ArcOSAUR: ArcGIS Operations for Surface Analysis Using Rasters

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Abstract

Herein I present new methodologies for studying the functional morphology of fossil surfaces and articular cartilage from extant organisms: a suite of automated processing tools, called ArcOSAUR, created by using ArcGIS 9.2 geographic information system (GIS) software. Using the ArcOSAUR toolbox, 3D data acquired via computed tomography (CT) or laser scanning can be converted from computer-aided design (CAD) formats to triangulated irregular networks (TIN) and then rasterized into digital elevation models (DEM). In addition to calculating surface relief and basic Euclidean measurements, the tools can be used to analyze surface convexity and concavity, identify and characterize topographic landmarks such as muscle scars and bone pathologies, and even create 3D "pseudofossils" from 2D digital photographs. Additionally, analyses need not be limited to planar surfaces such as dentition or fossils *in situ*: various trigonometric operations include the identification of centers and axes of rotation along curvilinear joint surfaces; in turn these markers can be exported for use as kinematic references in modeling software. To illustrate the utility of these processing tools, forelimb elements of theropod *Deinonychus antirrhopus*, alligator *Alligator mississippiensis*, and pigeon *Columba livia* were digitized with a high-resolution laser surface scanner and reconstructed in Maya 5.0. ArcOSAUR was then used to import and process the data, analyze the topology of articular surfaces, and reconstruct cartilaginous tissue for *D. antirrhopus* within an extant phylogenetic bracketing paradigm.

Introduction

- **GIS** — *geographic information service, a computer software and hardware system used for the display, management, and analysis of spatial data.*
- **CAD** — *computer-aided design, a system used for drafting and design in a digital environment.*
- **raster** — *a grid-based graphic file format composed of pixels (referred to here as cells); also known as a bitmap image. This format includes photographs, satellite imagery, and DEMs.*
- **DEM** — *digital elevation model, a raster wherein the values of each cell denote the relative or absolute elevation at that point*
- **TIN** — *triangular irregular network, a vector-based GIS format for representing surface morphology*

Functional morphology has traditionally been constrained by the limitations inherent in actualistic methodologies. Range of motion studies, for example, require precise and accurate measurements of structure and motion, a quantitative rigor not often provided by the traditional MO of chemistry clamps, protractors, and plasticine. These methods are also unable to provide sufficient means to manipulate objects and visualize complex movements within a 3D environment. Additionally, the role of articular cartilage in determining range of motion and kinematics – the basis for many paleobiological inferences – remains largely unexplored and qualitative in nature.

The paleontological "digital revolution" has addressed some of these limitations by bringing *in situ* fossils to an *in silico* environment – fostering the use of digital scanning and modeling software for the 3D visualization and animation of extinct organisms. Yet, such programs often remain unsuitable for quantitative and surficial analysis. Recently, GIS software has been used to identify and characterize various dental morphologies, but this has been limited to relatively planar manifolds (occlusal surfaces of mammalian teeth) and Euclidean geometrics (e.g., distance and orientation) (Pljusnin et al., 2008; Evans et al., 2007; Ungar, 2004; Evans et al., 2001; Jernvall and Selanne, 1999; Zuccotti et al, 1998; Jernvall et al., 1996).

In order to explore other uses of GIS software for paleontology – and specifically functional morphology – I used ArcGIS, the industry-standard software suite made by ESRI (Environmental Systems Research Institute, Inc., Redlands, CA, USA) that includes ArcMap (for 2D data), ArcScene (for 3D data), ArcCatalog (for data management), and ArcToolbox (for data analysis). These programs allow the user to visualize electronic maps and spatial data (e.g., census blocks, orthography, satellite imagery), and certain ArcGIS extensions, such as 3D Analyst and Spatial Analyst, contain functions for analyzing terrain. Using the ArcToolbox environment, which provides the ability to develop custom operations, I was able to create a suite of processes that can import and export digitally scanned fossil data, quantitatively measure and analyze the surfaces and structures, and even move beyond the program's limitation of "singular verticality" – that from the earth's surface, there is only one "up" (sky) and one "down" (gravity). Thus, the operations designed to analyze the topology of the earth's surface can now be exapted to analyze the surface topology of the organisms once buried beneath it.

