Three Dimensional Quantitative Analyses of Human Pubic Symphyseal Morphology: Can Current Limitations of Skeletal Aging Methods Be Resolved?

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ABSTRACT

During the past century, several aging methods based on pubic symphysis morphology have been introduced. Many of these methods represent modifications of the original method described by Todd (1920). Recently, Hoppa (2000) has explored some of the problems and challenges associated with using modern reference samples to estimate the pattern and rate of age related changes in bone morphology observed in past populations. His results outline the current limitations of skeletal aging methods, in particular, those that rely on changes to the pubic symphyseal face.

In this paper, we introduce a novel approach that may, in future years, help alleviate some of these methodological problems. We present the results of quantitative analyses of the age-related morphological changes displayed by the Suchey-Brooks pubic symphysis casts. All twenty-four male and female casts were scanned using a 3D laser scanner and geometrically modeled. The resulting virtual 3D symphyseal faces were analyzed using various geometric analytical techniques enabling the extraction of quantitative data best representing qualitative features of interest.

Preliminary results suggest the ability to quantitatively describe the age-related changes to the pubic symphysis may provide potential for future method refinement. Continuing research is committed to developing a computerized, web-accessible database of 3D pubic symphyseal faces from individuals of known age-at-death, sex, and biological affinity. It is hoped that this work will lead to further refinements of the pubic symphysis aging method, especially in regard to differences between populations, as well as serving as an education and research tool.

INTRODUCTION

Newly developed technologies involving modeling and visualization techniques have become essential research tools in many scientific and creative disciplines. Theoretical and technical advances in data capturing and geometrical modeling techniques present the opportunity to advance 3D knowledge into scientific disciplines such as physical anthropology. Current research projects at the Partnership for Research In Stereo Modeling (PRISM) at Arizona State University (ASU) surround the development of practical and analytical tool sets for handling 3D data. These tool sets allow for improved 3D data representation and extraction while also enabling query and data mining opportunities. The research goals are to facilitate the knowledge discovery processes involved in various disciplines, including physical anthropology. In order for this facilitation to occur, specific features of interest to the domain scientists must first be identified.

Specific features of interest vary depending on the particular domain of research. For instance, cell biologists may define the shapes and forms of intra-cellular structures as features while archaeologists may want to recognize the various shapes inherent to ceramics and pottery. For physical anthropologists specializing in human osteology, features typically relate to variation in bone morphology. Morphological variation can be described either qualitatively or quantitatively. An objective of this study is to determine whether qualitative features generally associated with the aging process can be extracted from a bone surface in the form of quantitative data.

Establishing the age-at-death of an individual from skeletal remains is a critical component of physical anthropology. One of the most widely used methods for estimating age-at-death of adults is based on the morphological changes of the pubic symphyseal face (i.e., the anterior pelvic bone joint). Several aging methods based on pubic symphysis morphology have been presented over the past eighty years; however, the majority of these represent refinements of the original method described by Todd (1920). Today, especially in North America, the Suchey-Brooks method (Brooks and Suchey, 1990; Katz and Suchey, 1986) is the most widely accepted and utilized. Their method involves the use of special casts that illustrate the bony changes through different age categories for males and females. There are twelve casts for each sex and these are subsequently divided into six age stages with an early and late stage of development being represented for each stage. In this study, 3D geometric models of all 24 casts are subject to various extraction algorithms to determine the utility of a 3D approach to examining the pubic symphysis for age changes as well as for improving research and education opportunities for physical anthropologists.

METHODS & RESULTS

At PRISM, considerable experience has been gained over the past six years in collecting surface data from 3D objects. In particular, these objects have included bones (~ 600) and other archaeological artifacts such as ceramic vessels (~150). Presently, PRISM has four laser digitizers, which are highly accurate devices and can accommodate a wide variety of surface types and sizes of objects to be scanned. The high resolution of the laser scanners produces high-density triangular meshes (averaging over 1000 points per cm^2). However, the approach taken at PRISM goes well beyond surface data alone. Modeling volume data (e.g., CT scans, MRI and Ultrasound data) is also an area of active research. In this manner, the need for practical and analytical software that enables various researchers to extract and analyze 3D features of interest from various 3D-acquired data sets, all within a user-friendly interface is being anticipated.

The methods used in this investigation involve the following procedural steps: 1) acquisition and 3D geometric modeling of 24 pubic symphysis casts (12 male, 12 female), which represent the age categories described by Suchey-Brooks; 2) generation of curvature maps showing the relative areas of high, medium, and low curvature for each symphyseal face; 3) segmentation of each symphyseal face using a watershed-based algorithm, and 4) extraction of absolute curvature values from all vertices representing each segmented symphyseal face. The purpose of this research is to determine if this methodological approach is appropriate to warrant further investigation of the age related changes to the pubic symphysis.

