A Human Surface Prediction Model Based on Linear Anthropometry

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***Abstract*—Body information is needed in product design, medical, archaeological, forensic and many other disciplines. Therefore, anthropometric studies and databases have been developed. Anthropometric measures are useful to some extent, but due to technological innovations, there is a shift toward surface anatomy. As a result, there is a need to shift from linear anthropometry tables to surface model databases. This study provides a general modelling technique, to convert linear anthropometry to complex surface model using recursive regression equations technique (RRET) and scaling technique. The technique makes use of similarities and differences between people. The similarities or standard shape are represented by averaging, while the differences are captured by using anthropometric measures. In order to build the surface model, some scanned data is needed for generating the standard shape. Using RRET techniques a few anthropometric measures are used to predict more anthropometric measures that are then used to scale the standard shape in order to generate a predicted 3D shape. Results indicate that the prediction model is accurate to few millimeters. This level of error is acceptable in different applications. This technique can be applied to generate 3D shape from anthropometry of external shape as well as internal organs. This model is essential to convert the existing large scale anthropometric databases into surface models. It can be applied to product design, sizing and grading, reconstructive surgery, forensic, anthropology and other fields.**

Keywords-anthropometry, surface antropometry, digital human model, recursive regression equation.

I. INTRODUCTION

Shape modelling from linear anthropometry is a new field of study with important applications [1]. It takes advantages of anthropometry, is an old field of study dating back to Renaissance [1,2] and merging it with new technologies to create human shape models. Luximon and Chao [1] proposed a basic model for shape modelling from linear anthropometry. This paper expands the previous paper to including validation of the model on foot model.

Anthropometry emerged in the nineteenth century largely by German investigators in the physical anthropology discipline, while they needed to study the quantitative description of the human body reliably [3,4]. Anthropometry techniques can be applied to humans as well as plants and animal. According to the World Health Organization [5], Anthropometry is a method to assess size proportion and composition of the human body. Some of anthropometric measures include weight, lengths (e.g., foot length), widths (e.g., Head width), heights (e.g., Stature), girths (e.g., Chest Girth), angles (e.g., hand flexion angle), and calculated indexes (e.g., Body mass Index (BMI)). Anthropometric studies are carried out internationally because it requires inexpensive, non-invasive simple tools such as rulers, tapes, callipers and goniometers. These tools can be easily transported to any location. World Health Organization [5], uses anthropometric measures to assess medical conditions of people by comparing with average values.

The basic anthropometric techniques developed during the nineteenth century are still used today [3]. The different anthropometric measures are represented in percentile values in anthropometric tables [2,6] and since the values are statistical values, they cannot be combined to create a single human body [7]. The anthropometric percentage values are generally used to compare different populations and to design for a given population. Anthropometric data has been widely used in fields ranging from engineering to arts. It has been widely used in product and workplace design [7,8]to determine sizing, grading, proper fit and comfortable design based on different body sizes and proportions. It has been used in forensic investigation [9,10] for better estimation and narrow down the forensic search. It has been used in growth and nutrition evaluation [5,11] worldwide to check malnutrition, proper growth and early detection of growth and nutrition problems. It has been used in medicine [12-14] and reconstructive surgery for screening problem, evaluations and corrections. It has been used in archaeology and cultural studies [15-17] to identification and classification. It has been used in many other studies including sports science and fitness evaluation [18-20], since the body proportion and composition is different for different sports.

Even now, anthropometric studies are carried out because of its non-invasiveness [5], inexpensiveness [4], simplicity [5], portability [21] and reliability [22]. Furthermore, as the anthropometric dimensions vary among different groups of population, anthropometric tables have been developed based on age, race, region, and occupation [5]. Anthropometric studies are very important; however, in many applications, anthropometric data alone is not sufficient. Surface geometry is required. Recently, due to technological innovations, it is possible to acquire whole body or selected body parts surface data.

Surface model describe the size and shape as well as the 3D surface geometry of the human body [23]. It is possible to combine surface scan data and internal measurements [24], thus anthropometric techniques can be used to find the size, shape and proportion of the external as well as internal structures of the body. Thus in this modern world, data collected from Magnetic Resonance Imaging (MRI), Computed Tomography (CT) or Computed Aided Tomography (CAT), sound, optical (laser or structured light) or any scanning devices can be used to create surface model of the external as well as the internal structures of the body. Since surface model provides information on the complex surfaces of the human parts, in addition to the common linear anthropometry measures, it can be used for many applications such as planning and assessment of facial surgery, design and manufacture of implants and prostheses, facial reconstruction in forensic applications, archaeology, psychology, genetics, and comparative and evolutionary anatomy [25]. In addition, there are growing uses of synthesize 3D digital animated images of human models in science fiction movies and 3D digital dummies for equipment testing [26]. Although surface model seems to be very useful, it has several disadvantages. Surface scanning equipment is relatively expensive and is not widely available. It is relatively difficult to operate and require special skilled technicians to capture the dynamic and complex body shape. Furthermore, the data obtained from the scanning equipment requires additional processing and statistical data analyses are not trivial resulting in only few large-scale studies. Still, surface model is very useful for different applications and there is a need to simplify the method to acquire surface model, reduce the cost of equipments and develop surface model databases. In this study, a method to predict accurately the surface model by using simple, reliable and non-invasive linear anthropometry measurement techniques are proposed. As a result, the use of expensive surface scanning devices is minimized to model building and simple cost effective linear anthropometry measures can be used for surface model prediction.