Methods

Fig. 1. Workflow

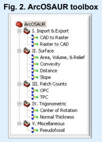
specimen → *[digital scanning]* → *point cloud* → *polygonal mesh* → *CAD* → *TIN* → *DEM*

Schematic displaying sequence of data format conversion, from fossil specimen to final GIS raster format

I. Preprocessing

1. Postmortem range of motion data was taken from an alligator and a pigeon specimen in order to examine the maximum excursions about the glenoid and humeral joints.
2. High-resolution 3D surface scans of defleshed and disarticulated forelimb elements from the alligator, pigeon, and *Deinonychus antirrhopus* (YPM/MCZ) specimens were acquired with a ModelMaker H laser scanning head on a FARO Silver arm, with a 2 Sigma single point accuracy of +/- 25 microns. Extant species were scanned twice, with and without cartilage.
3. Raw point cloud data was converted into high-count polygonal meshes by using ModelMaker 4.4 software.
4. Polygonal meshes were imported into Maya 5.0 and composited.
5. Alignment (distal humerus): elements were rotated about condylar (x-) axis so that y-axis bisected the angle between maximum flexion and extension at that joint (based on measurements taken in Step 1, above). Elements were then rotated about z-axis to align tops of cartilaginous condyles.
6. Articular surface was extracted and rotated to align with ArcGIS Cartesian coordinate system ([X,Y,Z]→[Z,X,Y]).
7. CAD plug-in was loaded [Windows > Settings/Preferences > Plug-in Manager: *dwgTranslator.mll*] and file exported in .dwg format.

Fig. 2. ArcOSAUR toolbox

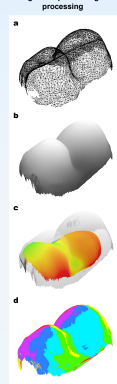


ArcOSAUR menu, displaying the suite of processing tools grouped by category

II. Processing

1. The various processing tools comprising the ArcOSAUR toolbox (Fig. 2) were created in ArcGIS 9.2 by using the ArcToolbox ModelBuilder visual programming environment and the 3D Analyst and Spatial Analyst extensions. See Results for descriptions of specific tools.
2. Polylines (.dwg) were imported into ArcGIS using the *CAD to Raster* tool. Tool parameters include:
   - *Output Data Type = FLOAT*
     (cell of new raster layer uses floating-point values)
   - *Method = LINEAR*
     (cell values calculated using linear interpolation of TIN)
   - *Sampling Distance = CELLSIZE 0.01*
     (cell size of output raster; determines processing precision)

Fig. 3. Preprocessing & processing



Mediodistal view of distal ends (cartilaginous condyles) of left humerus of *Alligator mississippiensis*, as a: a). TIN, b). DEM, c). semitransparent raster displaying underlying epiphysis, d). raster processed using ***Slope*** tool, with cells color-coded according to aspect (compass directions)

Results

- Import & Export > ***CAD to Raster***
  Converts CAD polyline file (.dwg) to an intermediate TIN format and then to a DEM raster file.
- Import & Export > ***Raster to CAD***
  Converts raster to an intermediate point shapefile (.shp) and then to CAD format (.dwg, DWG-2000).
- Surface > ***Area, Volume, & Relief***
  Generates a .txt file with 2D and 3D areas, volume, and relief of bone or cartilaginous surfaces.
- Surface > ***Convexity***
  Measures relative convexity/concavity over surface by comparing true slope to nearest neighbor-averaged slope.
- Surface > ***Distance***
  Calculates Euclidean, absolute (Eq. 3), and surficial distances between two cells ($cell_1$ and $cell_2$)

$$\sqrt{([cell\ value]_1 - [cell\ value]_2)^2 + [EucDist]_{12}^2} \quad \text{(Eq. 1)}$$

- Surface > ***Slope***
  Calculates aspect (Fig. 3.d), slope, and slope of slope (rate of change).
- Patch Counts > ***OPC***
  Calculates Orientation Patch Count and Orientation Patch Diversity (Evans et al., 2007), by grouping contiguous regions of cells classified by orientation (eight compass directions) of downward slope.
- Patch Counts > ***TPC***
  Calculates Topographic Patch Count and Topographic Patch Diversity (Evans et al., 2007), by grouping contiguous regions of cells classified by topographic elevation (contour levels).
- Trigonometric > ***Center of Rotation***
  Calculates the instantaneous center of rotation for circular and spherical surfaces (Fig. 4). This is found by taking the slope at points along the lines of articulation and calculating the mean position of the individual centers, using the following equation:

$$[cell\ value]_{rotation} = [cell\ value]_a - \frac{\sqrt{[EucDist]_{ac}^2 + ([cell\ value]_a - [cell\ value]_c)^2}}{2 * \sin([Slope]_c / 2)} \quad \text{(Eq. 2)}$$

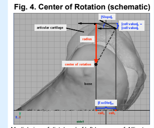
This is based on the following assumptions: 1). geometric optimality – that the radius of the best-fit circle along the lines of articulation defines the center of rotation, 2). bone and cartilage deformation is negligible, and 3). the ≈50 micron thickness of the synovial film between articular surfaces remains constant and negligible.