1) Data Acquisition and 3D Modeling. One of us (MWT) scanned all 24 Suchey-Brooks pubic symphysis casts (courtesy of Dr. Diane Hawkey, ASU Department of Anthropology) using the portable Cyberware Model 15 laser digitizer. All scanning took place at ASU.

The digitized data initially consist of 3D point clouds, with each point cloud represented by thousands of point coordinates. The coordinates represent specific locations on the symphyseal surface defined by their digitized x, y, and z values. The Model 15 laser digitizer captures surface data points less than 300 microns (0.3mm) apart. This resolution results in approximately 1100 coordinates per square centimeter for each scanned pubic symphysis. At this stage, there is no actual surface structure associated with the point cloud. Triangulation of the digitized points enables the point cloud to become geometrically structured or modeled. Modeling is accomplished through the transformation of each digitized point into a vertex of a triangle, thereby adding topology to the geometry. Figure 1 shows the process of transforming a point cloud into a triangular mesh and subsequently applying a surface to the mesh. The resulting 3D models of the Suchey-Brooks pubic symphysis casts are shown in Figure 2.

2) Generation of Curvature Maps. This procedure is carried out using research software developed at PRISM wherein the absolute curvature values of the vertices were approximated in relationship to one another following the methodology described by Pulla and colleagues (2002). Areas of high relative curvature are shown in red, medium in green, and low in blue (Figure 3). The results provide a visual display of curvature change to the symphyseal face across the represented age categories.

3) Feature Segmentation. The next step involves determining whether an algorithm can identify specific features on the pubic symphysis that are of interest to forensic anthropologists. The research goal is to evaluate a watershed-based algorithm's ability to segment the pubic symphyseal face into meaningful regions, which would allow researchers to quantify age-related changes to pubic symphysis morphology.
The segmentation methodology being developed by PRISM researchers relies on a watershed-based hybrid segmentation scheme for triangular meshes (Mangan and Whitaker, 1999; Pulla et al., 2002; Razdan and Bae, 2002). Mangan and Whitaker (1999) have used discrete curvature (locally estimated) on polygonal meshes for segmentation. Pulla and colleagues (2002) considerably improved the quality of segmentation by

applying more accurate and robust curvature estimation techniques. However, this method results in many disconnected edges and thereby incomplete feature loops. Razdan and Bae (2002) developed a hybrid method that takes advantage of the watershed technique combined with dihedral angle method to create regions with complete feature loops. This segmentation scheme is applied to each modeled pubic symphysis.

The process of watershed-based segmentation can be explained as follows. In geography, watersheds form the dividing line between drainage basins. Similarly, the computerized watershed segmentation scheme defines the areas of a 3D surface where water would flow if it were a geographical region. In geography these areas are determined by elevation whereas in 3D image analyses various curvature values represent the determining factor. These defined areas of relatively low curvature are referred to as minima, which can be combined or merged to adjacent, similar regions. The surface is automatically segmented into regions of similarity based on the threshold values of the algorithm as defined by the researcher (Figure 4). Three-dimensional data can then be extracted as surface features as opposed to reducing them to 2D data in the form of linear measurements (Figure 5).

4) <u>Data Extraction</u>. After segmentation, regions defined by the watershed procedure were manually merged to define the symphyseal face as a single feature. Absolute curvature values of the vertices on each symphyseal face were calculated. Mean absolute curvature values for each male and female age stage are shown in Figure 6. A general trend in decreasing curvature is observed over the progressive age stages. Although fluctuations are present, especially in male stage 5 and female stage 6, these results show the potential

of using curvature as the quantitative measure for future analyses. Note that the red areas indicating high curvature in male phases 5a and 5b as well as female phase 6b are concave indentations of the symphyseal face as opposed to the ridge and furrow systems seen in the early phases (Figure 3). Absolute curvature values are always positive providing a measure of curvature that does not take into account the direction of the curve (i.e., concave or convex). Other measures of curvature, such as Gaussian curvature, provide measures that also describe curvature direction. Further research will focus on targeting specific features on the symphyseal surface, as is done in the current qualitative methodology (Brooks and Suchey, 1990), using curvature values to initiate region segmentation. These individual sub-regions can then be analyzed independently, using various measures of curvature (e.g., absolute, Gaussian, root mean square, etc.) for quantitatively describing the patterns of age-related change to their surface topology.

DISCUSSION

Aging human skeletal remains is an important aspect of physical anthropology, particularly in forensic analyses and paleodemographic reconstruction. To establish age-at-death, anthropologists must rely on standards that involve the visual comparison of certain skeletal features with established aging criteria. Currently, these criteria exist primarily in the form of photographs or casts. To date, one of the most reliable methods for estimating adult age-at-death involves a visual subjective assessment of the morphological changes of the pubic symphyseal face by comparing it to a series of casts (Brooks and Suchey, 1990; Katz and Suchey, 1986).

