Human Head 3D Dimensions Measurement for the Design of Helmets

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Abstract. With the helmet systems becoming increasingly complex, head 3D dimensions are needed for the higher precision, but the traditional anthropometry could not meet the design accuracy. In this paper, a non-contact method of head 3D dimensions measurement was presented to improve the design accuracy of helmets. The boundary 3D coordinate data of head slice was extracted from DICOM images based on the MRI technology. The mathematical model of head slice was described through 2D and 3D coordinate systems. Then we adopted the Fourier transform to fit the boundary of slice and obtained a parameter model with a series of Fourier coefficients. The standard headforms was constructed based on the characteristic slices and nine standard headforms were divided by Head Breadth-length Index and Head Height-length Index in order to preserve analogous facial characteristics. The head 3D data measured by this approach had been applied to the design of helmets.

Keywords: Head, 3D, Standard headform, Slice, Boundary.

1 Introduction

The human head characteristic is the most complex part of human body and the anthropometric points have approximately 32 landmarks [1]. Human head dimensions are the basis of the design of head protective equipments, such as helmets, gas masks, ear cups, visual devices, etc. With the advent of more complex helmet systems that include night vision goggles and helmet-mounted displays, as well as advanced sound attenuation components, the imprecision and inadequacy of old style of anthropometry becomes very apparent. The traditional anthropometric methods require Frankfurt Plane orientation, which is made more difficult to accomplish by the fact that the anthropometric information available to most designers is misleading and can lead to poor helmet sizing [2].

Laser scanning technology for three-dimensional (3D) surfaces digitizing which can capture hundreds of thousands surface data points in a matter of seconds as the digitizer circles around the subject's head [3]. However, a large quantity of 3D data points influence processing speed and storage requirement. The data reduction algorithm is used to improve the application efficiency, which reduces the accuracy of head data measures [4]. An analysis technique was discussed which used the Fourier

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transform to model two-dimensional (2D) horizontal cross-sections of human head. In this study, the stereo photometric points were transformed into values called curvatures which subsequently transformed into a series of Fourier coefficients. One difficulty noted by the authors was in the selection of the Fourier coefficients which are most useful in discriminating shapes. Another difficulty noted was the fact that very different entities, such as the ear and the nose, may contribute to the same Fourier coefficient on one person and not on another [5]. In order to achieve helmet systems development, the digital system integrated technology is employed to accomplish 3D virtual assembly and unified sizing of helmet. The helmet system design from modularization to integration is now a necessity to fulfill each other compatibility. Therefore, an advanced method of head 3D dimensions measurement is needed to establish a head 3D database based on scientific theory and reliable data.

This paper discussed an approach that provided non-contact measurement of head 3D surface anthropometric data for the design of helmets. The boundary coordinate data of head slice was acquired from 2D medical images. The mathematical model of head slice was constructed through coordinate systems and the Fourier transform. The standard headforms was constructed based on the characteristic slices.

2 Materials and Methods

2.1 Acquiring Boundary Data of Head Slice

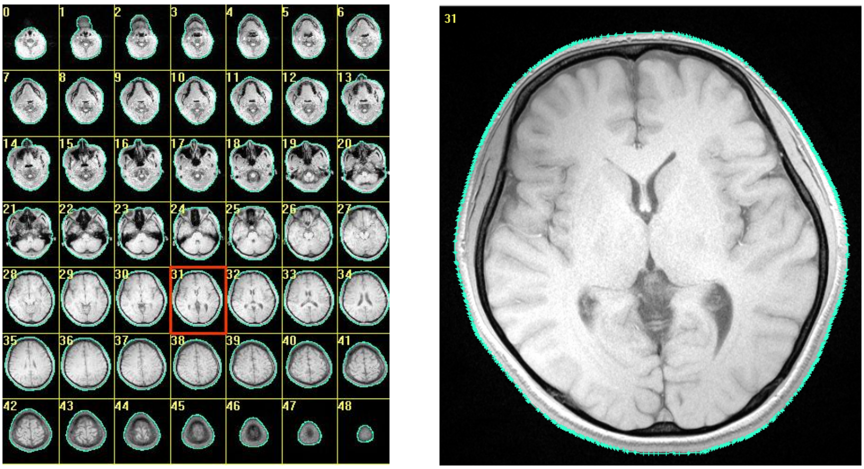
The approach employed slice scanning method that Magnetic Resonance Imaging (MRI) scanned head using Siemens Magnetom Trio 3T MRI Scanner. The average value of Chinese male adult's head height is 223mm (5th percentile 206mm and 95th percentile 241mm) [6]. In order to ensure data storage and processing efficiency, the scanning spacing was made as 5mm on the premise of accuracy; thereby the slices of head had approximately 40 to 52 vertically from vertex to gnathion. The Frankfurt Plane of the subject's head should be kept uprightness and lateral symmetry in the process of MRI scan, which needed about 5 minutes. The head slice images that are accorded with Digital Imaging and Communications in Medicine (DICOM) standard were derived from MRI scanner. The scan parameters that were set by scanner are given in Table 1.