II. Related Work

The basic technique for 3D Surface (Surface model) prediction is to determine the similarities and then modify based on differences (Figure 1). For example, although we know there are variations in shape and sizes of face, we can easily know a human face from other body parts or other animals. There are similarities between faces. The similarities can be grouped based on age, gender, and culture. The differences are related to some dimensions which can be captured based on anthropometric studies. Surface model prediction involves spline curve and surface fitting [27], recursive regression equations [28,29] and scaling techniques [28]. In this study, a general prediction model with several variations is provided so that more body parts can be predicted using this simple method. Then, an example related to foot prediction is discussed. The main parts are data pre-processing and standard shape generation; model development; surface model prediction; and prediction model validation.

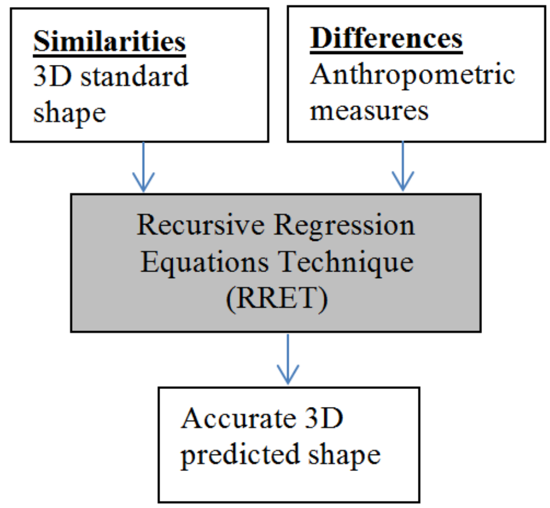

Figure 1. Method for surface prediction model.

The paper is organization in five major sections in order to develop a general surface model from linear anthropometry. These include data pre-processing; standard shape generation; model development; surface model prediction; and validation. During the model building a generic model method is used that can be applied to all body parts. For the validation, an accurate foot shape model prediction has been developed and error calculated. The conclusion and future work provide the importance of this method and its future application are further emphasized.

III. Data Pre-Processing

Most scanning technologies have error resulting in missing data or noisy data points. The flow chart for data preprocessing is shown in Figure 2. The steps involve surface data acquisition. Then the data is 'cleaned'. Human body shape has variations hence, there is a need for careful alignment of the data. The cleaned and alignment data provide a representation of the body shape, which may be affected by accuracy of scanning system, but in this study this data is considered the 'true' shape.

A. 3D scanning

For 3D scanning, any type of scanner to capture the external shape of the body or any specific part can be used. Figure 3 shows a whole body scanner at the Hong Kong polytechnic university. There are also specific scanners for head [29] and foot [28], since the whole body scanner does not provide accurate data for these extremities (Figure 4). Since a general method to build the prediction model has been proposed, some changes may be required to adopt for specific parts. It is assumed that N_s number of participants is used for the model development. In this formulation, left and right sides of the parts are not distinguished, but during the formation of a specific part, the differences between left and right sides can be included as in Luximon and Goonetilleke [29]. For the i^{th} participant the scanned part has P_{si} number of points. The points are p_{ik} (where $i = 1,...,N_s$; $k = 1,..., P_{si}$). The coordinates of the point p_{ik} is (x_{ik}, y_{ik}, z_{ik}). The point cloud from the scanner is unstructured and includes hundreds of thousands of data points.

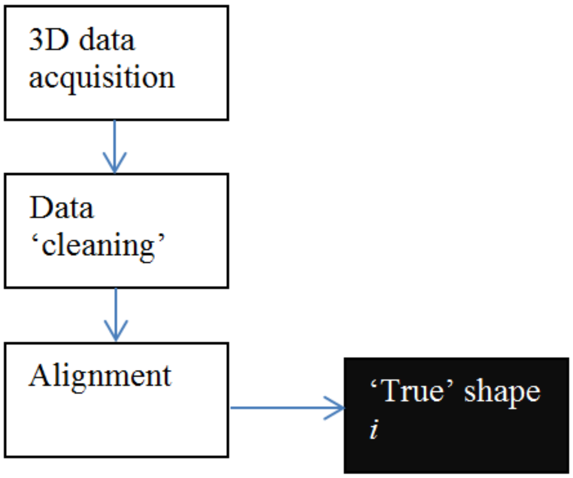

Figure 2. Flow chart for data preprocessing.

Figure 3. TC[2] whole body scanner (www.itc.polyu.edu.hk).

Figure 4. Laser scanned data.

B. Data cleaning

Since scanning is usually disturbed by noises arising from various sources, the noise can be cleaned manually using software such as Rapidform (www.rapidform.com) or using algorithm methods such as Adaptive Moving Least Squares method [30]. Furthermore, there are cases of missing data that are filled using commercial software Rapidform2006 software. The points after data cleaning is represented by p_{ik} (where $i = 1,...,N_s$; $k= 1,...,P_i$). P_i is the number of points.

C. Alignment

Since all the scanned part might not be aligned in the same reference axis, all the parts have to be aligned on a consistent axis. The axis of alignment can be based on some anthropometric landmarks, commonly used axis or based on mathematical and statistical methods (such as principle component methods). For example, for the case of the human foot, heel centre line is commonly used [31]. For the arm, leg and body principal component can be used. For head data, eye and ear landmarks can be used for alignment [32]. After alignment, the coordinates of point ${}_ap_{ik}$ is (${}_ax_{ik}$,${}_ay_{ik}$,${}_az_{ik}$) as shown in Figure 5. The part is aligned to have the axis with the highest variation along the Z-axis.