Using 24 casts to represent age-influenced biological variation in populations separated in both time and space is a clear methodological problem. Recently, Hoppa

(2000) discussed some of the major problems and challenges associated with using modern reference samples to estimate the pattern and rate of age related changes in bone morphology observed in past populations. Using two target samples of known age, he evaluated the ability of the Suchey-Brooks methodology to estimate individual age within each target sample (Hoppa, 2000). The results of his analyses suggest that significant differences between the reference sample (i.e., Suchey-Brooks sample) and the two target samples may exist in the timing of age-related changes to bone (Hoppa, 2000). His results outline the current limitations of skeletal aging methods, in particular, those that rely on changes to the pubic symphyseal face (Hoppa, 2000).

Several researchers have suggested and discussed various sophisticated statistical techniques to handle these methodological problems (e.g., Bouquet-Appel and Masset, 1996; Konigsberg and Frankenberg, 1992; Muller et al., 2002). These techniques are extremely important as they attempt to reconcile problems associated with estimating age-at-death distributions and/or paleodemographic profiles. However, Jackes (2000) has noted, "… that proposed statistical techniques do not provide the magic answer, and we could hardly expect this to be so" (Jackes, 2000:451). She suggests reexamining reference samples for 'stages of skeletal change' while realizing that perhaps no more than 30% of the changes may actually be related to the aging process, providing "a foundation for analysis of these data across time and space" (Jackes, 2000:452). In this regard, 3D modeling is a likely approach to developing a foundation for future skeletal aging research.

The results of this study suggest that inherent methodological problems of the pubic symphysis technique can be approached from the standpoint of improving the accessibility of researchers to various osteological reference samples through the development of a Visual Query Interface (VQI) (Figure 7). The VQI can archive 3D models of pubic symphyses from individuals of known age, sex, and biological affinity. In this manner, 3D models along with the associated vital statistic information can be acquired from various skeletal collections (e.g., Suchey-Brooks collection, Terry collection) and stored in a combined database that can be accessed for education and research purposes. Using the 3D segmentation and extraction methods described herein, qualitative features can be quantified using various algorithmic approaches. Once quantified, examination of the distribution of features within large samples, such as the proposed VQI database, would enable researchers to extract the maximum amount of information contained in the reference samples. Combining improvements in 3D data accessibility and analyses with the continued development and refinement of statistical techniques for osteological data will likely significantly increase the knowledge and understanding of age related changes to the pubic symphysis.

CONCLUSIONS

In this study, all 24 Suchey-Brooks pubic symphysis casts were laser scanned and 3D modeled. The models show a high level of surface detail and are practically indistinguishable to the eye from their real world counterparts. The ability to accurately replicate pubic symphyses is extremely exciting as it opens the door to being able to combine reference collections housed at various institutions around the world. Using curvature values to segment the symphyseal surface into various regions was also successful. Continued research is focused on segmenting regions on the symphyseal face that best represent the qualitative features of interest to physical anthropologists, enabling qualitative observations to be examined quantitatively.

In summary, the results of this study indicate that changes to the symphyseal face can be quantified using various measures of curvature. Through the continued acquisition of 3D modeled pubic symphyses from individuals of known age, sex, and biological affinity, the knowledge and understanding of how surface curvature changes relate to the biological processes of aging can be furthered.

Future research objectives include the following: 1) 3D acquisition of pubic symphysis morphology, from individuals of known age-at-death, sex, and biological affinity, from human skeletal collections housed at various museums and research institutions around the world; and 2) The continued development of quantitative shape description and geometric modeling techniques, and visual queries to recognize, measure, and analyze the morphological attributes of pubic symphysis morphology.

To conclude, new technological approaches to research, such as 3D modeling, should be considered in perspective. Fifteen years ago, Maples (1986) discussed the use of the microcomputer in physical (forensic) anthropology. In his article, he described the potential benefits of word processing, graphics, and statistical programs to physical anthropologists. He concluded, "Microcomputers will be with us until replaced by more advanced technology. Technology will never replace expertise, but that expertise must adapt to the new technology" (Maples, 1986:319)

In this regard, the results presented herein should not be considered only in terms of the question, 'does or will a 3D approach significantly improve or refine the current accepted standards'? That question can only be answered in the years to come. More importantly, these results show considerable promise for improvements in the education and training of physical anthropologists, and also in the way and manner physical anthropologists are able to conduct osteological aging research.

