Parametric Design of Custom Foot Orthotic Model

Samuel J. Lochner[1], Jan P. Huissoon[2] and Sanjeev S. Bedi[3]

[1]University of Waterloo, sjlochne@engmail.uwaterloo.ca
[2]University of Waterloo, jph@uwaterloo.ca
[3]University of Waterloo, sbedi@uwaterloo.ca

ABSTRACT

Custom foot orthotics are commonly used in the treatment and prevention of a variety of medical conditions pertaining to the foot and overall body biomechanics. Traditionally, orthotics are made by vacuum forming material to a plaster cast of a foot. Podiatrists have control over the end result through the addition and subtraction of plaster from the cast. Digital scanning and computer aided surface modeling techniques are the current state-of-the-art in orthotics production, yet many podiatrists still prefer to use traditional plaster cast methods, partly due to the superior control afforded by plaster manipulation. We propose a novel state-of-the-art solution that achieves the necessary level of control over the orthotic's geometry in the form of input parameters.

Keywords: custom orthotics, foot orthotics, automated design.
DOI: 10.3722/cadaps.2012.1-11

1 INTRODUCTION

A custom orthotic is a medical device that fits in a shoe, often replacing the standard insole. The orthotic transmits the force from the foot to the shoe during loading. Thus it is within the orthotic's ability to influence the foot's posture as well as the distribution of force the foot experiences while it is weight bearing. A common paradigm in orthotic design is to create a surface similar to the foot's plantar surface when it is non weight bearing and in a desired posture. It is theorized that this will result in the maintaining of the desired posture while weight bearing as well as achieving optimum pressure distribution [8].

Custom foot orthotics produced with such a paradigm are widely accepted by medical practitioners as beneficial devices in the treatment and prevention of various medical disorders pertaining to the foot and overall body biomechanics [8],[9]. Prior to recent advances in computer aided design and automated manufacturing, the majority of orthotics were created by hand directly about plaster foot casts (henceforth referred to as traditional manual techniques). Various publications have helped standardize traditional manual techniques [8],[9]. The following is a summary of the steps required to produce an orthotic using traditional manual techniques.

- The foot is analyzed to determine the postural manipulations required to address the patient's needs
- A negative cast of the foot is created with the mid-tarsal joint locked

- The positive cast is created by pouring Plaster of Paris into the negative cast
- Various modifications are applied to the positive cast by removing or adding plaster thereby achieving various postural modifications
- One or more layers of the intended orthotic material(s) are heated until malleable and then vacuum formed to the positive cast
- Additional material is added to the bottom of the orthotic in order to fulfill the required postural manipulations determined from the first step. This is commonly known as *posting*
- The orthotic is manually finished to ensure proper fit in the intended shoe
- The orthotic is subject to a break in period by the patient. A follow up appointment reveals any adjustments to the orthotic that may be necessary.

Postural modification assessment and implementation is an art and varies among practitioners. Though these steps may vary from one medical professional to the next, they are all similar in that a considerable amount of skilled labor is required. Consequently, the cost of manufacturing orthotics via traditional manual techniques is directly impacted by the rising cost of skilled labor. Because of higher costs, it is becoming more difficult to acquire custom orthotics. Luckily, modern technology is poised to revolutionize the field. Recent strides in robotics, computer graphics, and automated manufacturing present great potential. Already there are a multitude of technology companies distributing commercial solutions for the custom footwear market [4],[6]. However, there is a clear trend towards diminishing standardization. For example, it is possible to digitize the foot with a variety of methods such as scanning the underside of the foot as it rests on a glass plate, scanning the fully non weight bearing foot as it rests on a pedestal, or scanning the impression left by a foot in a foam box. These three methods produce significantly varied foot geometry. Technological advances allow for unlimited possibilities in the field, however, they come at the cost of diminishing standardization. As well, these technological strides are not well mirrored in the literature.

Where most modern systems do coincide is that they strive to achieve digitally what traditional manual techniques achieve physically. The most promising modern solutions first digitize the foot, then create a digital orthotic about the digital foot, and then finally the digital orthotic is manufactured into the physical orthotic. The stage at which postural modifications are made may vary, sometimes occurring directly on the foot model and sometimes as a post operation on the orthotic model. Considerable research has been done into optimizing digital orthotics [1],[3], however, a concise explanation of how to create a digital orthotic is entirely lacking from the literature. Rather, it is often implied that the orthotic is simply a replica of the plantar surface of the foot [5],[7]. This is far from the truth; though an orthotic is designed about the non weight bearing foot, it must accommodate changes exhibited by the foot during standing and the stance phase of gait such as tissue expansion and minute repositioning of the foot with respect to the shoe. Such changes are not sufficiently accommodated by an orthotic that is merely a duplicate of the plantar surface of the non weight bearing foot [9].

