Digitizing Large Fossil Skeletal Elements for Three-Dimensional Applications

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ABSTRACT

Methods were developed to use the portable *Microscribe* three-dimensional digitizer to capture external morphological data from numerous sauropod appendicular elements for a biomechanical study. Digitized data was found to be useful because it could be quickly captured by the individual researcher, was cost efficient, and consisted of relatively small digital files that were easily manipulated on a standard laptop or desktop computer. The benefits of digitized data make them especially useful in morphometric, ontogenic, and biomechanical studies. However, potential problems, such as extra time needed to assemble skeletal elements and accuracy limitations of digitized data, should be considered when contemplating using a three-dimensional digitizer to capture morphological data.

INTRODUCTION

This paper describes the application of three-dimensional digitizing in vertebrate paleontological studies, specifically biomechanical studies of sauropod dinosaurs. The use of three-dimensional modeling techniques in vertebrate paleontology has received attention recently by Chapman and Weishhampel (1998) and Rowe et al. (2001). Currently, the main source of three-dimensional data is computed tomography (CT) scanning, which primarily is used for evaluating the internal anatomy (Rowe et al. 1999). This study focuses exclusively on the external morphology of the appendicular skeleton, and for this reason, a three-dimensional point digitizer was used to gather three-dimensional morphological data. While the focus of this study was the functional morphology of the sauropod appendicular skeleton, three-dimensional digitized data would also be useful in morphometric studies, studies involving ontogenetic variation, and virtually any other study which focuses on external skeletal morphology.

Figure 1. Microscribe digitizer connected to a notebook computer and ready to collect data.

THREE-DIMENSIONAL DIGITIZING TECHNIQUE

Equipment

Over 100 individual sauropod appendicular elements from 10 different institutions were digitized using the *Immersion Microscribe* three-dimensional point digitizer. (see Appendix I for procedure). The point digitizer proved to be transportable, cost effective, and reliable. The input device for the *Microscribe* used in this study was modified for use with either a mouse or foot pedal. A Pentium II PC with a 400MHz processor and 128 MB of RAM was connected to the digitizer via a serial connection cable (Figure 1). The *Rhinoceros* modeling program (Version 1.0) was used to obtain digital data, which was processed with *Surfacer* (Art Anderson, Virtual Surfaces). Clay was used for stabilizing specimens and white paper correction fluid for marking registration points. All animations were made using Discreets' *3D Studio Max.*

Prerequisites

Specimen selection is critical when digitizing fossil bones. For the purposes of this study, each element had to be complete, relatively uncrushed, identifiable to genus, and free from the effects of ontogeny. The six major limb elements (humerus, radius, ulna, femur, tibia, and fibula) were considered to be complete if five measurements, length (L), greatest proximal breadth (GP), least breadth (LB), greatest distal breadth (GD), and least circumference (LC) could be made on the bone. The girdle bones were considered complete if approximately 90 % of their edges were intact. The degree of crushing in a given specimen was much more difficult to estimate because there are very few sauropod appendicular elements that are totally free of distortion. For this study, elements were assumed to be relatively uncrushed if the key features of the bone (i.e., muscle scars, trochant-ers, fenestrae, etc.) were clearly visibly, and no off-set fractures were apparent.

Any study that involves composite skeletons must consider the effects of ontogeny in reconstructions. The effects of ontogeny on sauropod appendicular material have been addressed by Carpenter and MacIntosh (1994**)** and Wilhite (1999). Wilhite (1999) found that the limbs of *Camarasaurus* exhibit isometric growth patterns with very little evidence of allometry. Similarly, Carpenter and MacIntosh (1994) noted isometric growth patterns in the limbs of *Apatosaurus.* The current study involves only diplodocid and camarasaurid sauropods. Therefore, it is assumed that all appendicular elements digitized are free from the effects of ontogeny and can be scaled to match other elements when composite limbs are necessary.