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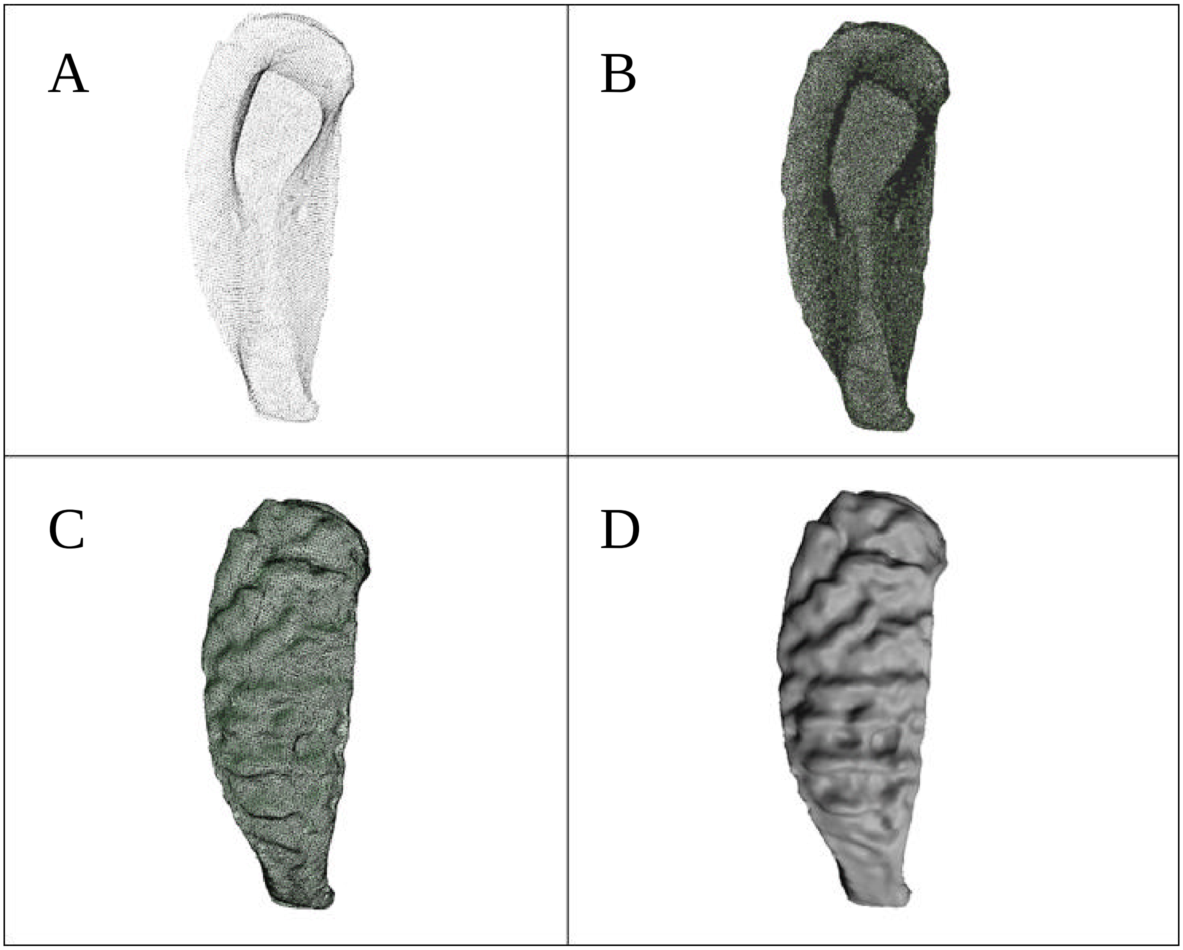

Figure 1. The process of transforming a point cloud into a workable 3D model: 3D point cloud (A); triangulated point cloud (B); triangulated point cloud with flat surface mesh (C); final geometrically modeled 3D pubic symphysis (D).