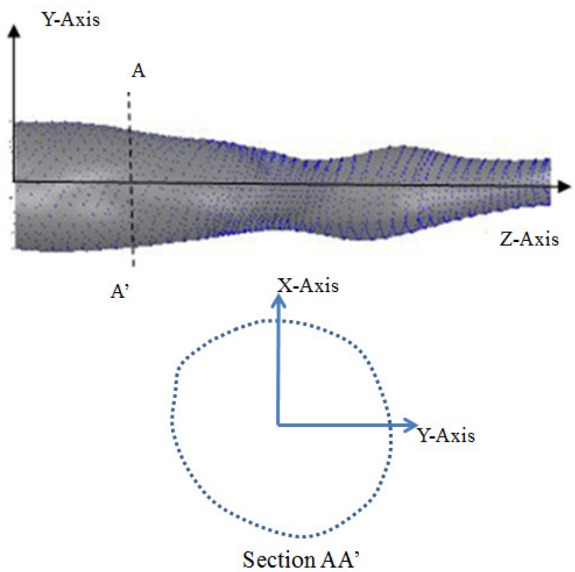

Figure 5. Aignment.

IV. STANDARD SHAPE GENERATION

In order to generate the standard shape, first the scanned data that has been cleaned and aligned ('true' shape) is sectioned and sampled (Figure 6). Sampling creates same number of points for all participants. The participants' data are then averaged to create a standard shape.

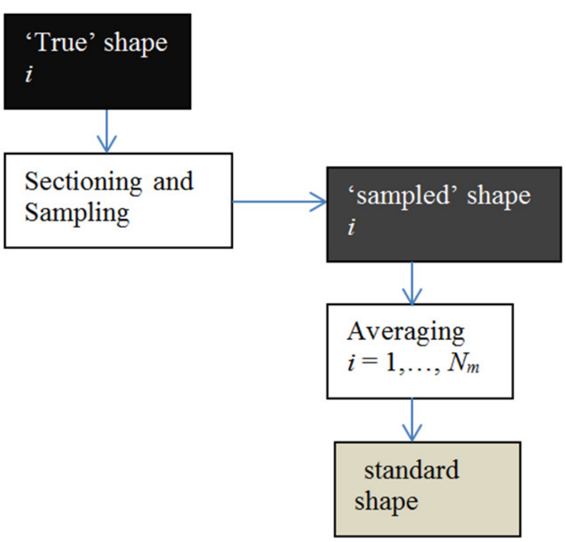

Figure 6. Flow chart to create standard shape.

A. *Sectioning and sampling*

During sampling fixed number of points is created for all participants. Different sampling methods can be used. When using cylindrical coordinate system, the part can be sectioned along the *Z*-Axis, which represents the maximum variation (Figure 7).

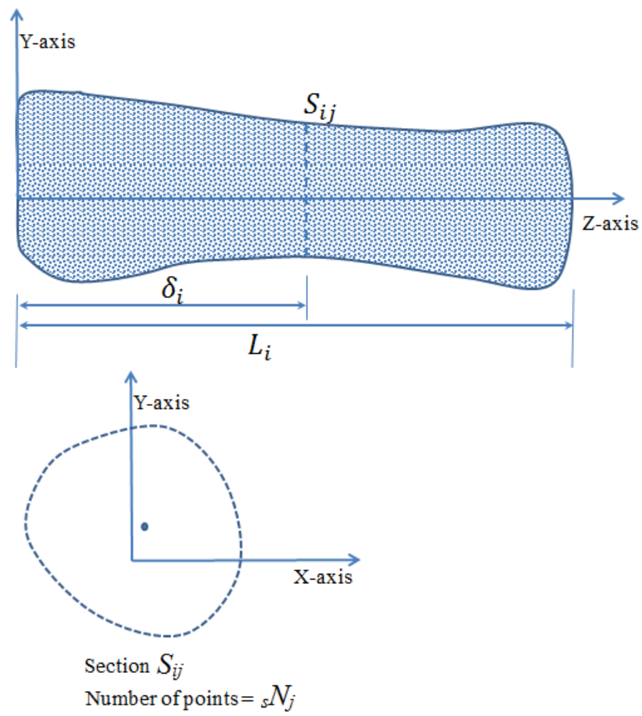

Figure 7. Sectioning and sampling in cylindrical coordinate system.

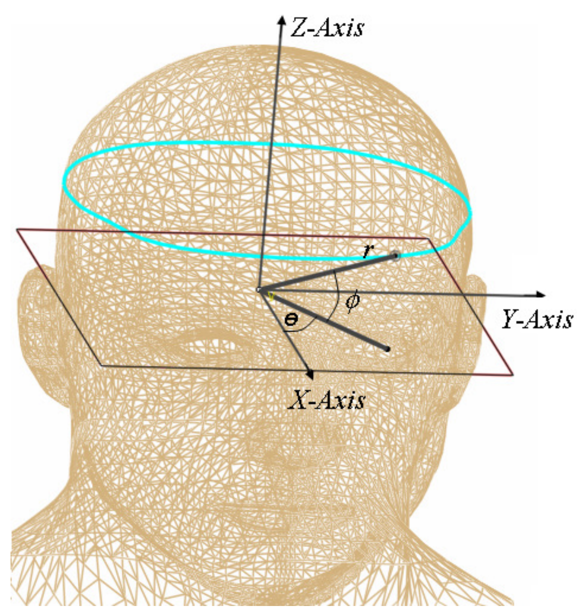

Figure 8. Sectioning and sampling in spherical coordinate system.

