Landmark-driven Statistical Morphometry of the Human Ilium bone as a Base for Obtaining Subject Specific 3D Model

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Abstract - **The human ilium bone, as an entity of the hip bone, represents a very complex morphological structure of irregular shape. Building accurate subject specific 3D model requires complete geometric morphometry of given bone. Therefore, it is necessary to define reliable anatomical landmarks as points which have unique and consistent positions at the each bone, defined by coordinate values. Due to the fact that the number of these point depends on the complexity of the shape, in the case of the ilium bone 15 bilateral landmarks are separated. Based on these landmarks 26 parameters are determined as linear distances. Using statistical approach it is possible to predict coordinate values for 11 landmarks, based on the values for 4 points whose positions are easy to determine. Input data in the form of coordinate values are taken from anatomical points, localized at the sample of 32 polygonal models of the ilium bone. The tools of descriptive statistic and regression analysis are used for establishing proper dependencies between coordinate values, which results in 33 mathematical equations (6 linear, 18 squared and 9 logarithmic). These results are statistically significant, due to the the value of variance R^2 (up to 0.83511) and the p-value which is less than 0.01 for regression coefficients. Based on measured and predicted coordinate values it is possible to calculate values for all parameters, using an expression for distance between two points in 3D, in proper Graphical User Interface (GUI) developed for the purpose of this study. The results of study, tested on randomly chosen male hip bone, proved proper accuracy. Landmark-driven approach presented here allows simple and fast prediction of the subject specific morphometry as the first step in building 3D bone surface model.**

I. Introduction

Landmark-based morphometry is essential for geometric modeling of personalized missing parts of the hip bones and creating subject specific 3D ilium bone models. The first step in this procedure is to determine a sufficient number of anatomical points in the form of bilateral landmarks and to detect their accurate position. For complete morphometry, *i*n order to capture the shape of the ilium bone, it is necessary to separate 15 anatomical landmarks and to define 26 parameters [1]. These parameters, as straight lines, represent linear distances between chosen anatomical landmarks. Guided by the fact that identification and localization of that number of points is time consuming, the number of points is reduced without measuring the parameter values using a statistical approach.

Unique morphology of the human hip bone makes it the subject of interest for many anatomical and forensic anthropology studies. Morphological evaluation, metrical methods and geometric morphometry are useful tools for sex estimation and studying variations among populations, but only in the cases when key morphological features can be observed and measured [2]. Some studies include metrical and non-metrical (morphological) entities [3], defining 105 points on the right half-pelvis, measuring their coordinates and calculating 28 anatomical distances [4]. Set of 27 anatomical landmarks at the hip bone was defined from a sample of 1443 adult hip bones (891 males and 552 females) originating from Africa, Europe, Asia and America. Inter-linear distances between these landmarks were measured and the analysis was conducted using different statistical means and techniques [5].

Metric and non-metric traits and measurements were taken at the ilium, ischium and pubic bone. Visual and statistical analyses were conducted [6]. Non-metric sex estimation was conducted on a sample of 59 left hip bones of unknown age at death, sex, and ancestry. The same sample was used for representation of the hip bone and sexual dimorphism. At each of the hip bones 30 landmarks of all three types were established so that they can independently represent the shape of the ilium, ischium, and pubis, so as the ilium-ischium, ilium-pubis, and ischium-pubis regions. Procrustes superimposition and Procrustes analysis of variance were used for aligning the landmark, while Principal Component Analysis was used to locate areas of the pelvis where sexually dimorphic shapes exist [7].

Presented metric techniques are useful tools for sex estimation and establishing differences between male and female hip bone in the cases when all proposed landmarks and morphological entities are present and well preserved, but none of them indicate the way to predict subject specific morphometry, even in the cases when some of the landmarks are missing. On the other hand, non-metric (visual) methods depend on the experience and skills of the observer. To avoid errors which can occur during the estimation process, we suggest a landmark-driven approach which uses statistical tools. Such procedure will allow accurate description of the size and shape of the ilium bone and represents the prerequisite for 3D geometric bone modeling as a whole or its parts using information from polygonal model, obtained from CT scans.

