Sex differences in cranial form assessed via non-rigid deformation analysis of high-resolution CT images

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Abstract:

The use of computed tomographic (CT) imaging in fossil and skeletal studies has increased substantially in recent years. Because these images are essentially density measurements in three-dimensional (3D) space, they can be used to assess complex shapes in mathematically interesting ways. Image analysis methods developed for functional brain imaging studies allow the morphing of objects (e.g., crania) into common coordinate systems, resulting in transformation maps that describe, in detail, where and by how much a given object differs from another object. The methods used to create these maps are anatomically reasonable, in that they focus on local distortions, rather than simply globally scaling the entire object. In principle, these methods can be applied to 3D images of any type (MRI, CT, laser scan, etc.). They can also be applied to sets of images, resulting in population maps of localized morphological variation, as well as allowing comparisons of localized differences between populations.

We illustrate the usefulness of these techniques by showing how sex differences in cranial form can be assessed in a population of male and female crania from the Morton collection at the Museum of Archaeology and Anthropology at the University of Pennsylvania (CT's were obtained from the Open Research Scan Archive at Penn, http://grape.anthro.upenn.edu/~lab/pennct/). Maps of significant t-values for sex differences at each point in 3D space will be shown. Comparison with previous studies of sex differences in cranial form will be discussed. The usefulness of these methods for a wide range of anthropological analyses will be discussed.

Difficulty of assessing complex morphology:

The cranium has been the focus of a great deal of paleontological and anthropological interest because of its importance for understanding changes in the brain, the senses (vision, auditory, olfactory, equilibrium, etc.) and masticatory adaptations during human evolution. It is, however, an extraordinarily complex 3-dimensional structure. Describing, assessing, and comparing morphological variation in this part of the human anatomy has traditionally been done via sets of linear cord and angle measurements. The selection of these measurements has largely been driven by an inevitable tradeoff of validity and reliability. Complex shape and size differences and similarities are often most easily assessed ('seen') only qualitatively.

Techniques for mathematically assessing complex 3D structure have been developed in recent years for functional and anatomical studies of the brain. Specifically, methods now allow one to morph brains into a common coordinate system (an 'atlas' brain). These techniques use a combination of simple global scaling, isometric shearing along orthogonal axes, and highly localized distortion to mathematically describe how to transform one brain into another. Early functional imaging studies used these transformations simply to ensure brain functional activation data from different subjects was properly overlapped on the same anatomical areas. However, because these transformations are unique to each individual – essentially representing a fingerprint of morphological uniqueness of a given individual – recent studies have used these transformations specifically for assessing morphological variation across subjects. In essence, these methods describe individual differences in complex morphology through estimating the optimal set of localized (voxel-by-voxel) distortions needed to 'create' individual brains from a given atlas.

These methods make the assessment of complex morphological variation across subjects relatively straightforward: one can compare the degree of distortion needed to transform a specific location in an atlas to any number of individuals. One can also divide individuals into populations, e.g., healthy and diseased brains, and compare the average distortion needed at each point to get from the atlas to the average healthy vs. average diseased brains. Standard t-values can also be calculated for each voxel and color-coded to illustrate where the two populations differ most significantly.

Although these algorithms have been developed specifically for MRI brain studies, they should in principle be applicable to scans from any imaging modality, provided there is sufficient morphological information in the image (i.e., grayscale gradients).

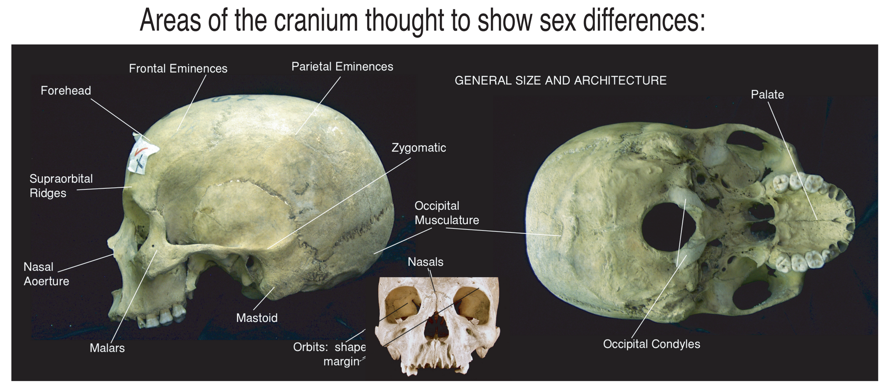
Sex differences in the cranium

The assessment of sex differences in the cranium is of potential usefulness not only for forensic studies, but also for demographic studies of anthropological and paleontological osteological samples.

