A COMPUTATIONAL METHOD FOR AGE-AT-DEATH ESTIMATION BASED ON THE PUBIC SYMPHYSIS

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A significant component of forensic science is analyzing bones to assess the age-at-death of an individual. Forensic anthropologists often include the pubic symphysis in their studies. Subjective methods, such as the Suchey-Brooks method, are currently used to analyze the pubic symphysis. This project examines a more objective, quantitative method. The method analyzes 3D surface scans of the pubic symphysis and implements a thin plate spline algorithm which models the bending of a flat plane to approximately match the surface of the bone. The algorithm minimizes the bending energy required for this transformation. Results presented here show that there is a correlation between the minimum bending energy and the age-at-death of the individual. The method could be useful to medico-legal practitioners.

Introduction

- The pubic symphysis is a small surface connecting the left and right pubic bones in the front of the pelvic girdle.
- Throughout life, the surface of the pubic symphysis changes at a more-or-less predictable rate.
- For many decades, researchers have been interested in developing techniques for age estimation based on the changing morphology of the pubic symphysis. Such methods include Todd, McKern and Stewart and the most popular one - the Suchey-Brooks method.
- There is a definite need for an objective, quantitative method.

Method Overview

- The method uses 41 scans from white male individuals with known ages.
- It reads in and cleans scan data from ASCII PLY files.
- It applies Principal Component Analysis (PCA) to standardize the position of the scans in space.
- It selects two sets of equidistant control points forming square grids.
- It uses thin plate splines (TPS) to give each scan surface a quantitative representation.

3D-scan data

The purpose of 3D scanners is to generate a dense point cloud or a polygonal mesh. They capture the geometry of a physical object with hundreds or thousands of measurements. The 3D shape is represented as numerous small adjacent triangles that are called faces. Every face has three vertices and each vertex has three coordinates that specify its location in space. The data from the scans are stored in binary or text files that are essentially lists of numbers. The files store the coordinates of all the vertices and the information on how they are connected to form the triangles. Examples of 3D surface scans of pubic symphysis are shown below.

Principal Component Analysis (PCA)

The next step of our method is standardizing the orientation of the scans. It starts by translating the scan to the center of the coordinate system and is followed by PCA. The goal is to position the bone in such a way that its center matches the center of the coordinate system and the x, y, and z axes define the dimensions with the largest variance (x), the second largest variance (y) and the smallest variance (z). This way the $x-y$ plane approximates the articular surface of the bone, and we can study the distances in the z direction.

Algorithm

In the current application, the PCA algorithm uses a mean-centered data matrix, A, that is an $n \times 3$ matrix where n is the number of vertices and the three columns correspond to the x, y and z coordinates of each vertex after the mean-centering. First, the 3×3 matrix defined by $A^T A$ is calculated. To do an eigen analysis on the matrix we use singular value decomposition. The $A^T A$ matrix is factored into a 3×3 diagonal matrix S that has the singular values as its diagonal entries and two orthogonal 3×3 matrices U and V (in our case $U = V$ because $A^T A$ is a symmetric matrix) such that

$$A^T A = USV^T.$$

The $n \times 3$ matrix AV gives the coordinates for the vertices after the PCA rotation.

Selecting control points

To select the first set of control points (the points lying on the flat plane), the method scales the bones to be of uniform length equal (in our case) to 20. It then selects 51 equidistant points in the x-direction and however many points fit in the y-direction. This results in a square uniform grid of size 0.4. We can choose any length size and number of points but these numbers are used for convenience. Then, we find the projection of the first set of control points onto a valid triangle (face) on the scan. The projection points become the second set of control points. A non-existent projection means that the given point is outside of the surface scan and is removed.

Thin Plate Splines

Given the two sets of control points, one lying in a plane and the other consisting of corresponding points on the symphysis surface, we can bend the plane so that the two sets of points match exactly.
The implementation of the method involves solving a linear system, $\vec{b} = M\vec{x}$, and finding a solution vector $\vec{x}$. The components of the solution vector may be used to interpolate the rest of the points or to find the minimum bending energy required for bending the plane to match the surface of the pubic symphysis. Let $\vec{w}$ be the first k components of $\vec{x}$, where k is the number of control points in one of the 2 sets and a_1, a_2, a_3 be the last 3 elements of $\vec{x}$. To interpolate the points we can use the exact equation for z that is

$$plane_z^l = a_1 + a_2 plane_x + a_3 plane_y + \sum_{i=1}^{k} w_i U ||plane^i - plane^l||_2.$$

If $plane^l$ is one of the control points on the plane, then its z-value will exactly match the z-value of the corresponding control point on the symphysis surface.