II. METHODOLOGY

Research is conducted through few steps:

- processing CT scans, generating 3D models from DICOM images,
- model reconstruction in CAD program and obtaining polygonal models,
- determining landmarks and parameters,
- measuring of coordinate values,
- statistical analysis of data and calculating statistical values,
- determining correlations between point coordinates values,
- choosing, testing and establishing proper regression models for coordinates, and
- selecting the proper regression model, according to statistical indicators such as the level of statistical significance and the highest value of variance.

Data from CT scans, written in DICOM format are converted to STL format and exported to a CAD program with the aim to obtain polygonal models of bones. For some models it was necessary to reconstruct the surfaces. Input data in the form of points' coordinates for determined anatomical landmarks are measured at each of the 32 polygonal models of bone in Computer Aided Design (CAD) program. These anatomical landmarks are defined in such way to capture the shape of the bone. The measured values are analyzed using statistical tools and appropriate correlations coefficients between them are established. The set of coordinate values for anatomical landmarks, labeled as 1-10, ZS, DS, PS, NISUA and NISUP, is divided into 12 independent and 33 dependent variables. Anatomical landmarks and parameters as linear distances between chosen landmarks in anteroposterior (A-P) and lateral projection are presented in Fig. 1.

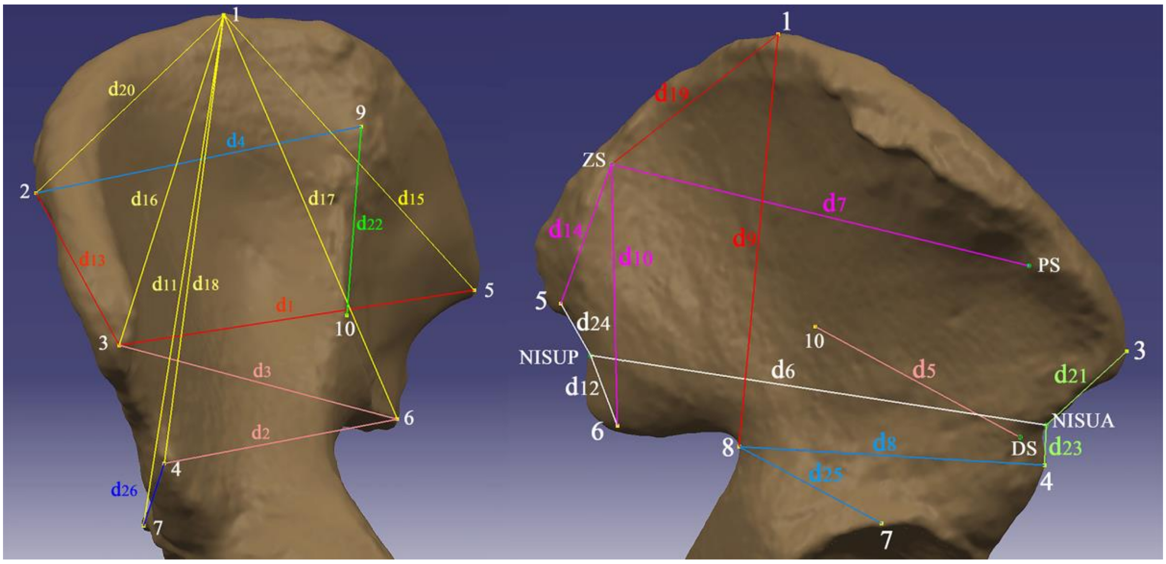

Figure 1 Anatomical landmarks and parameters at the ilium bone in A-P and lateral projection (modified from [1])

