A NEW PARALLELIZABLE DEFORMATION METHOD
Automatic Comparision between Foot and Last

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Abstract: This document shows the research project developed by the Computer Graphics and Vision Group in collaboration with Inescop.–The main objective of this project is to define a new methodology to design shoes exactly adapted to the shape foot. The system proposed is based on a biomechanical anatomical structure of the foot and using a deformable shape. Using with several joints adapted the different foots to different shoe last evaluating the error between the surfaces. The system is automatic driven in the selection of significant foot points. We consider several anthropometrical parts of the foot in order to apply the deformations of the shape with different axis. The proposed system is implemented in software. An associated Application Programming Interface (API) is also developed for commercial use of the system. Also the results presented evaluate the error between deformations.

1 INTRODUCTION

The footwear manufacturers from Europe, and particularly from Spain, need to go towards highly technified and added value products, since they cannot compete in price against the low cost producing countries invading the markets. Personalisation is an ideal strategy: It offers a high added value and links the client to the enterprise. Once the scanned feet of the client are registered, the client could demand his personalised shoes from the catalogue, even through the Internet, knowing the shoes will fit. The system presented in this paper project completes and follows one of the research and development lines which is being carried out at the INESCOP for several years, and is a clear example of collaboration between industry and university research group. Until now this project (European ERGOSHOE project: http://www.ergo shoe.inescop.es; also CEC-made shoe project: www. cec-made-shoe.com) led to the development of a low cost 3D foot scanner, a high precision 3D last scanner and a software tool (Forma-3D) for last design which also allows to superimpose and compare different volumes (e.g. foot and last). However there are still unsolved issues. With the general aim in mind of improve the automatic process of personalising footwear, in this paper we address the issue of virtually deform the foot in order to predict his geometry once it is placed upon an elevated sole profile (e.g. high heels), basing on the scan performed at feet flat on the ground and the profile of the last sole. It is necessary to be able to utilise the foot scan of the flat foot for multiple lasts, and most of the lasts have a certain amount of heel rise. The elevated sole profile is determined by the last.

The idea of "measuring" the shoe fit to the foot is not new. Jacob Lowe in 1927 obtained a patent for a fluoroscope intended to check the fit of the shoes visually (Lowe, 1927). However, and having the right technology, have not made great progress since then. The process of digitizing a foot and change the last shape from its numerical representation is something that is already being done at the theoretical and practical level (Luximon et al., 2005; Luximon et al., 2003; Mochimaru et al., 2000). There have been some advances in foot volume parameterization from 3D coordinates of discrete points (Luximon et al., 2003; Luximon et al., 2004; Luximon et al., 2003b), and numerous mathematical models have appeared for describing the foot motion (Arampatzis et al., 2002; Carson et al., 2001), however, offer no information on the volume of the foot. There are also models that describe the shape

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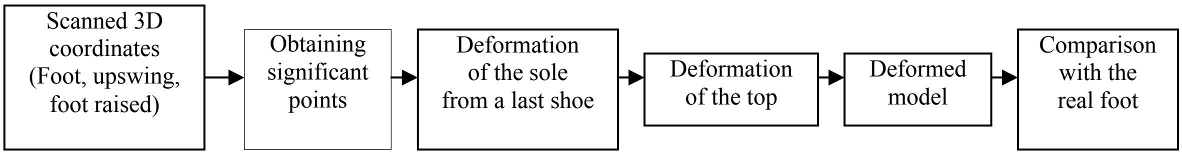

Figure 1: Description of the deformation virtual process.

of the foot, but these tend to be static (Luximon et al., 2004), some of then described the deformation of the foot depending on the load (Houston et al., 2006) and there are also attempts to record real-time full volume during walking (CEC made shoe project). But, in our concern, we have not found articles performing deformation models of the foot for applications with time restrictions.