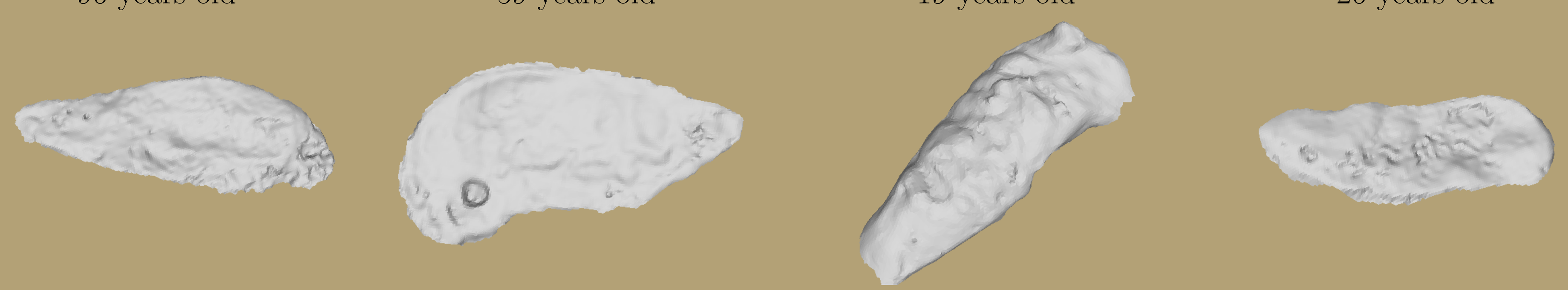
Minimum Bending Energy

As we said, the TPS algorithm models the bending of a metal plate to match another surface. Some force needs to be applied to the metal plate to transform it. The minimum bending energy, as the term suggests, is the least amount of energy required to transform the perfectly flat plane into the shape of the surface scan. It minimizes the integral

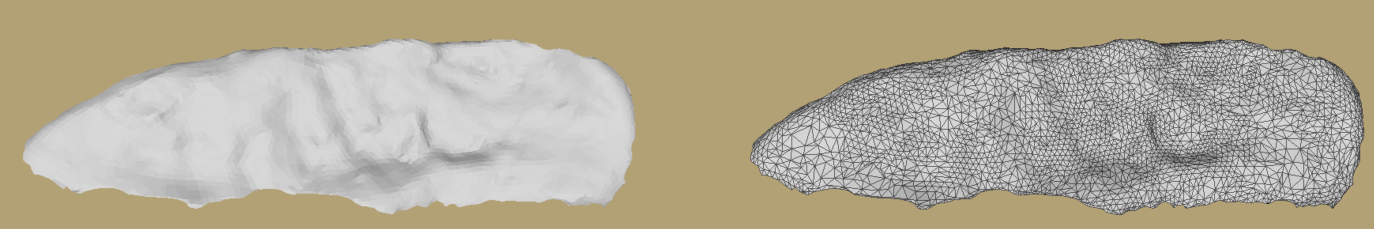
$$\iint_{R^2} \left(\left(\frac{\partial^2 z}{\partial x^2}\right)^2 + 2\left(\frac{\partial^2 z}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2 z}{\partial y^2}\right)^2 \right) dx\, dy.$$

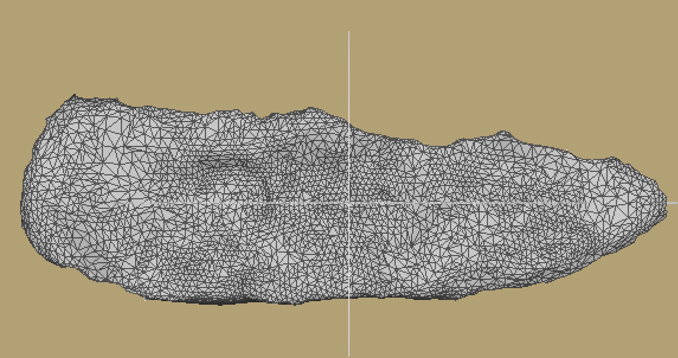
The value of the minimum bending energy is given by, $E_{min} = wCw^T$.
The minimum bending energy is a measure of the complexity of the surface scan, which is, in part, the basis of the subjective methods currently in use. A correlation between the age-at-death and the minimum bending energy could be used to estimate the age-at-death.