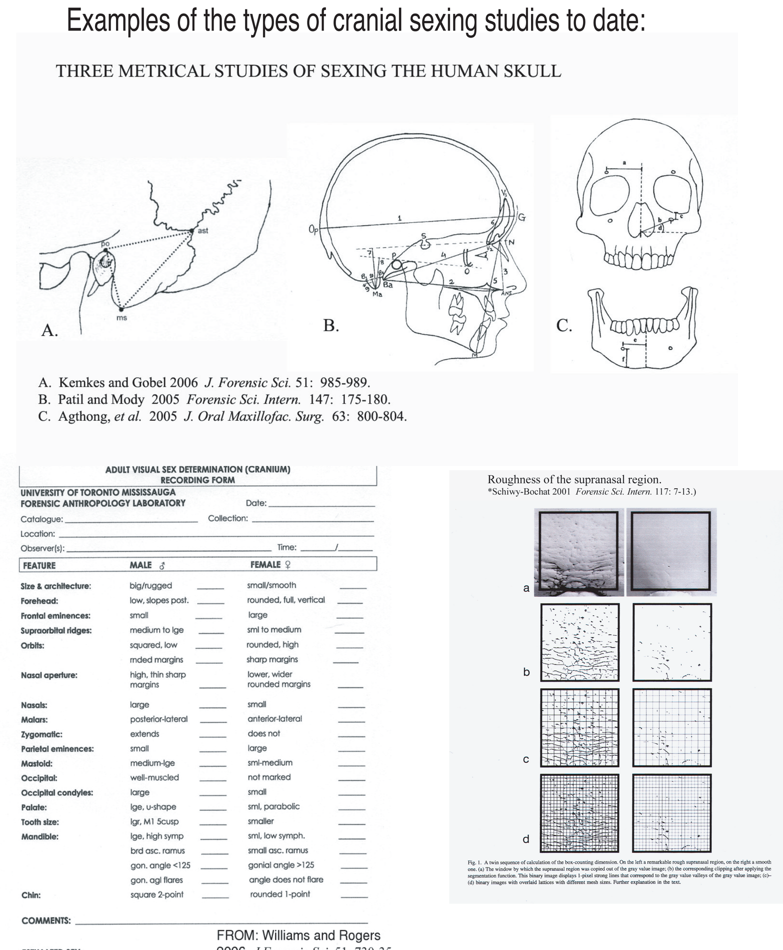
Various methods have been applied in an attempt to increase the accuracy and reproducibility of the attribution of sex to cranial materials. These methods most often employ the scoring or seriation of a series of features into discrete categories although several recent authors have moved towards the application of metric criteria to establish the sex of unknown individuals.

The most frequently chosen scored features include elements related to the relative size difference between males and females especially in cranial features associated with either muscle attachment areas or to areas that appear to be associated with the dispersal of masticatory forces. The most common of these include for example, the superciliary arch form, the mastoid process, the degree of muscularity on the occipital bone, although some researchers advocate the use of over 20 cranial and mandibular features.

Areas of the cranium thought to show sex differences:



Examples of the types of cranial sexing studies to date:



Results of these endeavors (but not an exhaustive list):

1. Virtually all of these methods report an accuracy of sexing of the cranium to between 70 and 80 percent when applied to the reference skeletal samples of known age and sex (or when compared to the sex attribution derived from the pelvis).
2. It seems likely that in many cases, both the criteria developed (metric and categorical) as well as the statistical analyses performed on those specimens, can only be applied with accuracy to cranial specimens that derive from the very same population used to construct the effective measures or features.
3. Some bias in the degree of expression, as well as the scoring of features, may result from the malleability of some sexing features that occur through the life span of individuals with the result that sex is misattributed especially to the cranium of older-aged individuals.

Goals of the current study

Here we attempt to explore the possible uses of deformational analysis of CT images to the problems associated with the sexing of the cranium. This preliminary research was directed towards two related problems:

1. the consistent and cross-populational attribution of sex, through the use of as much of morphological information as possible
2. establishing the degree and direction of bias that may occur in sexing over the decades of adulthood in the female cranium.