Cylindrical coordinate system can be used for most body parts. Once the part has been aligned, cross sections are extracted perpendicular to the *Z*-axis, called the 'main' axis. The length of the aligned part along the main axis is L_i (where $i = 1,...,N_s$). Cross-sections perpendicular to the main axis at δ_j (where j = 1,...,N_{sec}) of L_i are extracted, where N_{sec} is the total number of cross-sections extracted (Figure 7). δ_j is monotonically increasing with j. The separation between the sampled cross sections needs not be uniform, but it has to be consistent between the different participants. The extracted sections are S_{ij}(where i = 1,..., N_s; j = 1,...,N_{sec}) and the z-value for the sections are given by Equation (1). Then, for each section, a fixed number of points are extracted using different sampling methods [30]. When using spherical coordinate system, the shape can be sectioned based on angle (Figure 8). Spherical coordinate system is more appropriate for the head and face model [32].

Once the shape has been sectioned either using cylindrical coordinate system or spherical coordinate system, data points are extracted from the sections. Uniform polar sampling at β degrees intervals (Figure 9) and uniform sampling at δ mm along the edge (Figure 10) are common methods. The number of points for section S_{ij} is $_sN_j$. For participant i, the number of points is same. The points after sampling are $_sp_{ijk}$,where i = 1,..., N_s; j = 1,...,N_{sec}; j= 1,...,$_sN_j$.

$$_sz_{ij} = \delta_j * L_i \quad (1)$$

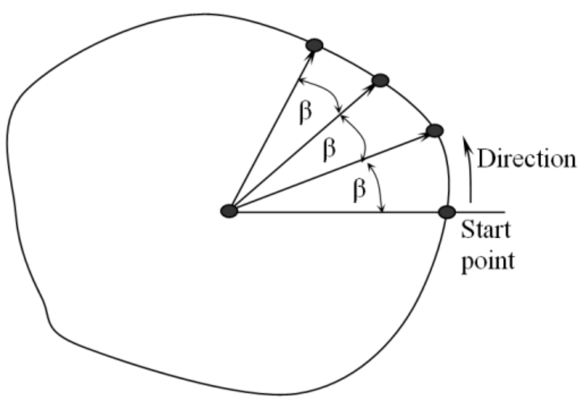

Figure 9. Polar sampling.

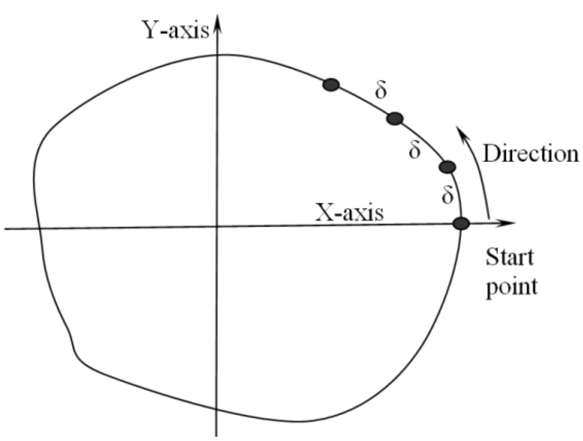

Figure 10. Uniform sampling.

B. Standard shape

Some of the part shape data can be used to generate the model, while other shape data can be used for model validation. Assuming that the standardmodel is generated using part shape data of N_m subjects where N_m<N_s. The coordinates of the point used to generate the standard part are ($_sx_{ijk}$, $_sy_{ijk}$, $_sy_{ijk}$) where where i = 1,...,N_m; j= 1,...,N_{sec}; j= 1,..., sN_j. The standard shape is the representation of the given part for a given population. There can be several methods to generate the standard shape, based on different statistical methods such as geometric mean, arithmetic mean, mode, median etc. Equations (2), (3), and (4) show the x, y, and z coordinates of the standard shape when arithmetic mean is used. The standard foot shape has N_{sec} number of sections. The standard shape represents the shape of a given population and it can be stored in a database.

$$\bar{x}_{jk} = \frac{1}{N_m}\sum_{i=1}^{N_m} {}_sx_{ijk} \quad (2)$$

$$\bar{y}_{jk} = \frac{1}{N_m}\sum_{i=1}^{N_m} {}_sy_{ijk} \quad (3)$$

$$\bar{z}_{jk} = \frac{1}{N_m}\sum_{i=1}^{N_m} {}_sz_{ijk} \quad (4)$$

V. MODEL DEVELOPMENT

While the standard shape is being developed, parameters of each section can be extracted from the cross sections of the sampled shape. The flow chart for the RRET model development is shown in Figure 11. The number of parameters per section will determine the accuracy of the model. Parameters for a section can be length and widths. Then regression equations are developed to generate equation between parameter of one section to another section.

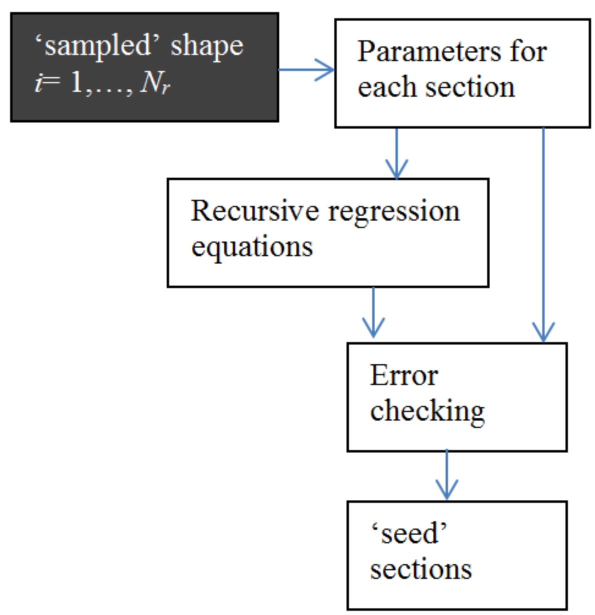

Figure 11. Flow chart for model development.

