Morphometrics in forensic science: steps towards the development of population specific standards

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CFS

THE HULL YORK MEDICAL SCHOOL

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INTRODUCTION

The statistics of error and uncertainty are intertwined with ascertaining the admissibility of forensic evidence in a court of law. This issue was especially examined in the 2009 National Academy of Science review of forensic practice.

In the analysis of unidentified skeletal remains it is, thus, crucial to formulate a biological profile that gives not only stated errors, but also accuracy and precision of the raw data. In particular, the most accurate biological profile is achieved by using contemporary population-specific standards.

We are currently working towards developing a suite of population specific standards in various skeletal regions. Because there are almost no reference skeletal material (of contemporary Australian populations) our morphometric approach involves analysis of current multi-slice computed tomography (MSCT) scans.

MATERIALS

Using a variety of traditional and novel approaches, we discuss here the validity of formulating Australian forensic standards from 3D landmarks acquired in CT-reconstructed bones. We then outline how 3D multivariate descriptors of size and shape can be used to estimate sex with higher accuracy than usual. We show the effect on classification accuracy when non-population specific vs. population-specific sexing standards are applied. Standards from other populations do not represent well the modern Australian population; they thus introduce unacceptable levels of error.

METHODS

1. Traditional Morphometrics: from 3D volume rendering, the 3D coordinates of 41 landmarks on the pelvis were acquired using *OsiriX*® (v.4.1.1). A total of 15 linear measurements **(Figure 1)**, suitable for complete and/or a fragmented bone, were calculated using *Morph Db* (an in-house developed database application). Statistical analyses including discriminant functions are performed using *IBM® SPSS® Statistics 20.0*.

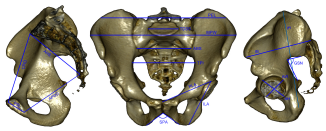

Figure 1: Linear measurements of the pelvis.

2. Geometric Morphometrics: 230 traditional and semi-landmarks (**Figure 2**) were analyzed using *morphologika* (v. 2.5). Principal components, multivariate regression, wireframe models and thin-plate splines explored the relationships between male and females. Sexual dimorphism was quantified using permutation tests for mean differences.

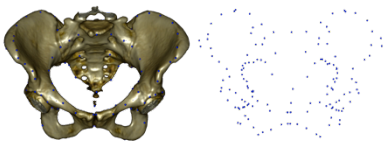

Figure 2: Landmarks used in geometric morphometric analysis.

ACKNOWLEDGEMENTS

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GRANT SPONSOR

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RESULTS

Traditional Morphometric

The means and standard deviations, demarking points, and performances of multiple and step wise cross-validated discriminant analyses for these studies are all available but not tabulated here. The most dimorphic measurements, as would be expected, are supra-pubic angle, angle of the greater sciatic notch, transverse pelvic outlet and acetabular width. These variables had an expected accuracy of more than 80% and a sex bias of less than 5%. The most accurate single variable was the supra-pubic angle (93%).

The potential accuracy of multiple measurement standards are given from direct ('non-stepwise) DFA's. They showed expected cross-validated classification accuracies between **82.5-94.0%**, with associated sex-biases of **0-4.5%**; the best 10 variables referred **100%** of individuals to their respective sex.

Geometric Morphometrics

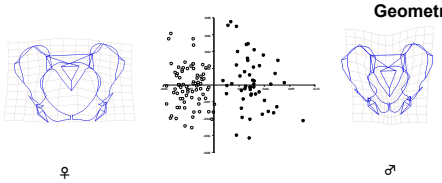


Figure 3: Plot of PC 1 vs. PC 2. Antero-superior views of wireframe images and horizontal transformation grids show variation in pelvic shape represented by PC 1, from negative (-0.06) to positive (+0.11) extreme. Grids calculated to show deformations exaggerated 2x to aid visualization of shape changes.

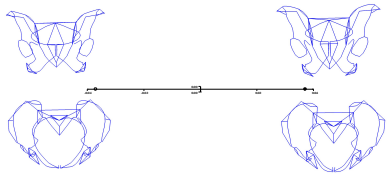


Figure 4: Anterior and superior views of wireframe images show the variation in pelvic shape between the mean female (left) and male (right) configurations; permuted difference in mean shape is significant (P <0.001).

Figure 5: Multivariate regression of shape (PCs 1-5) onto sex. Images show antero-superior views of derived estimates of pelvic shape from female to male extremes.

The PCA analysis demonstrates a complete separation of individuals according to sex on PC 1 (22.4% total variance); deformations of the transformation grid indicate that the pelvic shape configurations represented on that axis primarily relate to variations in the sub pubic angle and the pelvic inlet and outlet **(Figure 3)**. The shape changes visualized by morphing between the sex means are shown in **Figure4**.

From **Figure 5** it is evident that males (relative to females) demonstrate an acute sub-pubic angle, narrow and short pelvic inlet/outlet, long and narrow ilium and an interiorly curved sacrum. In **Figure 5** the latter shape variations are further elucidated by visualizing the regression of sex onto PCs 1-5 (50.2% of total variance; Wilks' λ = 0.930, corresponding to an F statistic of 3.133 with 3 and 124 df [p = 0.028]).

These methods are also applicable to other skeletal elements

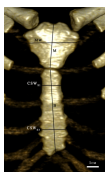
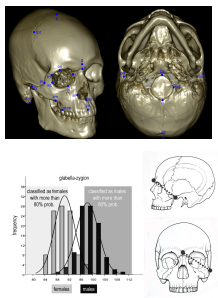
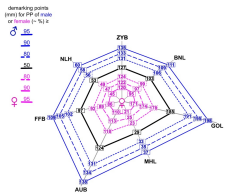


Figure 6: Sternum
Cross-validated accuracies
Univariate, stepwise, and direct function are 72.2 –84.5%, Sex bias is less than 5%, in Western Australians





Figures 7, 8 and 9: Results for Cranium
Spider web plot of cranial demarking points (in mm) of male (blue) and female (pink) measures against corresponding posterior probabilities of 0.5 (black line is mid-point) 0.8, 0.9 and 0.9

DISCUSSION AND CONCLUSIONS

The aim of the present study, using geometric morphometric approaches to sexual dimorphism as examples, is to instil an awareness of the value of population-specific forensic anthropological standards. Highly significant size and shape dimorphism is clearly apparent in the WA population sample, explaining up to 64.5% of the variance. The pelvic regions expressing the greatest dimorphism were those (e.g. dimensions of the true pelvis) associated with childbirth. Other regions can also be studied.

The use of multiple variable DFA's offered little improvement in predictive accuracy compared to single measurements, such as the sub-pubic angle and transverse pelvic outlet; the 3D visualizations confirm the highly dimorphic nature of those morphological regions. If, however, fragmented specimens require evaluation, then there are suitable single variables that are sufficiently dimorphic to enable an accurate estimation of sex; e.g. angle of the greater sciatic notch.

We show the value of medical (MSCT) scans as sources of contemporary Western Australian population-specific skeletal data. Sex can be estimated with high expected accuracy using traditional measurements; cross-validated accuracy rates are well above 90%, with associated posterior probabilities above 0.80 on average among correctly classified individuals.

This study represents one of several forensic investigations in progress to formulate standards from 3D landmarks acquired from CT-reconstructed bones. This is especially necessary for Australia, where there are almost no population-specific skeletal materials, and where standards from non-Australian populations are inappropriate with high error. It is applicable to any bone even if fragmented. This use of multi-slice computed tomography scans in many anatomical regions can help to better meet the *Daubert* admissibility requirements.

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