Specimen size is also an important final consideration when digitizing. In this study, the *Microscribe* digitizer and *Rhinoceros* data capture program make it possible to scan any known vertebrate element regardless of size. However, the radius of the digitizer arm used for this study is 70 cm, and elements longer than about 2 m had to be digitized in four or more parts, doubling the time needed to digitize a single element. If access time to museum collections is a consideration, specimens that fit into the size range of the digitizer arm are preferable.

Overview of the Digitizing Procedure

While a detailed description of the digitizing procedure used here is given in Appendix I, an overview of the procedure is necessary before the benefits and potential problems associated with it can be addressed. The *Rhinoceros* program is capable of storing data from the *Microscribe* point digitizer as points or as curves. When stored as points, data is in the form of a point cloud which must be surfaced. Point cloud data would be a good choice for very small bones since the entire surface can be sampled. However, this method was impractical for the large (greater than 30 cm) specimens used in this study because of the time required to sample the entire surface with the digitizer. Instead the curve method was employed for this project (points were used for registration of the two digitized halves). Using this method, a series of curves is defined across the short axis of the bone at varying intervals along its length (see Appendix I). The intervals between curves varied because areas of a bone with significant morphological information were sampled at shorter intervals than those areas which lacked morphological features.
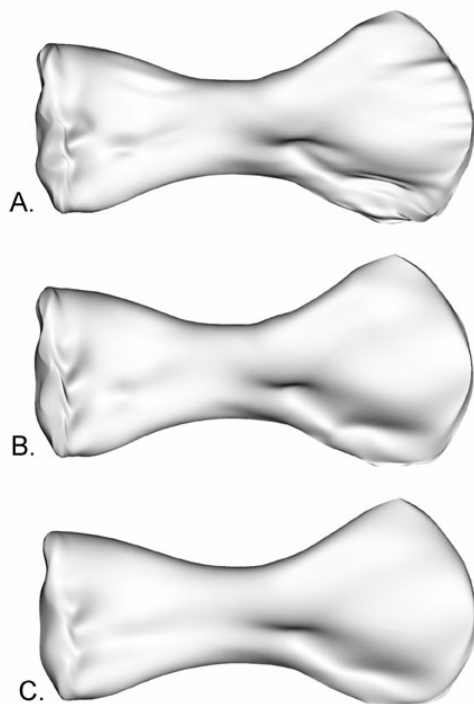
Figure 2. Lofted anterior surfaces of an *Apatosaurus* left humerus (AMNH 6114) using a) NORMAL/UNSIMPLIFIED, b) NORMAL/SIMPLIFIED, and c) LOOSE/SIMPLIFIED settings in the *Rhinoceros* program.

Figure 3. Screen capture of lofted, shaded surface of anterior half of an *Apatosaurus* left humerus (AMNH 6114) compared to original element in anterior view.

After one side of the bone was digitized, a surface was modeled over the curves using a process called lofting. The process of lofting a surface over the curves is explained in detail in Appendix I, but can be visualized as laying a sheet over an object. Even though the shape of the object is clearly visible, the sheet does not exactly conform to every detail of the object. If the sheet is pulled tightly over the object, however, it conforms much more closely to the shape of the object than if it were loosely draped over it. The LOFT function in *Rhinoceros* works in much the same way by giving the user multiple options which essentially drape the surface more loosely or more tightly over created curves depending on the settings. Figure 2 shows the digital model of AMNH 6114 lofted using several different settings. The different results obtained using the various settings make it clear that no single method will reproduce the actual surface of the original bone in perfect detail (see Figure 3 for photo of actual element).