Since there are many equations between the parameters, if we know the value of one parameter we will be able to predict the value of other parameters. Hence there is a need to determine the best starting parameter or 'seed' parameter.

A. *Parametization*

Each cross section can be parameterized using several anthropometric variables. Figure 12 shows some of the parameters that can be used, such as maximum *y* deviation(H^+), minimum *y* deviation(H^-), maximum *x* deviation(W^+), minimum *x* deviation(W^-), height (*H*), width (*W*) and radius (R_θ) at θ degrees and circumference (C). The number of parameterization will determine the accuracy and complexity of the model. Furthermore, anthropometric studies are needed to determine the importance of the different parameters. Goonetilleke et al. [33] and Luximon and Goonetilleke [34] have used principle component and factor analysis to find the relative importance of different foot related parameters.

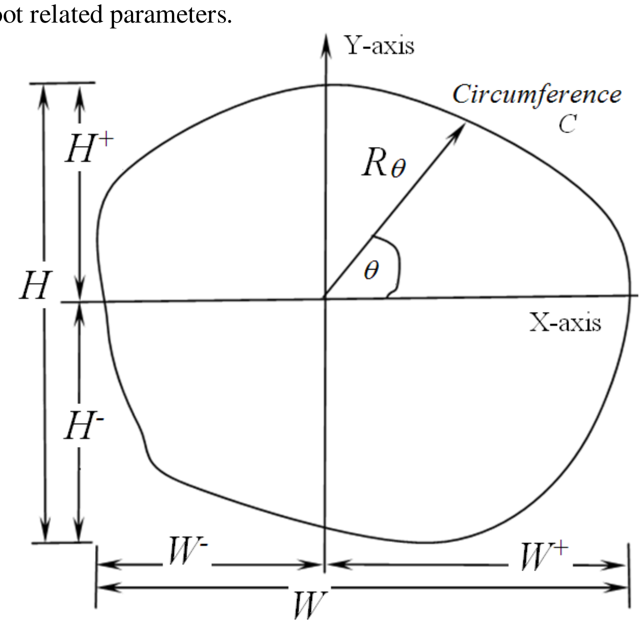

Figure 12. Anthropometric parametization.

B. *Recursive regression equation*

The purpose of the recursive regression equation is to find the relationship of the anthropometric dimensions of all the sections of the part given the anthropometric dimension of one section. For example, one regression equation is build from anthropometric measure height (H) at section *i* and height at section *j*. The R^2 values are also recorded. If we have N_a anthropometric measures and N_{sec} sections, we can generate N_a x (N_{sec}- 1) equations if we consider consecutive sections. Using these regressions equations, knowledge of one set of values for N_a anthropometric measures ('seed section), we will be able to predict all the N_a x N_{sec} anthropometric measure values.

C. *'Seed' section*

There are some ways to find the best 'seed' section and build the regression equations. Luximon and Goonetilleke [29] developed linear regression equations between the anthropometric measures of adjacent sections. The best 'seed' section was found by using different 'seed' section to predict the anthropometric measures and choosing section that provided the highest correlation between the original set of anthropometric measures. For complex models N_a x (N_{sec} - 1) x (N_{sec} -2) equations may be needed. This problem can be solved using travelling salesman method [34]. The salesman need to travel between cities (1,2,…,8). The traveling distance between each city is given. The salesman needs to travel all the cities without repetition and take the least distance. In the case of the proposed method, the distance can be substituted by $1/R^2$.

VI. SURFACE MODEL PREDICTION

Using few anthropometric measures, the parameters of the seed section is predicted. The flow chart for shape prediction is shown in Figure 13. Using the parameter values of the seed section and the linear regression equations between the parameter of the sections, the parameter values of all the sections are predicted recursively. The predicted parameter values are used to scale the sections of the standard shape creating a predicted shape.

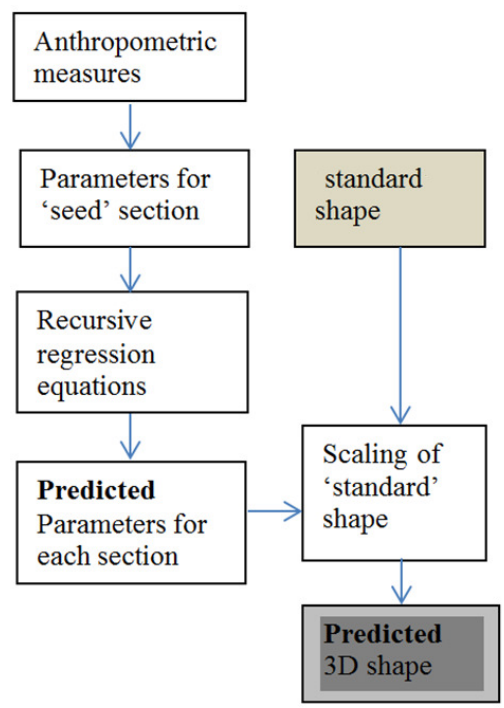

Figure 13. Shape prediction flow chart.