As described in the steps above, traditional manual techniques achieve the necessary divergence from the foot surface through the addition or removal of plaster from the positive cast. The process is artistic, requires considerable training, and is not easily quantifiable. The current work interprets these artistic methods and substitutes them with exact algorithms. This article provides a concise explanation of the algorithms required to design a digital orthotic about a digital foot.

2 PROPOSED SYSTEM

A complete system for creating orthotics encompasses everything from positioning the foot during digitizing through to final finishing of the physical orthotic. However, the focus of this article is on the algorithms required to design a digital orthotic about a digital foot. Thus the detailed description of our system will start with the assumption that a digital representation of a foot’s surface has been acquired and the foot's posture has already been manipulated either during scanning, or digitally after scanning (postural manipulations include raising the heel, twisting of the rear or forefoot, etc.). The detailed description will end prior to manufacturing the orthotic. The digital representation of the foot’s surface is simply a mesh made up of vertices and normals (Fig. 1). With this scope, the first step in the process is to obtain the anatomical landmarks of the foot.

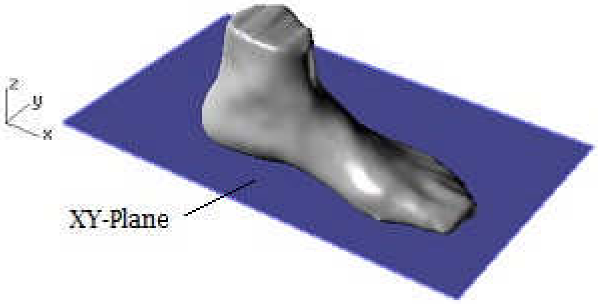

Fig. 1: A 3D model of a foot composed of approximately 8000 vertices and 16000 triangles. The XY-plane represents the surface the foot was resting on during scanning.

2.1 Manual Anatomical Landmark Selection

In addition to a surface mesh, the process of orthotic design requires knowledge as to the whereabouts of the various anatomical landmarks of the foot. The most accurate method for locating anatomical landmarks is to physically palpate them, mark them on the foot, and pick up the markings on the digitized foot model. The alternative is to locate the anatomical landmarks on the digitized foot model. Though the latter method compromises some accuracy, it has the advantage of reducing the knowledge requirement and time expenditure of the individual operating the scanner. Though either method is possible with the proposed system, the latter method is described here.

Physiologically, one human foot form is similar to the next. This would suggest that landmarks could be automatically detected on the foot mesh with relative ease. However, the geometry of various tissues may vary dramatically from one foot to the next making automatic landmark detection challenging (Fig. 2(a)). Thus the current system uses manual landmark selection as it only takes a few seconds and does not significantly detract from overall automation. The 4 key landmarks that need to be manually selected are:

- MPJ1Medial - the most medially prominent point of the first metatarsalphalangeal joint
- MPJ5Lateral - the most laterally prominent point of the fifth metatarsalphalangeal joint
- HalluxAnterior - the most distal point on the first ray
- MPJ2Inferior - the most inferior point of the second metatarsalphalangeal

To get these points, the user is provided with a bottom view of the foot and is asked to click on the various landmarks. The first three selections are constrained to the outside edge of the foot projected onto the XY-plane (Fig. 1) while MPJ2Inferior is provided no constraints (Fig. 2(b)). Afterwards, the 3D version of the points can be obtained by projecting a ray vertically and finding the intersection with the foot mesh.