After a surface has been lofted over the digitized curves and found to satisfactorily represent the actual specimen, the specimen should be turned over and the process repeated for the other side. Both hal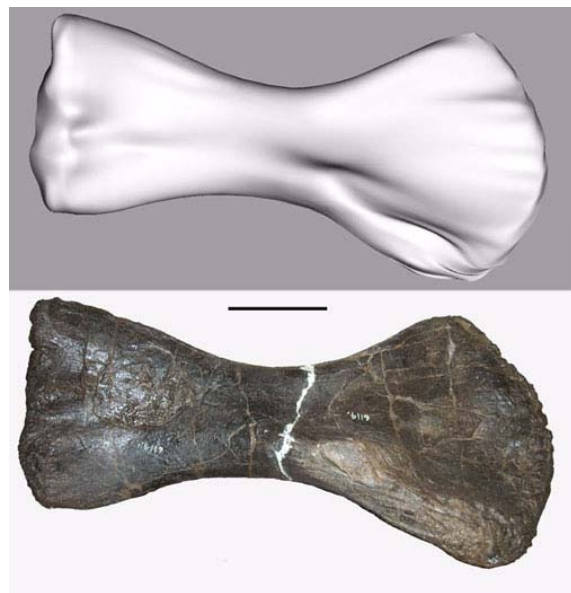ves can then be combined using a number of programs (in this case, Imageware's *Surfacer*). The resulting three-dimensional solid can be used for morphological analyses.

Benefits and Problems of Digitized Data

Digitized data offers several advantages over other methods of obtaining three-dimensional digital data. The components can be assembled or disassembled rapidly (in less than 10 minutes) so that even brief visits to museum collections may afford an opportunity to digitize important specimens. The cost of digitizing versus other techniques, such as CT scanning, is minimal. The *Microscribe* digitizer is portable and fits into a case no larger than an average suitcase. Elements also can be digitized very rapidly. For example, with familiarity to the equipment and techniques, I was able to scan a 1 m sauropod humerus in about 15 minutes. Digitized models can be compared to the original element in real time (Figure 3). It is imperative to compare each scan with the original element to check for accuracy, and the ability to correct errors in minutes without redoing the complete scan is an advantage when many elements need to be digitized. Finally, digitized data files are much smaller than those produced by other scanning techniques, making the resulting digital files easy to manipulate even on a modest computer system.

Despite the numerous benefits of digitized data, there are certain potential problems that may limit the technique's usefulness. Elements for this

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Figure 4. Two right *Diplodocus* fibulae showing the effects of ontogeny by scaling the two elements to the same size. Elements begin in medial view.

Figure 5. Animation of brachial and antebrachial joint motion in *Apatosaurus* (yellow), *Camarasaurus* (blue), and *Diplodocus* (red) in right lateral view.

study were scanned as two halves and later registered together. It can be difficult to assemble bones that were originally very flat (e.g., scapulae) because there is very little distance between the two surfaces, which causes difficulty in combining halves. A technique for which no registration of two halves is necessary would be better for these elements (Bonnan, pers. comm., 2002). Another potential problem is that the model surface is generated by interpolating between the curves generated using the digitizer, and therefore, the surface cannot be an exact copy of the original. Some morphological features, such as the rugosities on the ends of sauropod limb elements, may not appear in the digital model (Figure 3). Fortunately, the large size of sauropod limb elements helps to diminish the small inconsistencies between the model and the original element because morphological features are much larger. However, digitizing inconsistencies would prove to be much more critical for small elements (less than 30 cm)
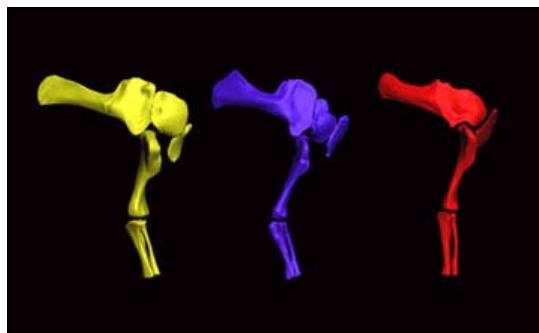
because even minor errors in the digitizing process, such as holding the point of the digitizer arm a few millimeters above the surface of a specimen, affect the final shape of the model. These errors are minimized when digitizing large bones because the same errors represent such a minor portion of the bone itself. If millimeter-scale accuracy is important, an alternative technique such as laser scanning (Lyons et al. 2000) or CT scanning (Ketcham and Carlson 2001) would be more appropriate.

