Locating Anatomical Points on Foot from 3D Point Cloud Data

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Abstract

Algorithms are proposed to automatically locate the foot anatomical points from scanned 3D point data based on a novel method that uses the pternion point for foot alignment, whereby variations in the different dimensions are minimized. The detected foot malleoli and arch point are used to classify the foot type. Based on the automatically detected anatomical points, 9 foot dimensions of 10 participants were determined and compared with manual measurements.

1. Introduction

Foot dimensions can be used to assess the degree of fit between feet and the footwear worn [1], and can also be used to generate the 3D shapes of feet [2]. The different dimensions are based on anatomical points or landmarks, which are generally defined differently by different researchers and organizations [3-4]. Traditionally, the simpler dimensions are measured using a ruler, tape, caliper, or special devices such as the Brannock, Ritz Stick, Scholl, etc. With the development of 3D digitalization and computer techniques, automatic foot measurement is possible even though locating anatomical positions may be better performed through palpation.

After the anatomical or surface points are manually determined, researchers have used various techniques to obtain the 3D coordinates of those manually determined points [5-8]. Typically, the 3D point data are then used to calculate heights, lengths, widths and angles [6,8]. Others such as Luximon et al [9] have used a limited set of landmarks to even model the shape of the foot. Point cloud, mesh or surfaces of objects can be modeled [10-11] even though the surface characteristics may not be perfect. If a set of representative points that describe the surface can be identified, the modeling errors can be minimized. However, Yahara et al [12] has shown that it is difficult to locate the anatomical points using algorithms. Some researchers [13-15] have proposed methods to detect characteristics such as edges from point cloud, mesh or surface of objects, but these are not always anatomical points on the surface of a person.

Contrary to previous studies, this paper proposes a series of algorithms to locate the anatomical positions on the foot surface from 3D point cloud data without any manual intervention. The detected anatomical points are then used for aligning the foot, classifying the foot and lastly obtaining the measurements of critical dimensions that can then be used for fitting footwear.

2. Data acquisition and foot alignment

The YETI foot scanner [16] was used to obtain 3D point cloud of the foot surface. The scanner manufacturer has specified the accuracy of the scanner to be ±0.5 mm. The total number of points in the point cloud depends on the length of foot, since the scan sections are set to be 1 mm apart and each section has 360 points.

Dimensional data are sensitive to the reference coordinate system and hence registration is required in order to compare the data from different sources. In manual measurements, such as when using the Brannock device (www.brannock.com), the rearfoot is placed in the heel cup and the arch length pointer is slid forward so that the inside curve of the pointer matches the ball joint of the foot. Then the width measuring bar is slid firmly to touch the lateral side of the foot to uniquely locate the foot. Liu et al [6] adopted a jig consisting of two perpendicular plastic bars with three little recess holes to define the reference frame (Figure 1). Prior to digitizing, the foot is positioned such that the first metatarsal joint and centre of the heel on the medial side touches the long bar (x-axis), while the rear part of the heel touches the short bar (y-axis). In this way, the authors established an anatomical coordinate system that can be used for measuring the foot dimensions.

Figure 1. Axis system used by Liu et al. [6]

In our study, manual measurements were taken using a template that resembles a heel cup. The heel part of the foot was positioned such that the heel was symmetrically located on a chosen curve, while the posterior point of heel or pternion touched the end wall of the measuring device. A clear transparency was used to align the foot on the scanner as a first approximation [17]. More accurate registration was performed using the 3D point data. Similar to the manual alignment, the algorithm for automatic alignment, including pternion location and foot rotation was as follows:

(1) Select the points no more than 25mm height from the standing platform, so that the points representing the foot malleoli can be excluded.

(2) Project the selected points on to the XY plane, and find two border points (point with the minimum Y value and point with the maximum Y value) of every scanned section.

(3) Fit a second degree polynomial $x = a * y^2 + b * y + c$ for the border points from the pternion to 25mm from it along X-axis (Figure 2(a)) using the least squares method in order to generate the heel curve (Figure 2(b)).

(4) Calculate the pternion point, $\left((4*a*c - b^2) / (4*a), -b / (2*a) \right)$, as illustrated in Figure 2(b).

(5) Find the center of the two border points of every section.

(6) Fit a line $y = a * x + b$ for all points between pternion and 20% of foot length using the least squares method.

(7) Rotate the point cloud around pternion in XY plane by $-\tan^{-1}(a)$ to make the fitted center line parallel with X-axis, as shown in Figure 2(c). In this process, the border points and center points are transformed from the gray colored points to the black points.