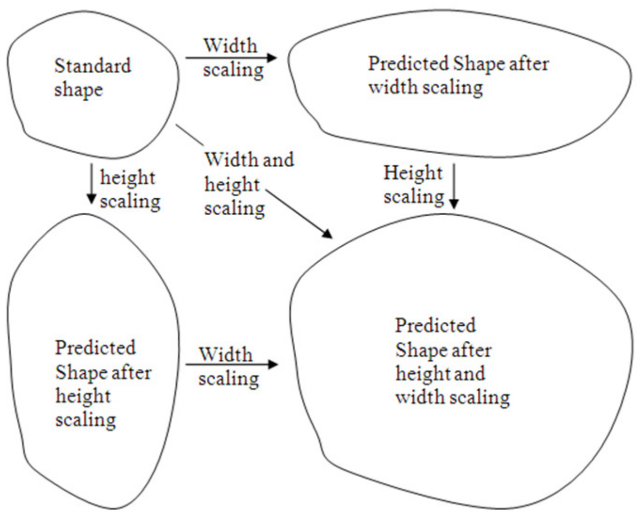

Figure 14. Scaling.

The model can be validated using 3D scanned data of a different set of N_v participants where N_v<N_s and N_v+ N_m= N_s. The model validation involves measurement or extraction of parameters of the 'seed' section, prediction of parameters of all the section based on the 'seed' section, scaling of the standard shape. Once the shape is predicted, the prediction error can be calculated when we compare it with the original data. Once we have the predicted parameters of the sections, the standard shape has to be scaled. There can be different scaling methods based on the different parameters. Luximon and Goonetilleke [29] have discussed proportional scaling. If the parameters are orthogonal (such as width and height) then the sections can be scaled independently (Figure 14). However, if the parameters are not orthogonal different scaling methods need to be developed. After scaling, the predicted shape has coordinates ($_px_{ijk}$, $_py_{ijk}$, $_pz_{ijk}$) where i = 1,...,N_v; j= 1,..., N_{sec}; k= 1,...,sN_j.

VII. PREDICTION MODEL VALIDATION

The flow chart for the validation of the predicted model is shown in Figure 15. The main component is the comparison of the 'true' shape with the predicted shape. For participant i the original shape after alignment has coordinates ($_ax_{ik}$,$_ay_{ik}$,$_az_{ik}$), where i = 1,...,N_v; k= 1,...,P_i. The coordinates of the predicted foot is ($_px_{ijk}$, $_py_{ijk}$, $_pz_{ijk}$) where i = 1,...,N_v; j= 1,..., N_{sec}; k= 1,...,sN_j.The error is computed based on the shortest distance [Equation (5)] from the predicted foot to the real foot [35]. The error can have signed (+ or -) to indicate either the predicted point is inside or outside the original shape. Different statistics can easily be calculated to compare prediction accuracy. Error plots are also useful to show the error distribution at different regions [29].

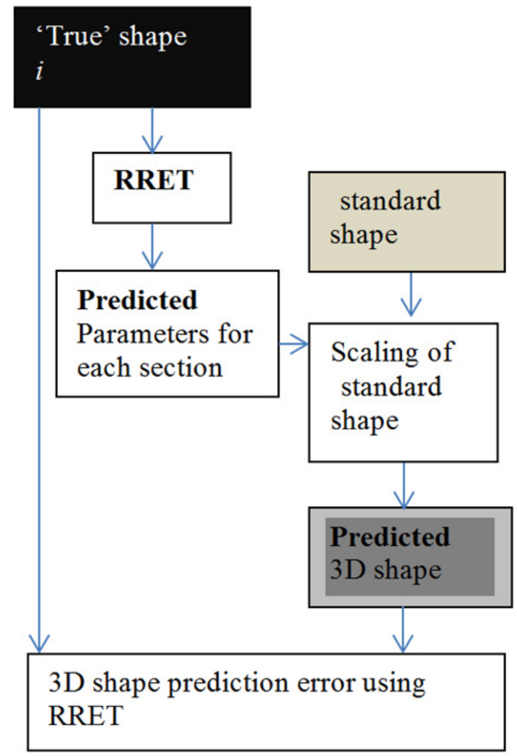

Figure 15. Error checking and validation.

$$e_{ijk} = min\left\{\sqrt{\begin{matrix}\left({}_px_{ijk} - {}_ax_{il}\right)^2 + \left({}_py_{ijk} - {}_ay_{il}\right)^2 \\ +\left({}_pzy_{ijk} - {}_ayz_{il}\right)^2\end{matrix}}\right\}$$

where i = 1,...,N_v; j= 1,..., N_{sec}; k= 1,..., sN_j; l= 1,...,P_i. (5)

VIII. FOOT SHAPE MODELING

The accuracy of the RRET technique is illustrated by using foot modeling as an example. The data was collected using a foot scanner (Figure 16) shows the scanned foot data. P_i is about 100,000 points. The sampled foot is shown in Figure 17. The foot is sectioned at 1% interval creating 99 sections. The extracted sections for participant i are S_{ij} (where j = 1,...,99). For each section points are sampled at 1degree interval based on polar coordinate sampling. The points after sampling are $_sp_{ijk}$, where j = 1,...,99; j= 1,..., 360.

Using data from 40 participants, a standard foot shape was created (Figure 18). The average age of the participants used for generating the standard shape was 22 years (standard deviation = 3.6). The average weight was 62.8 Kg (standard deviation = 8.5). The average stature was 171 cm (standard deviation = 5.5). The average foot length was 245mm (standard deviation = 11mm). The average foot width was 99 mm (standard deviation = 5mm).