Applicability

Having considered the benefits and limitations of three-dimensional digitized data, the applicability of the technique to different types of studies can be considered. Many morphometric studies could be greatly facilitated using this equipment. Previous studies relied on digitized points from photographs (Chapman 1990; Chapman and Brett-Surman 1990). The same data points could easily be captured in three-dimensional morphospace using the point digitizer. Ontogenetic studies could also be facilitated using three-dimensional digitizing techniques because many specimens representing different ontogenetic stages could be digitized quickly, and the three-dimensional solids generated could easily be scaled to the same size and qualitative ontogenic differences noted (Figure 4). Three-dimensional digitized elements are especially useful for modeling joint articulations in functional studies of exceptionally large animals such as sauropod dinosaurs (Figure 5). The relatively small data files allow for the assembly of complete skeletons using a standard personal PC (Figure 6). Also, digital models of large bones can be illustrated without parallax distortion and in exactly the same orientation-- making comparisons of morphological features more clear than with traditional photography (Figure 7).
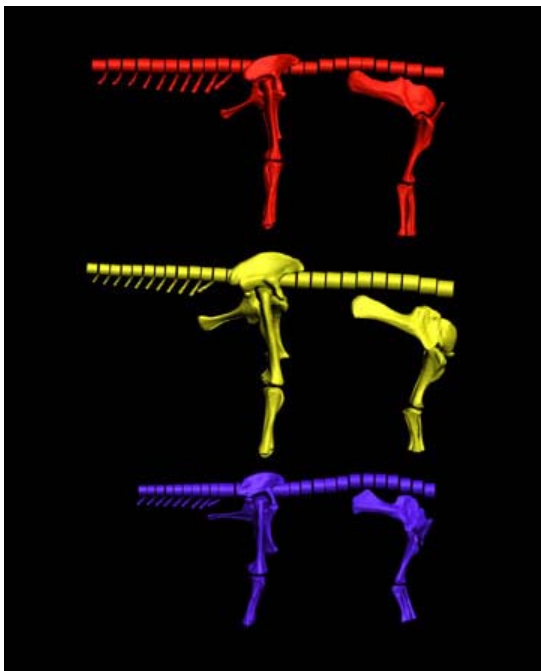
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Figure 6. Animation of reconstructed skeletons of *Diplodocus* (red), *Apatosaurus* (yellow), and *Camarasaurus* (blue). Animation begins with skeletons in left lateral view.
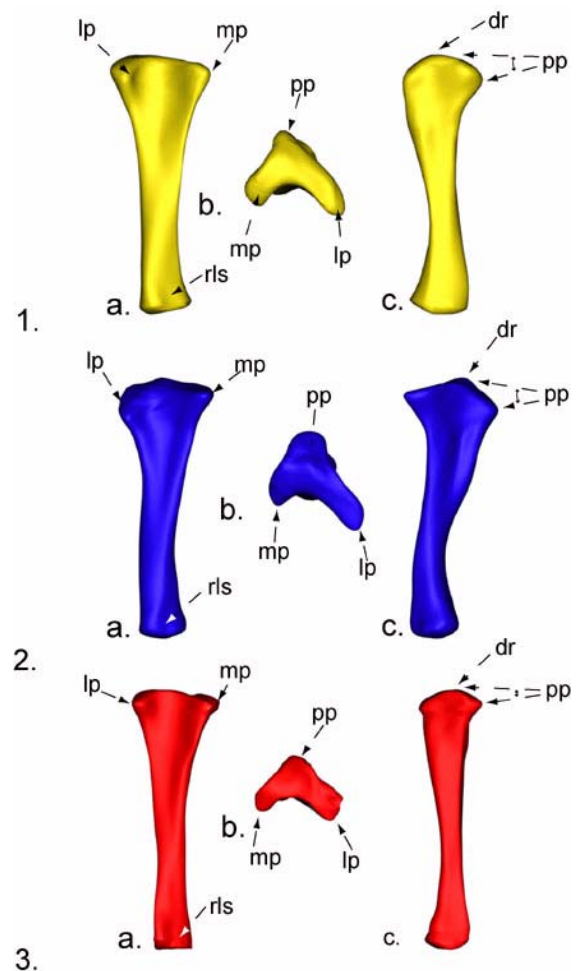

Figure 7. Sauropod right ulnae in a) anterior, b) dorsal, and c) lateral views. 1) *Apatosaurus*, 2) *Camarasaurus*, 3) *Diplodocus*. Abbreviations: **mp** = medial process, **lp =** lateral process, **pp** = posterior process, **rls** = radial ligament scar.