Table 1. The parameters of scanner needed to set at the front of scan, Sequence variant = Slice thickness + Spacing

Scanning sequence	Slice thickness	Spacing	Sequence variant	Resolution
Gradient-echo sequence	4.0 mm	1.0 mm	5.0 mm	512×448

Generally, a 3D image is stored as 2D slices in various formats, such as DICOM, TIFF, JPEG and BMP. Considering all slices of each head processed together, separate 2D image slices of each head were compiled into a single 3D stack (Fig. 1.A). The boundary of each head slice was composed of 2D data points (Fig. 1.B), so the process of image slices was extremely important, which can directly affect the location of data points and the accuracy of slice boundary. Finally, 3D coordinates of head were extracted from DICOM images and outputted as a data file.

Therefore, the head information was stored as a 3D coordinate data file and detached from original DICOM images. The data storage space was only occupied by about one percent of original image. When samples are large, the advantages of the storage will be very obvious.



A B

Fig. 1. A. The MRI slices of one subject's head were compiled together in sequence. **B.** The color curve is the boundary of one slice.

2.2 Mathematical Model of Head Slice Boundary

The 3D coordinates extracted from images can construct the head 3D model, but the model is unable to meet the specific applications. There are two reasons: (1) in terms of different head samples, their data points have large differences and do not directly use to statistical analysis; and (2) a large quantity of 3D data points influence processing speed and storage efficiency. Head slice boundary need to be described by the mathematical function whose parameters replaced data points [7].

We will assume that vertex is coordinate origin *O*, *O-XZ* plane is the mid-sagittal plane, and *Z* axis is upwards perpendicular with head slices. In that case, a Cartesian coordinate system was established here, see Fig. 2. The different slices of one headform had the same plane coordinate system *o-xy* which could change into the Polar coordinate system. Pole compared to origin O was moved to the face direction to fit well complex face figure, and the pole offset X_o of each headform was chose appropriately by the second slice measurement, X_o about between 20mm and 30mm.

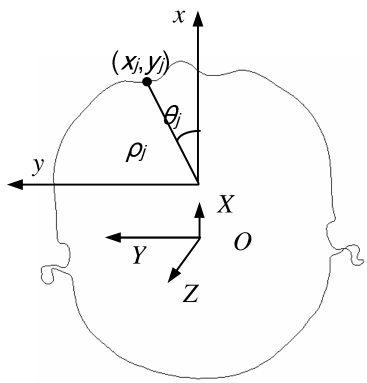


Fig. 2. The coordinate system of head slice, including a 3D coordinate system and a 2D coordinate system

Therefore, the contour of every slice was noted by polar radius $\rho(\theta)$, and the pole coordinates of every slice i was noted as $(X_o, 0, Z_i)$ in the Cartesian coordinate system. The coordinates j of boundary point were calculated using

$$\begin{cases} X_j = \rho_j \cos\theta_j + X_o \\ Y_j = \rho_j \sin\theta_j \end{cases} \tag{1}$$

The contour of boundary of slice was depicted by the above formula at the pronasale plane, see Fig. 3.A. A number of small sawtooth which resulted from the image resolution and the uneven distribution of data points was obviously detected in the curve.

