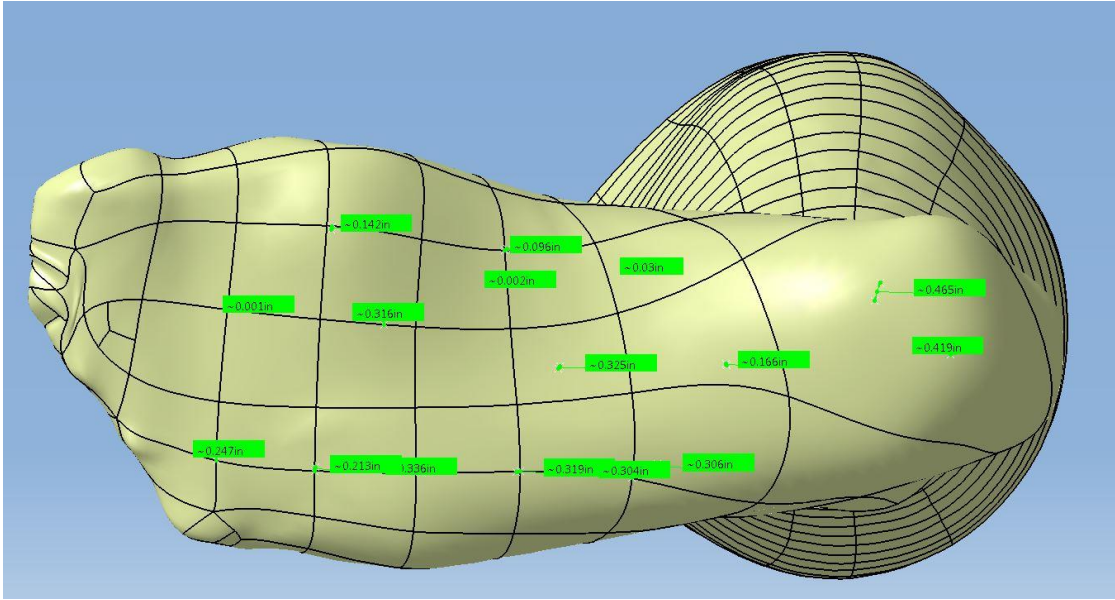


Figure H2: Point cloud projection analysis for a size 10. The average difference was .23 inches.

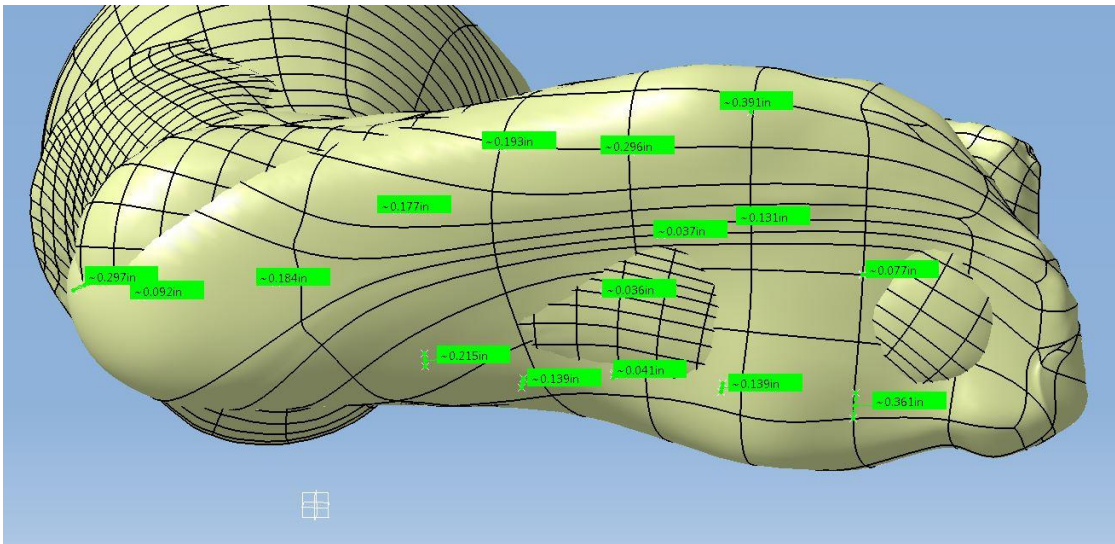


Figure H3: Point cloud projection analysis for a size 11. The average difference was .18 inches.

