Chapter 4
Laser Scanning: 3D Analysis of Biological Surfaces

Matthew W. Tocheri

Abstract This chapter introduces laser scanning to students and researchers who are interested in using this three-dimensional (3D) acquisition method for biological research. Laser scanning is yet another tool for transforming biological structures into 3D models that contain useful geometric and topological information. Current laser scanning technology makes it relatively straightforward to acquire 3D data for visualization purposes. However, there are many additional challenges that are necessary to overcome if one is interested in collecting and analyzing data from their laser-scanned 3D models. In this chapter, I review some basic concepts, including what laser scanning is, reasons for using laser scanning in biological research, how to choose a laser scanner, and how to use a laser scanner to acquire 3D data, and I provide some examples of what to do with 3D data after they have been acquired.

Introduction

As a teenager, most of my time was spent studying geometry, physics, and economics in an applied context. By that I mean I could invariably be found playing pool and snooker rather than attending class. I tried to supplement my educational experiences at the local pool rooms by reading as many how-to-play-pool books as possible. I always remember that while there were many books available, they all seemed to be missing one important chapter—how to actually play! Sure these books told you about the rules, necessary equipment, how to hold the cue, and how to stand, but they never described the thought processes that are necessary to approach even the most basic situations that occur again and again at the table. Instead, they always assumed you already knew what you were supposed to be thinking about. The reason I can say this is because I became a reasonably proficient

M.W. Tocheri
Human Origins Program, Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington DC 20013-7012, USA, e-mail: tocherim@si.edu

C.W. Sensen and B. Hallgrímsson (eds.), *Advanced Imaging in Biology and Medicine*.

player by learning the hard way what I should be thinking about at different times. Although my billiard career is long extinct, I have never forgotten that learning the thinking process behind any desired task is often critical for any long-term success.

Laser scanning is a lot like pool. It looks easy, almost magical when performed well, and it even has a certain "cool factor" surrounding it. In reality, however, it is extremely challenging, involving constant problem-solving, troubleshooting, and creative and critical thinking. Since 2001, this particular type of imaging technology has formed an integral part of my research program (Tocheri 2007; Tocheri et al. 2003, 2005, 2007). Over the years, I have given countless demonstrations to other interested students and researchers as well as general advice on how to incorporate laser scanning into their research. However, the high costs of equipment and software have precluded many from being able to do so. Even with access to a laser scanner, the combination of a steep learning curve and constant troubleshooting still often results in research efforts grinding to a halt despite initially high levels of expectation and excitement.

I hope this chapter helps reverse this unfortunate trend. Recent technological breakthroughs have resulted in laser scanners that cost only a fraction of what they did a few years ago. Given this new affordability, there is no doubt that more students and researchers are going to give laser scanning a try. To ensure that these newly acquired pieces of equipment collect 3D data rather than dust, my primary goal in this chapter is to convey some of the creative and critical thinking skills that are necessary to successfully incorporate laser scanning into an active research program. To accomplish this, I have focused the chapter around five main questions that continually arise every time I demonstrate the laser scanning process to interested students and researchers. By presenting information about laser scanning in this manner, I hope the reader is better prepared to solve the common problems (and their many variations) that they will encounter as the initial "cool factor" wears off and they are forced to face the many challenges that laser scanning will bring to their research.

What is Laser Scanning?

Laser scanning is simply a semiautomated method of 3D data capture. In other words, it is a method for generating a numerical description of an object. A straightforward way to describe an object numerically is to construct an array of coordinate values for points that lie on the object's surface (Bernardini and Rushmeier 2002). In principle, you could do this by hand by measuring how far away different locations on a surface are from a single designated location in space. The chosen location would represent the origin of a 3D coordinate system and you would convert your depth measurements into x, y, and z coordinates for each measured point on the surface.

Laser scanners accomplish these tasks for you by projecting a laser beam onto an object (Fig. 4.1). As the laser contacts and moves across the surface of the object,

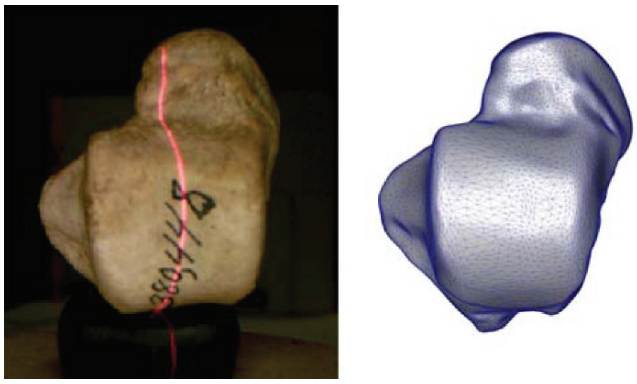

Fig. 4.1 By projecting a laser onto the surface of an object, depth information is recorded at particular intervals along the surface through a sensor (typically a CCD camera), which tracks the reflectivity of the laser on the surface (*left*). The depth values are converted into 3D point coordinates, which are used to generate a polygonal mesh that is a numerical description of the object's surface (*right*)

depth information is recorded at particular intervals along the surface through a sensor (typically a CCD camera), which tracks the reflectivity of the laser on the surface (Bernardini and Rushmeier 2002; Kappelman 1998; Zollikofer and Ponce de Leon 2005). Most often, the positions and orientations of the laser and the sensor are calibrated via triangulation. Therefore, the acquired depth information is converted into 3D point values (x, y, z) using the scanner's coordinate system. The result is a 3D point cloud of data that represents a collection of geometrical information about various locations on the object's surface. Generally, neighboring points are also connected by an edge (i.e., a straight line). Together, the edges form polygons (usually either triangles or quadrilaterals), resulting in a 3D mesh structure (Figs. 4.1 and 4.2). The resulting polygonal mesh is a numerical description that contains geometric information (x, y, z values) and topological information (how the points are connected) (Bernardini and Rushmeier 2002).