Methods

Selection of specimens

High-resolution scans were selected from the Open Research Scan Archive at Penn (ORSA) collection (http://grape.anthro.upenn.edu/~lab/pennct/). For this pilot study, 11 scans were selected: one to serve solely as the target 'atlas' cranium, and 10 for the actual morphing comparisons. Original scan resolutions were approximately .3mm x .3mm x .5mm. To simplify the analysis, the following selection criteria were used:

- Complete crania only
- Equal numbers of male and female crania for the morphing into the 'atlas' (target) cranium
- Same ages (two 30 year olds and three 40 year olds of each sex)
- Drawn from the same geographic area: India

A 30 year-old female from India was arbitrarily chosen to be the target atlas.

Image pre-processing

- Scans transformed into 8-bit, 1 mm cubic voxel format (required due to the extremely memory-intensive algorithms used)
- Non-cranial features were removed (e.g., CT cradle, cloth, mandible if present)
- Scans were cropped to minimize blank space around cranium (further reducing scan size)

Morphing

For each image, the following transformations were calculated:

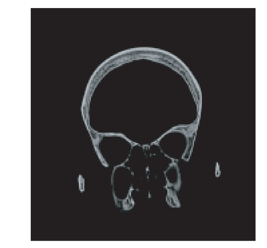
1. rigid alignment: determine the rigid transformation needed to align the morphing image with the target atlas image in 3D space
2. affine transformation: determine the optimal compression/expansion of the along each of the X, Y and Z axes of the morphing image such that it matches as closely as possible the target atlas image
3. diffeomorphic transformation: determine the localized distortions of the morphing image needed such that it matches the target atlas image
4. combine the transformations calculated in steps 3 and 4
5. calculate the localized scaling factors at each point (voxel) in 3D space implied by the combined transformations: specifically, determine the Jacobians of the matrix of partial derivatives of the vector functions describing the necessary transformations at each voxel of the target atlas

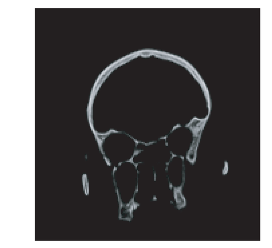
These steps create, for each subject crania, a new image, identical in shape to the target atlas, for which each voxel represents the localized distortion needed to map the target atlas cranium into a given individual subject's cranium.

Population analysis

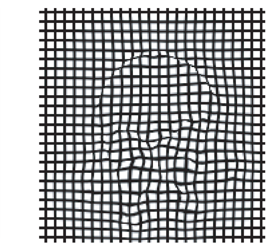
Since individual transformations are now described as distortions from the target atlas, voxel-by-voxel populations comparisons can be calculated:

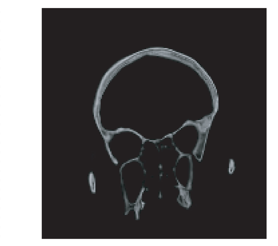
1. calculate the average and the variance of the Jacobians at each voxel of the atlas for each population
2. calculate t-values of the population differences for each voxel
3. threshold t-value maps at p<.001 (to help account for multiple comparisons)
4. repeat for each population comparison of interest (e.g., males vs. females, older vs. younger, whatever)


atlas coronal slice

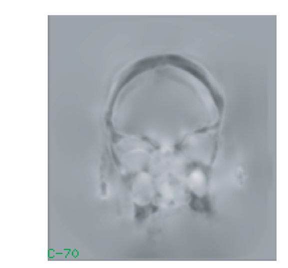

subject coronal slice

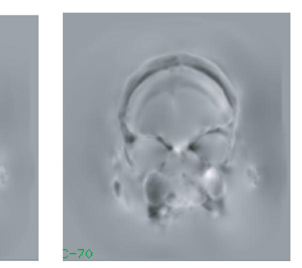

Jacobians of the transformations mapping atlas to subject (dark areas=contraction light areas=expansion)


grid illustrating localized distortion mapping atlas to subject (cf. D'Arcy Thompson)