Coordinates X, Y and Z for 4 points which are easy to localize on polygonal models, such as 1, 3, 4 and 8 (see Fig. 1), are treated as independent variables. Scatter plots are used for choosing regression models to be tested, for each of the coordinates from the second group. Linear, squared (2 types) and logarithmic (2 types) models proved to be the best fitted models, as follows:

a) linear: $X = a + b \cdot X_i$, $Y = a + b \cdot Y_i$, $Z = a + b \cdot Z_i$;

b) squared: $X = a + b \cdot X_i^2$, $Y = a + b \cdot Y_i^2$, $Z = a + b \cdot Z_i^2$;
$X = a + b \cdot X_i + c \cdot X_i^2$, $Y = a + b \cdot Y_i + c \cdot Y_i^2$, $Z = a + b \cdot Z_i + c \cdot Z_i^2$;

c) logarithmic: $X = a + b \cdot \ln(X_i)$, $Y = a + b \cdot \ln(Y_i)$, $Z = a + b \cdot \ln(Z_i)$, $X = a \cdot \ln(X_i)$, $Y = a \cdot \ln(Y_i)$, $Z = a \cdot \ln(Z_i)$.

Regression coefficients a, b and c in regression equation are calculated using least square method. The basic condition for the acceptance of the model is established in such way that the value of statistical significance (p-value) must be less than 0.01 for all parameters a, b and c. Value of variance R^2 is also determined. The model with the highest R^2 is selected from all the models which satisfy the condition for p-value.

III. SOLUTION/DISCUSSION

Research results for coordinates are presented in Table 1 as different linear and non-linear regression models: 6 linear (2 for Y and 4 for Z), 18 square (7 for X, 5 for Y and 6 for Z) and 9 logarithmic (4 for X, 4 for Y and 1 for Z), with the value of variance R^2 up to 0.83511.

TABLE I. REGRESSION EQUATIONS FOR X, Y AND Z COORDINATES

Point	Coordinates		
	X	Y	Z
2	$116.9800 + 0.0027 * X_1^2$	$-21.9027 + 0.6497 * Y_1$	$22.4701 + 0.7509 * Z_1$
ZS	$38.1184 + 0.0062* X_9^2$	$81.34804 + 0.0059 * Y_9^2$	$-22.8420 + 0.8310 * Z_9$
9	$34.1815 + 0.0026 * X_1^2$	$-187.6180 + 62.1670 * \ln(Y_1)$	$41.6248 + 0.9870 * Z_1$
5	$-190.7340 + 52.9200 * \ln (X_8)$	$70.4940 + 0.0081 * Y_8^2$	$-27.9766 + 0.0159 * Z_8^2$
6	$-171.5450 + 51.2550 * \ln (X_8)$	$-504.3640 + 140.0110 * \ln (Y_8)$	$-11.5918 + 0.8266 * Z_8$
10	$-227.9180 + 66.4690 * \ln (X_8)$	$33.6110 + 0.0050 * Y_8^2$	$-10.2140 + 0.0150 * Z_8^2$
PS	$68.1195 + 0.0033 * X_2^2$	$25.8461 + 0.0086* Y_2^2$	$-43.2636 -1.6641* Z_2 - 0.0328 * Z_2^2$
NISUP	$-197.7000 + 56.6670 * \ln (X_8)$	$65.9166 + 0.0079 * Y_8^2$	$-14.8708 + 0.0155 * Z_8^2$
7	$76.8264 + 0.0032 * X_4^2$	$47.7772 + 0.0280 * \ln (Y_4)$	$-56.7999 + 29.1380 * \ln(Z_4)$
DS	$77.3131 + 0.0061 * X_8^2$	$-142.9690 + 35.7600 * \ln (Y_8)$	$15.0963 + 0.0074 * Z_8^2$
NISUA	$69.5007 + 0.0040 * X_4^2$	$6.1900 + 0.6703 * Y_4$	$7.4413 + 0.00631 * Z_4^2$

The parameter values (d_k) are calculated using a simple expression (1) for Euclidean distance between two points in 3D, where $X_{i,j}$, $Y_{i,j}$ and $Z_{i,j}$ represent coordinate values (k = 1 - 26, i, j indexes indicate on points labels, as presented in Table I).

$$d_k = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2} \quad (1)$$

In order to test the obtained and adopted regression models, the coordinates for all 11 points and 26 parameters are measured at one randomly chosen right male hip bone. Predicted values are calculated, according to regression equations from Table I, using a Graphical User Interface (GUI), developed for the purposes of this study in Python programming language, using built-in graphical library Tkinter. This simple GUI allows the input of measured values of 4 points coordinates (1, 3, 4 and 8), using entry fields and automatic calculation of predicted values for points coordinates with a simple click on Calculate button (see Fig. 2).