By changing the position of the object and repeating the scanning process, additional scans of the object's surface are acquired. Using portions of surface overlap between multiple scans, these are then "stitched" together to form the 3D model of the object (Bernardini and Rushmeier 2002; Kappelman 1998). The task of stitching scans together may be performed manually or automatically, depending on the specifics of the scanning software. Most often, the stitching process involves first registering or aligning the multiple scans together. After the scans are aligned, they are then merged together to form a single polygonal mesh. Laser scanners are typically sold with accompanying software that enables you to perform the alignment and merging steps relatively easily.

Although every type of laser scanner operates differently (along with the accompanying software), the overall process is the same. Before describing in more detail how one goes about using a laser scanner to generate 3D numerical descriptions (hereafter termed "3D models") of real-world objects, I first want to discuss why

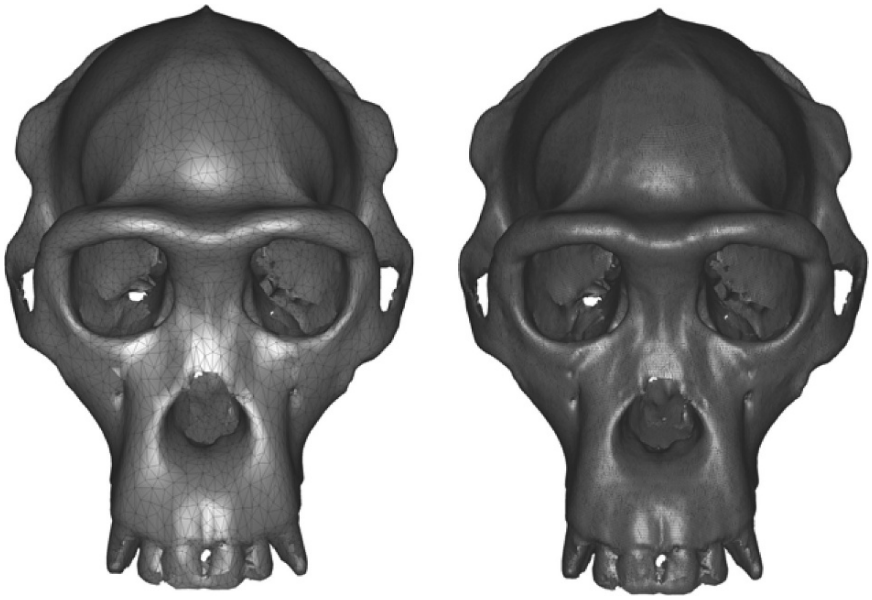

Fig. 4.2 Polygonal meshes are a combination of geometry (x, y, z values) and topology (edges that connect neighboring coordinates). Denser point clouds result in more surface detail; compare the mesh of a chimpanzee cranium on the *left* (15,000 triangles) to the one on the *right* (400,000 triangles)

a biological or medical researcher would want to use laser scanning to acquire 3D models.

Why Use Laser Scanning?

3D models can be acquired using many different kinds of technology, many of which are described in the other chapters of this book. Laser scanners are specifically used to acquire 3D models that contain surface information only, with no information about the internal properties of the object (Bernardini and Rushmeier 2002; Kappelman 1998; Zollikofer and Ponce de Leon 2005). Therefore, laser scanners should be used when the data of interest relate to the surfaces or external shape properties of an object (e.g., Ungar 2004; Dennis et al. 2004; Tocheri et al. 2003, 2005, 2007). While it is obvious that if the data of interest relate to the trabecular structure of bone then laser scanning is not the appropriate 3D acquisition method, there are other scenarios that are less obvious that deserve attention.

The "cool factor" of laser scanning results in many wanting to use the technology almost for the sake of using it. My general advice is if you want to take linear measurements then use calipers to measure the actual object or if you want acquire

3D landmarks for geometric morphometrics then use a point digitizer, again on the actual object. I say this because laser scanning results in a *model* of the actual object rather than an exact replica of it. In other words, a model is an approximation of an object, and its accuracy in representing the object is dependent on a variety of factors, including the equipment, software, algorithms, and expertise used to generate it. Therefore, a good rule of thumb is to use laser scanning when you want to measure some aspect of the object that is easier or more practical to do using a model of the object rather than measuring the object itself. It is true that you can take linear measurements and landmarks from a laser-scanned 3D model, but two factors argue against doing so if it is the sole reason you are using a laser scanner. First, you end up with a measure of the model that you could have easily acquired directly from the actual object. This may result in a loss of precision of the measurement, since it is being acquired indirectly from an approximation of the object. Second and most important, laser scanning simply takes longer. If laser scanning resulted in a complete 3D model in less time than it takes to acquire the caliper measurements or a set of landmarks, then any loss of precision could be better justified. But the fact remains that the laser scanners that are currently the most widely available to biological researchers simply do not produce measurable 3D models instantaneously. Instead, laser scanning often requires anywhere between at least 20 min to several hours to acquire a complete 3D model of an object. Until laser scanning technology can cost-effectively and rapidly produce 3D models that can be easily validated as practical replicas of their real-world counterparts, I would argue that it is a better strategy to try and use the current technology more appropriately.

Appropriate uses of laser scanning should directly involve or focus on surfaces, such as any type of surface visualization or quantification. Surface visualization benefits from the ability to manipulate the model on a computer screen, making it extremely easy to view the model from any angle without any fear of dropping or mishandling the actual object. In addition, most 3D software applications allow for complete digital control of lighting and other conditions that significantly enhance the visualization experience. These advantages justify the use of the 3D model despite the fact that it is an approximation of the actual object. Whether used for research or educational purposes, visualization of laser-scanned 3D biological surface data is a powerful tool.