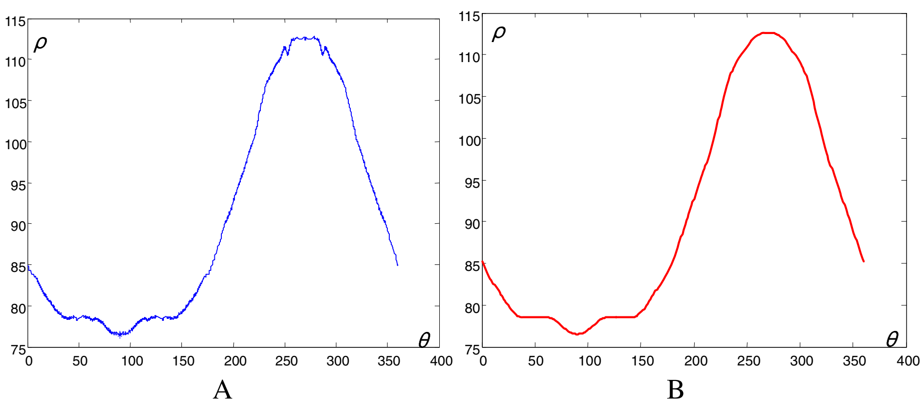


Fig. 3. A. The contour curve of boundary was depicted by Matlab at the pronasale plane. **B.** The same boundary was depicted by Matlab when it was fit by the Fourier transform.

The fitting curve must accurately reconstruct the close boundary of head slice and be smooth at the junction. The Fourier transform of cycle 2π fit the slice curve, as following formulas

$$\rho_i(\theta) = \frac{a_{i,0}}{2} + \sum_{n=1}^{12}(a_{i,n}\cos n\theta + b_{i,n}\sin n\theta) \tag{2}$$

$$a_{i,n} = \frac{1}{\pi}\int_{-\pi}^{\pi} f_i(\theta)\cos n\theta\, d\theta \tag{3}$$

$$b_{i,n} = \frac{1}{\pi}\int_{-\pi}^{\pi} f_i(\theta)\sin n\theta\, d\theta \tag{4}$$

where i is the number of slice, n=1~12, $a_{i,n}$ and $b_{i,n}$ are series parameters which were calculated by the integral of the original boundary curve $f_i(\theta)$. The formula (2) described a 3D stratified head model. The boundary data of each slice were completely described by only 25 parameters. Therefore, all 3D dimensions of headforms were calculated by pole offset X_o and the slice parameters $a_{i,n}$, $b_{i,n}$ and Z_i. The fitting curve was depicted at same slice, see Fig. 3.B.

2.3 Constructing Standard Headforms

The helmet designed to use anthropometric dimensions should be applicable to groups of persons, which requires obtaining a standard headform by statistical methods. The standard headform was averagely calculated by a number of headform samples.

In view of the complex head characteristics, the different characteristics are definitely distinguished through a certain way. Above the mathematical model of slice boundary, various characteristics of head had stored on the parameters of each slice. Although the figure of slice of various samples was different, the shape was continuous and smooth. The facial midline of headforms was used to mark facial characteristics of vertical direction (Z axis direction, see Fig. 2) on the mid-sagittal plane. Ten characteristic slices were defined on the headform and distinguished by Matlab program. They include: glabella slice, nasion slice, pronasale slice, subnasale slice, labrale superius slice, stomion slice, labrale inferius slice, supramental slice, pogonion slice, and gnathion slice [8], see Fig. 4. Ten characteristic planes represented facial characteristics and provided a basis for constructing standard headforms.

In order to obtain standard headforms at the 3D coordinate system, the function descriptor of slice i, the Z_i value of slice i and the pole offset X_o were averagely calculated by following formulas

$$\rho_i(\theta) = \frac{\sum a_{i,0}}{2M} + \sum_{n=1}^{12}\left(\frac{\sum a_{i,n}}{M}\cos n\theta + \frac{\sum b_{i,n}}{M}\sin n\theta\right) \tag{5}$$

$$\bar{Z}_i = \frac{\sum Z_i}{M} \tag{6}$$

$$\bar{X}_o = \frac{\sum X_o}{M} \tag{7}$$

where M is sample number, $\bar{z}_i$ and $\bar{x}_o$ are respectively the Z coordinate value and the pole offset of slice i of standard headform. The Fourier coefficients were made average calculation and the computation was largely reduced by the formula (5).