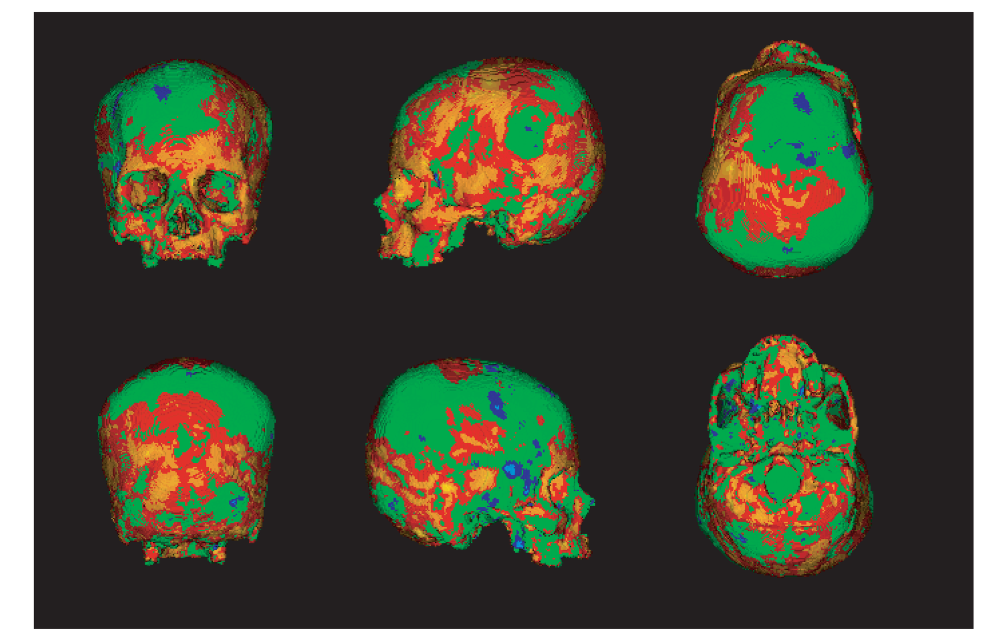

atlas morphed into subject space

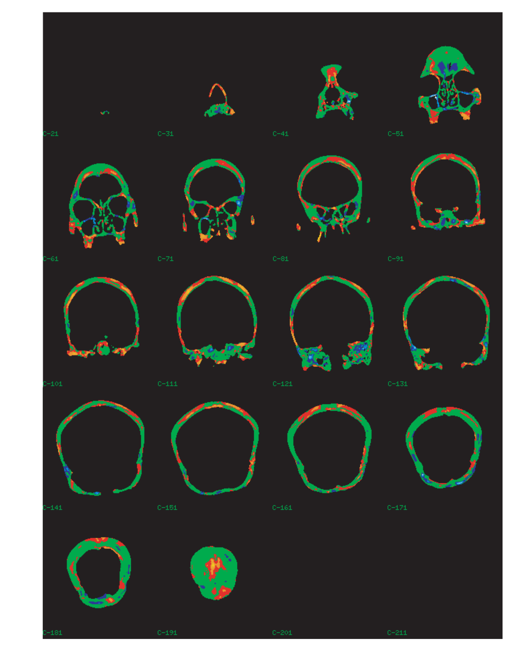
Population averages

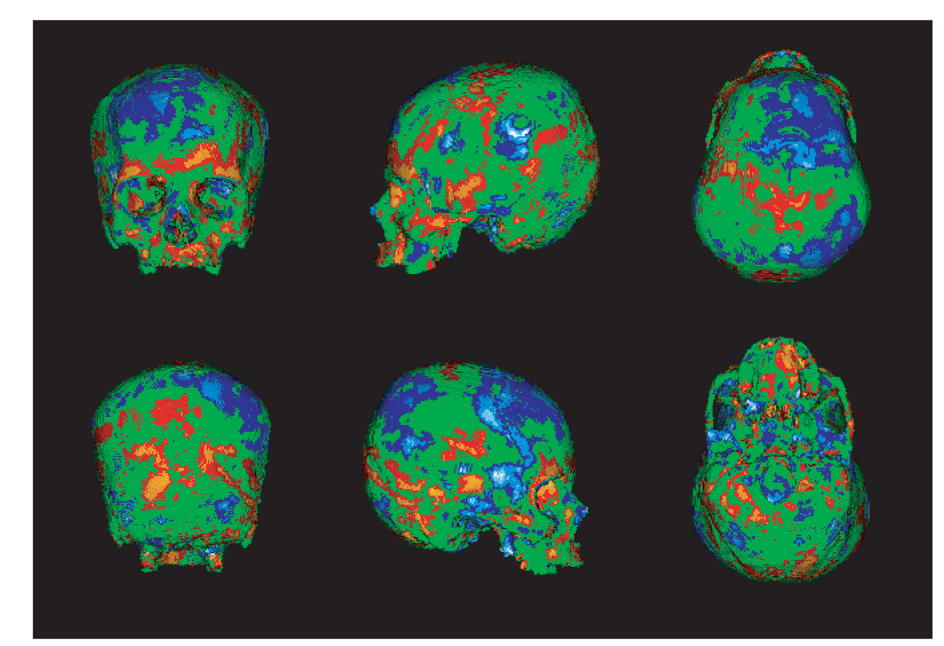

average male Jacobians

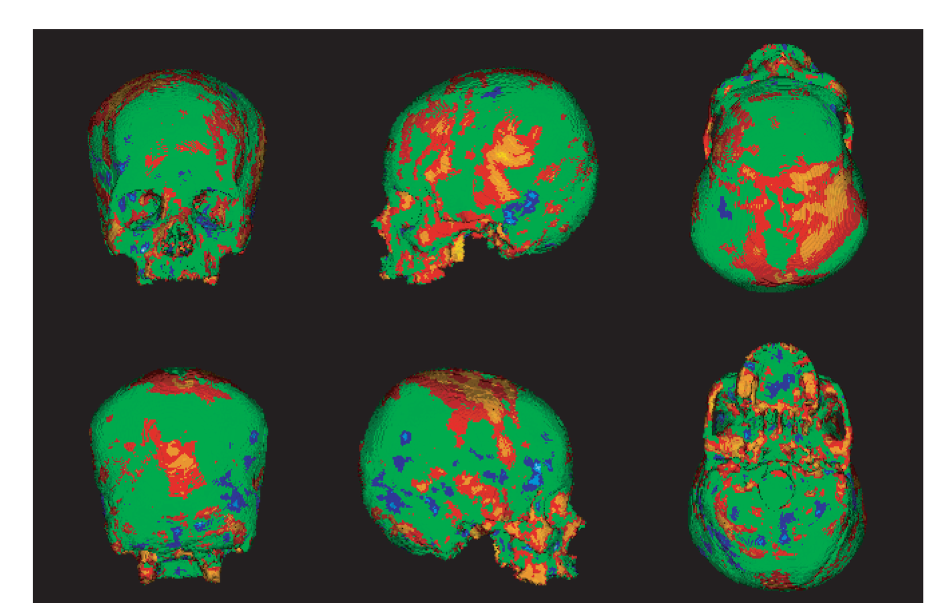

average female Jacobians

(Jacobians = localized scaling factors)


t-values of sex differences in cranial size and shape.
red-to-orange: males larger than females
blue-to-white: females larger than males
green: males ≈ females


t-values of age differences in cranial size and shape (coronal sections)


t-values of sex differences in cranial shape *only*.


t-values of age differences in cranial size and shape.
red-to-orange: older larger than younger
blue-to-white: younger larger than older
green: older ≈ younger

Results

Age differences:

Our sample appears to show differences in the cranium between the 3rd and 4th decades of life (the most common older-age category typically represented in archaeological skeletal samples):

1. the overall increase in the shape of the cranium associated with cranial bone thickening especially in the neurocranium.
2. a general increase in the asymmetry of the cranium especially in areas associated with the musculature of mastication (including the temporal, masseter and both pterygoids - although in different dimensions).
3. architectural changes in the contour of the nasal aperture and adjacent bone areas of the maxilla especially in the premaxilla.

Sex differences:

1. In this sample the most morphologically distinctive areas between males and females appear to be confined to features of the face. This includes both superciliary arch development, orbit position and shape, as well as the degree of projection of the zygomatic arches.
2. Areas associated with general muscularity appear to be varied in the degree of expression over the cranial surface. These would include mastoid size and shape as well as general rugosity of the nuchal area.

Further work and larger samples are needed to confirm these results, but the method appears to be useful for both describing and statistically assessing complex morphological variation.

Conclusions

Age differences

- increase in cranium associated with cranial bone thickening
- increase in asymmetry
- changes in nasal aperture and maxilla

Sex differences

- the most distinctive areas are in the face
- evidence of general muscularity varied in degree over the cranium

Methodology

- Rigid and non-rigid (morphing) methods from MRI-based functional imaging analysis can be usefully applied to CT images, and questions of anthropological interest
- These methods allow for the detailed quantitative assessment of complex morphological variation between and within populations
- Once morphing transformations have been calculated between each subject and a target atlas, different sub-population assessments can be made easily

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