Foot Measurement Using 3D Scanning Model

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Abstract

In a three-dimensional (3D) foot scanning, a 3D point cloud is generated and meshed to create a 3D foot model with depth information. In the previous analog process of foot scanning is to draw an outline of the foot and imitate the foot directly. This method has some disadvantage that has a measurement error, difficult to recreate, inaccuracy of reference point and an error by an expert abilities. In this paper, in-plane deformation measurement method is proposed to solve this problem. In-plane deformation measurement method is a novel method to measure foot size from a 3D foot scanning data. The Shrink-Wrap method is used to reconstruct a foot model, that estimate the foot model by wrapping the surface of a foot of the square template mesh model. For comparison, foot length, foot width and height of the instep is measured with the proposed method. In comparison with handcrafted method, the experimental results show that our proposed method has complexity reduction, higher precision and accurate reproducibility.

Keywords: Foot measurement, 3D scanning, In-plane deformation measurement

1. Introduction

Development and convergence of IT technology have led to significant improvement of producing a custom foot shaped item with scanning with three-dimensional (3D) printing. According to personalization and mass production of shoes, shoe manufacture companies apply a custom shoes making process with a 3D foot shape data. A 3D scanning method can be used for making assembled footwear like athletic shoes and outdoor shoes, however, this method is unsuitable for making customized dress shoes with the shoe lasting. Also, handmade shoes are made with only limited foot shape information and foot length. In a current shoe manufacturing process, each manufacture company has a limited type of shoe lasting machine, so there are few kinds of products. For satisfying the customers' needs, the company should have many kinds of shoe lasting types. But it is difficult to create various shoe last types with a CAD program. To solve this problem, various foot model measurement methods has been proposed [1–7]. However, current methods using Euclidean distance is difficult to measure curved foot surfaces. In this paper, a 3D foot shape measurement method for foot model dense reconstruction is proposed. The curved foot shapes are estimated from the definition of foot main points. The data obtained from 3D foot shape measurement can be used to manufacture customized shoes. With more accurate and more precise data, the shoes for comfortable walking can be made from 3D foot data [8–11].

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Figure 1. Korean foot shape classification (triangular type, square type, ladder type, and inverted triangular type).

2. Background

2.1 Characteristic of Foot Shape

According to the study on categorization of foot shapes, Korean woman foot shapes can be categorized into 4 types with 8 factors (foot breadth, ankle thickness, 1st toe shape, malleolus height, the heel to the top of the foot length, the ratio between toe-side, the 5th toe length, the ball of foot height).

The 4 types of foot shapes are triangular type, square type, ladder type and inverted triangle type (Figure 1). The frequency of each type is 20%-30%. In Table 1, the most frequent type is the ladder type which frequency is 30.2%, followed by the inverted triangular type, the triangular type, the square type [12–16].

2.2 Foot Measurement Definition

In a shoe lasting process, an accurate measurement is required for applying foot characteristic well. In case of a previous standard shoe last model, basis shape of last model is generated from 265 mm size foot model and the other size model is obtained from basis model with proportioning. This method just uses average size of the basic model, so the person using the other size model feels uncomfortable because the foot shape does not match exactly. In this paper, a measurement tool for 3D space with modeling foot scanning data is proposed for an accurate foot numerical measurement.

2.2.1 Foot point definition

For an accurate foot size measurement, a definition of main points of a foot is required. In Table 2, 3 points (foot length, foot width and height of the instep) are defined from a major factor in shape classification of the foot.

Table 1. Characteristic of Korean woman foot shapes according to the 4 kinds of foot shape category

Category	Characteristic	Frequency (%)
Triangular type	The ankle are thick. The foot breadth is short. The malleolus height is short. The 1st toe is bent normally. The ball center to heel length is longer than the ball center to 2nd toe length. The heel to the top of the foot length is long. The 5th toe length is short. The ball of foot height is long.	24.0
Square type	The ankle thickness are normal. The foot breadth is normal. The malleolus height is long. The 1st toe is very straight. The ball center to heel length is shorter than the ball center to 2nd toe length. The heel to the top of the foot length is long. 5th toe length is long. The ball of foot height is normal.	20.0
Ladder type	The ankle is thin. The foot breadth is normal. The malleolus height is long. The 1st toe is straight. The ball center to heel length is longer than the ball center to 2nd toe length. The heel to the top of the foot length is very short. 5th toe length is normal. The ball of foot height is short.	30.2
Inverted triangular type	The ankle are thin. The foot breadth is long. The malleolus height is normal. The 1st toe is very bent. The ball center to heel length and the ball center to 2nd toe length are similar. The heel to the top of the foot length is long. 5th toe length is long. The ball of foot height is long.	25.9