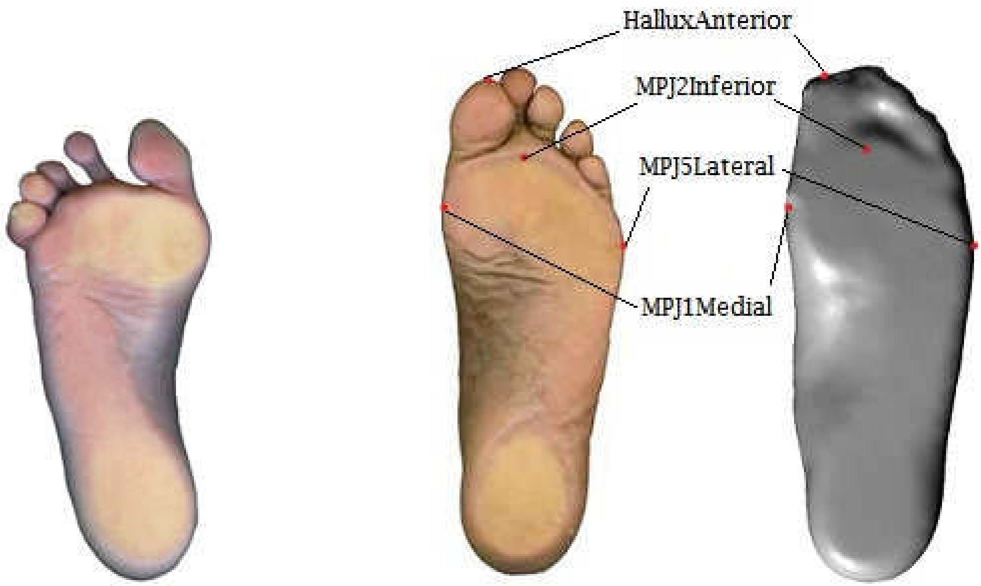

Fig. 2: (a) Common deformities make automatic landmark detection from a 3D model challenging, (b) Landmarks to be manually selected by user shown first on a digital image of the plantar surface of the foot and then on the corresponding 3D model.

2.2 Foot Alignment

When a foot is scanned, an attempt is made to center it and align it relative to the scanner. However, this attempt is only approximate and designing an orthotic requires a far more accurate alignment. Commonly, the foot's central axis is aligned with a particular axis in the model. The X-axis will be used for this purpose. There are 2 common methods for determining the central axis. Witana et al describe the methods as follows [11]:

- Brannock - The central axis starts at the pternion. The pternion is an anatomical landmark defined as the most posterior point on the foot (gauged from initial approximate alignment of the foot). The central axis is then constrained to pass 1.5" from MPJ1Medial (Fig. 3).
- Second Toe - The posterior point is calculated as the furthest point on the projected outline from the tip of the second toe. The central axis starts at the posterior point with a direction towards the tip of the second toe (Fig. 3).

The Brannock method uses the 1.5" constraint for feet of all sizes. Consequently, the Brannock method will result in central axes positioned too far laterally for narrow feet and too far medially for wide feet (Fig. 3). The second toe method is sufficiently defined and operates independent of foot size; however, it often fails due to common irregularities of the second toe (Fig. 2(a), Fig. 3) and the posterior calcaneus surface (Fig. 3). In light of these difficulties, the following extension of the second toe central axis technique will be used:

- Rather than using the tip of the second toe as the anterior point, MPJ2InferiorXY is used as it is far less subject to deformities. Additionally, the posterior point is replaced by the posterior contact point, where it is the furthest point on the foot from MPJ2InferiorXY that lies on the XY-plane. These two changes will result in central axes that are less subject to minor foot deformities. The foot in figure 3 exhibits deformities for which the Brannock and Second Toe methods perform poorly but not the proposed method.

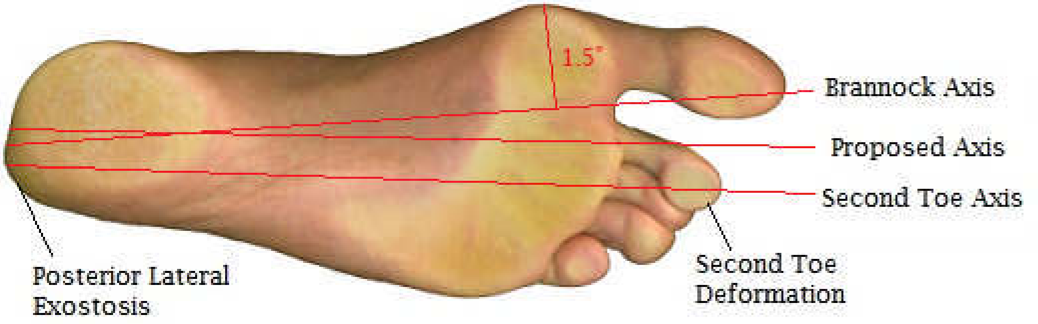

Fig. 3: An example of the Brannock and second toe methods performing poorly. The large size of the foot results in an overly medial Brannock central axis while the deformed second toe and posterior lateral exostosis undesirably influence the second toe central axis. The proposed axis is not subject to these factors.