Surface quantification involves an attempt to measure some property of the surface. A simple and straightforward example is the calculation of surface area. Using a laser-scanned 3D model to calculate the surface area of an object (or a portion thereof) is appropriate because the surface area of the actual object cannot be quantified in any standard manner but the surface area of the model is easily computed (exceptions include objects of standard geometric shape for which there are formulae for calculating surface area). Inherent in the surface area measurement of the model is the notion that it is an approximation of the "real" surface area, but since the actual object cannot be measured directly an approximation of the measure is appropriate. The same basic principle is true when measuring angles between surfaces, surface curvatures, and surface cross-sections to name a few—they all are approximate measures of surface properties made possible by the model.

Whether laser scanning is used for surface visualization, quantification, or both, an additional benefit is the ability to archive surface data (e.g., Rowe and Razdan 2003). Laser-scanned 3D data are not just an approximation of some real surface; they are an approximation of some real surface at a particular moment in time. Therefore, laser scanning automatically results in a digital archive of 3D surfaces and objects. Such data can be used if the actual object is no longer accessible (e.g., to take additional measurements) or it can be used to compare how an object's surface properties have changed over time if the object is laser scanned more than once (e.g., before and after plastic surgery; Byrne and Garcia 2007).

Choosing a Laser Scanner

There are hundreds of makes and models of laser scanners available today. Deciding which laser scanner is best suited for particular biological research is challenging. I do not wish to endorse any particular laser scanner over another; however, there are several key factors that I think should be considered if you are choosing a laser scanner for biological research purposes. These key factors include object size, auto-alignment capability and performance, 3D model acquisition speed, and portability.

Unfortunately, there is no one-size-fits-all laser scanner available. Instead, laser scanners are invariably configured to handle a particular range of object sizes. You want to purchase a scanner that is optimized for the sizes of object that you intend to scan the most. Laser scanners are configured to have maximum precision within a field of view that is a particular distance from the object (some scanners may have multiple fields of view). Therefore, you want to ensure that your object fits within a field of view that is configured for maximum precision. If the objects you want to scan are bigger than the optimized field of view, then the scanner is not appropriate for your research needs.

You also need to consider whether the objects you want to scan are too small for the field of view of the scanner. This will depend on how many points the scanner is capable of sampling as the laser moves across the surface of the object. Remember that scanners will on average sample the same number of points per millimeter within its entire field of view. Therefore, the smaller the object is in comparison to the field of view, the smaller the number of points sampled. If the field of view is about the size of a page (e.g., $8.5'' \times 11''$), then objects the size of a quarter are probably not going to scan very well, simply because not enough points on its surface are being sampled.

One of the most important factors to consider is the ability of accompanying software to align consecutive scans together. The basic idea of a laser scanner is to automatically sample a large number of points from a surface so that you do not have to spend hours or days manually digitizing each point by hand. However, the majority of laser scanners do not have the ability to automatically align consecutive scans together. Instead, the user has to manually align scan after scan by selecting common points on each surface and then waiting for an algorithm to complete

its best mathematical guess at the alignment. This is a huge issue for biological research, where (in most cases) we do not want to invest hours or days generating a 3D model for each specimen we want to include in our analyses. My advice is that if the laser scanner does not come equipped with additional hardware and software that performs automatic alignment of consecutive scans robustly and accurately, then it is most likely not useful for any type of biological research that requires reasonable sample sizes—it will simply require too much time to generate enough 3D models for the research. Ideally, the laser scanner should come equipped with an attachable turntable and software that includes an auto-alignment feature. The best algorithms for auto-alignment take into account how far away the turntable is from the laser and sensor and how many degrees the turntable moves in-between consecutive scans. Incorporating such information enables consecutive scans to be aligned and merged with maximum precision.

Auto-alignment capability directly leads to the next important factor: 3D model acquisition speed. Notice that the emphasis is on 3D model acquisition, not individual scan acquisition. Almost all laser scanners can acquire 3D data reasonably quickly and efficiently. However, the first question you need to ask yourself is: what is it that you are going to visualize or measure? If you are going to use individual scans then scanning speed is all you need to worry about. But if you want to visualize or measure a 3D model, which is generated from a combination of individual scans, then you need to reliably estimate how long it will take you to acquire such a model. This includes scanning time plus alignment, merging, and any additional post-scanning procedures necessary to acquire the 3D model. Remember that if it takes you longer to first make a copy of the object you want to measure rather than measuring it directly, then how are you justifying making a copy in the first place? Determine how long it takes you to acquire one 3D model and then multiply this by how many models you estimate you will need to reach your research objectives. You may well realize that the amount of time you require just to generate the sample of 3D models far exceeds the time you have available. For example, it took an average of 30 min to acquire each of the 1,250 3D bone models used in my dissertation research sample (Tocheri 2007): roughly 625 h of scanning and post-processing, equivalent to about four months of focused effort (e.g., 8 h/day, 5 days/week). The bottom line is to not allow the "cool factor" of laser scanning to cloud your judgment regarding how much time and effort is needed to acquire a reasonable sample of 3D models for you research. Of course, I think it is worth investing the time and effort if the research question justifies it; but I would be lying if I told you that I had not seen many research projects fall apart because they did not realistically take into account this important factor.

Finally, portability is an additional factor to consider. This includes whether it is the laser scanner, the objects, or both that are portable. You need to consider how you will get the laser scanner, the computer that runs it, and the objects you want to scan together in the same room. Unfortunately, as is the case with most manufactured products, portability typically means you are getting less but paying more. Portable laser scanners are generally restricted in some capacity in comparison to their nonportable equivalents. The same is true of laptop computers, which are often

necessary to run portable laser scanners. These factors need to be weighed against whether the 3D models you will acquire are sufficient for your research objectives.