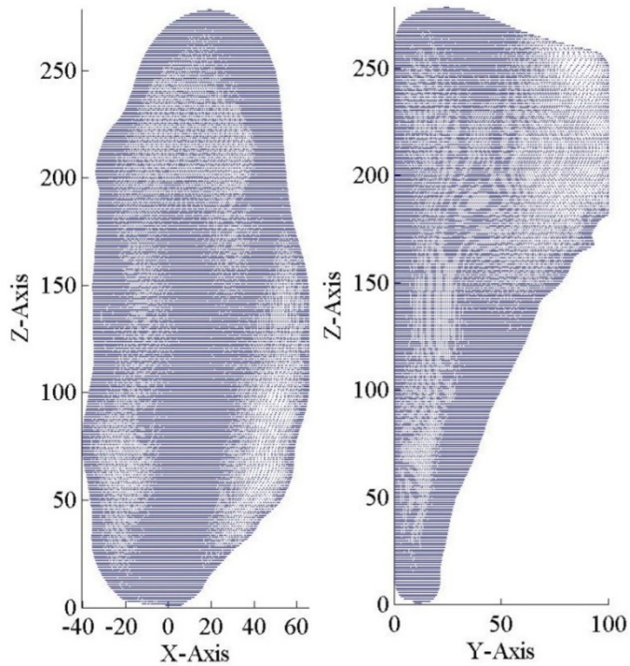

Figure 16. Foot laser scanned data (unit mm).

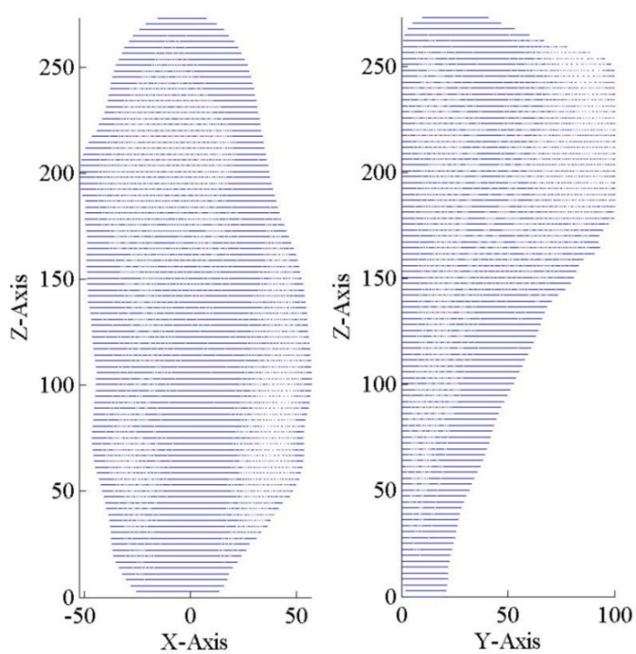

Figure 17. Sampled foot shape(unit mm).

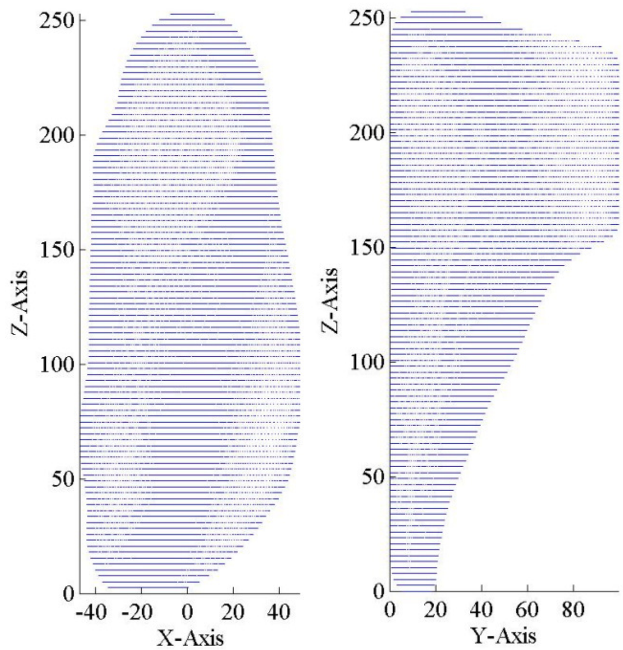

Figure 18. Standard foot shape (unit mm).

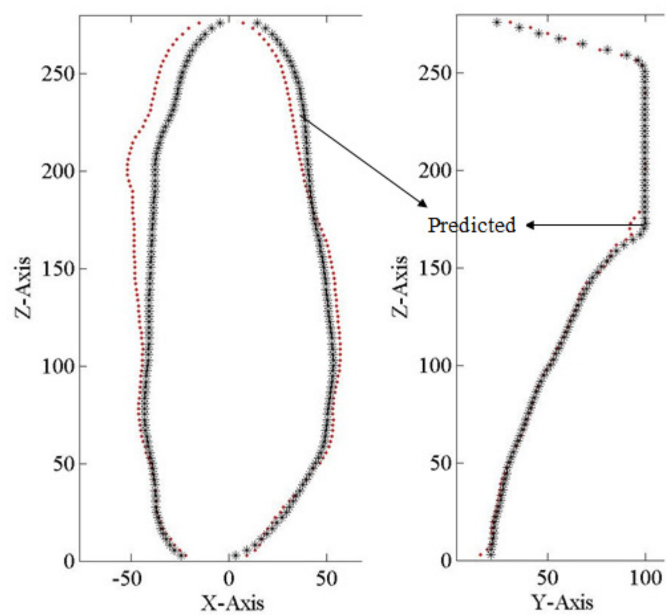

Figure 19. Parameter prediction (unit mm).