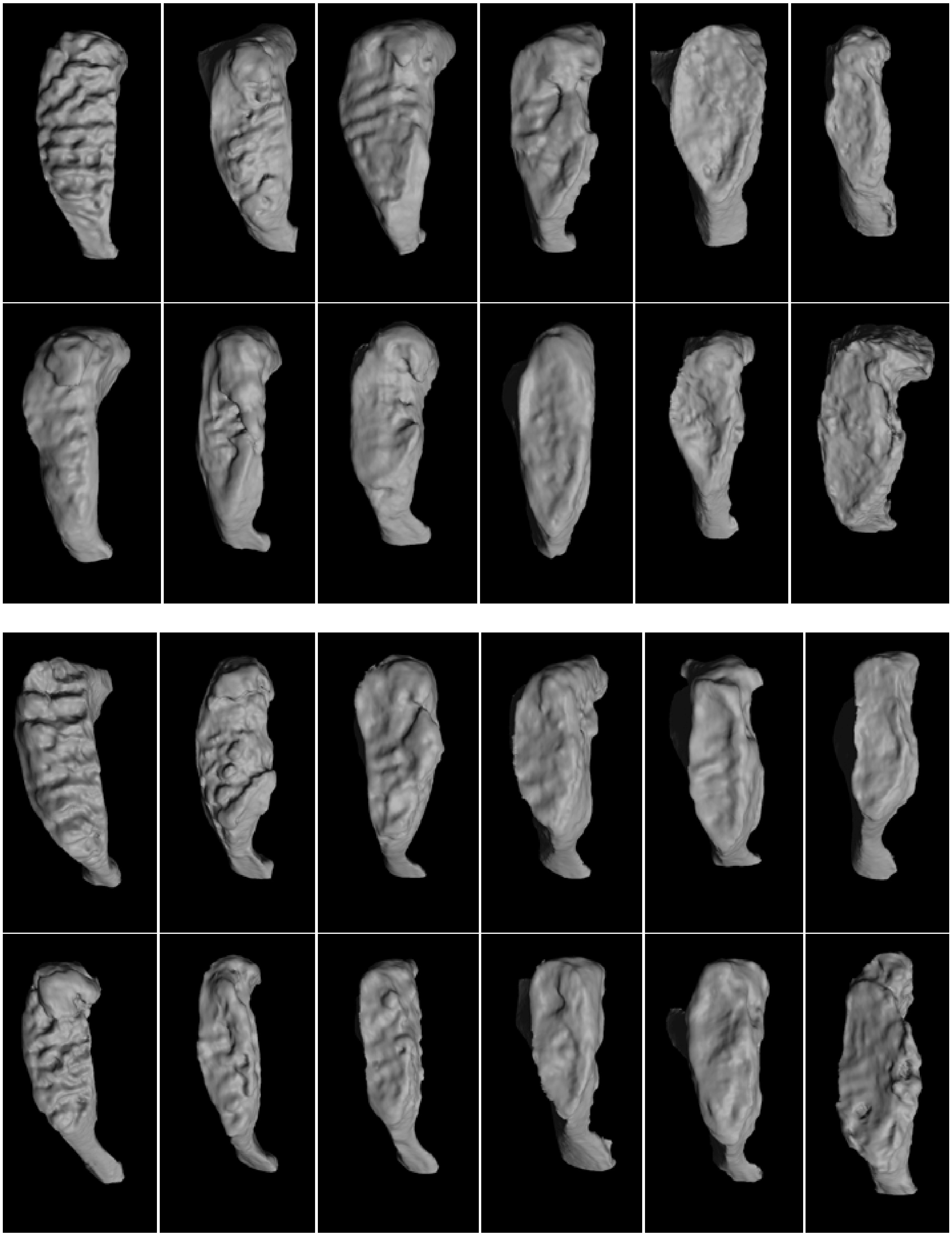

Figure 2. Age changes occurring to the male (top two rows) and female (bottom two rows) pubic symphyses through age stages 1 to 6 (left to right) as described by Brooks and Suchey (1990) and Katz and Suchey (1986). Rows 1 and 3 represent early changes within each stage while rows 2 and 4 represent later changes.