There may be additional factors to consider depending specifically on the research objectives, such as the ability to capture texture information. For the most part, however, the four discussed here should be sufficient as a starting guide for narrowing down the wide variety of available choices. New laser scanners with improved capabilities become available every year, and they continue to become more affordable. When making your decision about which laser scanner to use, always remember that it is only a tool to help you reach your research objectives. Therefore, stay focused on issues relating to the size, quality, and speed of the 3D models it generates, and factor in the required time and effort to build up the required study sample.

How to Laser Scan

A good rule of thumb when laser scanning is to be patient, flexible, and willing to experiment. Keep in mind that laser scanning is like a form of 3D digital sculpture, wherein you as the sculptor are attempting to acquire a digital representation of the object you are scanning. You must be flexible and willing to experiment in everything from how you place the object in relation to the laser and the sensor, how you edit (clean) each scan, to how you perform the alignment and merging. Patience, flexibility, and experimentation will enable you to become comfortable using many different laser scanners and 3D software packages and will ultimately result in final 3D models that are more accurate digital representations of the objects you scan.

The first step involves some imagination and decision-making. You must decide how you are going to place your object in relation to the laser and the sensor. My general advice is to pretend that you are the object; can you, metaphorically speaking (i.e., do not actually try to look directly at the laser), "see" the laser and the sensor simultaneously? Remember that you must be able to "see" the laser (typically straight in front of you) and the sensor in order for the depth information to be captured. Any portion of the object's surface which is not in the line-of-sight of both the laser and the sensor will not be captured, resulting in holes in the digital surface reconstruction (Bernardini and Rushmeier 2002; Zollikofer and Ponce de Leon 2005). Additional consideration must be given to the surface topography. Biological surfaces tend to be quite complex with lots of curves and indentations. Because of the triangulation procedure used by the laser and sensor to capture surface information, portions of the surface that are more perpendicular to the direction of the laser will be captured with higher precision (less error) (Kappelman 1998). Therefore, the further portions of the surface are from being perpendicular to the laser, the more erroneous the resulting surface reconstruction. To avoid this problem, you need to consider how to best position your object so that you maximize the amount of surface that is close to perpendicular to the laser. Remember that, as you take multiple scans from different orientations, different portions of the surface will be more perpendicular to the laser. This means that data acquired from one

scan poorly because of its position in relation to the laser may be acquired more precisely from another scan. This is where a good imagination comes in handy. Imagine that you are digitally reconstructing the object by creating different pieces of the object (like pieces to a 3D jigsaw puzzle). Each scan results in an additional piece. You want to think about how you are going to create each piece such that you maximize the amount of high-precision data within each piece. Understandably, this decision-making process is not always easy, but as you gain experience in scanning differently shaped objects, you will notice improvements in how long it takes you to scan an object as well as the accuracy of the resultant 3D model.

A good strategy involves positioning the object such that you maximize the amount of surface that is captured perpendicular to the laser while minimizing the amount of surface that will not be captured. Using a scanner that has an attachable turntable is advantageous because multiple scans can be acquired, each at a slightly different orientation. For example, if we decide on eight scans, then after the first scan is complete the turntable rotates 45° (360/8) and begins the second scan. After scanning is complete, it is a good idea to inspect each scan and delete any data that do not belong to the object. For instance, if you used plasticine or modeling clay to stabilize the object, or if you notice any data that appears odd, such as curled edges or proportionately large triangles, then you will want to delete it from the model.

After cleaning the scans, each of them now consists of a collection of coordinates (x, y, z values) and topological information (how the coordinates are connected). Consecutive scans share a certain amount of scanned surface with each other. This overlapping surface information is what is used to align the scans with one another. Many 3D software packages include the ability to select points on the surface that are shared by two scans. An algorithm, usually some variant of the ICP (iterative closest point) algorithm (Besl and McKay 1992), is then used to align the scans with one another. This process is continued until all the scans are aligned. Alternatively, laser scanners that utilize turntables are advantageous in that if the software knows how far away the turntable is from the scanner then the different scans can be aligned with one another automatically—an important time-saving feature that also often reduces errors that result from manually aligning multiple scans with one another.

After initial alignment, reinspect the scanned data for any inconsistencies that are not apparent on the actual object and edit the individual scans accordingly. Once you are satisfied with the aligned set of scans, you can merge the scans together. Merging involves using an algorithm to compute a final nonoverlapping mesh to represent the entire scanned surface both geometrically and topologically. Merging algorithms typically generate an average surface based on overlapping scanned areas. Now you reposition the object and go through the same steps in order to generate a second mesh that includes areas that are missing from the first mesh and vice versa. These two meshes are then aligned and merged as above, resulting in a 3D model of the object.

If there are still large areas of surface missing from your model, then you need to take additional scans following the same steps as above in order to fill in these "holes" in the surface mesh. Alternatively, you may choose to simply fill small holes in the mesh using a hole-filling algorithm. After you have deleted any unwanted

polygons that do not correspond to the object's surface, you may wish to make some general improvements to the mesh overall such as global smoothing. Always keep in mind that your acquired 3D model is an approximation of the actual object. Do not fall into the trap of thinking that the initially acquired point cloud and surface mesh data are necessarily the most precise numerical representation of the actual object. The precision of the 3D data is dependent not only on the particular laser scanner you use, but also the software and algorithms that are used during the various steps that are necessary to generate a final model, as well as your levels of expertise in performing each step. Additional modeling procedures such as hole-filling and smoothing will often result in a 3D model that is better for visualization and analytical purposes, and may in fact also be a more accurate numerical representation of the actual object. For example, if the sampling error of the depth measurements from the surface is truly random, then the acquired points will tend to always fall around the actual surface rather than directly on it. This will result in a modeled surface that appears rougher (or "noisier") than the actual surface. By applying a smoothing algorithm to the acquired point data, the sampling error is averaged out, resulting in a modeled surface that more accurately represents the actual surface.