CONCLUSIONS

Numerous techniques have been developed in recent years for the collection of three-dimensional morphological data in vertebrate paleontology. The current project involved obtaining three-dimensional morphological data from the appendicular skeletons of sauropod dinosaurs using the portable *Microscribe* three-dimensional digitizer. Digitized data acquisition is cost efficient, data can be quickly captured by the individual researcher, and data is easily manipulated on a standard laptop or desktop computer. Three-dimensional digitized data is useful for several types of studies including morphological, ontogenetic, and biomechanical projects. However, potential problems such as extra time needed to assemble elements and the limited accuracy of digitized data should be considered when contemplating using a three-dimensional digitizer for a project.

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APPENDIX

The technique used to obtain the three-dimensional data during this study is described below. The following technique is presented as a series of steps in order to make the process as clear as possible. Many of the steps are required for other methods common to the instrument, but it is relevant to the description of the new method to include them here. The software used was *Rhinoceros V1.0* for windows. Hardware included an *Immersion Microscribe* three-dimensional digitizer connected to a Pentium II, 400 MHz PC.

1. Select a suitable specimen for digitizing. For the purposes of this study each element needed to be complete and relatively undistorted. Other studies may not require such rigorous standards. Figure 3 shows a sauropod humerus that meets the necessary requirements of the current study.

2. Position the digitizer, computer, and specimen relative to one another. The computer must be positioned so that commands can be entered while digitizing is in progress. Position the digitizer and specimen relative to one another so the digitizing arm has the maximum possible range of motion around the bone. It is important not to move the specimen or the digitizer during a scan. In the following steps, it is assumed that the digitizer is positioned behind the specimen and in front of the user with the digitizer power switch and ports facing away from the user (Figure 1). Also, the foot pedal is assumed to be positioned such that the cables coming from the pedal face away from the user.

3. Position and stabilize the bone for digitizing. It is best to find the most stable orientation. In this study, the humerus and femur were found to be most stable when positioned with either the anterior or posterior side laying on the floor or table. The lower limb bones are more stable when oriented with the lateral or medial side facing up or down. An exception to this is the sauropod ulna, which is difficult to stabilize so that it can be digitized from both sides easily. Place clay underneath corners of the bone until it is stabilized and will not move with normal hand pressure.

4. Mark registration points on the specimen. Because the specimen will need to be digitized from both sides, it is essential to mark registration points to facilitate integration of scanned halves. Initially, numerous registration marks were made around the bone, but it was soon realized that four registration points are adequate for most elements. White correction fluid was used here, but a pencil mark could have been used as well. Remove marks after digitizing is complete.

5. Initialize the digitizer. Before setting up the digitizer, make an XY coordinate plane on the surface that the digitizer and specimen are resting on. Select TOOLS, DIGITIZE , CONNECT from the main task bar, or press the digitizer icon and select the appropriate digitizer. Follow the prompts and enter the origin, x-axis and y-axis by moving the digitizer stylus to the appropriate location on the coordinate grid and pressing the right foot pedal or mouse button. The XY axes must be entered in the positive direction; otherwise the digitized image will appear upside down. The digitizer is now ready to receive data.

6. Set up the program to receive data. In the *Rhinoceros* program there are no default units selected. Go to the TOOLS menu and select OPTIONS and then select UNITS. Here the user can select the desired units of measurement for data collection. Millimeters were chosen for the current project. Next select the method by which data will be collected. This can be done either by pressing the SKETCH CURVE button (dotted curved line on the digitizing menu) or by selecting TOOLS, DIGITIZE, SKETCH CURVE from the main menu.