The average values for absolute error for coordinates are 3.538, 7.224 and 6.067 mm, for X, Y and Z respectively, while the average value of relative error for calculated parameters is 5.244 %.

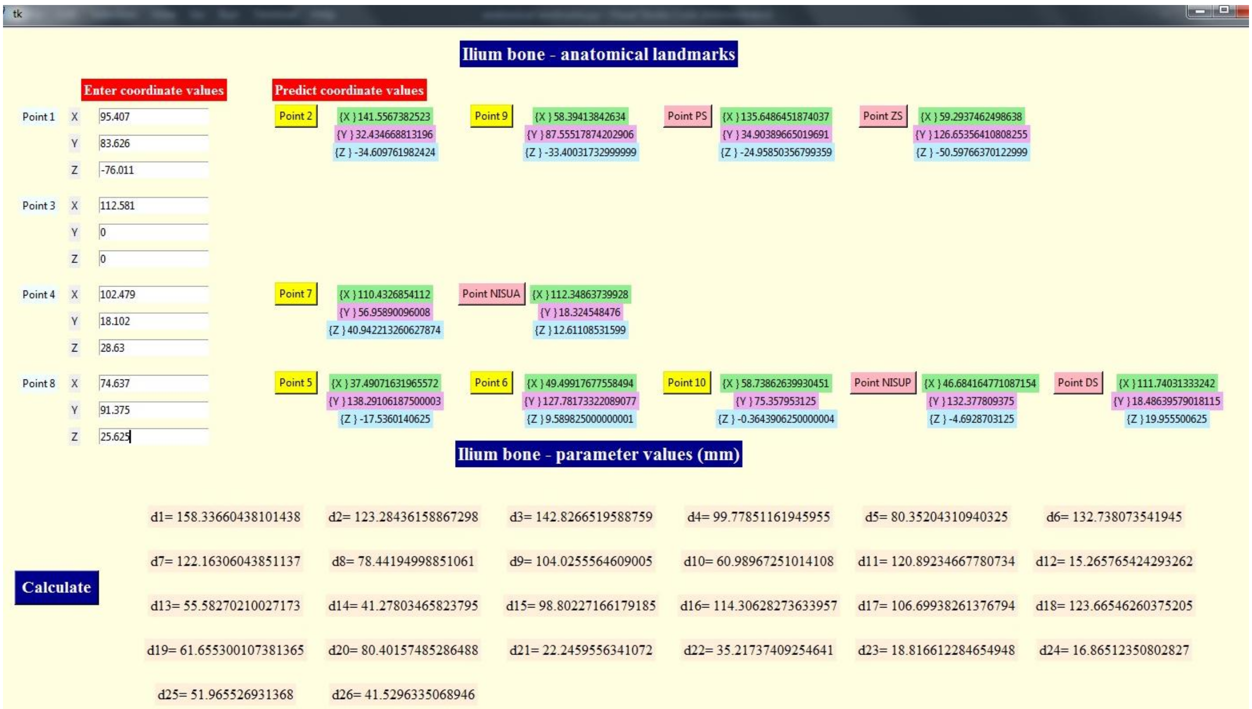

Figure 2 GUI for input data and prediction of parameter values

IV CONCLUSION

Proposed measurements are simple and fast and could be implemented on polygonal models of the ilium bone, so the subject specific morphometry is easy to predict. Defined anatomical landmarks and parameters are the base for creating geometrical entities such as points, intersecting planes, curves and surfaces. The methodology is also applicable on other human bones. Described procedure can be applied on the left ilium bone and acquired landmarks could be defined and measured either on the left or on the right bone, depending on the degree of damage, even if some landmarks are missing.

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