Table 2. Main foot point definition

Measure point	Definitions
Foot width (M1)	The distance from the right endpoint of the foot (P1) to the left endpoint of the foot (P2)
Height of instep (M2)	The distance from the instep (P3) to sole (P4)
Foot length (M3)	The distance from the longest toe (P5) to heel point (P6)

Figure 2 is a foot description on top view point. M1 is the foot width defined as the distance from P1 to P2.

Figure 2. Foot width measurement definition.

Figure 3. Foot width, foot height definition.

Figure 3 is a point description of the side view of the foot. M2 is the height of instep defined as the distance from P3 to P4. M3 is the foot length that is the distance from P5 to P6.

2.2.2 Existing measurement methods

Many techniques have been proposed for foot measurement [1–5]. The optical techniques and caliper measurements is used for foot size measurement [1]. Each technique had an advantage in accuracy and time consumption. Zhao et al. [2] proposed a method that customize foot size using 6 foot girths. This method shows that the error is less than 5 mm between the proposed method and manual measurements. Another experiment using the data from X-ray and manual measurements is conducted by De Mits et al. [3]. The result of the obtained data proved to be highly accurate. The 3D measurement method can be used to evaluate an abnormalities of foot structure. In foot 3D digitizer has good validity for quantifying an abnormal foot posture and deformities [4, 5].

Although many previous studies for a 3D foot model measurement have been developed, the Euclidean distance is a simple method to measure the 3D model. The Euclidean distance is the method that calculates the length of the line segment connecting two points. In 3-dimension environment, if the two points are $P = (p_1, p_2, p_3)$ and $Q = (q_1, q_2, q_3)$, the formula

Figure 4. Foot scanning data (obj file).

of the Euclidean distance is as follows.

$$Distance = \sqrt{((p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_3 - q_3)^2)}. \quad (1)$$

Current 3D distance measurement method is usually a Point-to-Point measurement in the custom shoe industry. To be more specific, the distance between the longest toe and the heel is defined as foot size. However, it is difficult to accurately measure the foot model because the surfaces of the 3D foot model is curved. Many shoes are made in the prescribed units which are obtained from the linear approximation. To produce more accurate custom shoes, a method to measure the precise foot size is necessary. In Section 3, we propose the new method that accurately measures the curve of the foot using the definition of the main point of the foot. Furthermore, We compared the proposed method with the point to point method.

3. System Overview

3.1 Foot Measurement

In Figure 4, 3D point cloud foot scanning data is connected with mesh. Mesh reconstruction is a method that expresses the surface of an object. Mesh model is obtained from the 3 point connected triangles. We generate a proposed template model that can measure the distance from any point of the foot in various view points.

In the template model, foot width, the height of the instep, foot length are pre-defined. Also, the size of the template model must be larger than a real foot model. The template model estimates the size of the foot with the in-plane deformation measurement.

Figure 5. Template model and foot model and built-in in-plane deformation measurement.

Figure 6. Bounding box hierarchy (BBH) tree.

Figure 7. Axis-aligned bounding box of collision detection model.

In Figure 5, the in-plane deformation template model from the mesh model is described. With foot shrink-wrap algorithm [17], we can reconstruct an accurate foot model by wrapping the surface of the foot from the in-plane deformation measurement template model [18, 19]. The main idea of Foot Shrink-Wrap algorithm is that compare a 3D point cloud set and calculate an optimized point of the surface. To obtain an accurate foot model, the shortest distance is calculated from the point cloud of the template model [20].

In Figure 6, the mesh data is constructed as Bounding box hierarchy (BBH) tree. Then, axis-aligned bounding box (AABB) collision detection model is used for the construction [21].

Figure 8. Template mesh model.

In Figure 7, AABB is the method that checks whether two bounding box aligned to basis axis is overlapped. Because the bounding box is aligned to basis axis, the bounding box can express as two points (x, y, z) and the collision detection is easy.