Foot deformation into a high level position, as we can see in Fig. 4, is not so simple. Techniques such as Free Form Deformation (Mochimaru et al., 2000) or warping to the silhouette of the shoe last will not produce satisfactory results for such cases. Using an analytical model of foot bones that will lead to surface deformation could produce useful results (Carson et al., 2001), but has a high consuming time. Leon Kos et al. (2002) propose that the scanned foot in the flat position should be matched with a similar foot from the database to obtain land mark similarities for the fitness analysis. J. Leng et al. (2005) propose to use a distance map to indicate how well the selected shoe last fits the specific foot shape and to guide the deformation, in this case, the idea is to deform existing last model to fit a consumer’s foot shape with minimally affecting the original last style, this process is achieved by minimizing an equation. Only results using men’s shoes with low profile are shown. As we can see a typical idea is to select from an existing shoe lasts database or deform an existing shoe last model into one that fits the scanned foot data (Luximon et al., 2005; Li et al., 2004; Mochimaru et al., 2000; Kim et al., 2002; Cheng et al., 1999).

In this paper we propose a system to predict and study the deformation of a consumer's foot when it adapts to different lasts, for in a subsequent process, design the best last that fits its foot.

The proposed system uses as input, a scanned three-dimensional model of the foot, obtained through the INESCOP 3D scanner (see (Telfer et al, 2010) for other 3D surface scanning), and also a model of the last sole. The foot is scanned over a flat plane and its orientation is irrelevant, since the system is designed to automatically reposition the foot to agree with the last sole orientation. The process described in this paper is shown in Figure 1. Moreover, the computations for each vertex of the 3D foot model are independently, therefore the whole process is easily parallelizable. This fact is important because it can have to compare the last and foot deformation obtained with several last sole, then the computation time is extremely important.

The paper is organized as follows. Section 2 is devoted to the description of the deformation process of the foot. The analysis of the results is carried out in Section 3. Finally, the paper ends with the conclusions and future work

2 DEFORMATION

In this section, we describe the method used for foot deformation.

Through a 3D capture system for feet, we scan three fundamentals elements: the foot, the platform shoe and both together. We can process these three elements by means of our algorithm. We will describe the five steps of our algorithm: obtaining significant foot points, division of foot areas, calculation of the deformed sole, calculation of the foot’s top and fusion of both parts.

2.1 Significant Foot Points

To obtain an accurate deformation we need to calculate several significant foot points. The most important points are IH, IF, MT, MF, HA and HB (see Figure 2). To obtain these points we have that the length of the foot is the x-coordinate, the width is the y-coordinate and the height is the z-coordinate. HF is the point with lowest x-coordinate and IF is the point with the lowest distance between the point HF and all the points of the top’s foot border line.

Now we divide the length of the foot in two parts: forefoot (from the middle of the foot to the toes) and hindfoot (from the middle of the foot to the heel). In the forefoot we find the points MF and MT. MF is the point with the lowest y-coordinate and MT is the point with the highest y-coordinate. Doing the same in the hindfoot we have that HA is the point with the lowest y-coordinate and HB is the point with the highest y-coordinate.

With the points MT and MF we create the plane

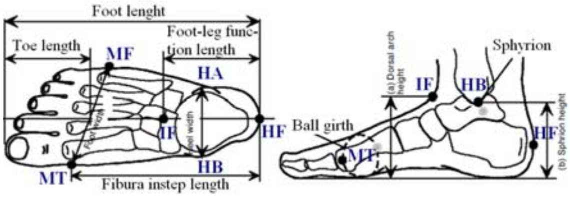

Figure 2: Foot dimensions.

that divides the toes from the instep (Figure 3, left) and with the points IF and HF we create the plane that divide the instep from the ankle (Figure 3, left).

2.2 Division of the Foot Areas

The planes delimit the different parts of the foot. We divide the foot into three areas as you can see on the left of the Figure 3.

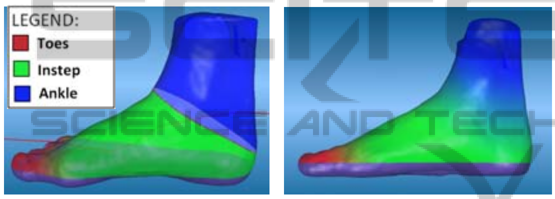

Figure 3: Left: planes of the foot. Right: areas of the foot.

We separate the foot into two principal parts: (see Figure 3, right): the sole (purple colour) and the top (red, blue and green areas). Each part will suffer a different type of deformation according to their characteristics.