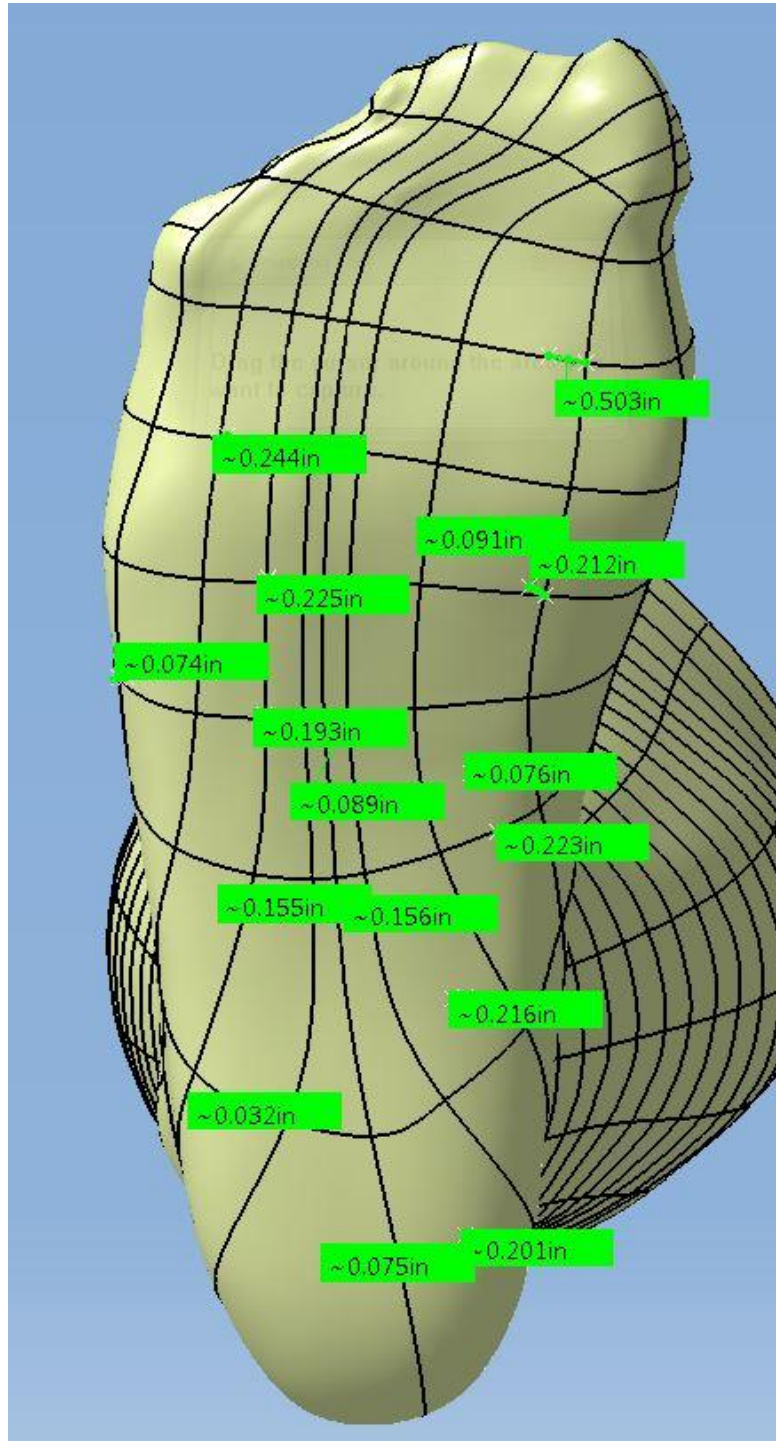


Figure H4: Point cloud projection analysis for a size 11.5. The average difference was .17 inches.