2.3 Insole Geometry

In addition to landmarks on the foot, the outer boundary of the orthotic must be known prior to designing the orthotic surface. This information can be determined from the shoe geometry. A shoe's geometry is dictated by its corresponding shoe last’s geometry. However, it is a rare case when making orthotics that the digital geometry of the respective shoe last is known. Thus the current system asks the operator to select an appropriate last from a database and grades it to the size of the intended shoe with independent 1-dimensional linear scaling along the X, Y, and Z axes. Its central axis is then lined up with the model foot central axis followed by any further manual orientation adjustments that may be necessary. The primary piece of geometry required from the shoe last is the outside silhouette when viewed from the top. This will serve as the orthotic boundary. To capture this, an outline of the last is created in the XY-plane. This will be referred to as BoundaryXY (Fig. 4).

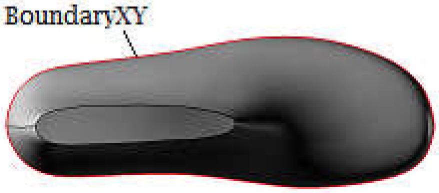

Fig. 4: BoundaryXY determined from a standard shoe last.

2.4 Surface Design

The next step in the process is to build an orthotic surface about the foot geometry. There are two ways that the orthotic surface differs from the manipulated foot surface.

Firstly, the orthotic surface must allow space for the tissues of the foot to expand. As described by Philps in "The Functional Foot Orthosis", the tissues of the foot expand during weight bearing [9]. This phenomenon will be accommodated by allowing the orthotic surface to deviate from the foot surface near the perimeter of the orthotic.

Secondly, the orthotic must allow for movement during standing and the stance phase of gait. As pressure is applied to the foot, the tissues deform and the relative positioning of the bones adjusts. In particular, the arches of the foot deform as they act as shock absorbers [8],[10]. Changes to the geometry and position of the various segments occur predominantly along the length of the foot and this is the reason for the recommended 10-15mm of toe allowance in most footwear. To accommodate this, the foot should sit on a smooth surface that does not inhibit natural movement. The geometry of the foot in the toe region is highly irregular and thus is not suitable as an orthotic surface. To address this, the forefoot will be provided a smooth surface that does not closely match the geometry of the toes.

Traditional manual techniques incorporate both of these requirements through the addition and subtraction of plaster from the positive cast. The first issue is primarily relevant to the rearfoot and midfoot whereas the second issue is applicable primarily to the forefoot. To accommodate this, the rearfoot and midfoot sections will be designed first in a single surface called the posterior orthotic surface and then the forefoot will be addressed with the anterior orthotic surface. A direct transition between surfaces of differing methodologies will inevitably result in discontinuities. To avoid this adverse result, the transition orthotic surface will provide a smooth blend (Fig. 5).

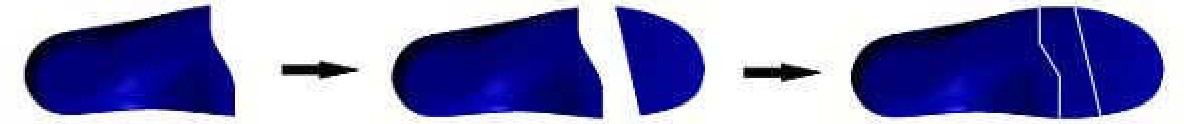

Fig. 5: First the posterior orthotic surface is designed, then the anterior orthotic surface, and finally the model is completed by adding the transition orthotic surface.

It should be noted that what is being created is considered a full length orthotic as it supports the full length of the foot. A common alternative is the 3/4-length orthotic where the area supporting the toes is omitted. Use of a full length orthotic is justified as it avoids the potential discontinuity that results during significant forefoot posting [9].

2.4.1 Posterior Orthotic Surface Design

The rearfoot and midfoot parts of the foot contain all geometry posterior to the ball curve and the surface of the foot in this region will be referred to as the posterior foot surface. For the most part, the posterior orthotic surface resembles the posterior foot surface. Where they differ is near the perimeter where adequate space must be allotted for tissue expansion. Traditional manual techniques achieve this through the addition of plaster to the plaster cast of the foot (Fig. 6). Philps describes the use of a spatula for smoothing down added plaster and describes the process as follows: "... the convex shape is maintained but some allowance is made for the spreading of the soft tissues on weight bearing" [9]. Philps also points out that the amount of added plaster varies with the location on the foot. The result is a casting that no longer represents the foot, but rather the geometry of the eventual orthotic.