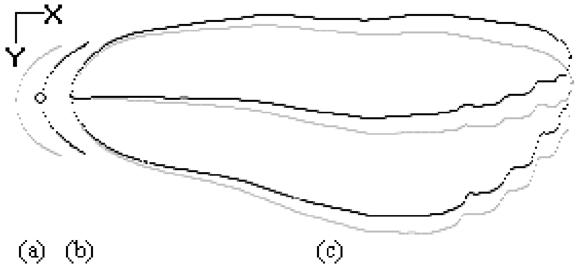

Figure 2. Automatic foot alignment (a) border points (b) heel curve (c) foot before and after alignment.

3. Type classification

Foot classifications are generally based on arch height. The wet foot test, where a visible footprint is left, is a useful way to check if a foot has a low, normal or high arch. The flat foot has a low arch and leaves an imprint that looks like the complete sole of the foot. The normal foot has a “normal” arch and leaves an imprint that shows the forefoot and heel connected by a “normal” or wide band. The high arched foot leaves an imprint with a narrow band connecting the forefoot and heel.

In this study, a method to classify feet using 3D point cloud data is proposed that can replace the manual 2D wet foot method. To implement this method, the foot malleoli should be located first, and the location algorithm is as follows:

(1) Project the point cloud data on to the XZ plane, and find two border points (point with minimum Z value and point with maximum Z value) of every scanned section.

(2) Calculate the average of the first bottom border point and the bottom border point that starts to touch the platform, and take it as the heel point.

(3) Calculate the 2D distance from the heel point to each top border point from the start of the vamp to 50% of foot length.

(4) Take the top border point with the minimum distance as the ankle point, as illustrated in Figure 3(a).

(5) From the intersection points between the point cloud and the plane across the ankle point, which is parallel with the XY plane, find the two candidates for the foot malleoli as the point with minimum Y value and the point with maximum Y value.

(6) Define two areas with these two points as the center points such that the projections of the two areas on XZ plane are squares with each side of length 15mm.

(7) From the two areas find the foot malleoli as the point with minimum Y value and the point with maximum Y value, as shown in Figures 3(b) and 3(c).

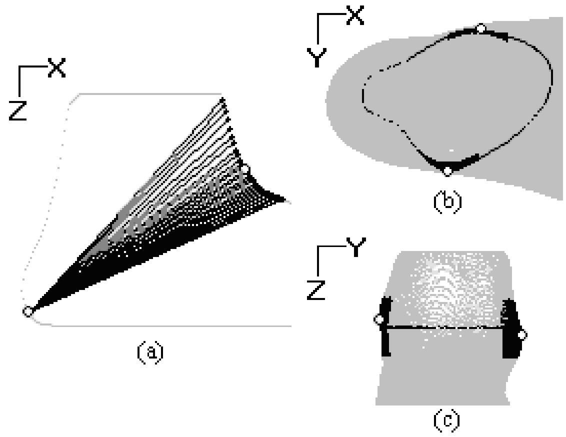

Figure 3. Location of foot malleoli

After the arch point is detected, the proposed vertical and horizontal ratio may be used to classify feet. The proposed classification algorithm is as follows:

(1) Select the points between 15% and 30% of foot width from the medial side of the foot, and divide them equally into 10 sections along Y-axis.

(2) From the points of every section, find the top-most point in the bottom curve, as shown in the upper left of Figure 4.

(3) Find the mean of the 10 top-most points from 10 sections as the arch point, as shown in the upper right of Figure 4.

(4) Let the distance between the foot platform and the mean of two foot malleoli points along Z-axis be $D\_malleoli$. Let the distance between foot platform and the arch point along the Z-axis be D_arch as shown in the top of Figure 4.

(5) Calculate the vertical ratio, $R\_vertical = D\_arch / D\_malleoli$. A foot with a higher arch will have a higher vertical ratio.

(6) Select the points no more than 3% foot height from the platform, as shown in the lower left of Figure 4.

(7) From those points, find the point with minimum Y value and the point with maximum Y value while they have the same X value as the arch point, and take the difference between the two points along the Y-axis as $D\_3\%$.

(8) Select the points no more than 25mm height from the platform, as shown in the lower right of Figure 4.

(9) From those points, find the point with minimum Y value and the point with maximum Y value while they have the same X value as the arch point, and take the difference between the two points along Y-axis as D_25.

(10) Calculate the horizontal ratio, $R\_horizontal = (D\_25 - D\_3\%) / D\_25$. Feet with a higher arch will have a higher horizontal ratio.

(11) The parameter that can be used for type classification can then be defined as $R = R\_vertical * R\_horizontal$, with higher arches having a higher parameter R.