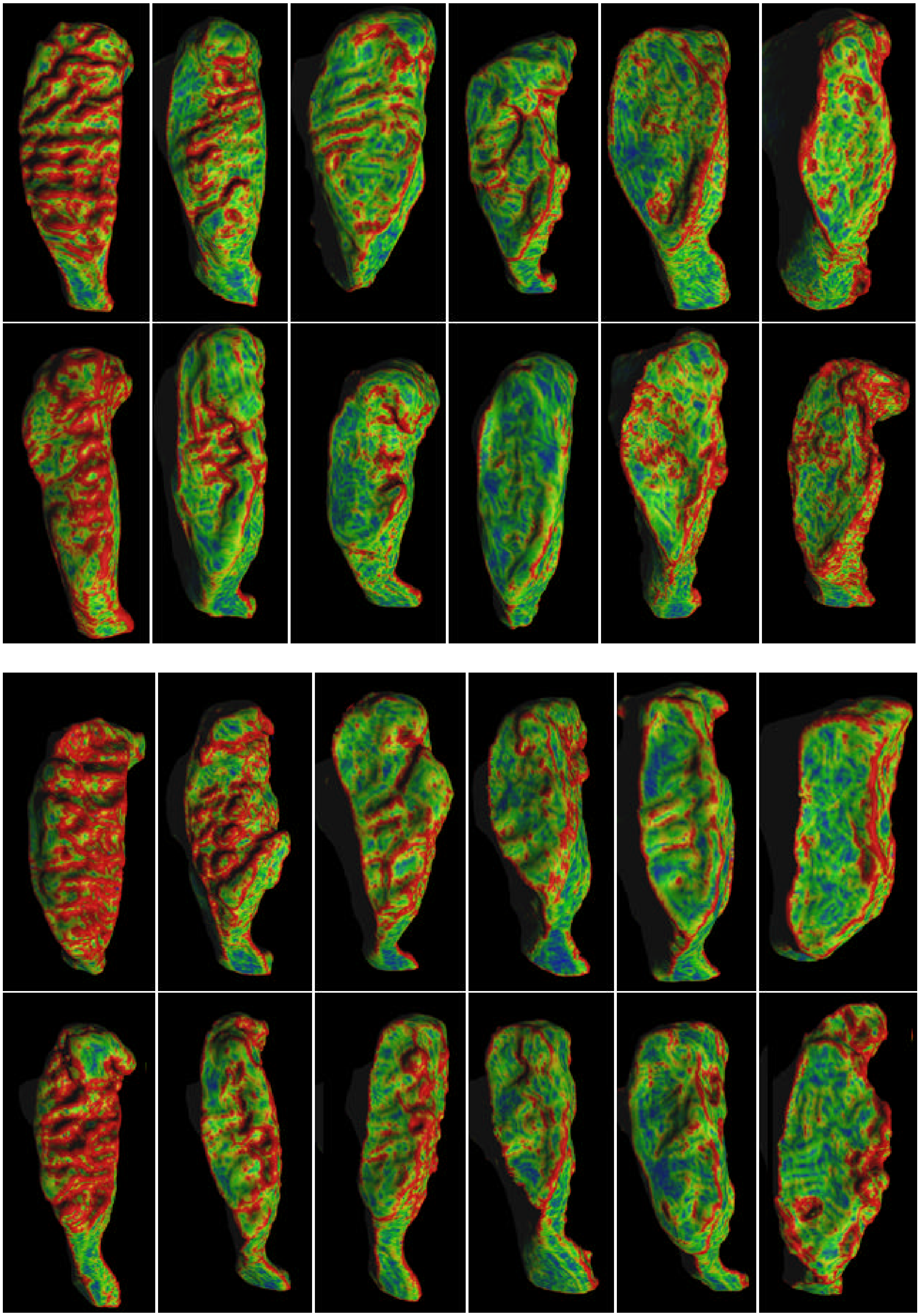

Figure 3. Age changes as shown by areas of relative curvature (high in red, medium in green, and low in blue). The results provide a visual display of curvature change to the symphyseal face across the represented age categories (same as Figure 2).

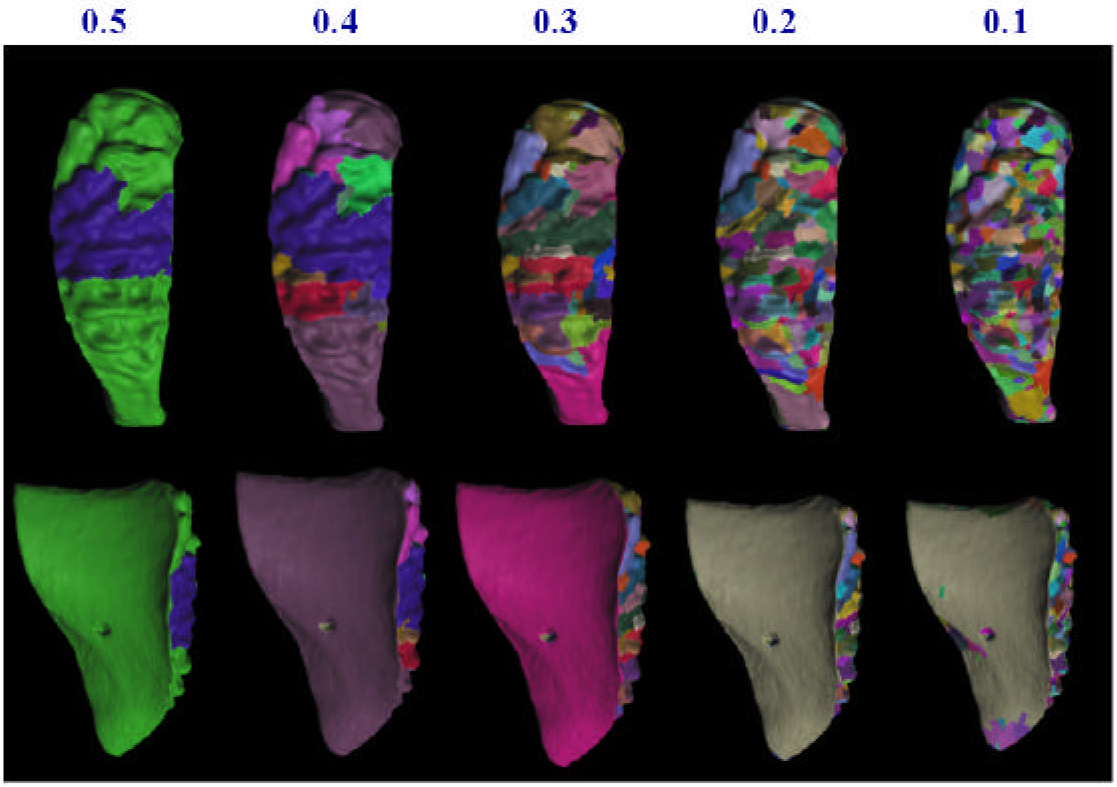

Figure 4. Illustration of a modeled pubic symphysis (male phase 1a) segmented at five different threshold levels. Different threshold levels allow the researcher to combine or split surface regions until the specific feature(s) of interest is segmented.