When unsure, however, run experiments to empirically determine how any scanning or modeling procedures you are using are affecting the 3D model and the measurements being derived from it. For instance, scan the same object multiple times and calculate the same measurement from the resulting 3D models. You will immediately discover how precise your selected measurement is relative to your acquisition and measuring procedures, and you can use this information to determine whether the measurement will be useful in the selected comparative context. The comparative context is an important distinction that separates the use of laser scanning for typical biological research rather than for reverse engineering purposes. In the latter, the goal is often to produce a replica that is as close as possible to the original; therefore, the laser scanned 3D data must be simultaneously precise and accurate. However, because variation is pervasive in biology, accuracy in measurement is often more critical than precision. For example, in biological research it is often less important to determine precisely that the area of a specific surface of one individual is exactly $10.03 \pm 0.01\,\mathrm{cm}^2$, and more important to determine that the mean areas of a surface differ significantly between two or more groups. In other words, measurement errors should be random and proportionately small enough not to have a significant effect on the overall accuracy of the results.

Using Laser Scanned 3D Data

As if choosing an appropriate laser scanner and then figuring out the best scanning protocol were not challenging enough, the biggest hurdle facing individuals who want to incorporate laser scanning into their research is working out what to do after they have acquired their 3D models. Just as there are a variety of laser scanners available on the market, there are also countless commercial software programs and

applications to work with laser-scanned 3D data. Unfortunately, there is no one-size-fits-all category for 3D software either. Therefore, for those interested in biological research, most often the only solution involves serious compromise.

Commercial 3D software is invariably geared toward the reverse engineering or computer animation markets. While many of these are extremely powerful programs, none have been designed specifically with the biological researcher in mind. This is not surprising given the fact that Hollywood production and automobile manufacturing companies have considerably bigger operating budgets than your typical biological researcher. How should the researcher face this challenge? My general advice on this matter is to become familiar with as many 3D programs as possible. In other words, try to diversify as much as you can. Note also that I use the word "familiar" rather than "expert." By familiar I mean that you are capable of opening and saving a 3D file within the software environment, and that you are comfortable navigating through some of the specific options available in that environment. You will soon discover that every program has different capabilities and some are better suited for certain tasks over others. As an example, some researchers have been very successful in using geographic information system (GIS) software to analyze their laser-scanned 3D models (Ungar and Williamson 2000; M'Kirera and Ungar 2003; Ungar and M'Kirera 2003; Ungar 2004). For your own research needs, do not be surprised if you find yourself using multiple programs. In fact, mixing and matching to best suit your research needs will enable you to capitalize on the strengths of each program while avoiding particular weaknesses.

In order to use various 3D programs, you will need to become familiar with multiple 3D file formats and their corresponding three-letter extensions (e.g., .stl, .obj, etc.). Do not let the barrage of file formats available intimidate you. In most cases, these different file formats are simply different ways of organizing the various components of a 3D model in a textual form. Remember that a 3D model is a numerical description of an object. Exactly how this numerical description is written down as textual data corresponds to a file format (Fig. 4.3). A basic 3D model consists of *x*, *y*, *z* coordinate data only. Thus, written as text, such a 3D model is simply a list of the numerical values for each coordinate. More complex 3D models must include text that describes additional model information such as faces, normals, and sometimes even texture (Fig. 4.4). As you may imagine, there is more than one way of listing all of this information as text, and different 3D file formats represent different ways of accomplishing this task. Sometimes the only major difference between two types of 3D file formats is how information is listed in the header, which is simply text that appears above the actual numerical description.

It is important to recognize exactly what model information each 3D file format contains, so that you understand what data are lost when you convert from one format to another. For example, if you take any polygonal 3D file format (e.g., .stl, .obj, .ply, etc.) and save the file as a point cloud or vertex only file, then you will lose all of the information except for the *x*, *y*, *z* coordinate values. If you do not know how a particular file format is organized, try opening the file using a simple text editor, such as Notepad or Wordpad, or search the Internet for documentation on the specific file structure. Knowing the structure of the file format allows you to either

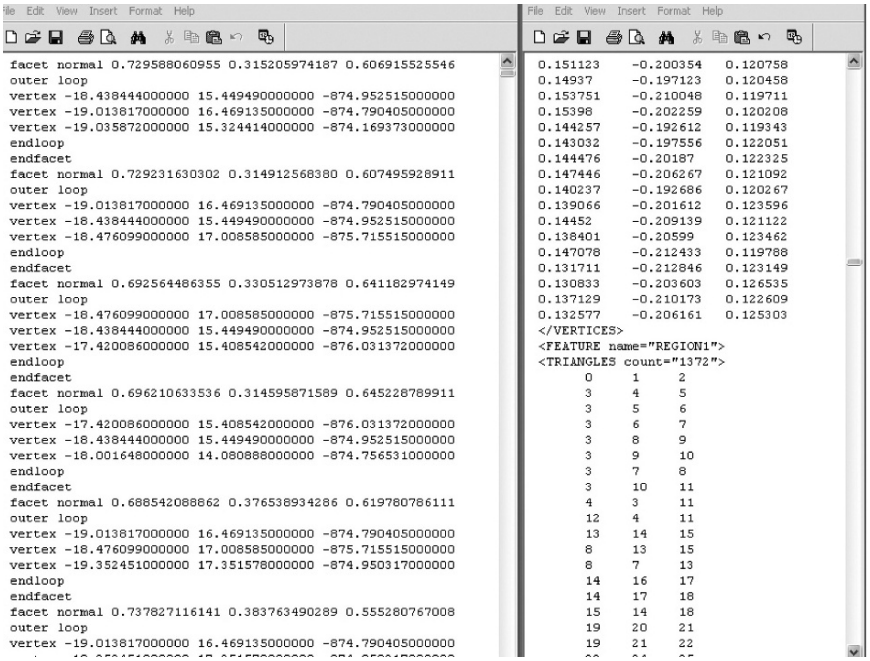

Fig. 4.3 Two examples of how 3D data is stored as a text file. On the *left*, each triangle is described by listing each vertex (i.e., point) that belongs to it as well as its normal vector. Note that each vertex belongs to more than one triangle. On the *right*, the file consists of an ordered list of vertices followed by a list of the vertices that together form triangles. Note that this structure also indicates which triangles belong to a given region of the 3D model by listing the triangles within a "FEATURE" name