   Next, the user must select what kind of data is to be collected. For the first part of the digitizing process, point data must be collected in the form of registration points. To do this, deselect CLOSED CURVES and CURVES; then select POINTS. Data spacing (the interval at which data points will be captured) must also be set at this point. For large limb elements such as sauropod bones, 10 mm seems to work well. If the element is smaller, a shorter interval is necessary. Finally, press the OK button and move to Step 7.

7. Input registration points. Select the SKETCH CURVE icon and move the digitizer arm to one of the marked registration points and press the right mouse key or foot pedal (remember to immediately release the mouse button or foot pedal or the digitizer will continue collecting data). A point will appear on the appropriate spot on the displayed grid (it may be necessary to zoom out to see the point if a large specimen is being digitized). Next press the left mouse button or left foot
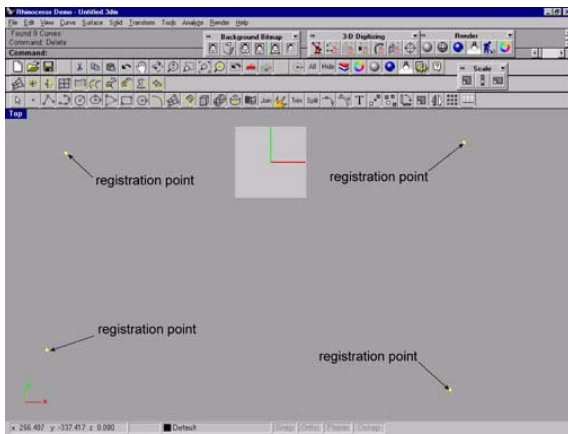
Figure 1A. Screen capture showing how registration points should appear when properly digitized (labels added for clarity).
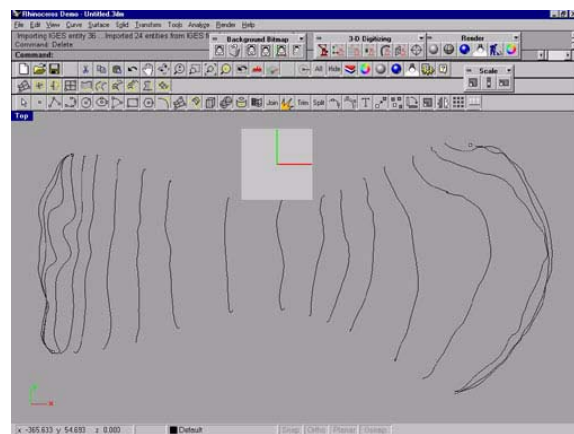

Figure 2A. Screen capture of digitized anterior half of an *Apatosaurus* left humerus (AMNH 6114) showing digitized curves capturing the shape of the bone.

pedal, and the previous command line will reappear. Move to the next point and repeat the process. Do this for all the preselected registration points. After entering the last registration point, zoom out and check that all the registration points appear on the screen (Figure 1A) and go to Step 8.

8. Digitize the first half of the element. Select the SKETCH CURVE icon, press the O key, and then press ENTER to display the DIGITIZE OPTIONS menu. Deselect POINTS and select CURVES (be sure that the CLOSED CURVES option is not selected). Then select OK. Move the digitizer stylus to the desired starting point. It is not necessary to begin a scan at one end of the element; however, all but a small number of elements in this study were digitized from end to end. Starting on the side farthest from the user, position the stylus roughly halfway down the side of the element. This may also be done on the near side, but it was found to be very difficult to push the stylus away from the operator in a smooth curve over the surface of the element. Press the right input button and continue to hold it as the stylus is pulled approximately halfway down the other side of the bone and release the input button. The curve described will display as a series of points at the selected interval as the stylus is being moved and will change to a solid curve after the input button is released. After finishing the first curve, press the left input button and the cursor will reappear. Move the stylus to the next desired starting position and press and hold the right input button. From this point, follow the same procedure as before and continue down the length of the element to the other

end (Figure 2A). The interval between each curve is arbitrary, but curves should be drawn more frequently over areas exhibiting key features such as muscle scars. The wider the interval, however, the smoother the lofted surface will be. Make fewer curves in areas where there are minimal morphological data, such as the shaft of limb bones.