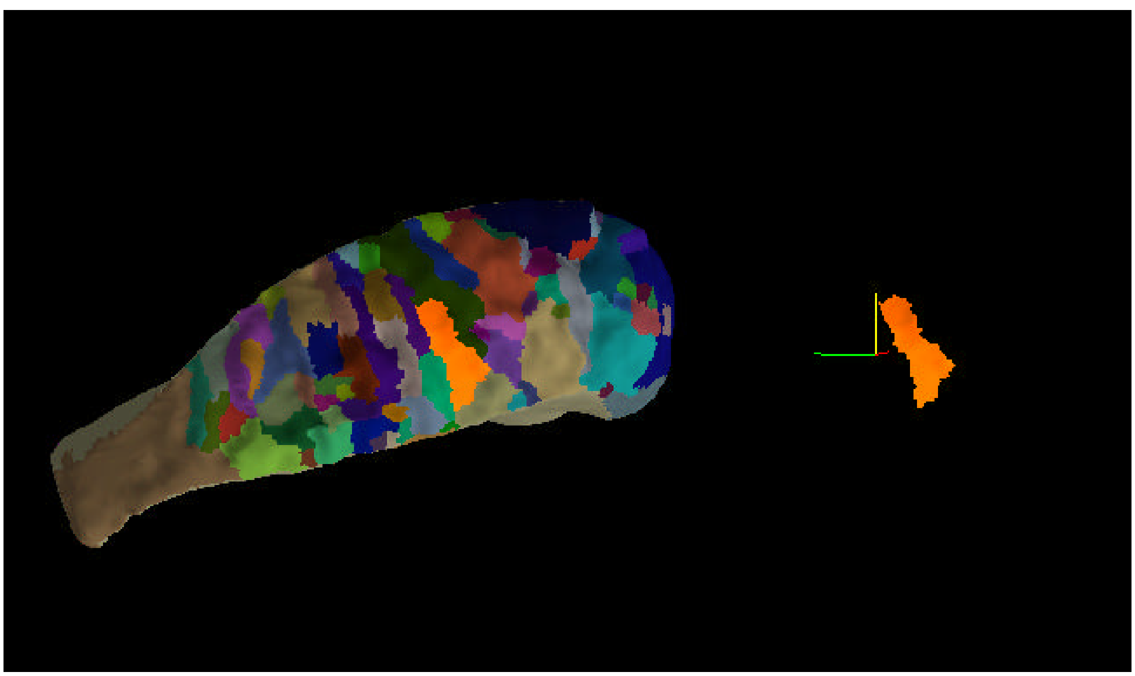
Figure 5. Illustration of the process of extracting data in the form of surface features after the desired segmentation has been achieved.