write your own analytical routines using programs such as MATLAB, or to better communicate exactly what you are trying to accomplish using your 3D models to programmers you collaborate with. The bottom line is that it is a good idea to always have a clear understanding how the raw 3D data of your models directly relate to the metrics you are interested in quantifying.

Putting All the Steps Together

There are now many examples of laser scanning being utilized in biological research, including forensics (Park et al. 2006), medicine (Byrne and Garcia 2007; Da Silveira et al. 2003; Hennessy et al. 2005; Wettstein et al. 2006), and physical anthropology (Aiello et al. 1998; M'Kirera and Ungar 2003; Tocheri et al. 2003, 2005, 2007; Ungar 2004; Ungar and Williamson 2000; Ungar and M'Kirera 2003). A majority of the studies that have been published or presented at meetings thus far, however, still principally deal with the potential applications of laser scanning to their respective biological discipline. I think it is safe to say that laser scanning is a useful

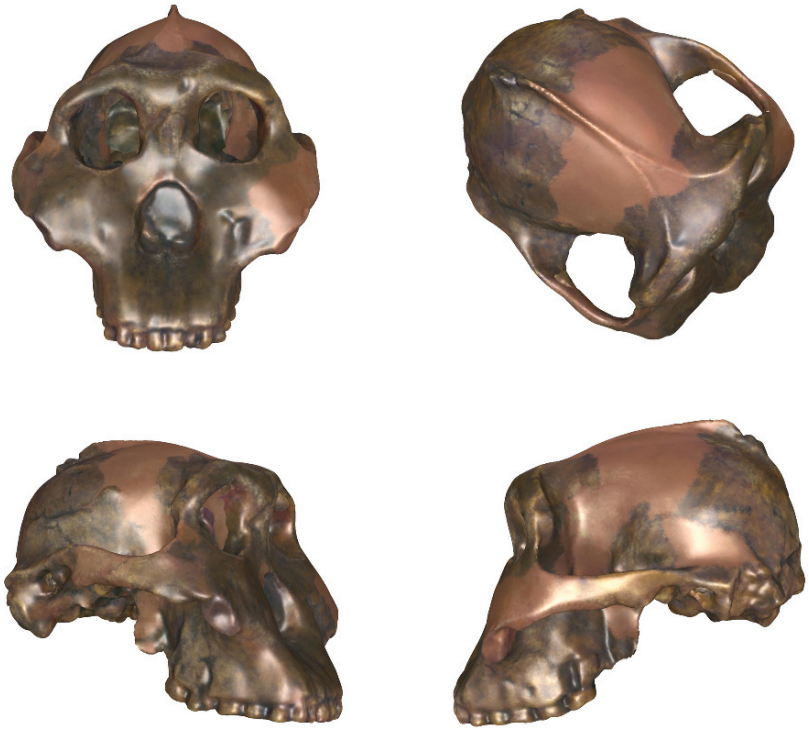

Fig. 4.4 Many laser scanners are also capable of acquiring texture information in addition to the geometry of the object. The texture data are superimposed onto the geometry, enhancing the visualization experience. Shown here are four views of laser scans of a cast of OH 5, a fossil cranium belonging to the extinct hominin species *Paranthropus boisei*. Note that the texture information provides additional surface detail (e.g., the lighter brown areas indicate which parts of the fossil were reconstructed)

technology that has incredible potential for different areas of biological research, but the onus falls on interested students and researchers to more fully develop the ways in which they use this technology to answer specific research questions. Since the primary readers of this chapter probably have little or no experience working with laser scanners and laser-scanned data, it is probably useful to provide a brief overview of my own experiences with using laser scanning in biological research.

My first introduction to laser scanning occurred in 2001 when I was a first year graduate student in physical anthropology at Arizona State University (ASU). I attended a public seminar that summarized how researchers from a variety of disciplines at ASU were using methods such as laser scanning to acquire 3D data for research purposes. I was immediately struck by the idea of transforming real world objects into digital information that could then be visualized and analyzed using computers. To make a long story short, I arranged to see one of these laser scanners in action and very quickly made the decision that I wanted to incorporate this technology into my graduate student research.

As a physical anthropologist, I was initially interested in using laser scanning to acquire 3D models of human skeletal material with the goal of developing methods to better quantify biological variation. This interest soon expanded into a larger evolutionary framework wherein I wanted to quantitatively compare the skeletal morphology between humans and our closest living relatives, the great apes. Such comparative data could then be used to evaluate the morphology of fossil hominids (extinct members of the human–great ape family Hominidae) in both a functional and evolutionary context.

I began to brainstorm about what laser scanning was giving me (i.e., 3D coordinate data and resulting surface representation) and how I could use it to calculate metrics that would capture shape differences. I now recognize this brainstorming stage as a critical step that everyone must perform if they want to use laser scanning successfully in their research. It is imperative that you figure out exactly how the data you want to collect from your laser scans relate to the data your laser scanner gives you. Remember that your 3D model is a numerical representation and that any metric you try to quantify from it is some function of the numbers behind the model. For example, if your laser scanner gives you a triangular mesh, then you can quantify the surface area of the mesh (or any portion thereof) by summing the areas of each included triangle.