2.2.1 Cut Section of the Sole

The sole of the shoe last is a fundamental part to create a custom shoe because its shape will depend on the user's weight distribution on footwear. This fact influences in the comfort of the shoe.

From the scanned and the significant points we determine the cut of the sole, which is malleable to the deformation line (see the red line of the Fig. 4). The calculation of this cut is realized with the MT point (Figure 2). All points that are below this point are the sole.

2.2.2 Cut Section of the Top

The top requires a different type of deformation. Must be generate a virtual skeletal from the 3D foot model scanned and the joint axes allowing a more accurate deformation. The foot model has two principal joints: the metatarsal joint and the ankle joint. Then the top is considered as the part that it doesn't belong to the sole.

2.2.2.1 Metatarsal Joint

The metatarsal bones are those responsible for the toes movement. This joint is essential in the virtual deformation, because it allows the correct rotation of the forefoot. In this paper, we consider that this joint is the most important for a good deformation, because it is the most influential in the final shape of the foot.

To find this joint, we get the most prominent points of the forefoot (MT and MF). The axis of rotation passes through these two points (see Fig. 2).

2.2.2.2 Ankle Joint

The ankle joint is obtained from the most prominent points of the hindfoot (HA and HB). The axis of rotation passes through these two points (see Figure 2) allowing joint movement.

2.3 Deformation of the Sole

The deformation of the sole is the first step to obtain the final deformed foot. This part must be adapted with precision to the deformation line. So, it needs a different deformation to the top of the foot.

Once obtained the cut section that delimits the sole, we need to obtain the deformation line. This line is obtained from the platform. We cut the platform by a plane that crosses longitudinally.

Then, we obtain the normal to every point of the line. This is necessary to correctly locate points on the deformed sole. The distance between them varies according to deformation line. Thus we get simulate the deformation suffered by the foot. In the Figure 4, we show an example of the final deformation where you can see the final deformation of the sole.

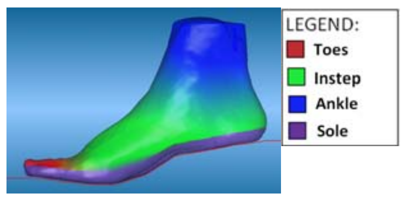

Figure 4: Deformed foot and the final deformation of the sole in purple.

2.4 Deformation of the Top

On the right of Figure 3 we divide the foot into four areas, but as we only want the top, we have three parts: the toes area, the instep area and the ankle area.

Each area is separated by a joint and it has a different rotation angle. To join all parts, we must make a smoothing. The result meets the C1 continuity. Therefore, we apply an interpolation between the different areas (see Figure 4).

2.4.1 Rigid Areas

The toes, the instep and the ankle are considered rigid parts of the foot. When the foot is deformed, we apply it a composition of transformations:

$$M = T \cdot (R \cdot T^{-1}) \cdot \quad (1)$$

It is basically moves the object to the origin (T), rotates (R) and returns it to its original point (T^{-1}). Then,

$$T = \begin{pmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad T^{-1} = \begin{pmatrix} 1 & 0 & 0 & -x \\ 0 & 1 & 0 & -y \\ 0 & 0 & 1 & -z \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (2)$$

$$R = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

The axis of rotation is the y-axis both for the metatarsal joint and the ankle joint, as we explained above. Then,

$$M = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha & -x\cos\alpha - z\sin\alpha + x \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & x\sin\alpha - z\cos\alpha + z \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (4)$$

To determine the rotation angles, we consider three areas:

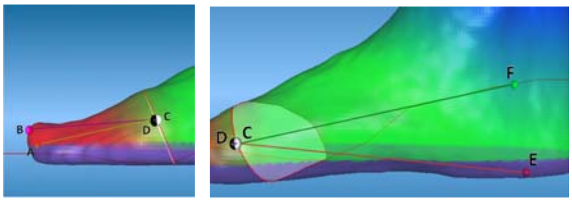

Figure 5: Left: rotation angle of the toes. Right: rotation angle of the instep.