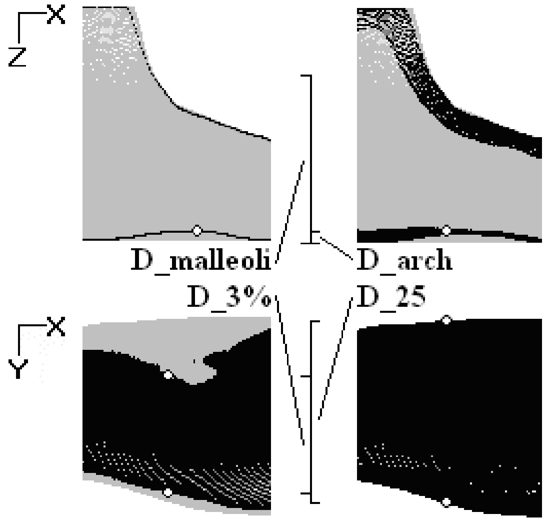

Figure 4. Parameters for type classification

4. Dimensional measurements

Foot dimensions measured in our project include lengths along the X-axis, widths along the Y-axis and heights along the Z-axis. Their definitions are as follows:

(1) Lengths

Foot length is the distance between pternion and the point with maximum X value.

Heel to 5th toe is the distance between pternion and the tip of the fifth toe.

Heel to medial malleolus is the distance between pternion and the medial malleolus.

Heel to lateral malleolus is the distance between pternion and the lateral malleolus.

(2) Widths

Foot width is the distance between the point with minimum Y value and the point with maximum Y value.

Mid-foot width is the distance between the point with minimum Y value and the point with maximum Y value at 50% of foot length from pternion.

Bimalleolar width is the distance between the medial malleolus and the lateral malleolus.

(3) Heights

Medial malleolus height is the distance between the platform and the medial malleolus.

Lateral malleolus height is the distance between the platform and the lateral malleolus.

Besides the aforementioned anatomical positions, tip of the fifth toe is also detected automatically, and the location algorithm is as follows:

(1) Project the point cloud to the XY plane, and find the two border points (point with minimum Y value and point with maximum Y value) from every section, as shown in Figure 5.

(2) Select the border points on the lateral side and more than 60% of foot length from pternion.

(3) From them, find the 1st border point, which is on the ith scanned section.

(4) Find the border point whose difference with its previous border point in Y value is no less than 0.1mm, and take it as the 2nd border point.

(5) Repeat Step 4 to find the 3rd, 4th and 5th border points.

(6) Fit a straight line $y = a * x + b$ for these 5 points using the least squares method, and take a as the first gradient value.

(7) Take the border point of the $(i+1)th$ section as the 1st border point, and update the section number i as $i = i + 1$.

(8) Find the 2nd, 3rd, 4th and 5th border points in the same way as Step 4 and Step 5.

(9) Fit a straight line $y = a * x + b$ for these 5 points using the least squares method and then calculate the difference between a and the first gradient value.

(10) Repeat steps 7, 8 and 9 until the difference between a and the first gradient value is more than 0.5, at which condition it can be assumed that the lateral side of the 5th toe has been reached.

(11) Repeat steps 7, 8 and 9 until a is less than the gradient value of the fitted straight line from the previous iteration, which indicates that the tip of the 5th toe is reached, as illustrated in Figure 5.

Figure 5. Detection of the 5th toe

The algorithms for dimensional measurements [17] were evaluated by comparing the dimensions obtained (SM) with manual measurements (MM) of 10 participants (Table 1). The differences (mean value, max value, min value and standard deviation) between MM and SM are relatively small, indicating that the proposed algorithms can be used as long as the differences are acceptable for footwear manufacture.

5. Conclusion

Anatomical positions, such as pternion point, foot malleoli, arch point, tip of toe, etc., can be located automatically from 3D point cloud of foot surface with no additional landmarks, and algorithms are proposed for such an evaluation.

A method for foot alignment is also presented to place the foot on the center line of the platform, which helps the detection of anatomical points. A method for foot type classification is also proposed, using 3D information, whereas the traditional wet foot test is a manual 2D approach. Methods for nine dimensional measurements including lengths, widths and heights are described, and results of the simulated measurements are compared with those of the manual measurements. The approaches and algorithms presented may be helpful for custom shoe manufacture.

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Table 1. Descriptive statistics of dimensional measurements obtained from MM and SM (unit: mm)

Foot Measurements	Mean		Max		Min		Std. Dev.	
	MM	SM	MM	SM	MM	SM	MM	SM
Foot length	250.6	250.2	274	273	231	231	12.7	13.1
Heel to 5th toe	199.7	198.9	212	214	179	179	10.5	11.3
Heel to medial malleolus	61.4	61.7	71	73	51	53	5.8	6.3
Heel to lateral malleolus	53.0	52.3	60	60	43	43	4.9	4.9
Foot width	97.2	96.2	106	105	87	87	6.1	5.8
Mid-foot width	91.6	90.2	104	101	80	80	6.7	6.4
Bimalleolar width	68.5	67.4	78	75	61	60	4.7	4.6
Medial malleolus height	76.6	76.9	87	87	69	70	4.7	4.9
Lateral malleolus height	65.7	65.2	75	74	54	55	6.2	5.6