For symmetrical standard headforms, the original boundary curve $f_i(\theta)$ can be described even functions and the sine functions coefficients of formula (4) are zero. For unsymmetrical standard headforms, the value of sine functions coefficients is very small and can be omitted as symmetrical headforms. The formula (2) was improved as following formula

$$\rho_i(\theta) = \frac{a_{i,0}}{2} + \sum_{n=1}^{12} a_{i,n} \cos n\theta \tag{8}$$

As the symmetry of single headform sample is not fine, the symmetrical process was used to standard headforms. Therefore, the standard headforms were described by only 13 parameters, X_o, $a_{i,n}$, and Z_i.

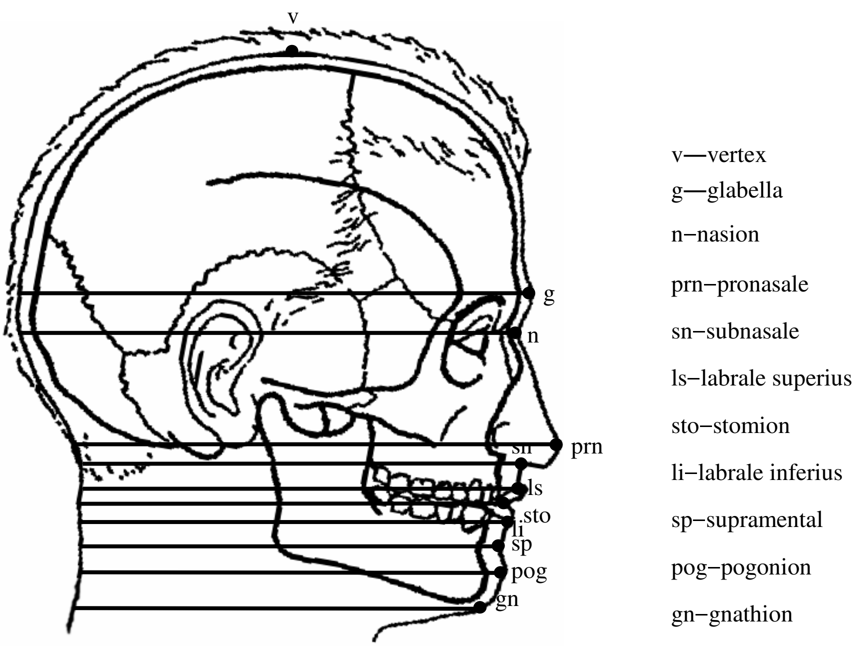


Fig. 4. Ten characteristic points of facial midline are corresponding to ten horizontal cross-sections

3 Results

We had measured a large quantity of subject's head of male adult and established a database of head 3D dimensions. Head Length L, Head Breadth B and Head Height H were calculated by polar coordinate and we defined that Head Breadth-length Index (B_I) and Head Height-length Index (H_I)

$$B_I = B / L \bullet 100 \quad (9)$$

$$H_I = H / L \bullet 100 \quad (10)$$

The head samples were respectively divided into three groups based on two indexes: Middle, Round and Superround based on B_I; Fit, Tall and Supertall based on H_I. Nine standard headforms were obtained by B_I and H_I 2D distribution [9], see Table 2. The standard headforms grouped preserved analogous facial characteristics in each headform and prevented to mixing different facial characteristics in a headform.

Table 2. Nine standard headforms were divided by B_I and H_I

B_I	H_I		
	≤119.99	≤129.99	≥130.00
≤79.99	Middle-fit headform	Middle-tall headform	Middle-supertall headform
≤89.99	Round-fit headform	Round-tall headform	Round-supertall headform
≥90.00	Superround-fit headform	Superround-tall headform	Superround-supertall headform

4 Conclusion

In this paper we described a method that measured head 3D surface dimensions for the design and size of helmets. The boundary coordinate data of head slice was acquired from DICOM images by the MRI technology. The mathematical model of head slice was depicted through 2D and 3D coordinate systems, and then the boundary was fit by the Fourier transform. The standard headforms were constructed by average calculation on the basis of the characteristic slices. Finally, nine standard headforms were divided based on B_I and H_I in order to preserve analogous facial characteristics.

The database of head 3D dimensions will provide basic data for head equipment design. The helmet size based on headforms can be applied to the design of helmets. People R. China national standard *3D dimensions of male adult headforms* was accomplished on the basis of study on head 3D dimensions measurement. Future research planned includes the extension of the technique to the algorithm of the Fourier coefficients, and the development of methods for the fit of slice boundary.

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