For my dissertation research, I investigated shape differences in wrist anatomy between humans, great apes, and fossil hominins (Tocheri 2007). As part of this research, I laser scanned 1,250 hand and wrist bones from more than 300 individuals. After I had acquired my study sample of 3D models, my goal was to quantify two aspects of wrist bone shape that could be measured because of the numerical properties of each model. The two selected metrics were the relative areas of each articular and nonarticular surface, and the angles between articular surfaces.

In order to generate these two metrics, I first needed to identify which points belonged to each articular and nonarticular area. There are many commercial 3D programs that allow you to select and label particular regions of a model, and there are also particular 3D file formats (e.g., .obj) that will retain region information within the file structure (see Fig. 4.3). In other words, I was able to transform each initial 3D model into a segmented 3D model. The former consisted of an unorganized list of x, y, and z coordinate values and the triangles to which each coordinate belonged, whereas the latter added to which articular or nonarticular region each coordinate and triangle belonged.

Using these segmented 3D models, surface areas of the mesh were quantified by summing the areas of each included triangle. I calculated relative areas by dividing each articular or nonarticular area by the surface area of the entire bone, resulting in scale-free shape ratios (Jungers et al. 1995; Mosimann and James 1979). To quantify the angle between two articular surfaces, a least-squares plane was fit to each articular surface by performing a principal components analysis on the coordinates of each surface. Each angle was calculated as 180° minus the inverse cosine of the dot product of the normal vectors of the two respective least-squares planes (note the eigenvector associated with the smallest eigenvalue is the normal vector of each least-squares plane). Notice that both of these metrics relate specifically to the

surface information acquired by laser scanning and are easily quantified because of the numerical properties of a 3D model.

Using these two metrics, I was able to statistically demonstrate major quantitative shape differences in wrist bone morphology between humans and great apes (Tocheri 2007; see also Tocheri et al. 2003, 2005). Moreover, these multivariate analyses demonstrated that Neandertals and early humans show wrist bone shapes that are characteristic of modern humans, whereas earlier hominins, such as species of *Australopithecus* and early *Homo*, show wrist bone shapes characteristic of African apes (Tocheri 2007). After my dissertation, this comparative dataset became a critical component of a collaborative study on the wrist remains of *Homo floresiensis* (Tocheri et al. 2007)—the so-called "hobbits" of hominin evolution.

One of the potentials of incorporating laser scanning in biological research involves the ability to combine a statistical evaluation of biological shape properties along with simple yet extremely informative visualization techniques for sharing the analytical results. It is this particular potential that I and my collaborators used to demonstrate that LB1, the holotype specimen of *Homo floresiensis*, retains wrist morphology that is primitive for the African ape–human clade (Fig. 4.5). For example, Fig. 4.5 shows our comparison of the trapezoid, the wrist bone situated directly proximal to the index finger. Each row corresponds to a particular view of trapezoid

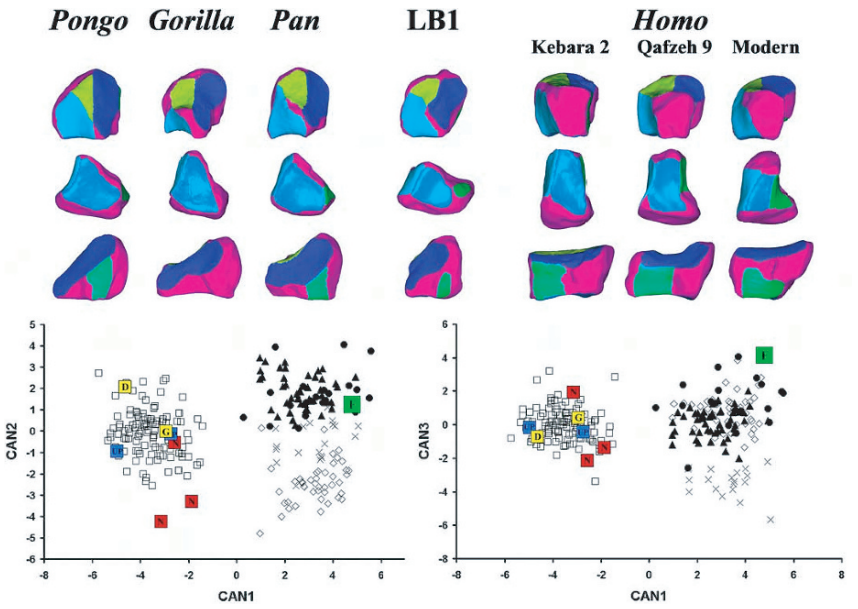

Fig. 4.5 Results of a comparative analysis of trapezoid morphology in modern and fossil hominids using laser-scanned 3D models. *Above*: each row corresponds to a particular view of trapezoid anatomy obtained using the segmented 3D models that illustrate the different articular and nonarticular surfaces that were quantified in the analysis. *Below*: the results of the statistical analysis are summarized in canonical plots generated from a quantitative comparison of the relative areas and angles (see Tocheri et al. 2007 for the full caption)

anatomy using laser-scanned and segmented 3D models that illustrate the different articular and nonarticular surfaces that were quantified in the analysis. Below the visual comparison of the segmented 3D models, the results of the multivariate statistical analysis are summarized in canonical plots generated from the quantitative comparison of the relative areas and angles. Without laser scanning and the ability to work with and analyze the resulting 3D models, a figure such as this, which effectively and succinctly summarizes years of research, would not be possible. The surface visualization informs the statistical analysis and vice versa.