The prediction model was developed using foot length, maximum x deviation (W^+), minimum x deviation(W^-), and maximum y deviation(H^+). For left foot, the seed section for W^+ was at 7% foot length. The seed section for W^- was at 10% foot length. The seed section for H^+ was at 57% foot length. For right foot, the seed section for W^+ was at 9% foot length. The seed section for W^- was at 8% foot length. The seed section for H^+ was at 57% foot length. Figure 19 shows the predicted and actual values for a participant. Figure 20 shows the 3D sampled and predicted foot shape. The mean prediction error is 2.93 mm and the standard deviation is 4.34 mm. Figure 21 shows the color-coded error on the surface of the foot.

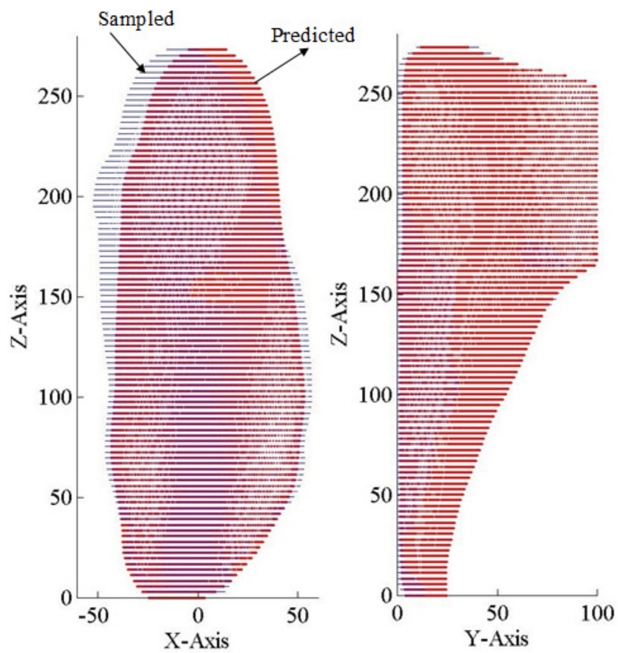

Figure 20. 3D prediction (units mm).

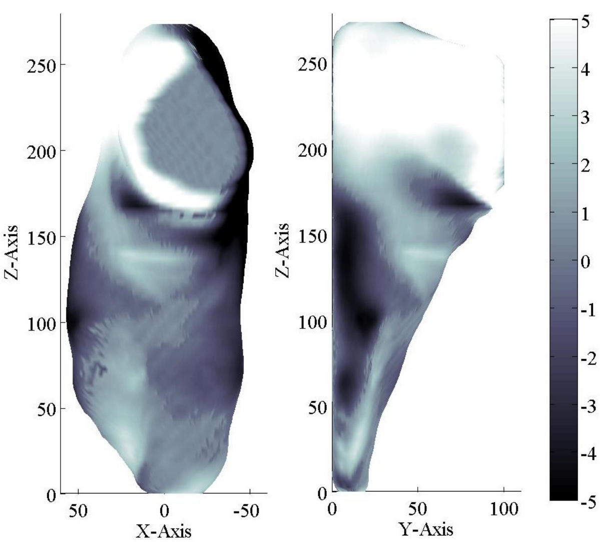

Figure 21. Prediction error plot (unit mm).

IX. Conclusion and Future Work

Linear anthropometrics have existed for centuries and it is relatively very easy to measure linear anthropometric dimensions. Linear anthropometric is widely available based on age, race, region, and occupation and methods to capture linear anthropometry are non-invasive, inexpensive, simple, portable and reliable. For instance, if we want to buy custom-made shoes through the internet, it is much easier to provide a set of anthropometric measures (such as length, width, height, heel width).

Anthropometric measures have been widely used, but recently, there is a shift from linear anthropometric measures to surface anthropometric data in order to satisfy the ever-changing needs of the society. Anthropometry may be useful for sizing and selecting product, but in the design phase 3D shape information is required. For example, it is difficult to design shoes with only few measures. People are constantly looking for comfortable and 'proper' fitting wearable that not only match the linear anthropometric dimensions but also accommodate the complex surface of the body. In addition, more surface information is needed in medical, archaeological and forensic disciplines. As a result, the linear anthropometric table even though useful is not able to satisfy with the current demands. Thus, in order to have accurate information on body dimensions, surface model database has to be developed. Hence, many types of equipment (e.g., 3D scanners) to capture surface model have been developed.

In one side we have low cost traditional anthropometric measures and the other side we have accurate but expensive 3D scanners. Both of them are use full in some applications. The general method is to acquire anthropometric measures from surface scan data. This implies that existing huge database on anthropometric measures are not well utilized. In this study, a general model was proposed to generate surface model from linear anthropometry and standard shape. The standard shape can be stored in database based on age, sex, race, gender, etc. Simple recursive regression equations technique and scaling technique were used to build the prediction model. Model building involved data collection, alignment, cross sectioning, point sampling, averaging and regression equations development. Once the model has been built, given a few anthropometric measures, the standard shape can be scaled to generate a predicted 3D shape. Studies in foot modelling have shown that this method can predict the foot shape accurately using only 4 parameters including length, width, height and curvature. The accuracy of the predicted shape will generally be higher if more anthropometric measures are used. The model parameters can be adjusted to obtain the required accuracy depending on different applications. The application of this study is reconstructive surgery, forensic, anthropology, design, psychology, and other fields involving digital human models.

Further studies include making use of the most common anthropometric measures to create whole surface model; accurate model for specific parts; sensitivity analysis on the use of number of anthropometric measures; and the use of the predicted data in product design.

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