9. Loft a surface over the curves. It is essential to create a rendered surface model of each completed scan in order to check the accuracy of the model. Select the LOFT option from the SURFACE menu or select the LOFT icon. Using the computer mouse, select the first curve at one end of the element. The curve will turn yellow indicating it is selected (Figure 3A). When the curve is selected, the point at which the cursor is placed on the curve determines the direction of the curve.
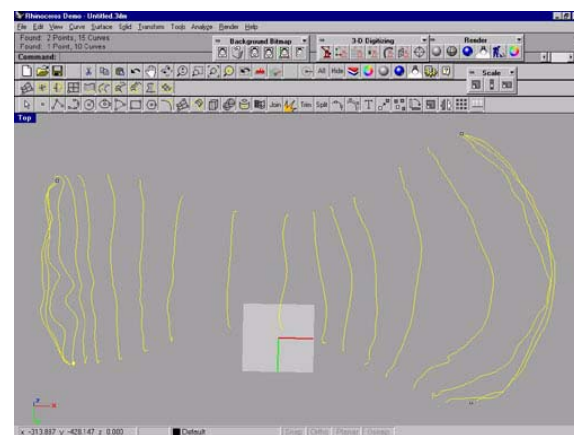

Figure 3A. Screen capture of digitized anterior half of an *Apatosaurus* left humerus (AMNH 6114) showing digitized curves which have been properly selected for lofting.
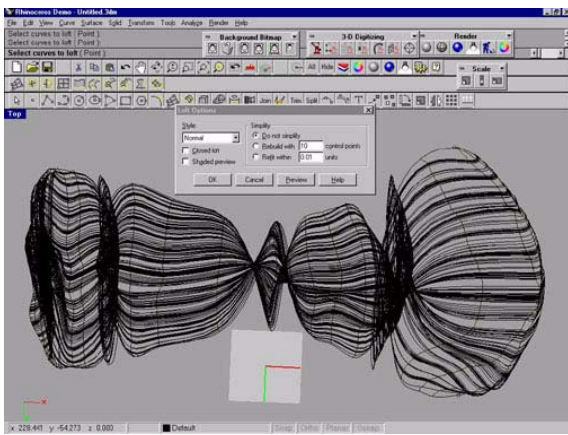
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Figure 4A. Screen capture showing an incorrectly lofted surface in which curve direction was not consistent.

Figure 6A. Screen capture of digitized wireframe surface of the anterior half of an *Apatosaurus* left humerus (AMNH 6114) showing a correctly lofted surface.

That is, if the point selected is to the right or left of the midline of the curve that direction will be assigned as the direction of the curve. It is essential that each curve be selected by moving the cursor to the same side of the curve midline. Failure to do this will produce a twisted surface (Figure 4A). Also, each curve must be selected in order from one end of the element to the other. Failure to do this will produce a surface that doubles back on itself (Figure 5A). Curves may be skipped but not subsequently selected for a given lofting operation. After all the curves have been selected, press the ENTER key. A wireframe surface will appear over the curves and a dialog box entitled LOFT OPTIONS will appear (Figure 6A).
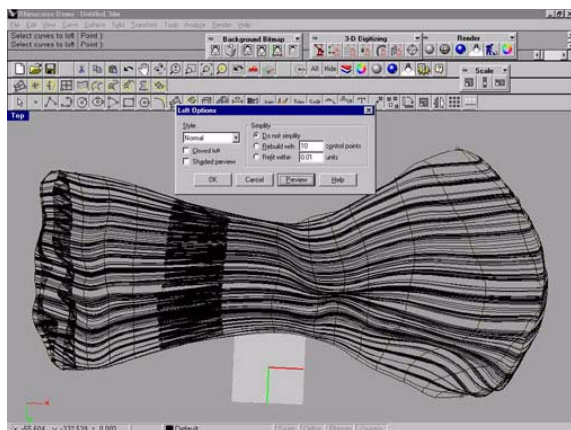
It is at this point that the surface must be evaluated for accuracy. There are many ways to do this, but I have found the following sequence to produce the quickest and best results. Leave the default settings and select SHADED PREVIEW. The screen will now show a shaded surface. Compare this surface to the original element (Figure 2). Rotate the element by selecting the ROTATE option under the VIEW menu or by selecting the rotate icon from the taskbar. Holding down the left mouse key, rotate the surface in various directions and check for errors in the surface relative to the original. If any errors are apparent, select CANCEL in the LOFT OPTIONS dialog box and delete the erroneous curve or curves. At this point, a new curve can be added following the instructions above, or the surface may be lofted again minus the erroneous curve. Assuming the surface accurately represents the element being digitized, other options in the LOFT OPTIONS dialog box may be changed as the user desires. When the desired surface function is found, select OK.