The proposed solution takes a fundamentally different approach. The foot remains in its unaltered natural shape at all times. Rather than modifying the foot, the deviations between the foot and orthotic are achieved via parametric equations. Below is an explanation of the proposed algorithms.

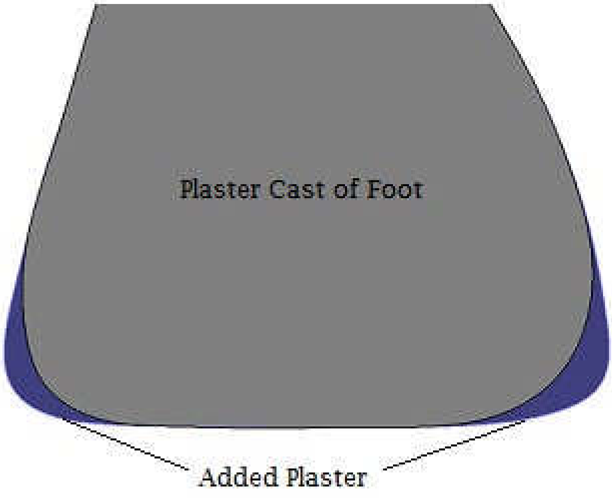

Fig. 6: Traditional manual techniques add plaster to the plaster cast of the foot. An orthotic built about the modified cast will allow for tissue expansion during weight bearing.

A series of points are found on the domain of BoundaryXY that are posterior to the ball curve. At each of these points, an arc is created (Fig. 7). The arcs deviate from the foot surface and represent the region of the orthotic that allows for tissue expansion on weight bearing. Referring to figure 8, the arc at each point is fully defined by 4 parameters:

1. Start Angle: The angle between the XY-plane and a vector tangent to the foot's surface. This angle dictates the final contact point of the orthotic with the foot's surface (while non weight bearing). The user has control over this parameter.
2. End Angle: The angle between the XY-plane and a vector tangent to the arc at the arc's end point. This angle dictates the geometry of the orthotic around the boundary. The user has control over this parameter.
3. Start Point: The point at the start of the arc is found by incrementally seeking a point on the foot's surface that satisfies the start angle. This point is dependent on the start angle, the geometry of the foot, and the geometry of BoundaryXY.
4. End Point: The point at the end of the arc has the same X and Y-coordinates as the corresponding point on BoundaryXY. It's Z-coordinate is driven by the above 3 parameters.

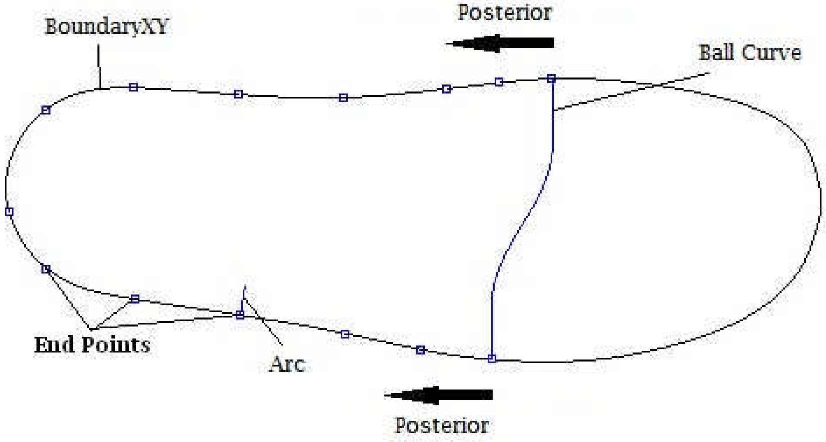

Fig. 7: A series of points are found along BoundaryXY posterior to the ball curve and an arc is created for each point.