Four sample syphysis scans of people of different ages

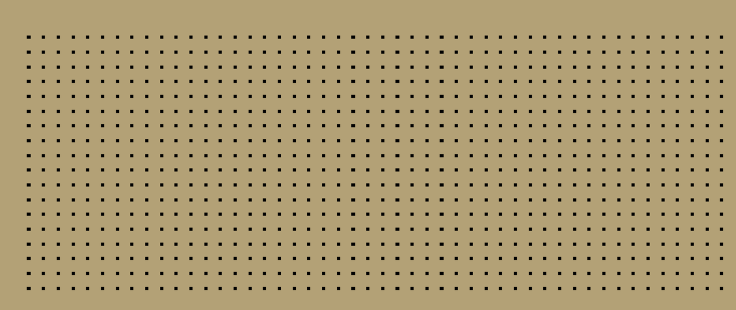


A 3D scan shown as a smooth surface vs a number of adjacent triangles

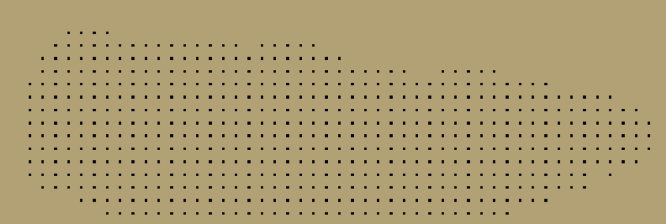




Position with axes after PCA



Uniform square grid



First set of control points (on the plane)

Results

The results presented here were generated using 51 control points in one set.

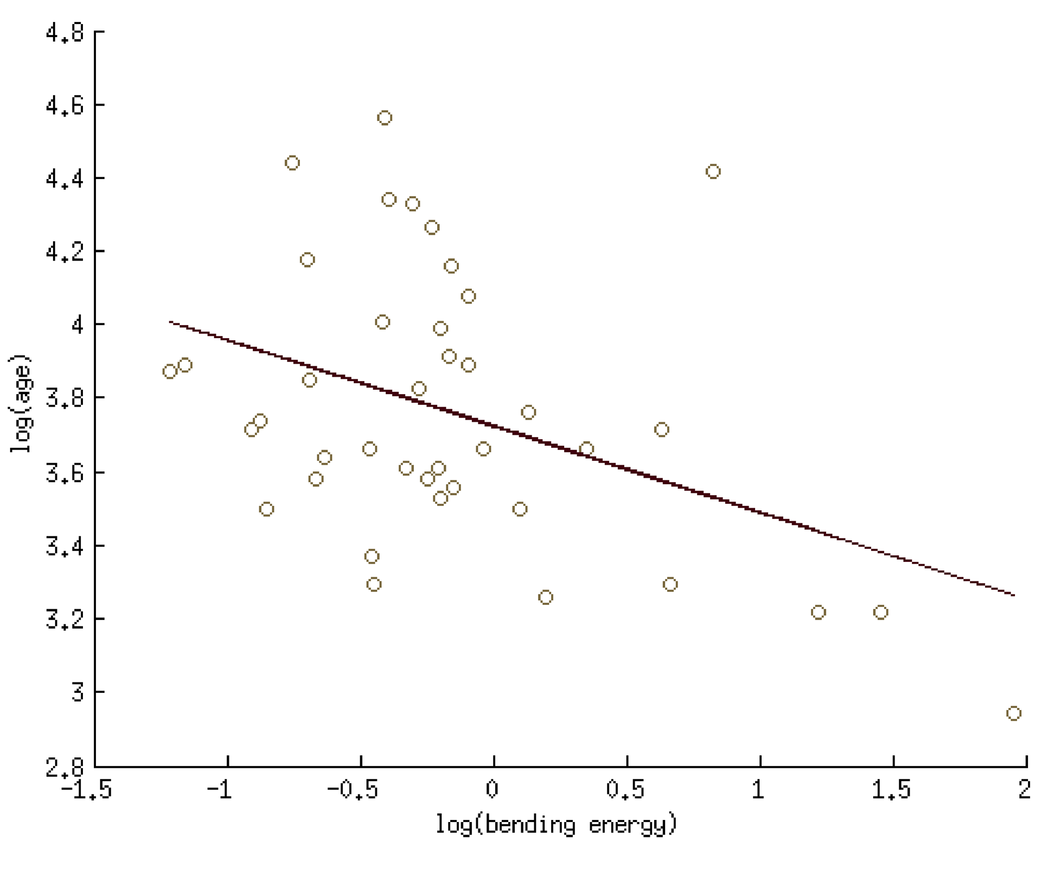
	Correlation	Linear Regression
Coefficient	0.4913	−0.1879
p-value	0.0011	0.0011

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}(estimated_i - exact_i)^2} = 17.0358,$$

where n is the number of bone scans that we use. The results of all 41 sample bones were consistent with the Suchey-Brooks method. For example, a person whose exact age-at-death is 36 is estimated to have been 38 at the time of death. According to the Suchey-Brooks method, a 36 year old person can fall in any of 4 different "phases" that range from 21-46, 23-57, 27-66 and 34-86.

Leave-One-Out Cross Validation Analysis

- RMSE = 0.8554 compared to the estimated age using all data.
- RMSE = 17.5909 compared to the exact age of the individuals.



A plot of the results showing log(age-at-death) vs log(bending energy) and the best fitting line that goes through the points.

Future Work

- Outline Analysis
- Different methods for analysing the surface
- Using two different regressions - one for younger people and one for older people.
- and more ...

References

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