- Toes area. It calculates the most prominent point of the foot, with the foot without deforming (point A) and with the deformed foot (point B). Then you need the furthest point in the toes area. It is located at the height of the plane that divides the toes area and the instep area. We find this point with the foot without deforming (point C) and with the deformed foot (point D). The angle is formed by the vectors C-A, D-B (see Figure 5, left).
- Instep area. You take the same point C and D calculated for the toes area. We estimated the farthest point that it is in the heel: the point with the foot without deforming (point E) and with the deformed foot (point F). The angle, as shown in Figure 5 on the right, is the vector formed by the E-C, D-F.
- Ankle area. The angle used to rotate the ankle is the same that is used for the instep area, except that now it will be negative. With this we get that the ankle turn back to be straight because first the instep is rotated and this affects the ankle too (Figure 6). So, it was subsequently applied the same rotation but with a negative angle (Figure 7 and 8).

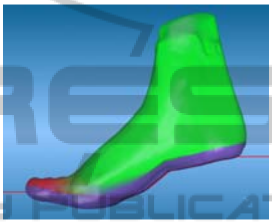

Figure 6: Deformed foot without rotated ankle.

It should be noted that the IF and HF points (Fig. 2) create the first plane that delimit the ankle area.

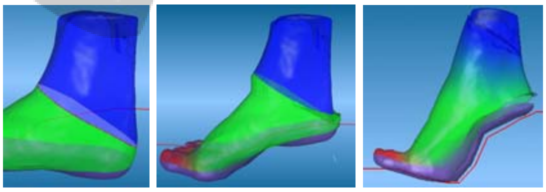

Figure 7: Left: unrotated ankle (one plane). Middle: rotated ankle (one plane). Right: interpolation with one plane.

As shown in Figure 7, with one plane; the vertices get into the sole. To avoid this problem in the first stage is realized an interpolation in this area (see the right side of Figure 7), but results are not entirely satisfactory. This is because the cut of the sole has a different deformation. Thus, it was considered convenient to use also a second plane (Figure 8) to avoid the problem. Later we will realize an interpolation that it is described below.

When we apply the interpolation we are obtained more satisfactory results and more tight according to the line of deformation. We can compare the results obtained by the interpolation using one plane (Figure 7, right) and two planes (Figure 8, right), respectively.

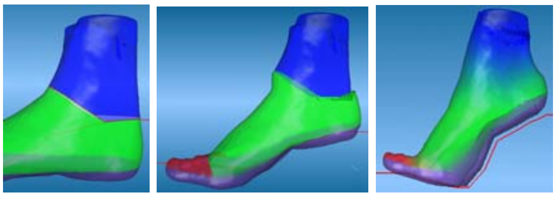

Figure 8: Left: unrotated ankle (two planes). Middle: rotated ankle (two planes). Right: interpolation with two planes.

2.4.2 Interpolation Areas

Figure 9 shows the interpolation areas, which are bounded by the planes where there are the colour transitions. The interpolation process is similar to that used in the paper (Kavan, 2003).

Figure 9: Interpolation areas.

This zone is delimited by t_{min} and t_{max}. Where t_{min} is the lower plane and t_{max} is the higher plane. The t’ is the distance between the point and the lower plane. It is positive for points in the n direction. Negative for points behind the plane (in the –n direction) and zero for points incident to the plane. The interpolation parameter is:

$$t = \frac{t' - t_{\min}}{t_{\max} - t_{\min}} \tag{5}$$

Therefore, we apply an interpolation of the angle (β) when we rotate all vertex of this zone. Where $\beta = \alpha \cdot t$, α is the angle calculated for the rigid zones. That is,

$$M = \begin{pmatrix} \cos\beta & 0 & \sin\beta & -x\cos\beta - z\sin\beta + x \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\alpha\beta & x\sin\beta - z\cos\beta + z \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{6}$$

This way, we obtain a simple implementation of the deformation, which allows for an acceptable computational cost. This allows obtaining tight results to real deformation that suffers the foot.

2.5 Fusion of Parts

Once we have both the top and bottom of the deformed model, it is necessary to merge both into a single three-dimensional model that represents the client's foot placed on the platform. This 3D model can be compared a posteriori with different shoe lasts and so, you can check the comfort of them.