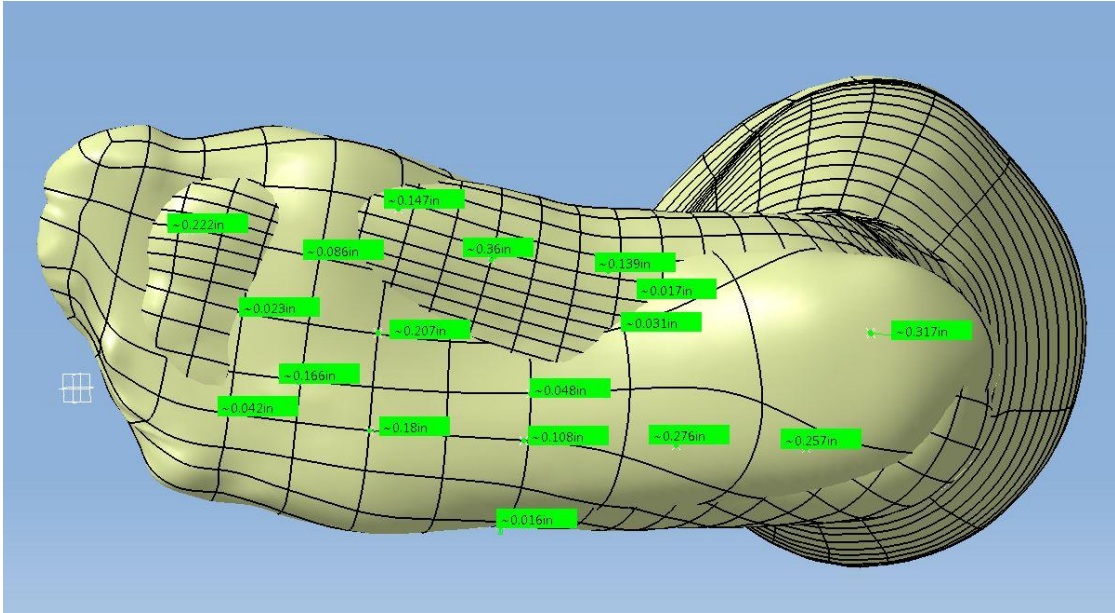


Figure H5: Point cloud projection analysis for a size 12. The average difference was .15 inches.

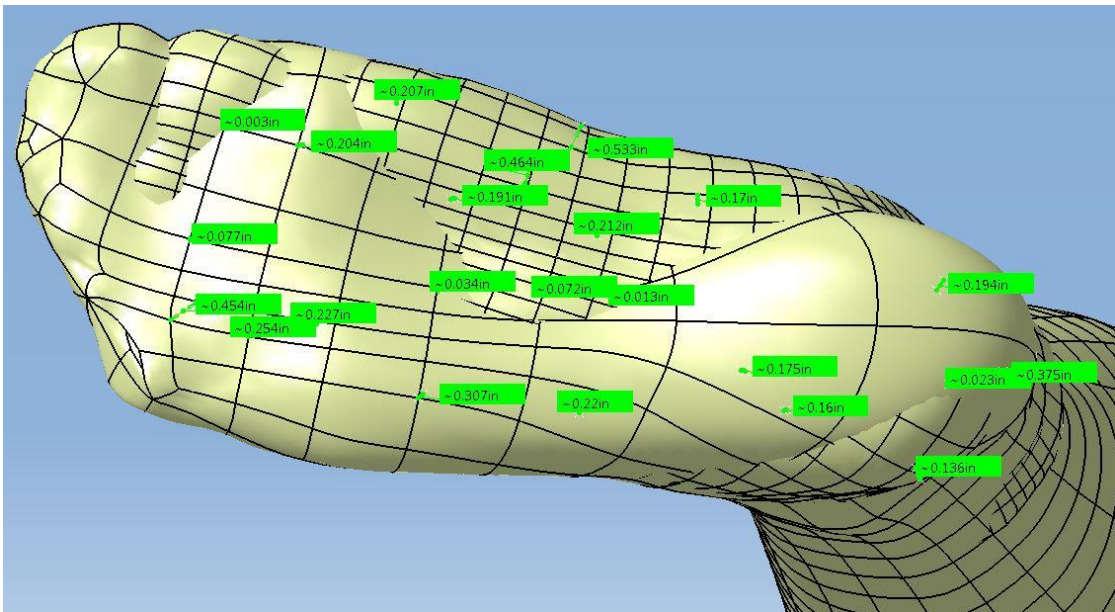


Figure H6: Point cloud projection analysis for a size 12.5. The average difference was .20 inches.