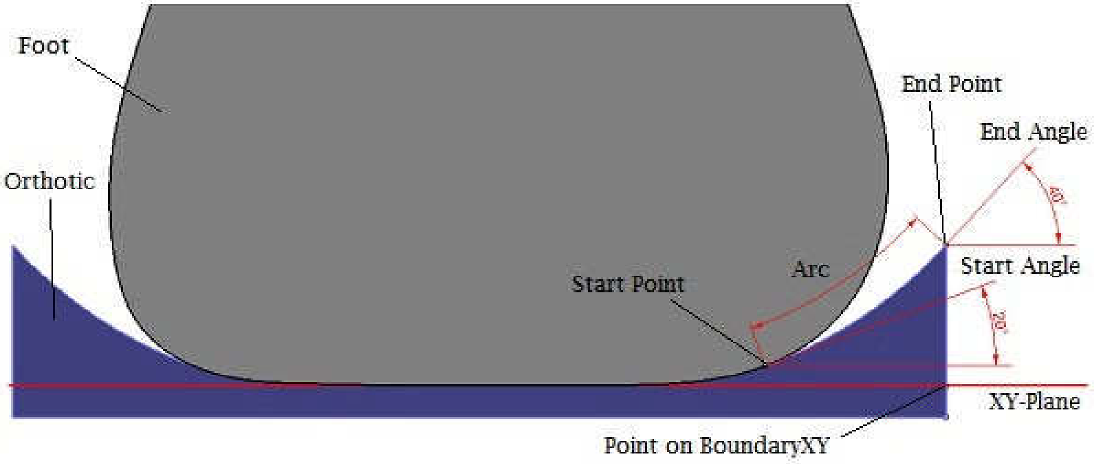

Fig. 8: Designing the arc. Note that the extension of the orthotic beyond the edge of the foot is exaggerated for clarity.

The amount of tissue expansion around the rearfoot varies depending on the region of the foot. For example, the heel tissue tends to expand more than the arch tissue. Thus the system is designed to allow independent inputs for the start and end angles for the arcs corresponding to various regions of the foot. A lower start angle leads to more space for expansion.

Preliminary experimentation found 40° to be an acceptable end angle for most regions. This isn't so steep that the material becomes fragile, but nicely cups the foot. The arch region is unique in this respect. In order to reduce the overall height of the orthotic, a lower end angle may be used, perhaps even 0 degrees (Fig. 9). This can save considerably on material usage (see manufacturing steps below). The start and end angles for the arc are important inputs for the system and further analysis may show that they should be properly considered and adjusted on a per patient basis. Future research will investigate the relationship between the various parameters and foot biomechanics.

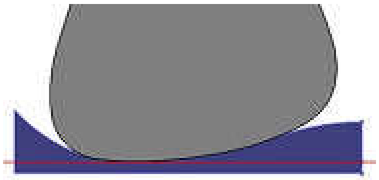

Fig. 9: An end angle of 0 is advisable for the arch region of the foot.

Next, a surface will be fit through the arcs in combination with other geometry to create the posterior orthotic surface. The remaining geometry required is created as follows:

The ball curve is projected vertically to the foot. A curve is interpolated through the start points of the arcs and joined with the projected ball curve. This curve is pulled to the foot to ensure full contact (now referred to as the Inner Perimeter). An array of points is projected to the surface of the foot that is contained by the Inner Perimeter (now referred to as Contact Points). The Outer Perimeter is created by interpolating the ends of the arcs and then pulling the interpolated curve to a surface created by extruding BoundaryXY vertically. The Outer Perimeter curve is closed by joining it with the projected ball curve. The Posterior Orthotic Surface is created by fitting a surface through Contact Points, Outer Perimeter, Inner Perimeter and the arcs followed by trimming it to the Outer Perimeter (Fig. 10).

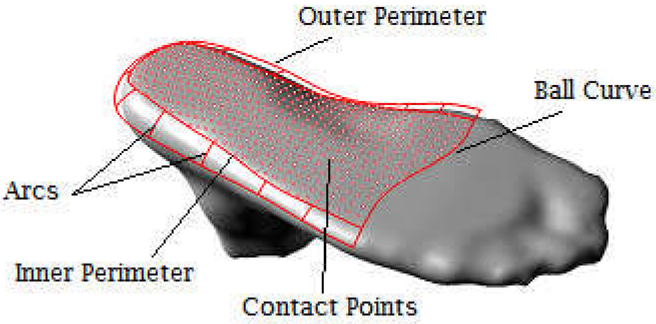

Fig. 10: Curves and points used to construct the posterior orthotic surface.

2.4.2 *Anterior Orthotic Surface Design*

The anterior orthotic surface differs considerably from the anterior foot surface. The anterior orthotic surface is relatively flat and does not mimic the complex geometry exhibited by the toes. Rather, it provides a smooth forgiving surface that can easily accommodate shifts in position. The geometry is created as follows:

Referring to Figure 11, a primary arc is created that starts at the first ball joint inferior point. This arc is tangent to horizontal at the start. The radius of the arc is determined by incrementally decreasing it from a large initial value until it intersects the Hallux. This arc is a building block for a smooth surface that just contacts the Hallux. Normally, this technique will result in a near flat curve and could easily be replaced by a straight line. However, the use of an arc provides a more robust solution that can adapt to a greater variety of possible foot irregularities.