The fusion is a simple process, since it is based on linking two three-dimensional models into a single one, considering the shared points. These points will form a union that can present certain anomalies product of the deformation process, so it is smoothed using the Laplacian smoothing technique. This process is also known as diffusion. Fusion equation takes the form,

$$\frac{\partial X}{\partial t} = \lambda L(X), \tag{7}$$

where X is the vertex of the mesh, is the Laplacian, and λ is a scalar which controls the rate of diffusion. Assuming that the Laplacian operator is linear, the smoothing equation can be written as the following difference equation forward.

$$X(n+1) = (I + \lambda dtL)X(n). \tag{8}$$

Doing this we do not achieve changing the connectivity of the mesh. Each step changes the position of the vertices, but the mesh topology remains unchanged. The relaxation of a given vertex only requires information about its immediate neighbours. In figures 11 and 12 you can see the deformation obtained at the end of the fusion process.

3 RESULTS

To check the results, we must conduct a comprehensive study comparing the error between the deformed foot and foot on platform real. In the first phase of the project we scanned sixteen women's feet with Europe size 37, considered a common size.

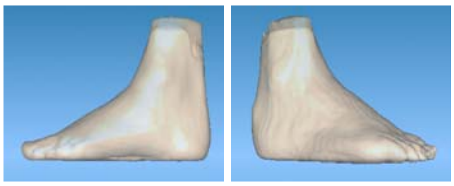

Figure 10: Example of different feet scanned. From left to right: foot 1, foot 2.

After obtaining the data (Figure 10), they are filtered and processed with the deformation algorithm. The following figures show the results of these deformations (Figures 11 and 12) with platform of 4, 25, 35, and 75 mm, used to lift the foot.

Figura 11: Deformation and inclined platform adjustment of the foot 1 in Figure 10. The deformation line is the red line.

Figure 12: Deformation and inclined platform adjustment of the foot 2 in Figure 10. The deformation line is the red line.

To estimate the error, the algorithm calculates the intersection of the normal of each polygon of the deformed model with each polygon of the real model, so that it generates a colour map. In Figure 13 you can see the map. Green means it is above the actual model, the red that it is below the actual model and finally the gray coincides with the model.

We realize a comparison of the deformed foot with the real foot on the same rise. We obtained the average error for each area (toes, instep and heel). The data obtained are shown in Table 1.

The error numbers can seem highs because of the process of scanning the foot on the platform. Some people put the foot obliquely on the platform, because the foot wasn't fixed to the platform. This causes that the toes protrude from the model on the outer part and the heel on the inside part.

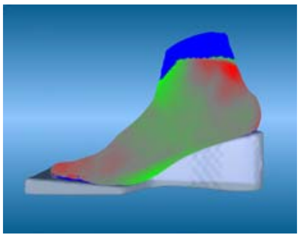

Figure 13: Colour map of the deformed foot.

Table 1: Error obtained.

Maximum average error	5.45 mm.
Minimum average error	0,93 mm.
Total average error	2,45 mm.

Footwear experts did a visual supervision of the results. They concluded that the result is more precise than initially estimated.

4 CONCLUSIONS AND FUTURE WORK

We have achieved virtual deformation of a consumer's foot and adapt it to a previously selected platform. In this way we will be able to determine the shoe that best fits to this foot.

With the final goal in mind of a global process of adaptation of the shoes to the feet of the customer, the speed of the process is essential. For this reason, we adopt in this simulation a deformation model based on geometry rather than based on physics. We sacrifice realism for speed and efficiency. A client can not wait long time to find out what type of shoe is best suited to his/her feet.

In this paper we present a system with low computational cost and a low error rate. The error rate has been supervised by experts in the design of footwear and has considered it acceptable. The control points needed to perform the deformation are detected automatically. It has been created a pleasant user interface easy to use. So this paper can be seen as an important basis for future improvements of a global process, in order to obtain a better fit of the footwear to the foot of the customer.

As we have seen the tests have been satisfactory, as well as we have seen the system is easily parallelizable. Therefore, an immediate future work will be to parallelize on GPU the deformation process, so it could be implanted in the footwear industry. Moreover will be performed a more comprehensive study of the error and is expected to evolve the deformation to make it more realistic in the critical points.

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