- Trigonometric > ***Normal Thickness***
  Calculates the thickness of a superior surface (in this case, articular cartilage) from the normal of a cell, done by combining absolute distance (Eq. 1) and trigonometric (Eq. 3) equations, (Eq. 4). This quantification allows for topographical characterization of soft tissue, which in turn can inform and constrain assumptions for reconstructing cartilage in extant phylogenetically-bracketed taxa (Fig 7).

$$[cell\ value]_c = [EucDist]_{bc} * \tan(90° - [Slope]_b) + [cell\ value]_b \quad \text{(Eq. 3)}$$

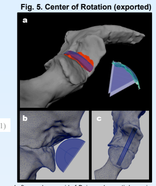
$$\sqrt{([EucDist]_{bc} * \tan(90° - [Slope]_b) + [cell\ value]_b) - ([cell\ value]_b)^2 + [EucDist]_{bc}^2)} \quad \text{(Eq. 4)}$$

Fig. 4. Center of Rotation (schematic)



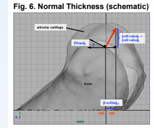
Medial view of distal end of left humerus of *Alligator mississippiensis*, illustrating components used in the computations (Eq. 2)

Fig. 5. Center of Rotation (exported)



Left scapulocoracoid of *Deinonychus antirrhopus* in Maya, illustrating instantaneous centers of rotation (in blue) at glenoid: a). posteroventral view (inset: articular surface and sector of rotation), and at humeral joint: b). anterior and c). posterolateral views

Fig. 6. Normal Thickness (schematic)



Medial view of distal end of left humerus of *Alligator mississippiensis*, illustrating components used in the computations (Eqs. 3,4). Cartilage at this joint forms large articular condyles that do not follow the topology of the bone; this change in size and shape can be quantified by calculating the thickness of cartilage from each cell at its normal. This is done by mathematically "locating" the cartilage surface cell along the normal of a specific bone surface cell, and finding the absolute distance between the two points.

Fig. 7. Normal Thickness (exported)

Proximal ends of left humeri – medial (top), proximal (bottom) views – of *A. mississippiensis* (green), *D. antirrhopus* (blue), and *C. livia* (red), with cartilage reconstructed in Maya. Scaled to humeral length.

- Miscellaneous > ***Pseudofossil tool***
  The purpose of this tool is to add a third dimension (depth) to photographic imagery, using grayscale values as a proxy for light intensity and in turn, distance. To illustrate this technique, a high-resolution color JPEG of the Berlin specimen of *Archaeopteryx* (Fig. 8) was converted to grayscale mode using the Gray Gamma 2.2 ICC profile in Adobe Photoshop 7.0 (Fig. 9, top). This was then imported into ArcScene and processed with the *Pseudofossil* tool, which applies the inverse-square law for light intensity (Eq. 5, intensity of light is inversely proportional to the square of distance) to the grayscale value of each pixel – ranging from 0 (dark) to 255 (light) – to calculate the appropriate scaling of depth, termed the Z unit conversion factor (Eq. 6):

$$I_1/I_2 = r_2^2/r_1^2 \quad \text{(Eq. 5)}$$

$$-255/\sqrt{[cell\ value]} \quad \text{(Eq. 6)}$$

Fig. 8. original color JPEG photograph

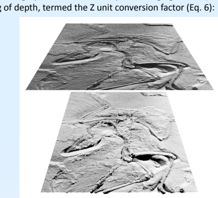


Fig. 9. 2D grayscale JPEG (top) and 3D "pseudofossil" (bottom)

Conclusions

- ArcOSAUR provides paleontologists with new digital tools for studying functional morphology that are precise, accurate, and offer analyses not possible with traditional actualistic methods.
- Digital scans of fossils can be imported into GIS software through step-wise conversion of polygonal meshes to triangular irregular networks (TINs) and then to digital elevation models (DEMs). After processing, rasters can be exported back to CAD format for use in modeling and animation software.
- In addition to calculating Euclidean geometrics and patch counts, ArcOSAUR can be used to calculate curvilinear and trigonometric measurements of surfaces and volumes, such as the thickness of articular cartilage and the location of centers of rotation, for kinematic reference (such as biomechanical animation). These results can also be used to inform and constrain assumptions for reconstructing articular cartilage using an extant phylogenetic bracketing approach.
- The primary limitation of these techniques is the inability to rotate surfaces within the ArcGIS environment, which by its nature was designed only to accommodate fixed maps and land surfaces. This limitation may also introduce bias into the calculations of certain non-trigonometric processes that don't take surface normals into account. Other limitations include the high cost and learning curve of the software, and the labor-intensive preprocessing.
- Future work will focus on: 1). refining preprocessing workflow and developing a direct voxel-to-DEM conversion for CT scanned data, 2). conducting sensitivity analysis of preprocessing alignment (see Methods -I.5), 3). statistically analyzing the role of articular cartilage in determining centers of rotation at joints, 4). exploring semi-automated cartilage reconstruction capabilities, and 5). using ArcOSAUR for new paleontological applications.

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