Next, the arc is copied to the fifth ball joint at either end of the ball curve, extending the start of the arc as necessary. A surface is then fit through the ball curve and the arcs. Finally this surface is trimmed by a line slightly anterior to the ball curve (a predetermined ratio of foot length) and the projection of BoundaryXY onto the surface. The resulting trimmed surface is the anterior orthotic surface (Fig. 11).

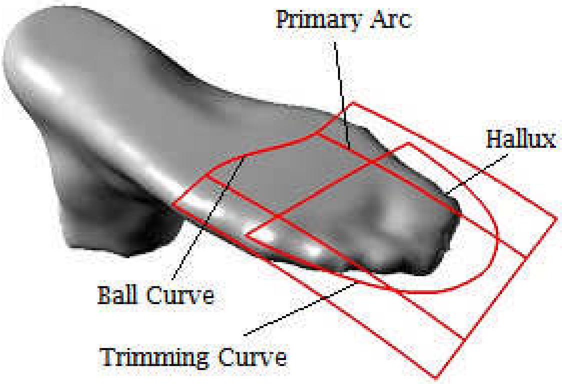

Fig. 11: Curves used to construct the anterior orthotic surface.

2.4.3 Transition Orthotic Surface Design

Aside from the divergence near the edge, the posterior orthotic surface closely resembles the foot geometry whereas the anterior orthotic surface is considerably different from the foot geometry. A direct transition between the posterior orthotic surface and the anterior orthotic surface would result in discontinuities. The transition orthotic surface provides a smooth blend between the posterior and anterior orthotic surfaces:

A surface is fitted through a series of curves passing from the posterior orthotic surface to the anterior orthotic surface. Each curve is a 3rd degree Bezier curve (4 control points) where the start of the curve is tangent to the posterior orthotic surface and end of the curve is tangent to the anterior orthotic surface. Fitting a surface to these curves results in the transition orthotic surface (Fig. 12(a), Fig. 12(b)).

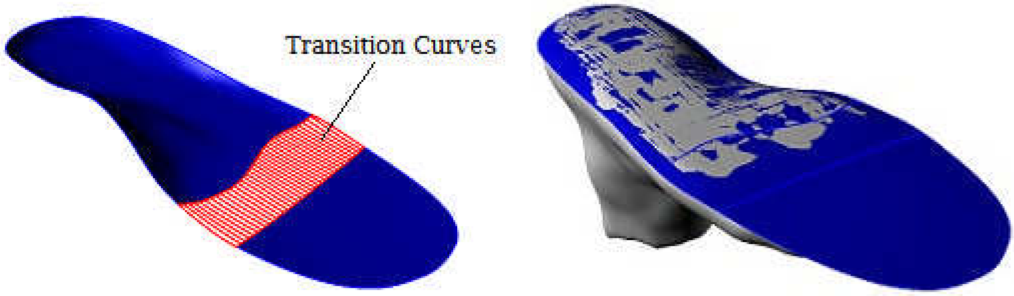

Fig. 12: (a) Curves used to construct the transition orthotic surface, (b) finished orthotic surface. The splotchy pattern signifies a close match between the orthotic and foot surfaces.

2.5 Manufacturing

Once the orthotic surface has been designed, it must next be manufactured to create the physical orthotic. The two leading technologies for this are 3D printing (or similar technologies such as laser sintering) and CNC Milling. 3D printing is beneficial as it offers no restrictions in geometry and does not generate the same amount of waste that CNC machining does. Its disadvantages are that it only works with certain materials and is both expensive to operate and purchase. Because of the availability of CNC equipment, flexibility in material choice, and reduced operating costs, CNC machining was used for testing. However, there is no reason why 3D printing couldn't replace CNC machining in the system in the future. After all, it (or similar technologies) has been proven successful in other orthotic design systems [5],[6].

The most important geometry of an orthotic is the top surface. This can easily be machined on a 3 axis vertical CNC mill. There are a great variety of materials used for orthotic manufacturing. For our tests, we will use Ethelyne Vinyl Acetate (EVA), a popular choice primarily due to its shock absorbing properties, durability, and ease of machining [9]. A vacuum table is used to hold down the raw stock. A ball nose 1/2” cutter and scallop finishing tool path were used to machine the surface and a 1/4” end mill was used with a ramping contour tool path to separate the orthotic from the raw stock. The ramping contour removes all but 1mm of thickness, leaving the final cut for manual finishing with a utility knife. Finally, material is manually ground away from the edges and bottom of the orthotic to ensure correct fit in the intended shoe (Fig. 13). Ideally the orthotic would be created via 2 sided CNC machining; however the flexibility of the material introduces considerable challenges. Crabtree et al solved this problem by freezing the raw stock with liquid nitrogen [2], however, this introduces complexity.