The shortest distance condition formula on each shape is as follows:

$$Max1(x, y, z) < Min2(x, y, z) \quad \text{or} \quad (2)$$

$$Min1(x, y, z) > Max2(x, y, z). \quad (3)$$

The point of the shape can be quickly found because the point is already constructed by BBH tree (Eq. (1)).

3.2 Sources Mesh

In Figure 8, if using too many meshes, the foot shape model is unnecessarily detailed. Also, many curves of surfaces that are unnecessary for measurement will appear and complexity of rendering has increased. Therefore, we tested surface subdivision process to optimized parameter for measuring the foot size [22, 23]. In Figure 9, the shape of the source mesh can be transformed easily into various forms.

3.2.1 Surface subdivision

Surface subdivision is the technique that has been used in 3D animation. With surface subdivision technique, the surface of the model is expressed as small polygon that divided per unit area. According to applying surface subdivision technique to previous rough model, the surface of the model becomes smoother.

In Figure 10, the mesh level can be subdivided. The number of vertices is determined to re-express the mesh on the surface.

Level	L1 (v: 8)	L2 (v: 98)	L3 (v: 386)	L4 (v: 1538)	L5 (v: 6146)
Mesh Shape

Figure 9. Five level mesh (L1, vertex 8; L2, vertex 98; L3, vertex 386; L4, vertex 1538; L5, vertex 6146).

Figure 10. Subdivision model.

Finally, We have built in-plane deformation measurements in the template model and foot model was inserted into the template model. In order to precisely measure the foot model, a shrink-wrap algorithm was applied to fit. Finally, the fitted template model can automatically measure the length through in-plane deformation measurements [24].

4. Experiment

Korean human standard information is used for experiment database. The result of an experiment with in-plane deformation measurement is in Figure 11 and Table 3. The error between the result data from the proposed algorithm and a real measured foot size is less than 0.5 mm. In Figure 9, as the level of the surface subdivision is higher, the number of vertices increased. We experiment with increasing the number of vertices. The post processing with surface subdivision level 3 is appropriate because the performance of the experiment with 3 or more levels are not well improved but it has high complexity.

Our proposed method of measuring template model with in-plane deformation is an accurate method because reflecting real foot characteristics with 3D foot shape. So the performance of foot size measurement is higher than the previous foot size

Table 3. Ground truth and in-plane deformation measurement comparison result (unit, mm)

	Method	Foot length	Foot width	Height of instep
Model 1	Ground truth	264	103	63
	Proposed method	263.8	103.3	63.5
	Point to point method	263.8	103.3	63.5
Model 2	Ground truth	251	95	52
	Proposed method	251.1	95.6	51.3
	Point to point method	250.4	94.1	52.4
Model 3	Ground truth	276	113	69
	Proposed method	276.2	113.4	69.4
	Point to point method	275.1	112.6	69.5
Model 4	Ground truth	266.1	109	65.6
	Proposed method	266.3	109.1	65.9
	Point to point method	267	101.4	63.5
Model 5	Ground truth	255.1	90.7	63
	Proposed method	255.1	90.3	63.5
	Point to point method	254.3	91.6	64.3

measure model. The generated model with in-plane deformation are good at reflecting real foot characteristics with 3D foot shape. So the performance of foot size measurement is higher than the previous foot size measure model.

5. Conclusions

In this study, accurate foot size measurement method with 3D foot scanning data is proposed. Using the proposed measurement method, a customers foot size data is easily analyzed and can be used as basic data for making custom shoes. The pre-

Figure 11. Foot measurement results using in-plane deformation measurement.

vious foot size measurement methods are designed by a shoe last 3D model using CAD and the way to depend on the experienced technicians. In the former case, the basic model of shoe last is generated from fixed size, for example, the size is 235 mm in woman case. Other sizes of the shoe lasting model is generated from basis model with proportioning. This method has the problem that it is hard to reflect the characteristics of individual foot, so the customer can easily feel uncomfortable to wear the shoes. In the latter case, the technician makes a shoe lasting model by hand. This method takes a long time to make a shoe lasting model. Also, due to making handcrafted lasting model from the aesthetic point of view, it is possible to feel the pain and fatigue when wearing the shoes long time. To solve this problem, the proposed method of 3D foot scanning data can give a solution that makes comfortable shoes. The proposed method shows better performance to estimate a foot size compared with the point to point method. In future works, the evaluation with the real shoes that manufactured from the proposed method will proceed to verify the performance of the 3D foot model.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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