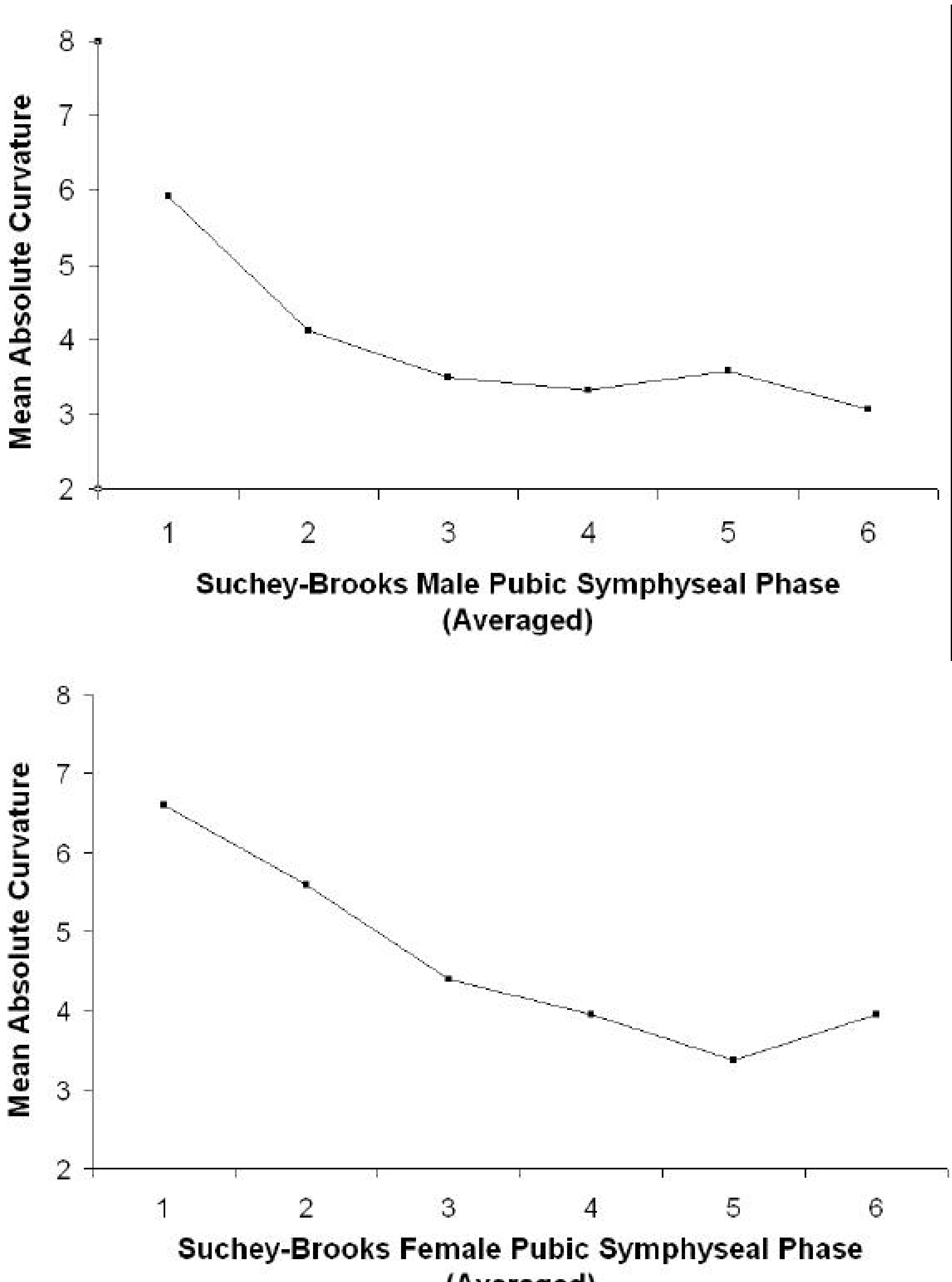

Figure 6. Mean absolute curvature values for each age stage by sex. Although fluctuations are present (e.g., male phase 5, female phase 6), these results illustrate the potential of using curvature as the quantitative measure for future analyses.

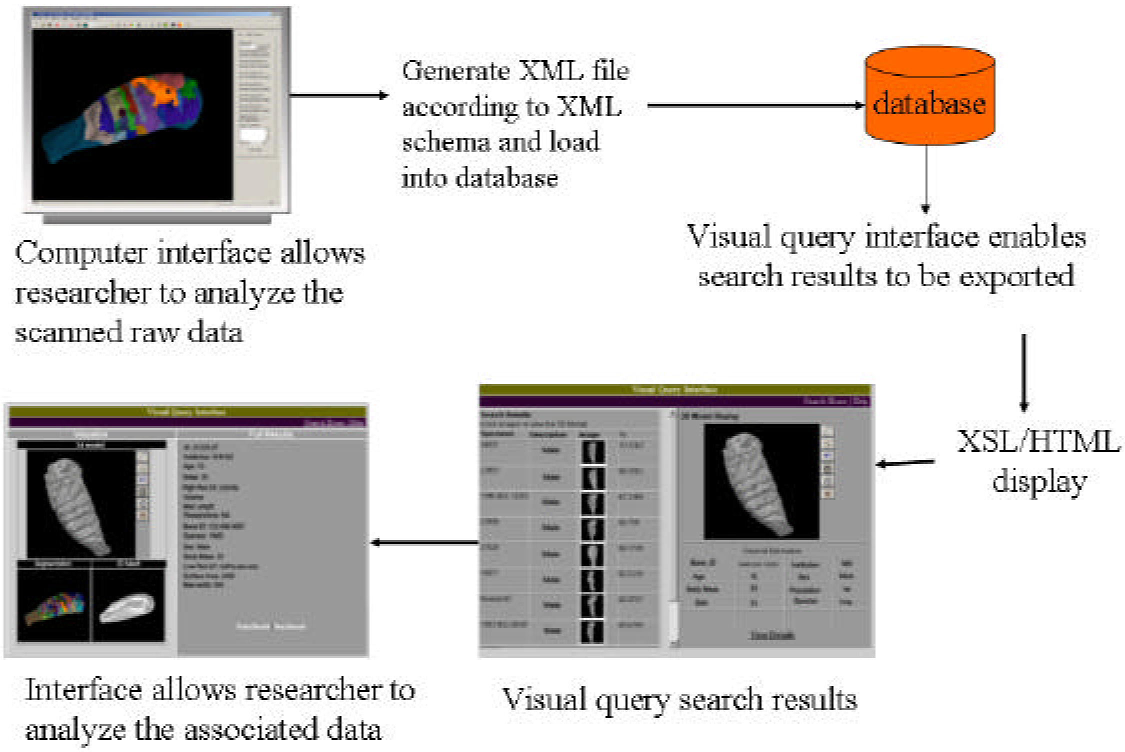

Figure 7. Prototype structure of the Visual Query Interface for 3D modeled pubic symphyses. The XML file represents the data, which includes extracted surface features as well as any associated information (e.g., age, sex, biological affinity, occupation, etc.) to be uploaded into the database.