This is only a single example of what can be done with laser-scanned models in biological research, but I hope it helps illustrate the main theme of this chapter: if you want to incorporate laser scanning into your research, be prepared to think creatively and critically at every stage of the process, from initial data acquisition to analysis and presentation of the results.

Summary and Conclusions

In this chapter, I have reviewed some basic concepts, including what laser scanning is, why it should be used for biological research, how to choose a laser scanner, how to use a laser scanner to acquire 3D data, and what to do with the 3D data after they have been acquired. In my experience, these are the kinds of questions that students and researchers most often ask when they are first introduced to laser scanning. My answers to these questions should be used as a rough introductory guide to help interested students and researchers make decisions relating to laser scanning and their short and long-term research goals.

There are many practical challenges surrounding laser scanning that relate to equipment and software availability and capability, but these can often be overcome with imaginative and creative solutions. However, do not make the mistake of thinking that laser scanning will solve all of your research objectives. Always keep in mind that laser scanning, like pool, often looks a lot easier than it is. Unless you are willing to dedicate a significant portion of your research time and effort to solving the many curves that laser scanning will throw at you, then it will probably not serve the purpose you hope it will. If, on the other hand, you are willing to put in the necessary time and effort it takes to respond to the many challenges involved in incorporating laser scanning into biological research, then it can be highly rewarding and effective method for accomplishing your research objectives.

References

Aiello L, Wood B, Key C, Wood C (1998) Laser scanning and paleoanthropology: an example from Olduvai Gorge, Tanzania. In: Strasser E, Fleagle J, Rosenberger A, McHenry H (eds) Primate locomotion. Plenum, New York, pp 223–236

Bernardini F, Rushmeier H (2002) The 3D model acquisition pipeline. Comput Graph Forum 21:149–172

Besl P, McKay N (1992) A method for registration of 3-D shapes. IEEE Trans Pattern Anal Machine Intell (PAMI) 14:239–256

Byrne PJ, Garcia JR (2007) Autogenous nasal tip reconstruction of complex defects: a structural approach employing rapid prototyping. Arch Facial Plastic Surg 9:358–364

Da Silveira AC, Daw JL, Kusnoto B, Evans C, Cohen M (2003) Craniofacial applications of three-dimensional laser surface scanning. J Craniofacial Surg 14:449–456

Dennis JC, Ungar PS, Teaford MF, Glander KE (2004) Dental topography and molar wear in *Alouatta palliata* from Costa Rica. Am J Phys Anthropol 125:152–161

Hennessy RJ, McLearie S, Kinsella A, Waddington JL (2005) Facial surface analysis by 3D laser scanning and geometric morphometrics in relation to sexual dimorphism in cerebral-craniofacial morphogenesis and cognitive function. J Anat 207:283–295

Jungers WL, Falsetti AB, Wall CE (1995) Shape, relative size, and size-adjustments in morphometrics. Yearbook Phys Anthropol 38:137–161

Kappelman J (1998) Advances in three-dimensional data acquisition and analysis. In: Strasser E, Fleagle J, Rosenberger A, McHenry H (eds) Primate locomotion. Plenum, New York, pp 205–222

M'Kirera F, Ungar PS (2003) Occlusal relief changes with molar wear in *Pan troglodytes troglodytes* and *Gorilla gorilla gorilla*. Am J Primatol 60:31–42

Mosimann JE, James FC (1979) New statistical methods for allometry with application to Florida red-winged blackbirds. Evolution 33:444–459

Park HK, Chung JW, Kho HS (2006) Use of hand-held laser scanning in the assessment of craniometry. Forensic Sci Int 160:200–206

Rowe J, Razdan A (2003) A prototype digital library for 3D collections: tools to capture, model, analyze, and query complex 3D data. Museums and the Web 2003, Charlotte, NC (see http://www.archimuse.com/mw2003/papers/rowe/rowe.html)

Tocheri MW (2007) Three-dimensional riddles of the radial wrist: derived carpal and carpometacarpal joint morphology in the Genus *Homo* and the implications for understanding the evolution of stone tool-related behaviors in hominins. Ph.D. dissertation, Arizona State University, Tempe, AZ

Tocheri MW, Marzke MW, Liu D, Bae M, Jones GP, Williams RC, Razdan A (2003) Functional capabilities of modern and fossil hominid hands: 3D analysis of trapezia. Am J Phys Anthropol 122:101–112

Tocheri MW, Razdan A, Williams RC, Marzke MW (2005) A 3D quantitative comparison of trapezium and trapezoid relative articular and nonarticular surface areas in modern humans and great apes. J Human Evol 49:570–586

Tocheri MW, Orr CM, Larson SG, Sutikna T, Jatmiko E, Saptomo EW, Due RA, Djubiantono T, Morwood MJ, Jungers WL (2007) The primitive wrist of *Homo floresiensis* and its implications for hominin evolution. Science 317:1743–1745

Ungar PS (2004) Dental topography and diets of *Australopithecus afarensis* and early *Homo*. J Hum Evol 46:605–622

Ungar PS, M'Kirera F (2003) A solution to the worn tooth conundrum in primate functional anatomy. Proc Natl Acad Sci USA 100:3874–3877

Ungar P, Williamson M (2000) Exploring the effects of tooth wear on functional morphology: a preliminary study using dental topographic analysis. Palaeontologia Electronica 3 (see http://palaeo-electronica.org/2000_1/gorilla/issue1_00.htm)

Wettstein R, Kalbermatten DF, Rieger UM, Schumacher R, Dagorov P, Pierer G (2006) Laser surface scanning analysis in reconstructive rhytidectomy. Aesthetic Plastic Surg 30:637–640

Zollikofer CPE, Ponce de Leon MS (2005) Virtual reconstruction: a primer in computer-assisted paleontology and biomedicine. Wiley, Hoboken, NJ