10. Save the file. The file may now be saved in one of a number of file formats. All files were initially saved as ProE\NT IGES (Initial Graphics Exchange Specification) files. The IGES format is compatible with most three-dimensional modeling programs.

Figure 5A. Screen capture of digitized anterior half of an *Apatosaurus* left humerus (AMNH 6114) showing incorrectly lofted surface. Dark bands indicate areas where surface doubles back on itself.
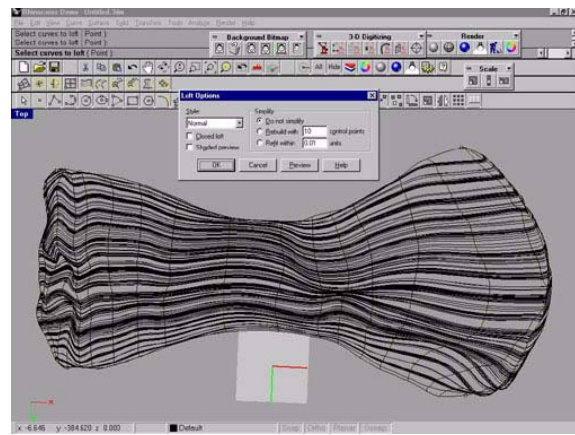
Turn the specimen over and stabilize it. At this point the user can either select NEW from the FILE menu or simply delete the data that was just collected and rename the file. Beginning with Step 7, digitize the other side of the element. With both
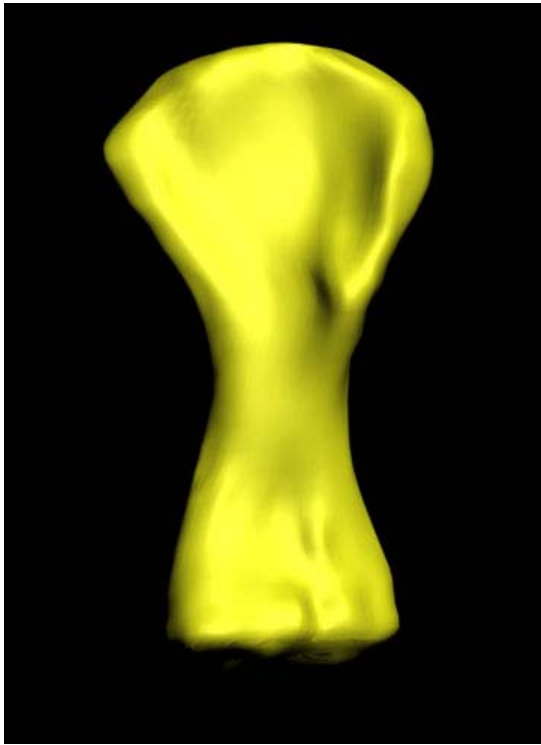
Figure 7A. Completed three-dimensional model of an *Apatosaurus* left humerus (AMNH 6114).

sides digitized, the two files can be imported into another program (e.g., *Surfacer*) and registered together to form a three-dimensional solid (Figure. 7A).

SOFTWARE SOURCES

Microscribe:
www.immersion.com/products/3d/capture/over-view.shtml

Rhinoceros3D:
www.rhino3d.com

Surfacer:
www.mayametrix.com/surfacer

3D Studio Max:
www.discreet.com/products/3dsmax/

Virtual Surfaces:
www.virtualsurfaces.com