Fig. 13: The finished orthotic.

3 pairs of orthotics were created for people who normally wear orthotics but do not have serious foot disorders. In all cases the orthotics created by the system yielded satisfactory results when compared to the manually made orthotics.

2.6 Discussion

Our testing was limited to 3 tests and evaluating the tests relied upon subjective opinion. Additionally, the tests only inquired about comfort, fit, and similarity to current orthotics made by the manual traditional means. No emphasis was placed on biomechanics which is of critical importance in orthotic prescription. Thus, the orthotics yielded by the current system are not yet worthy of clinical implementation. However, this was not the intention of the current research. Rather, the aim was to fill a gap in the literature in regards to designing digital representations of orthotics. This work is essentially a building block for future studies entailing design of custom footwear and orthotics from both geometrical and biomechanical perspectives.

Additionally, the algorithms required several input parameters whose influence on foot biomechanics should be thoroughly investigated. These parameters include the start and end angles of the various arcs around the perimeter of the posterior orthotic surface as well as the length of the transition zone with respect to the foot length.

3 CONCLUSION

Orthotics continue to be prescribed for the treatment of a host of medical conditions. Traditionally, laborious manual techniques were used to manufacture orthotics. Manual techniques are gradually being replaced by modern automated techniques. However, modern solutions are still very much in their infancy. This is particularly evident by the lack of detail currently found in the literature. The current work provided a concise description of the algorithms required to design a digital orthotic about a digital foot model, thereby filling a gap in the literature. Three tests were completed and demonstrated the successful design of digital orthotics. Prior to recommending the current system for clinical use, additional research must be conducted in regards to the impact the orthotics have on biomechanics followed by a comprehensive testing phase.

4 ACKNOWLEDGEMENTS

Financial support for this work was provided by PODO-Pal Inc. and the Ontario Centers of Excellence.

REFERENCES

[1] Cheung, J. T.; Zhang, M.: Parametric design of pressure-relieving foot orthosis using statistics-based finite element method, Medical Engineering & Physics, 30(3), 2008, 269-277. http://dx.doi.org/10.1016/j.medengphy.2007.05.002
[2] Crabtree, P.; Dhokia, V. G.; Newman, S. T.; Ansell, M. P.: Manufacturing methodology for personalized symptom-specific sports insoles, Robotics and Computer-Integrated Manufacturing, 25(6), 2009, 972-979. http://dx.doi.org/10.1016/j.rcim.2009.04.016
[3] Goske, S.; Erdemir, A.; Petre, M.; Budhabhatti, S.; Cavanagh, P. R.: Reduction of plantar heel pressures: Insole design using finite element analysis, Journal of Biomechanics, 39(13), 2006, 2363-2370. http://dx.doi.org/10.1016/j.jbiomech.2005.08.006 PMid:16197952
[4] OrthoModel, http://www.orthotics-cadcam.com, Delcam.
[5] Pallari, J. H. P.; Dalgarno, K. W.; Woodburn, J.: Mass customization of foot orthoses for rheumatoid arthritis using selective laser sintering, IEEE Transactions on Biomedical Engineering, 57(7), 2010, 1371(7)-1378.
[6] SoleCAD, http://www.ideas.be, Ideas.
[7] Sun, S.; Chou, Y.; Sue, C.: Classification and mass production technique for three-quarter shoe insoles using non-weight-bearing plantar shapes, Applied Ergonomics, 40(4), 2009, 630-635. http://dx.doi.org/10.1016/j.apergo.2008.05.001 PMid:18620334
[8] The biomechanics of the foot and ankle, Donatelli, Robert, Davis Co, Philadelphia, PA, 1990.
[9] The functional foot orthosis, Philps, J.W., Churchill Livingsone, Edinburgh, 1995.
[10] The mechanics and pathomechanics of human movement, Oatis, Carol A., Lippincott Williams & Wilkins, Baltimore, 2009.
[11] Witana, C. P.; Xiong, S.; Zhao, J.; Goonetilleke, R. S.: Foot measurements from three-dimensional scans: A comparison and evaluation of different methods, International Journal of Industrial Ergonomics, 36(9), 2006, 789-807. http://dx.doi.org/10.1016/j.ergon.2006.06.004